AD/A-007 243

T63 ENGINE VIBRATORY CHARACTERISTICS ANALYSIS

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General Motors Corporation

Prepared for:

Army Air Mobility Research and Development Laboratory

January 1975

EUSTIS DIRECTORATE POSITION STATEMENT

This program was one of three contractual efforts undertaken in an initial attempt to define a better engine-airframe-propulsion installation interface. The long-range goal is to provide adequate design and test methods to insure compatibility of the engine and airframe.

Analytical and experimental work was conducted relative to a comparison of engine/airframe vibratory interface design techniques. One analytical method produced satisfactory correlation with test data.

The technical monitor for this contract was Mr. James Gomez, Jr., Technology Applications Division.

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A study of the T63-A-5 engine vibratory environment installed in the OH-58 and OH-6 light observation helicopters is presented in this report. The purpose of the study is to develop a common language for use in engine/airframe (translational) vibration specifications and analyses related to future helicopter programs.

Mobility and modal synthesis techniques for coupled dynamic system analyses are developed. These techniques are then applied to the aforementioned helicopter systems for evaluation. (213)

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Block 20. Abstract - continued.

The mobility approach (using test-generated subsystem mobilities) shows poor correlation with test data. However, the modal synthesis approach (using analytically generated subsystem modal descriptions) shows reasonable correlation.

Recommendations are formulated for the use of the modal synthesis method of analysis as a specification methodology. Form and content of data required of the engine and airframe manufacturers are defined.

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PREFACE

Reported herein are the results of a research study program directed at obtaining a common language for engine/airframe vibration specification. This work was carried out under authorization of Contract DAAJ02-73-C-0019, Task 1G162204AA7201, issued by the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory. This program is an initial step toward specifying requirements for both the airframe and engine manufacturers which would help to ensure dynamic system compatibility.

Presented are the research theory and its application including the free-free shake test results for the T63-A-5 engine. A general list of symbols used in the methodology developments is provided, but specific definitions of symbols are given at the point in the text where they are used.

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INTRODUCTION

The coupled interaction between two or more dynamic subsystems has often been the source of vibration problems. This is particularly true when considering the helicopter as a dynamic system in which excitations can be generated by either the engine or the airframe. The problems of vibration-related interface compatibility in helicopter engine installations are usually complicated by the inherent coupling of the three major multi-degree-of-freedom systems: engine, rotor/drive train, and airframe. One typical inter-active factor which exists involves the selection of engine and drive train mounting to be used. A rigid mounting is desirable to minimize shafting alignment problems, and a soft mounting is desirable to uncouple the vibration of the engine and drive train from themselves and the airframe. The best design is obtained when each of these considerations is mutually satisfied. Achieving an optimum helicopter configuration requires trade-off studies of all the coupled effects of the various dynamic subsystems in the initial design phase.

The general military specification related to turboshaft engine/aircraft systems is Specification AV-E-8593B.[1] In this specification no specific requirements have been placed on either the engine or airframe to ensure dynamic compatibility. It has been required that certain data be made available. Paragraph 3.15.2 of this specification states "The estimated stiffness of the engine in resisting loads and moments applied at the outboard end of the output shaft, relative to the engine mounting points, shall be stated in the Prime Item Development Specification (PIDS). The first "free-free" lateral and vertical engine bending modes shall be specified." This paragraph is obviously intended only to define the engine stiffness in a static sense. Sufficient data are not specified to correctly perform even a simple dynamic compatibility analysis since no mass effects are present. An Aeronautical Design Standard, entitled Propulsion (Engine/Airframe) Interface surveys,[2] has been written by the U.S. Army Aviation Systems Command to serve as an Army specification covering airframe/engine interface surveys. This specification outlines the steps to be followed in developing an acceptable test procedure for submittal to the procuring activities for approval. The procedure is as follows.

a. The engine manufacturer will determine the effective engine masses, inertias, and stiffnesses and their required distribution, and will conduct an analysis to obtain the engine's natural frequencies and bending modes.

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1 ENGINES, AIRCRAFT, TURBOSHAFT, GENERAL SPECIFICATION FOR AV-E-8593B, 13 October 1972.

2 ADS-1, AERONAUTICAL DESIGN STANDARD, PROPULSION (ENGINE/AIRFRAME) INTERFACE SURVEYS, 1 December 1971.

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b. The engine manufacturer will conduct a free-free vibratory test of the engine to obtain the frequency response characteristics, natural frequencies, and mode shapes. These results will be compared with the analysis in Item a., and a determination will be made of the modifications of parameters required to achieve reasonable agreement between calculated and measured values.

c. The airframe manufacturer shall conduct a frequency analysis of the engine installation, taking into account the significant fuselage contributions, to determine the fundamental rigid and flexible-body natural frequencies in the plane(s) of predominant helicopter rotor excitations.

d. The airframe manufacturer shall tabulate and identify the inherent airframe excitation sources and their variations with helicopter rotor speed.

e. The engine manufacturer will review the results from Item c and d, and will identify potential problem areas.

f. The airframe manufacturer shall draft a test plan.

g. The engine manufacturer will review the test plan and either approve the plan or recommend modifications to the procuring activity.

h. The procuring activity will approve the test plan or request a modification.

i. The airframe manufacturer shall conduct the testing defined in the test plan.

This specification is a definite effort to require both the airframe and engine manufacturers to work toward a compatible interface. However, the method to be used in the analysis of the coupled system is not specified. Further, no requirement is made as to the form of the information which must be supplied by each party.

Requirements of this nature are needed to assure consistency in the analytical methodology used for future airframes, and to permit an easy interchange of technical data between airframe/engine designers.

The program presented here involves the study of the T63-A-5 engine installed in two lightweight helicopter designs, the OH-6 and OH-58 light observation helicopters. The primary objective of this program is to establish a common language for engine/airframe translational vibration specification and analysis to be used in future helicopter programs. The approach used to fulfill this basic objective has been to:

- Establish the T63 engine environment for the OH-6 and OH-58 installations
- Determine engine and airframe relative participation in the overall vibratory response
- Develop, investigate, and evaluate analytical procedures for examining coupled engine/airframe dynamics
- Identify those engine and/or airframe parameters affecting the coupled system dynamics
- Formulate recommendations for future helicopter programs

This report discusses the review of available flight data, the acquisition of supplemental data, the development of methods of analysis, and the verification of these analysis methods for the OH-58 and OH-6 helicopters, followed by a presentation of the conclusions and recommendations for future programs.

During the performance of this contract, a total of 320 free-free drive point and transfer mobilities of the T63-A-5 engine were generated. The entirety of these data are not included in this report but are recorded on microfiche and may be obtained from the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia.

REVIEW OF FLIGHT DATA

A thorough search to collect data related to the vibratory characteristics of the T63-A-5 engine installed in the OH-6 and OH-58 helicopter systems has been conducted under this contract and coordinated with Bell Helicopter and Hughes Helicopters. These data were identified and cataloged according to their content and usefulness to this program. Where sufficient data were available, a thorough analysis has been conducted. A review of the data and data analysis are presented for the OH-58 and OH-6 helicopters.

OH-58 FLIGHT DATA

A search of the vibrations files has yielded one applicable report[3] which covers the in-flight dynamics of the T63-A-5 engine in the OH-58 helicopter. This report has been categorized according to:

1. Aircraft mission
2. Instrumentation
3. Form of vibration data
4. Mode shapes
5. General appraisal

These data are included in this report as Appendix A. In general, the T63-A-5 engine vibrational data for the OH-58 helicopter installation is sufficient to define the flight environment for significant portions of the mission profile.

Analysis of the data contained in Reference 1 was performed to accumulate information relative to the definition of the engine environment during flight operation. This information was collected to be used in the analysis method development portion of the program.

The vibration intensity across the mission profile was determined for one representative transducer location. The turbine middle splitline (vertical) transducer was selected as a representative engine vibration. Figure 1 shows the total flight spectrum vibrational distribution for this transducer at the aircraft gross weight of 3000 lb and a forward center of gravity configuration.

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[3] ENGINE INSTALLATION VIBRATION SURVEY OF THE MODEL 206A-1 HELICOPTER, Bell Report 206-099-179, 1969.

The high vibration velocities (over 1.0 in./sec) occur less than 0.5 percent of the flight spectrum. The larger portion of the flight spectrum exhibits the lower vibration velocities. This kind of information may be useful in helping to establish a criterion of acceptance for a particular engine/airframe combination.

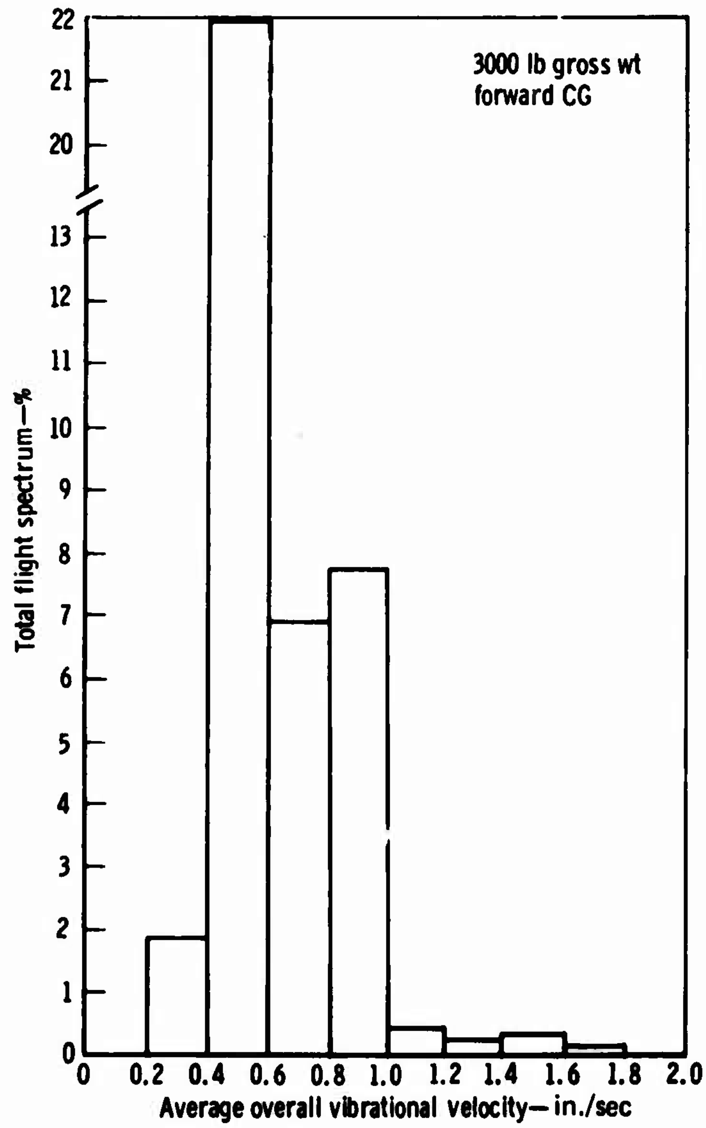


Figure 1. Total Flight Spectrum Vibrational Amplitude Distribution for the Turbine Middle Splitline Vertical Transducer.

The major portion of the OH-58 mission is spent during straight and level flight (60 percent between 0.8 and 1.0 V_h). In addition, the gross weight producing the highest overall vibration levels was found to be 3000 lb with a center of gravity location forward. This configuration was further studied for straight and level flight.

Figure 2 shows a time history plot of the turbine middle splitline vertical and lateral vibration velocity for various straight and level flight velocities. In general it can be seen that the vibration velocity increases with airspeed. A discrete frequency analysis of the V_h and V_{ne} airspeeds for the turbine middle splitline vertical transducer is shown in Figures 3 and 4, respectively. These plots show the predominant excitation sources for these conditions to be:

- Main rotor 2/Rev
- Main rotor 4/Rev
- Main rotor 6/Rev
- Tail rotor 1/Rev
- Output shaft 1/Rev
- Tail rotor 4/Rev

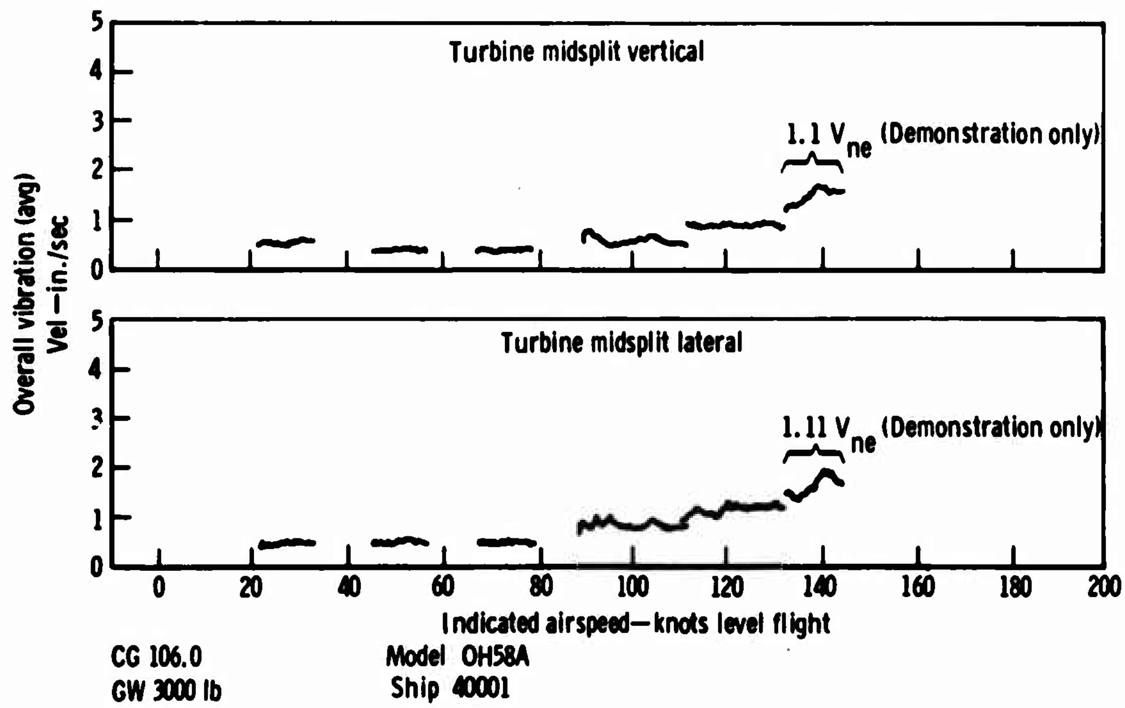


Figure 2. Vibration Time History—OH-58.

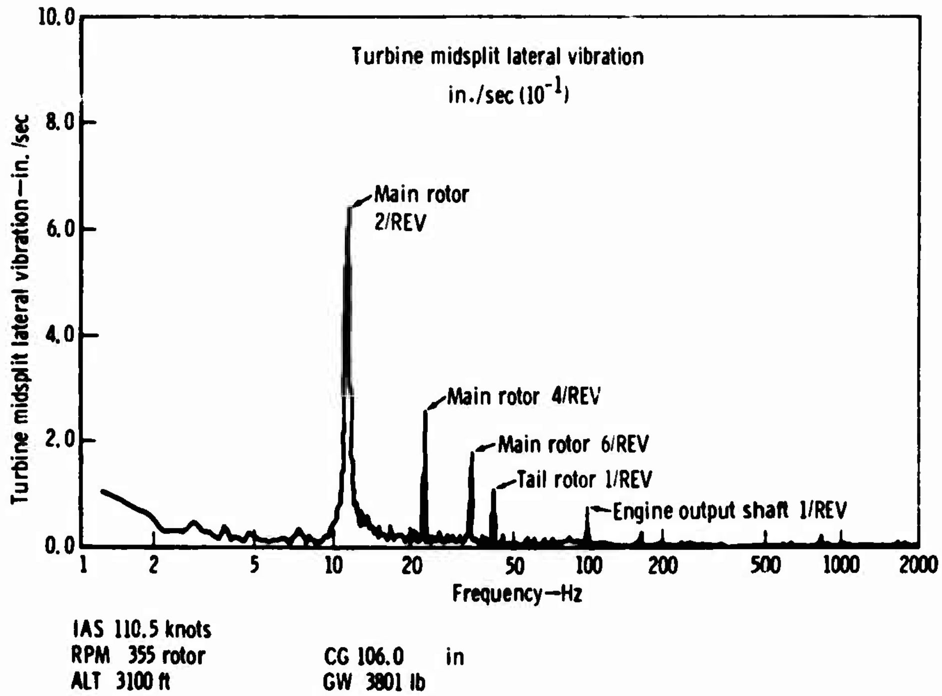


Figure 3. Discrete Frequency Spectra for V_H—OH-58.

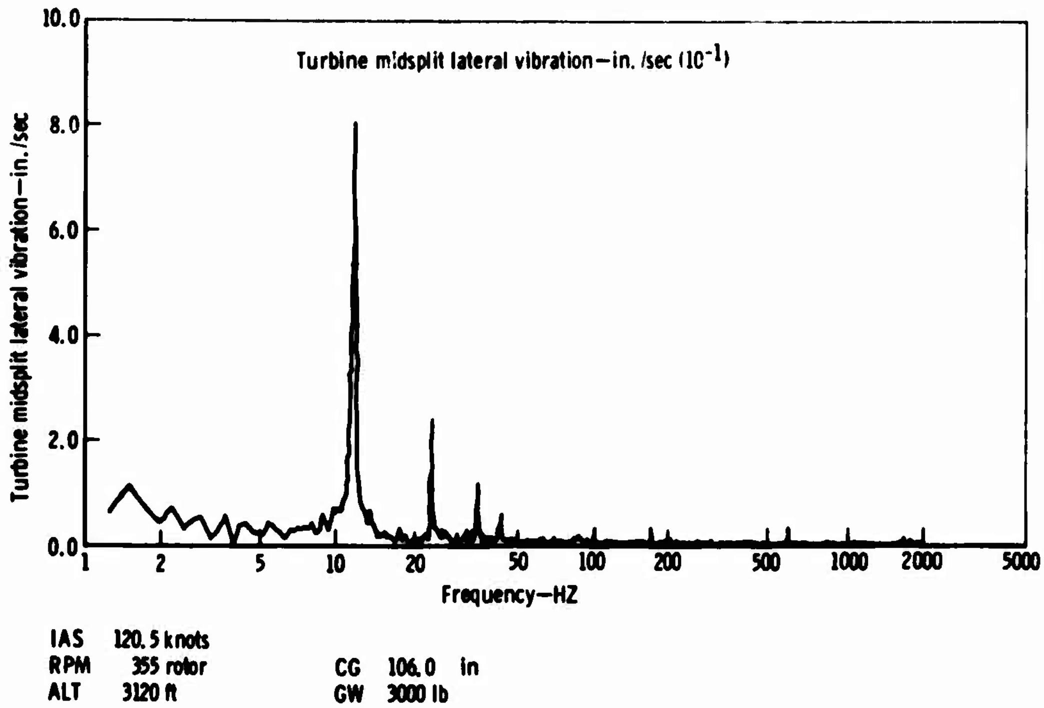


Figure 4. Discrete Frequency Spectra for V_{NE}—OH-58.

- Engine N_{II} 1/Rev
- Engine N_I 1/Rev

They also show that the main rotor is the prime contributor to the vibratory excitation by a large margin. Tables 1 and 2 are listings of the peak velocity responses of transducers located on the engine at various excitation frequencies and forward flight velocities of V_h (110 knots) and V_{ne} (130 knots), respectively.

TABLE 1. DISCRETE FREQUENCY VIBRATIONAL VELOCITY RESPONSE FOR VARIOUS ENGINE TRANSDUCER LOCATIONS AT A FLIGHT VELOCITY OF V_h (110 KNOTS)—(OH-58)

Excitation Frequencies—Hertz		Main Rotor					Tail Rotor		Output Shaft		N_{II}	N_I
		5.9	11.8	23.6	35.4	47.2	43.8	87.6	103.0	206.0	590	800
Turbine Midsplit	Y	—	0.68	0.25	0.22	0.03	0.07	0.03	0.07	0.02	0.01	0.02
	Z	0.03	0.20	0.08	0.30	0.03	0.10	0.02	0.02	--	0.05	0.07
Forward Compressor	Y	0.02	0.58	0.11	0.14	0.02	0.03	0.04	0.08	0.05	0.05	0.11
	Z	0.02	0.23	0.10	0.36	0.14	0.04	0.02	0.05	0.04	—	0.02
Igniter	Y	0.02	0.84	0.35	0.55	0.07	0.14	0.04	0.19	0.06	0.12	0.25
	Z	0.02	0.15	0.15	0.66	0.10	0.20	0.04	0.06	0.08	0.18	0.12
Top Gearbox	Y	0.02	0.26	0.10	0.30	0.07	0.08	0.04	0.08	0.04	0.12	0.34
	Z	—	0.23	0.05	0.04	0.05	0.04	0.02	0.06	0.02	0.01	0.04

TABLE 2. DISCRETE FREQUENCY VIBRATIONAL VELOCITY RESPONSE FOR VARIOUS ENGINE TRANSDUCER LOCATIONS AT A FLIGHT VELOCITY OF V_{ne} (130 KNOTS)—(OH-58)

Excitation Frequencies—Hertz		Main Rotor					Tail Rotor		Output Shaft		N_{II}	N_I
		5.9	11.8	23.6	35.4	47.2	43.8	87.6	103.0	206.0	590	800
Turbine Midsplit	Y	0.02	0.90	0.21	0.07	0.01	0.05	0.02	0.02	0.01	0.01	0.05
	Z	0.02	0.52	0.16	0.27	0.05	0.10	0.02	0.09	0.01	0.04	0.08
Forward Compressor	Y	0.02	0.78	0.10	0.10	0.03	0.10	0.03	0.03	0.06	0.03	0.11
	Z	0.03	0.37	0.18	0.37	0.12	0.03	0.01	0.06	0.05	0.03	0.03
Igniter	Y	0.08	1.16	0.34	0.27	0.04	0.10	0.04	0.02	0.04	0.04	0.36
	Z	0.03	0.49	0.32	0.65	0.13	0.22	0.06	0.28	0.04	0.02	0.16
Top Gearbox	Y	0.02	0.28	0.18	0.17	0.09	0.09	0.02	0.06	0.04	0.06	0.28
	Z	0.06	0.33	0.08	0.04	0.05	0.03	0.02	0.03	0.01	0.01	0.02

The final aspect of this analysis would have been to determine the mode shape of the response peaks. However, sufficient airframe and engine data were not present to accomplish this.

OH-6 FLIGHT DATA

A search of the vibration files has yielded one applicable report which provides T63-A-5 engine vibratory information during flight operation. This report[3] has been categorized according to:

1. Aircraft mission profile
2. Instrumentation
3. Form of vibration data
4. Mode shapes
5. General appraisal

These data are included in this report as Appendix B. In general there is only minimal data related to the OH-6/T63 vibratory environment during flight operation. However, there is sufficient discrete frequency information at one flight condition. This data, at a flight condition of 126 knots, straight and level, and an altitude of 5000 feet, points out the predominant excitation sources as:

- Main rotor 1/Rev
- Main rotor 4/Rev
- Tail rotor 1/Rev
- Tail rotor 2/Rev
- Output shaft 1/Rev
- Engine N_2 1/Rev
- Engine N_1 1/Rev

Table 3 is a listing of the peak velocity responses of transducers located on the engine at various excitation frequencies.

FUTURE PROGRAMS—REQUIRED DATA

Recommendations for types of data that should be obtained through aircraft/engine tests follow. These data are needed to fulfill the desired objectives of future study programs of the type presented in this report. The recommendations will be covered by describing the entire data package required to determine airframe/engine compatibility.

3 INSTALLATION SURVEY OF YT63-A-5 ENGINE INSTALLED IN HUGHES OH-6A AIRCRAFT. DDA Report 64B19, April 1964.

TABLE 3. DISCRETE FREQUENCY VIBRATIONAL VELOCITY RESPONSE FOR VARIOUS ENGINE TRANSDUCER LOCATIONS AT A FLIGHT VELOCITY OF 126 KNOTS—(OH-6)

		Main rotor		Tail rotor		N_{II}	N_I
		8.0	32.0	50.0	100.0*	590	800
Turbine Midsplit	Y	0.4	---	---	0.6	---	---
	Z	0.4	0.5	---	0.4	---	0.35
Forward Compressor	Y	0.25	0.7	---	0.6	---	0.35
	Z	0.5	1.2	---	0.9	---	0.2
Igniter	Y	---	---	---	---	---	---
	Z	---	---	---	---	---	---
Top Gearbox	X	0.25	0.65	---	---	---	0.5
	Z	---	---	---	---	---	---

*This is the output shaft speed also.

To fully evaluate the dynamics of the coupled airframe/engine system the data must necessarily be gathered during often-encountered flight conditions (i.e., 80 to 100 percent V_h) as well as the high transient vibration conditions (i.e., full autorotational landing). These data are needed to determine the vibratory environment of the installation, and to provide a basis for evaluating the various methods of compatibility analysis which are available.

The environmental data is used to:

1. Determine the amount of vibration the engine experiences at various critical transducer locations.

2. Determine the sources of vibratory excitation for various vibration peaks.

3. Determine the mode of vibration for various vibration peaks.

To satisfy these uses it is necessary that sufficient time history recordings of data from the selected engine and airframe vibration transducer locations be collected. These data must then be analyzed to determine the amplitude-frequency spectra. This discrete information can then be used to locate the predominant excitation sources. The time history data can further be phased to determine the vibratory response mode shapes, and thereby define the relative participation of the airframe and engine to the response.

Some additional data are required to verify any compatibility analysis. To predict the aircraft environment it is necessary to characterize excitation forces (amplitude and phase). These data can in part be obtained by instrumenting the mast with strain gages and providing load cells at the interface points.

These data, some of which are available in this program, are required to adequately study the dynamic compatibility between engine and airframe. Table 4 summarizes the data needed for a thorough compatibility analysis and evaluation. The available data on the OH-58 and OH-6 helicopters are denoted by the letters "B" and "H", respectively. A recommendation for a future program of the type presented in this report is to provide the information shown in this table.

TABLE 4. SUMMARY OF REQUIRED COMPATIBILITY DATA

Data Required	Straight and Level Flight (0.8-1.0 V_h)	Full Autorotational Landing
Time history recording of airframe and engine transducers	B[1]	B[1]
Amplitude-frequency spectra[2]	B H	
High response mode shapes[2]		
Excitation Amplitude Mast Forces Tail Forces Interface Forces		

[1]Data on plots.

[2]These data can be derived from the time history recordings.

SUPPLEMENTAL DATA ACQUISITION

To provide sufficient data to be used in this study, it was necessary to generate additional information relative to the vibratory characteristics of the engine/airframe combinations under consideration. For this program, the OH-6 and OH-58 helicopters, both powered by the T63-A-5 engine, were considered. Since the powerplant is the responsibility of the engine manufacturer, a laboratory shake test was designed and conducted at Detroit Diesel Allison to provide the necessary T63-A-5 engine vibration data. A definition of the test and description of the setup are followed by discussions of the test procedure and some pertinent observations. The test results and subsequent mode shape analysis complete the presentation.

The test objective was to experimentally determine the free-free drive point and transfer mobilities at the interface points and the free-free transfer mobilities at vibration measurement points by vibrating a T63-A-5 engine along three mutually perpendicular axes at each of the interface points. The accumulated data were to be displayed as analog plots of mobility amplitude and phase versus the excitation frequency with accompanying digital processing.

Since these data were to be used to study helicopter vibratory characteristics during flight operation, it was desirable to generate the engine mobilities under engine operating conditions (i.e., with the engine rotating). However, a laboratory shake test for an operating engine was beyond the scope of this study program. It was decided the test would be conducted with a nonrotating gas generator and power turbine.

TEST DEFINITION

A comprehensive laboratory shake test program was defined and developed through coordination with other users of the data—Bell Helicopter and Hughes Helicopters. An effort was made to generate sufficient data to satisfy the requirements of all candidate methods under consideration. The method which controlled the test definition was the mobility method of analysis. Data requirements for the other methods are a subset of those for the mobility method. This approach requires as input the driving point and transfer mobilities at each interface connection point and transfer mobilities at each point on the engine where responses are of interest. Both the OH-6 and OH-58 helicopter installations connect to the engine at three mount points (engine right, left, and lower mount pads) and the engine output shaft. Driving point and transfer mobilities are required at these interface points. In addition, the points of vibration measurement on the engine are specified on the T63 engine installation drawing (DDA drawing number 6850000). Since these points of measurement are of interest in a vibration survey, it is necessary that their transfer mobilities be obtained.

TEST SETUP

The vibration testing was conducted at the DDA vibration facilities in Indianapolis, Indiana. A description of the setup for this testing follows.

The engine used in the testing was a T63-A-5 engine (S/N 402279A) furnished by the Army. Since this was a bare engine, accessories were acquired from the DDA Test Project Department and installed. The resulting engine test gross weight was 158.25 pounds. The general arrangement and overall dimensions of a similar model are given in Figures 5 and 6, respectively.

The engine was suspended by flexible elastic cords to allow unrestrained normal mode response. This suspension system is shown in Figure 7.

The shaker equipment used to supply and control the input forces are:

- MB force generator, Model C10, rated at ±1200 pounds peak (initial experiments used Endevco force generator, Model 2953, rated at ±1.5 pounds peak).
- Endevco impedance head, Model 2110
- Krohn-Hite power amplifier, Model DCA-50A
- Spectral Dynamics sweep oscillator, Model SD104A-5
- Spectral Dynamics Amplitude servo, Model SD105B

The vibration measurements and data processing were accomplished with the following support equipment:

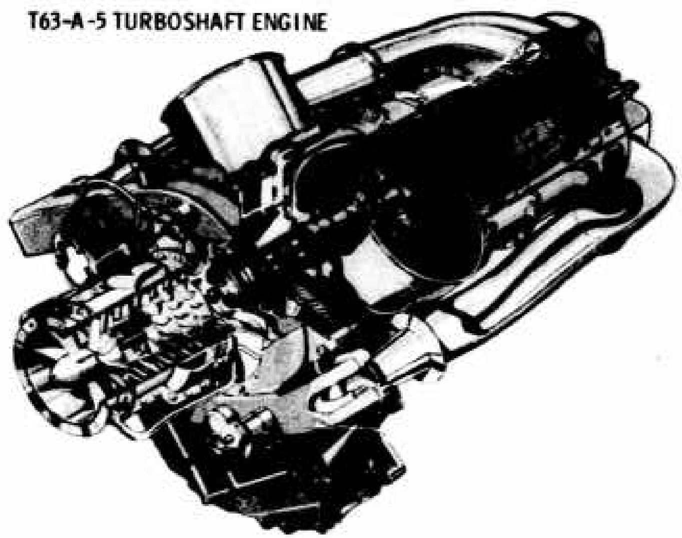
- Endevco accelerometers, Model 2213 and 2226
- Unholtz-Dickie charge amplifiers, Model D11MGV0
- Spectral Dynamics Mz/TFA control, Model SD127
- Spectral Dynamics tracking filter, Model SD121S
- Spectral Dynamics two-channel tracking filter slave, Model SD122
- Spectral Dynamics voltmeter/frequency log converter, Model SD112-1-H
- Hewlett-Packard two pin recorder, Model HP136A-02
- Miscellaneous signal conditioning and monitoring instruments, i.e., voltmeters, amplifiers, oscilloscopes, and electronic counters

In addition to the equipment listed, the DDA data processing facilities were used to record and digitize the analog signals. These data processing facilities are:

- SEL 840 MP computer
- SEL 600 digital data logger
- IBM 370/165

The test fixtures consisted of small steel adapters for coupling the force generator/impedance head assembly directly to the engine at points of airframe mounting.

T63-A-5 TURBOSHAFT ENGINE



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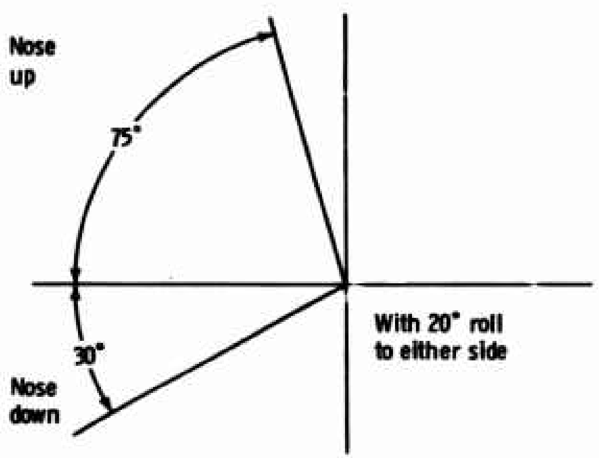

GENERAL ARRANGEMENT

The major engine components are the compressor, the accessories drive gearbox, the turbine and exhaust assembly and the combustion section. The gearbox provides the main structural support of the engine upon which are mounted the other engine components and the engine-driven accessories. Engine mount pads are located on the gearbox, one on each side and one on top and bottom. This general arrangement permits removal and replacement of the major engine components from the installed engine without disturbing the other components.

Six axial stages and a single centrifugal stage with its discharge scroll comprise the compressor section. Compressor discharge air travels aft to the single combustor through two external air ducts. A single fuel nozzle and a single spark igniter are located at the aft end of the combustion chamber. Combustion gases travel forward, expanding through the two-stage gas producer turbine and the two-stage power turbine, and then exit from the engine upward through the dual outlet exhaust duct. The gas producer turbine drives the engine compressor and engine accessories. The power turbine drives the engine output shaft through a two-stage helical gear train which incorporates a hydro-mechanical torque sensor unit. Engine power may be taken from either front or rear splines of the output shaft.

Figure 5. T63-A-5 General Arrangement.

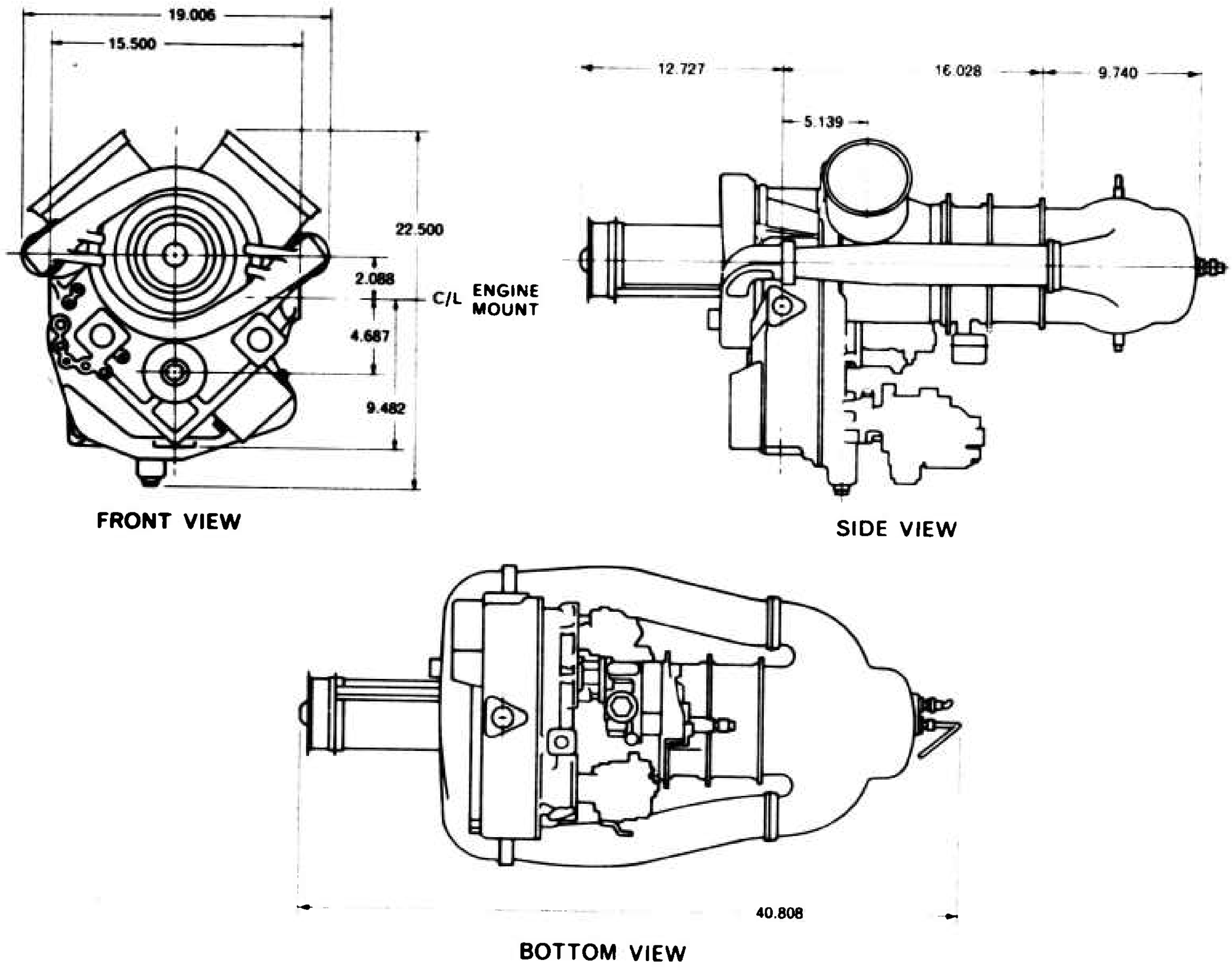

Figure 6. T63-A-5 Overall Dimensions.

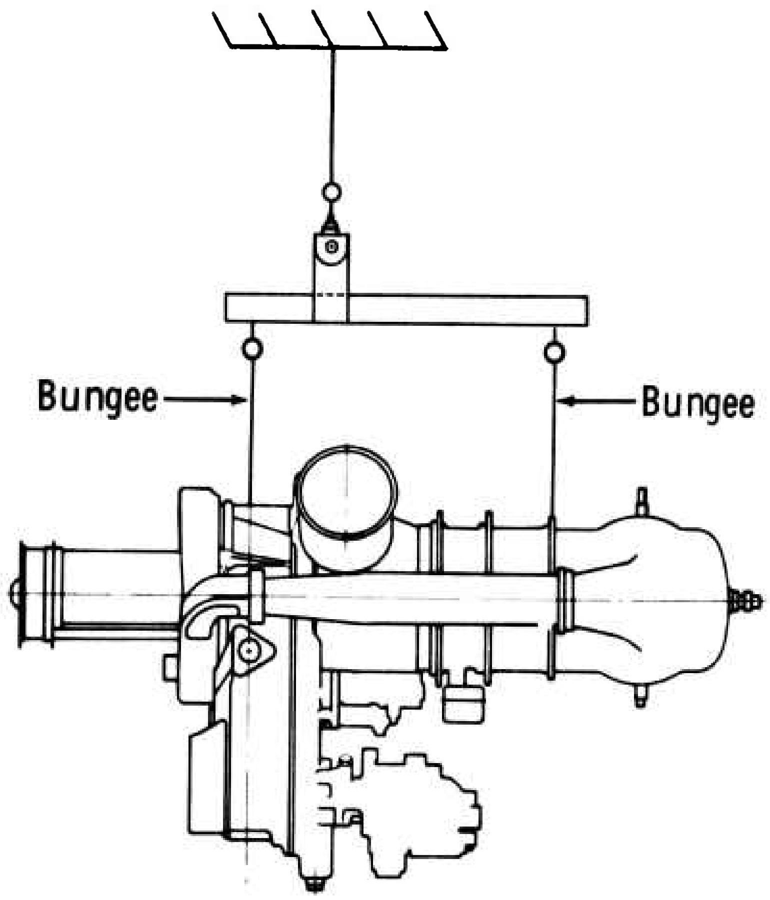

Figure 7. Test Engine Suspension.

The instrumentation and other major test equipment were arranged as shown in Figure 8. The drive point mobility was measured with the impedance head, which incorporates three force transducers and three accelerometers, all in the same plane. The force transducers in the impedance head were used in conjunction with a roving accelerometer to measure transfer mobilities. Simultaneously, with the on-line plotting of the analog mobility signals, the mobility amplitude and phase, along with the frequency, are automatically digitized for digital computer purposes.

The engine setup is presented in Figure 9, showing the T63-A-5 engine, the shaker equipment, and the instrumentation hardware.

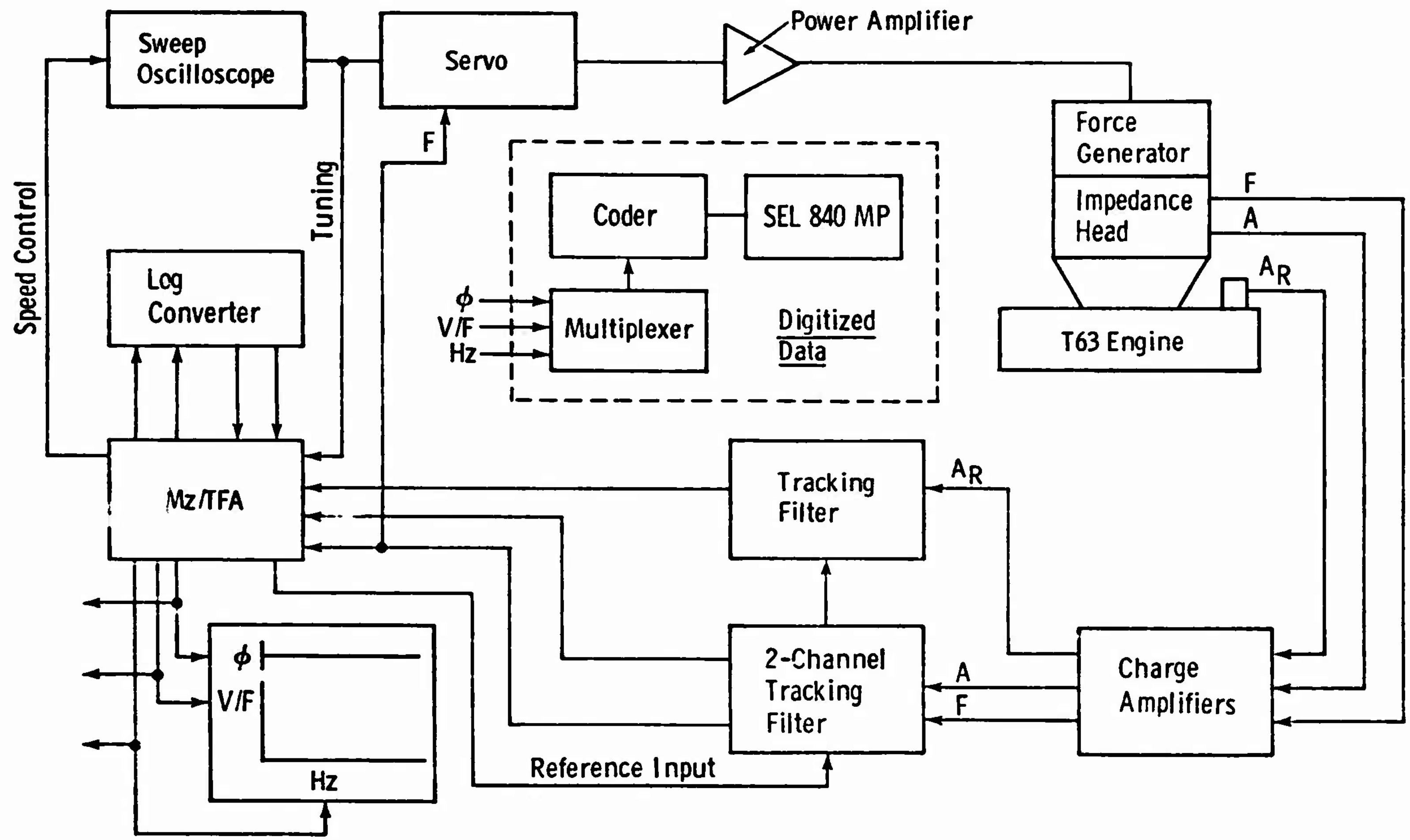

Figure 8. Instrumentation Block Diagram.

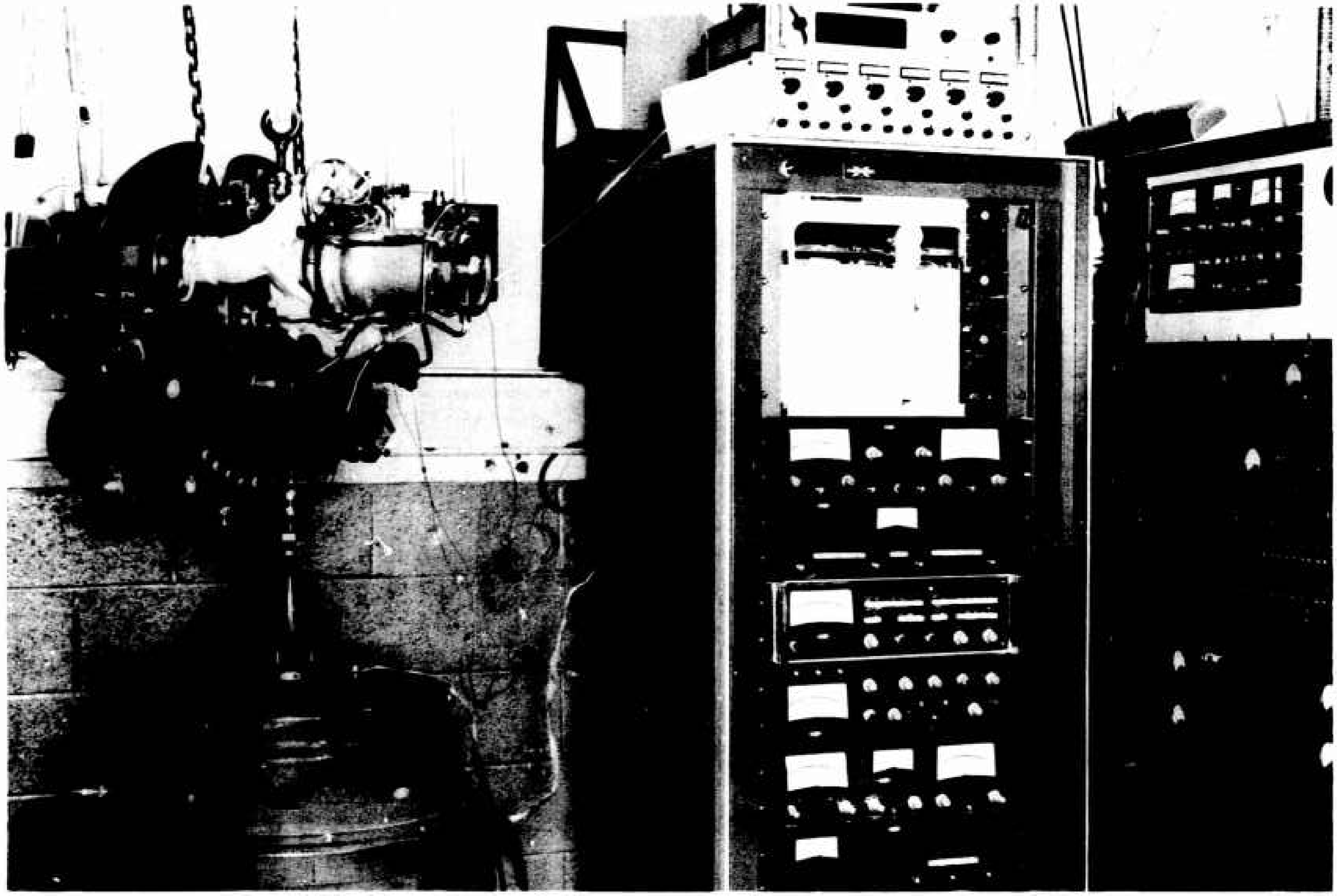

Figure 9. Engine Test Setup.

TEST PROCEDURE

Presented is the test procedure which was followed to obtain the free-free drive point and transfer mobilities of the T63-A-5 engine. Testing has adhered to MIL-STD-810B, Environmental Test Methods, as related to tolerances of test conditions and accuracy of test apparatus per paragraphs 3.1.2 and 3.1.3.

Precision weights and an accelerometer standard were used to calibrate the impedance head and to verify calibration of the Automatic Mechanical Impedance System.* The accelerometer and force gage sensitivities were determined by the comparison method specified by American National Standard Document No. ANS1 (S2-58), proposed for experimental measurement of dynamic mass and mechanical impedance. The analysis system calibration was verified and/or adjusted by exciting the static mass (precision weight) of known value.

Early experiments were conducted at excitation magnitudes ranging from ±1 pound to ±50 pounds. An excitation force of ±5 pounds was selected because vibratory responses on the nonrotating engine were acceptable and mobilities were essentially equal at ±5 pounds and above.

Experiments were also conducted with a very rigid connection between the shaker and impedance head as shown in Figure 10 and with a flexible rod connection as shown in Figure 11. A comparison of these two different connections. showed that the basic mobility profiles were the same except for the amplitudes at resonance and antiresonance. The flexible rod resonances and antiresonances showed a much sharper peak and valley, respectively. Consequently, the flexible drive rod shown in Figure 11 was used to permit maximum unrestrained response of the engine structure.

The engine free-free mobilities were experimentally determined at a constant sinusoidal force of ±5 pounds peak throughout the frequency range of 20 to 2000 Hertz for those responses in the direction of the imposed force and 20 to 500 Hertz for those responses not in the direction of the imposed force. All mobilities were plotted through these frequency ranges. Only the test mobilities through 500 Hertz were digitized.

The mobilities measured were obtained by applying force excitations at the following locations on the engine:

- Left mount fore and aft, lateral, and vertical
- Right mount fore and aft, lateral, and vertical

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*This system, Model SD1002E-42, was leased under this contract from Spectral Dynamics Corporation, San Diego, California, specifically for use in this contract. Subcomponents comprising this system are itemized in the section on test setup.

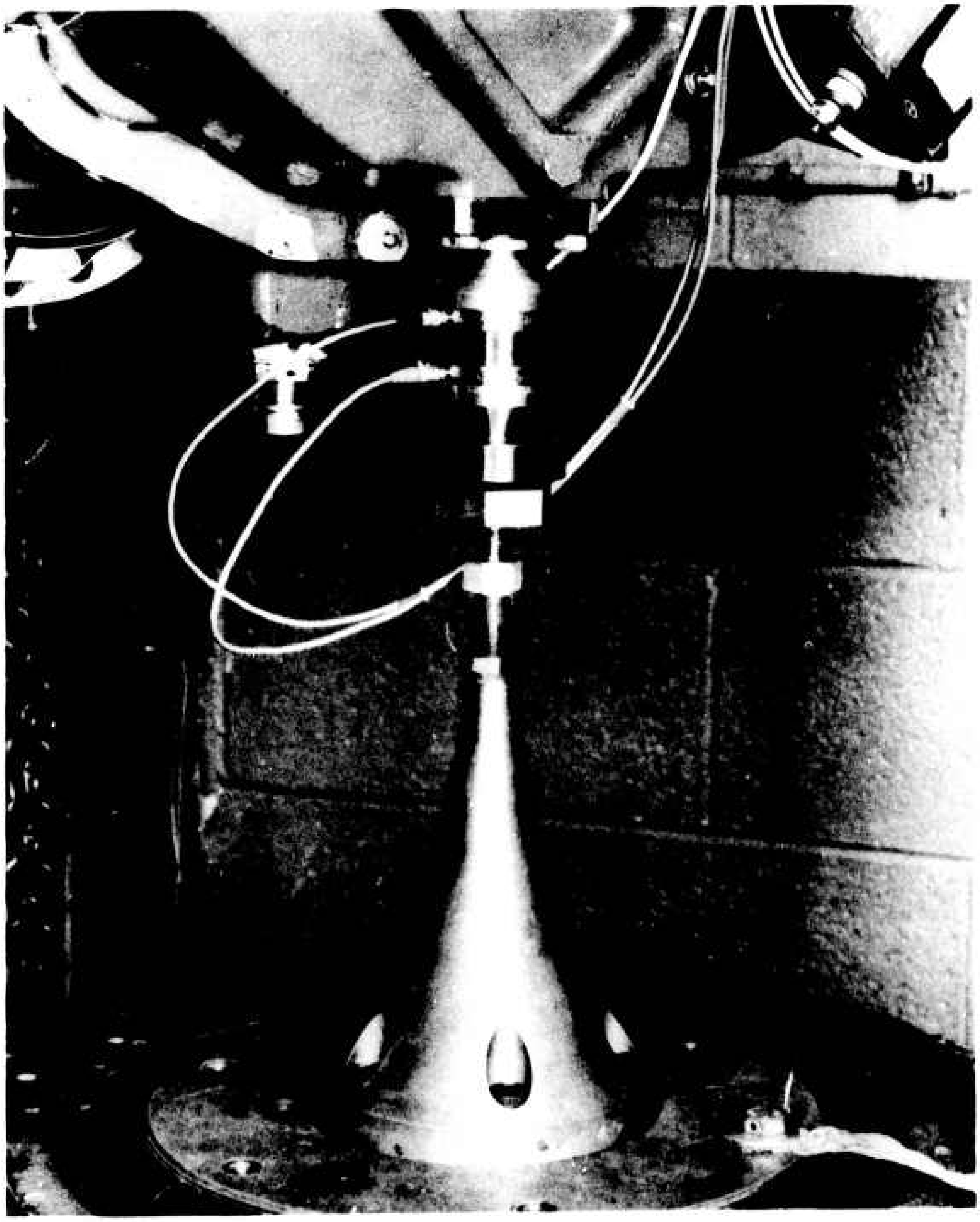

Figure 10. Rigid Connection Between Shaker and Impedance Head.

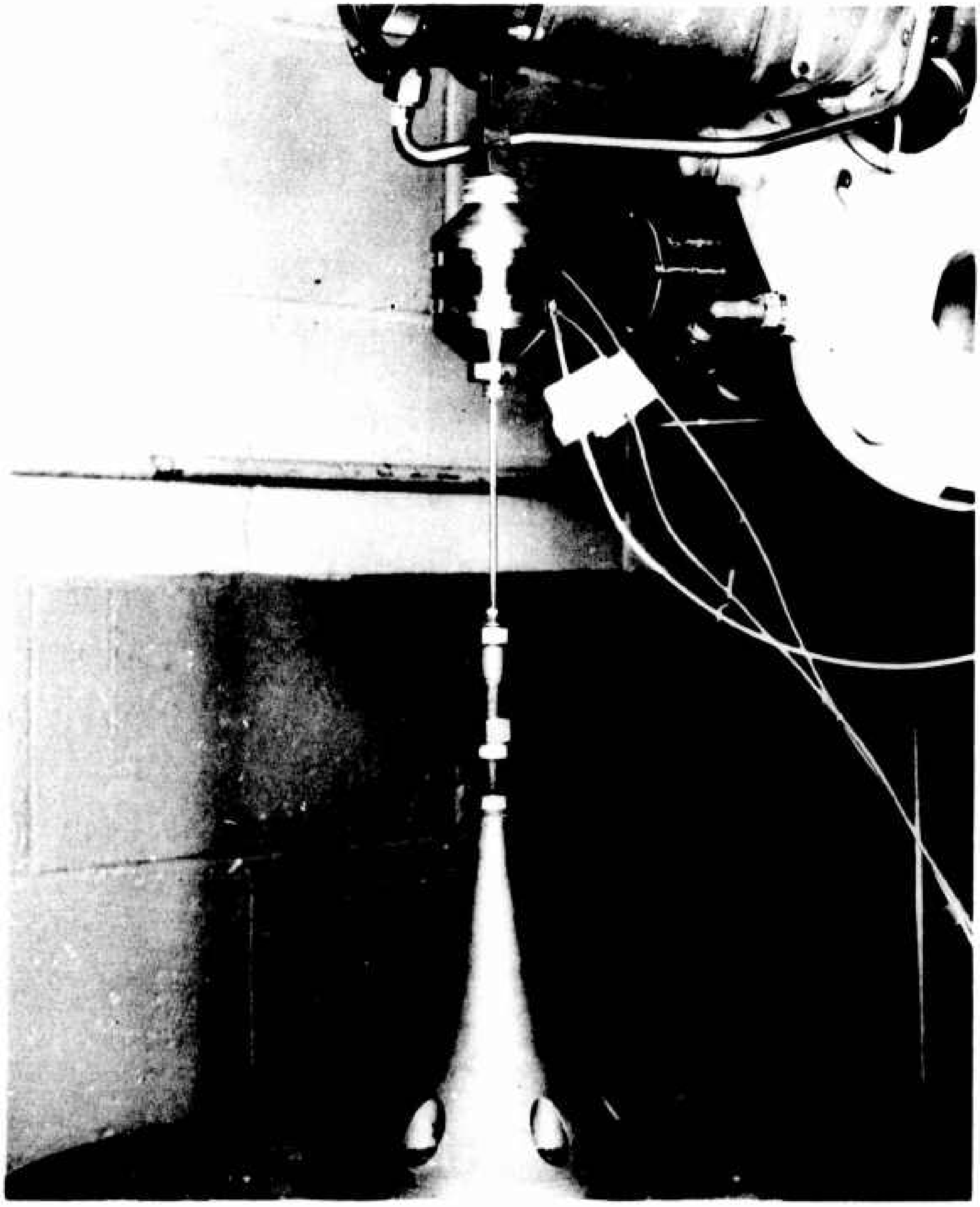

Figure 11. Flexible Rod Connection Between Shaker and Impedance Head.

TABLE 5. T63 ENGINE MOBILITY TEST MATRIX LOG

Excitations	Left mount X 1	Left mount Y 2	Left mount Z 3	Right mount X 4	Right mount Y 5	Right mount Z 6	Lower mount X 7	Lower mount Y 8	Lower mount Z 9	Output shaft X 10	Output shaft Y 11	Output shaft Z 12	Turbine midsplit Y 13	Turbine midsplit Z 14	Fwd compressor Y 15	Fwd compressor Z 16	Igniter Y 17	Igniter Z 18
1	158 3638 3945	158 3946 4246	158 4247 4543	158 4544 4843	158⊙ 4844 5142	158 5143 5441	158 5442 5743	158 5744 6044	158 6045 6346	158 6347 6648	158 6649 6947	158 6948 7250	158 7251 7543	158 7544 7842	158 7843 8142	158 8143 8446	158 8447 8743	158 8744 9047
2	136 5050 5315	136 5581 5846	136 5359 5580	136 618 922	136 923 1224	136 1225 1529	136 1530 1832	136 1834 2139	136⊙ 2142 2445	136 2446 2746	136 2747 3060	136 3061 3354	136 3355 3636	136 3637 3898	136 3899 4191	136 4192 4472	136 5 311	136 312 617
3	151 1492 1793	151 1193 1491	151 2424 2718	151 2094 2393	151⊙ 2719 3016	151 1794 2093	151 3017 3303	151 3304 3604	151⊙ 6001 6299	151 3605 3899	151 3900 4195	151 4196 4498	151 4801 5095	151 4499 4800	151 896 1192	151 307 601	151 5395 5697	151 5096 5394
4	159 4557 4853	159 4854 5148	159 4260 4556	159 5739 6043	159⊙ 5443 5738	159 5149 5442	159 3965 4259	159 3666 3964	159 3358 3665	159 3048 3357	159 2741 3047	159 2438 2740	159 2137 2437	159 1834 2136	159 1532 1833	159 1228 1531	159 922 1227	159 616 921
5	162 333 636	162 637 936	162 937 1234	162 1235 1536	155 5 304	162⊙ 1537 1837	155 2696 2993	155 2994 3286	155 3287 3581	162 1838 2141	162 2142 2444	162 2445 2750	155 1800 2097	155 1503 1799	155 305 610	155 611 906	155 2101 2397	155 2398 2695
6	152 1231 1531	152 932 1230	152 1532 1829	152 1830 2129	152 2429 2729	152 2130 2428	152 310 612	152 613 931	152⊙ 5 309	152 2730 3025	152 5533 5827	152 5828 6122	152 3026 3321	152 3322 3623	152 3624 4038	152 4039 4336	152 4337 4637	152 4638 4935
7	157 6699 7001	157 7002 7300	157 7301 7606	158 1512 1809	158 2117 2425	158 1810 2116	517 6083 6390	157 6391 6698	158⊙ 3329 3637	158 2426 2724	158 2725 3027	158 3028 3328	157 7607 7905	157 7906 8206	157 8207 8503	158 5 306	158 307 609	158 610 910
8	142 11342 11662	142 11966 12267	142 11663 11965	142 6163 6464	142 6767 7066	142 6465 6766	142 7682 7985	142 7067 7369	142⊙ 7370 7681	142 7986 8290	142 8291 8604	142 8605 8911	142 8912 9213	142 9214 9514	142 9515 9816	142 9817 10122	142 10123 10431	142 1043 1073
9	121 1260 1571	121 1879 2184	121 1572 1878	121 5 313	121 341 643	120 1745 2049	120 319 623	121 644 952	120 5 318	130 620 922	130 315 619	130 5 314	121 3395 3696	121 3697 3998	121 953 1259	117 313 609	121 2787 3098	121 309 3394
10	157 1203 1500	157 1802 2099	157 1501 1801	157 2698 3004	157⊙ 2399 2697	157 2100 2398	157 309 606	157 607 905	157⊙ 906 1202	157 5 308	157⊙ 5481 5781	157⊙ 5782 6082	157 3005 3308	157 3309 3610	157 3660 3958	157 3959 4256	157 4257 4568	157 456 487
11	138 1532 1837	138 2144 2461	138 1838 2143	138 917 1222	138 307 611	138 612 916	136 6178 6489	136 5848 6177	138⊙ 1223 1531	138 3692 3992	138 3993 4294	138 3386 3691	136 7402 7635	138 5 306	136 7095 7401	136 6792 7094	138 2462 2768	138 276 307
12	130 2135 2434	130 3942 4241	130 2435 2730	130 1832 2134	130 1527 1831	130 1226 1526	130 4242 4541	130 4542 4843	130⊙ 4844 5142	130 5143 5441	130 5442 5741	130 923 1225	134 5 308	130 3639 3941	130 3031 3338	130 2731 3030	134 309 613	134 614 921
13	143 325 618	143 5 324	143 619 921	143 922 1221	143 1222 1518	143 1519 1813	143 1814 2109	143 2110 2406	143 2407 2703	143 2704 2999	143 3000 3295	143 3296 3590	143 3591 3889	143 3890 4186	143 4187 4484	143 4775 5073	143 5074 5369	143 537 566
14	143 6267 6566	143 6567 6865	143 6866 7162	143 7462 7759	143 7760 8057	143 8058 8357	143 8358 8658	143 8659 8962	143⊙ 8963 9260	143 9261 9557	143 9558 9856	143 9857 10153	143 10154 10452	143 10453 10753	144 171 462	144 463 758	144 759 1054	144 105 134
15	142 4326 4630	142 4935 5243	142⊙ 4631 4934	142 5856 6162	142 5244 5549	142 5550 5855	142 918 1220	142 1221 1533	142⊙ 1534 1841	142 4020 4325	142 3377 3687	142 3688 4019	142 310 615	142 616 917	142 5 309	142 2450 2753	142 2754 3068	142 306 337
16	164 5 307	164 308 609	145 5 301	144 6677 6972	144 6377 6676	144 6079 6376	144 5782 6078	144 5484 5781	144 5187 5483	144 4890 5186	144 4597 4889	144 4301 4596	144 4008 4300	144 3712 4007	144 3419 3711	144 3121 3418	144 2826 3120	144 253 282

BLE 5. T63 ENGINE MOBILITY TEST MATRIX LOG

Responses													
ower mount		Output shaft			Turbine midsplit		Fwd compressor		Igniter		Top gearbox		
Y	Z	X	Y	Z	Y	Z	Y	Z	Y	Z	X	Z	
8	9	10	11	12	13	14	15	16	17	18	19	20	
158	158	158	158	158	158	158	158	158	158	158	158	158	← Day of year
5744	6045	6347	6649	6948	7251	7544	7843	8143	8447	8744	9048	9349	← SEL record No. start
6044	6346	6648	6947	7250	7543	7842	8142	8446	8743	9047	9348	9647	← SEL record No. stop
136	136*	136	136	136	136	136	136	136	136	136	136	136	
1834	2142	2446	2747	3061	3355	3637	3899	4192	5	312	4473	4774	
2139	2445	2746	3060	3354	3636	3898	4191	4472	311	617	4773	5049	
151	151*	151	151	151	151	151	151	151	151	151	151	151	
3304	6001	3605	3900	4196	4801	4499	896	307	5395	5096	5698	5	
3604	6299	3899	4195	4498	5095	4800	1192	601	5697	5394	6000	306	
159	159	159	159	159	159	159	159	159	159	159	159	159	
3666	3358	3048	2741	2438	2137	1834	1532	1228	922	616	317	5	
3964	3665	3357	3047	2740	2437	2136	1833	1531	1227	921	615	316	
155	155	162	162	162	155	155	155	155	155	155	155	155	
2994	3287	1838	2142	2445	1800	1503	305	611	2101	2398	1204	907	
3286	3581	2141	2444	2750	2097	1799	610	906	2397	2695	1502	1203	
152	152*	152	152	152	152	152	152	152	152	152	152	152	
613	5	2730	5533	5828	3026	3322	3624	4039	4337	4638	4936	5235	
931	309	3025	5827	6122	3321	3623	4038	4336	4637	4935	5234	5532	
157	158*	158	158	158	157	157	157	158	158	158	158	158	
6391	332[illegible]	2426	2725	3028	7607	7906	8207	5	307	610	911	1212	
6[illegible]98	3637	2724	3027	3328	7905	8206	8503	306	609	910	1211	1511	
142	142*	142	142	142	142	142	142	142	142	142	142	142	
7067	7370	7986	8291	8605	8912	9214	9515	9817	10123	10432	10734	11040	
7369	7681	8290	8604	8911	9213	9514	9816	10122	10431	10733	11039	11341	
121	120	130	130	130	121	121	121	117	121	121	121	121	
644	5	620	315	5	3395	3697	953	313	2787	3099	2185	2485	
952	318	922	619	314	3696	3998	1259	609	3098	3394	2484	2786	
157	157*	157	157*	157*	157	157	157	157	157	157	157	157	
607	906	5	5481	5782	3005	3309	3660	3959	4257	4569	4876	5178	
905	1202	308	5781	6082	3308	3610	3958	4256	4568	4875	5177	5480	
136	138*	138	138	138	136	138	136	136	138	138	136	138	
5848	1223	3692	3993	3386	7402	5	7095	6792	2462	2769	6490	3080	
6177	1531	3992	4294	3691	7635	306	7401	7094	2768	3079	6791	3385	
130	130*	130	130	130	134	130	130	130	134	134	134	134	
4542	4844	5143	5442	923	5	3639	3031	2731	309	614	922	1222	
4843	5142	5441	5741	1225	308	3941	3338	3030	613	921	1221	1523	
143	143	143	143	143	143	143	143	143	143	143	143	143	
2110	2407	2704	3000	3296	3591	3890	4187	4775	5074	5370	5666	5963	
2406	2703	2999	3295	3590	3889	4186	4484	5073	5369	5665	5962	6266	
143	143*	143	143	143	143	143	144	144	144	144	144	144	
8659	8963	9261	9558	9857	10154	10453	171	463	759	1055	1347	1641	
8962	9260	9557	9856	10153	10452	10753	462	758	1054	1346	1640	1934	
142	142*	142	142	142	142	142	142	142	142	142	142	142	
1221	1534	4020	3377	3688	310	616	5	2450	2754	3069	2148	1842	
1533	1841	4325	3687	4019	615	917	309	2753	3068	3376	2449	2147	
144	144	144	144	144	144	144	144	144	144	144	164	144	
5484	5187	4890	4597	4301	4008	3712	3419	3121	2826	2530	610	1935	
5781	5483	5186	4889	4596	4300	4007	3711	3418	3120	2825	909	2232	

X = fore and aft, Y = lateral, Z = vertical } Engine axes

The roving accelerometer used for transfer mobilities was oriented up, forward, or left with respect to engine axes, except as noted by symbol * to indicate 180-deg transducer phase shift.

- Lower mount fore and aft, lateral, and vertical
- Output shaft fore and aft, lateral, and vertical
- Turbine midsplit (turbine middle splitline at the top center) lateral and vertical
- Forward compressor (top center) lateral and vertical

Responses were measured at these force points and at:

- Igniter lateral and vertical
- Top gearbox (top mount) fore and aft and vertical

These excitation and response points form the 16 × 20 matrix presented in Table 5.

For each excitation point, 20 separate frequency sweeps were performed. During each sweep, analog plots of mobility amplitude and phase were recorded versus frequency and digitized. Digitizing was terminated at 500 Hertz for all test conditions. For the responses in the direction of the excitations, the plotting continued to 2000 Hertz. This procedure was repeated for the 16 excitation points. Table 5 shows the log of test data. The first number in each block refers to the day of the year 1973 in which the run was performed. The next two numbers refer to the SEL start and stop record numbers for digitizing purposes. As noted the table, the engine coordinate axes are defined as:

X = Fore and aft
Y = Lateral
Z = Vertical

These axes are defined with respect to the engine centerline. The roving accelerometer used for measuring transfer mobilities was oriented up, forward, and left with respect to the engine axes except as noted by the symbol ⊗. This symbol indicates a 180-deg shift in the transducer orientation.

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TEST RESULTS

A total of 443 plots were generated during the testing of the T63-A-5 engine. A sampling of the plots are discussed here, but the entire data package can be obtained on microfiche from the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia. The plots are keyed to the T63 mobility matrix of Table 5 by a condition code. This code is composed of two numbers separated by a slash mark, an example of which would be 10/3. This defines the plot as representing the mobility of the element in the tenth row and third column of the mobility matrix. The data would be the transfer mobility relating the vertical (2) response of the left mount to a fore and aft (X) excitation at the output shaft. Excitation have been considered at all interface points and are related to response at all points on the engine covered by the T63-A-5 installation drawing.

In addition to these analog plots, a digital tape has been prepared. This tape contains all the data which was digitized during the testing and is cataloged as Generation Data Set C460 and stored at the DDA Data Center, Indianapolis, Indiana.

Figure 12 is a representative analog plot of one test point. This particular data point is the drive point mobility relating the vertical response at the lower mount to a sinusoidal vertical excitation at the lower mount. This plot shows a characteristic low frequency (0 to 10 Hertz) resonant activity. These apparent engine resonances are the fixity modes caused by the low stiffness bungee cords. The first few resonances showing significant engine flexure occur above 100 Hertz, to obtain a visual picture of these modes, the mobilities, relating responses along the length of the engine to vertical excitations aft the lower mount and lateral excitations at the right mount, were normalized and plotted. The resulting mode shapes at resonant frequencies of 127, 145, 156, and 183 Hertz are shown in Figures 13 through 16, respectively. The resonance at 127 Hertz is a pitch plane mode of the compressor. Little yaw plane participation is evidenced. The resonance at 145 Hertz is a coupled pitch and yaw mode with slight roll. The 156 Hertz mode is almost a pure yaw plane cantilever resonance of the overhung compressor. The resonance at 183 Hertz is another coupled mode involving significant out-of-phase yaw plane bending of the front and rear of the engine.

This has been a presentation of a comprehensive laboratory shake test of the T63-A-5 engine. Driving point and transfer mobilities, necessary for the study of helicopter dynamic analysis methods, have been measured. Data have been presented as analog plots of mobility amplitude and phase versus excitation frequency. These data are also recorded in digital form for digital computer processing.

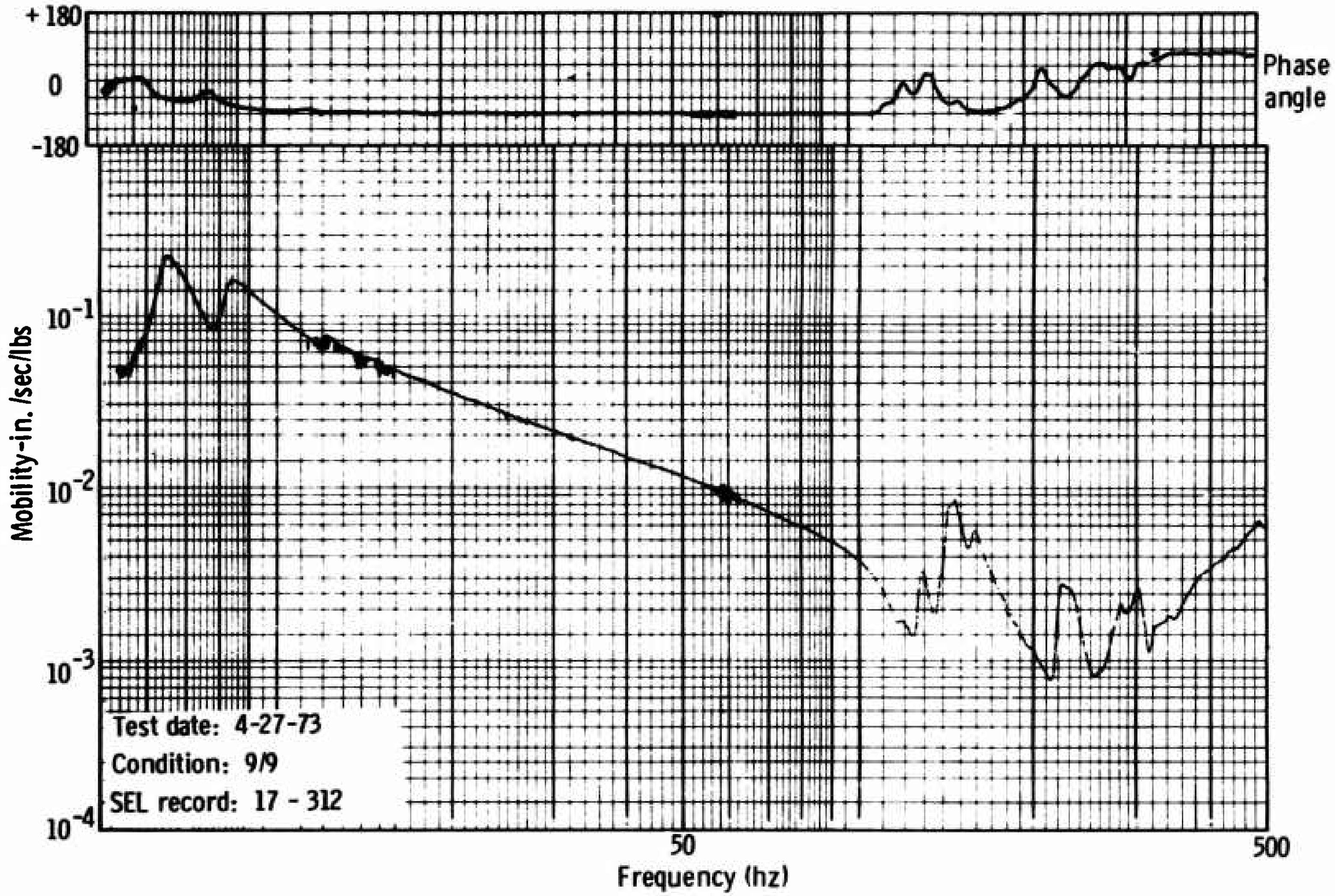

Figure 12. Representative Plot of Test Data—Drive Point Mobility.

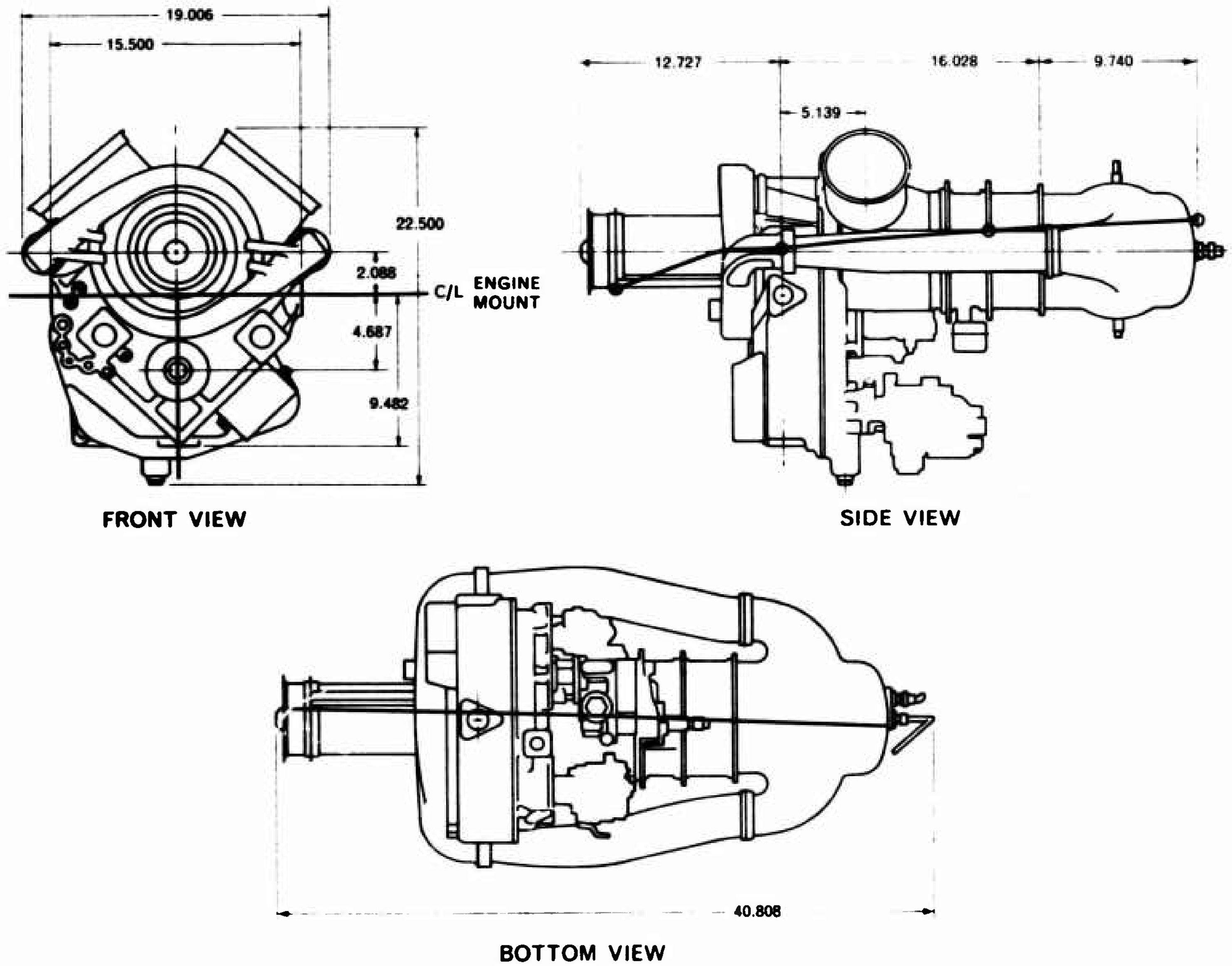

Figure 13. Engine Mode Shape at 127 Hertz.

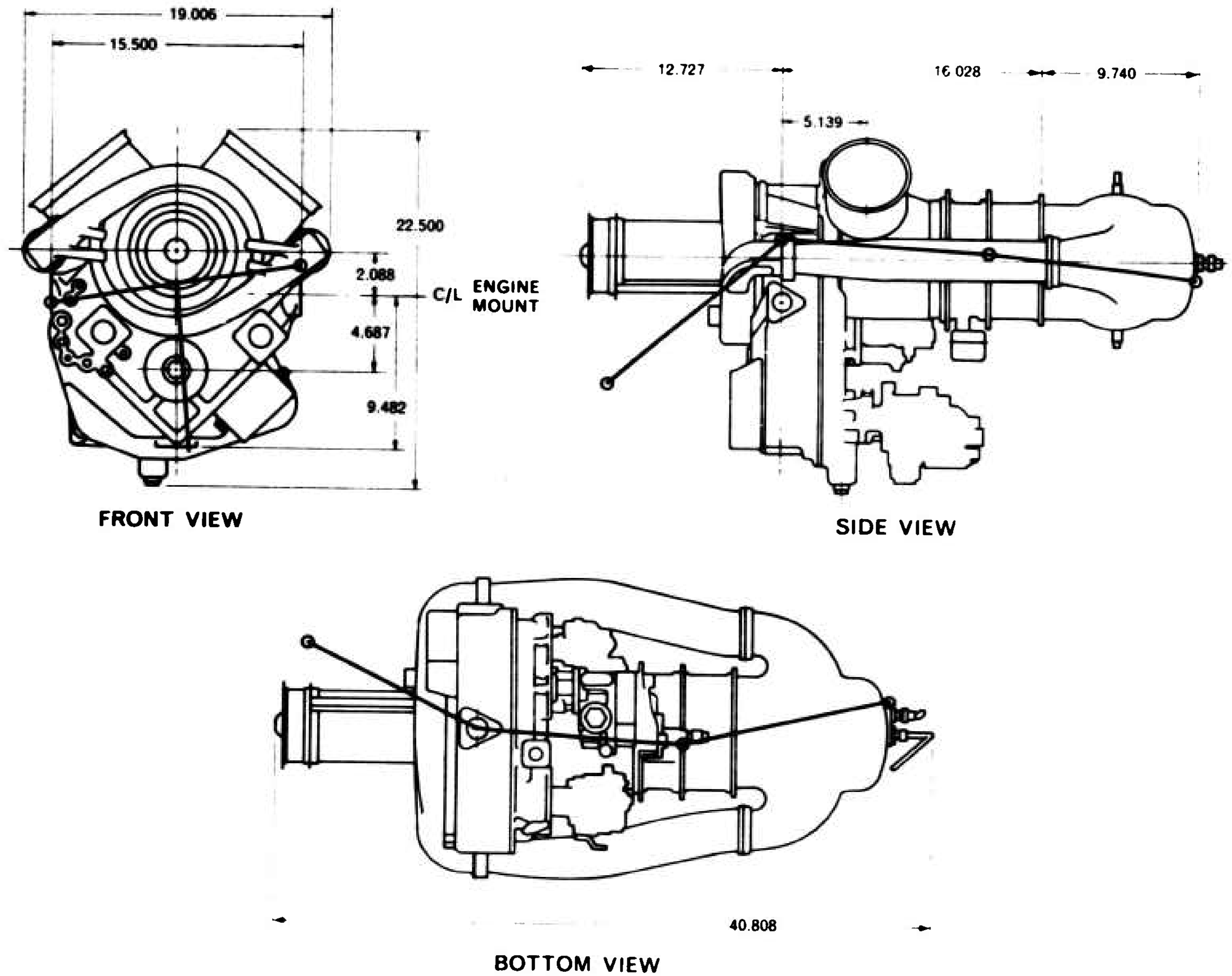

Figure 14. Engine Mode Shape at 145 Hertz.

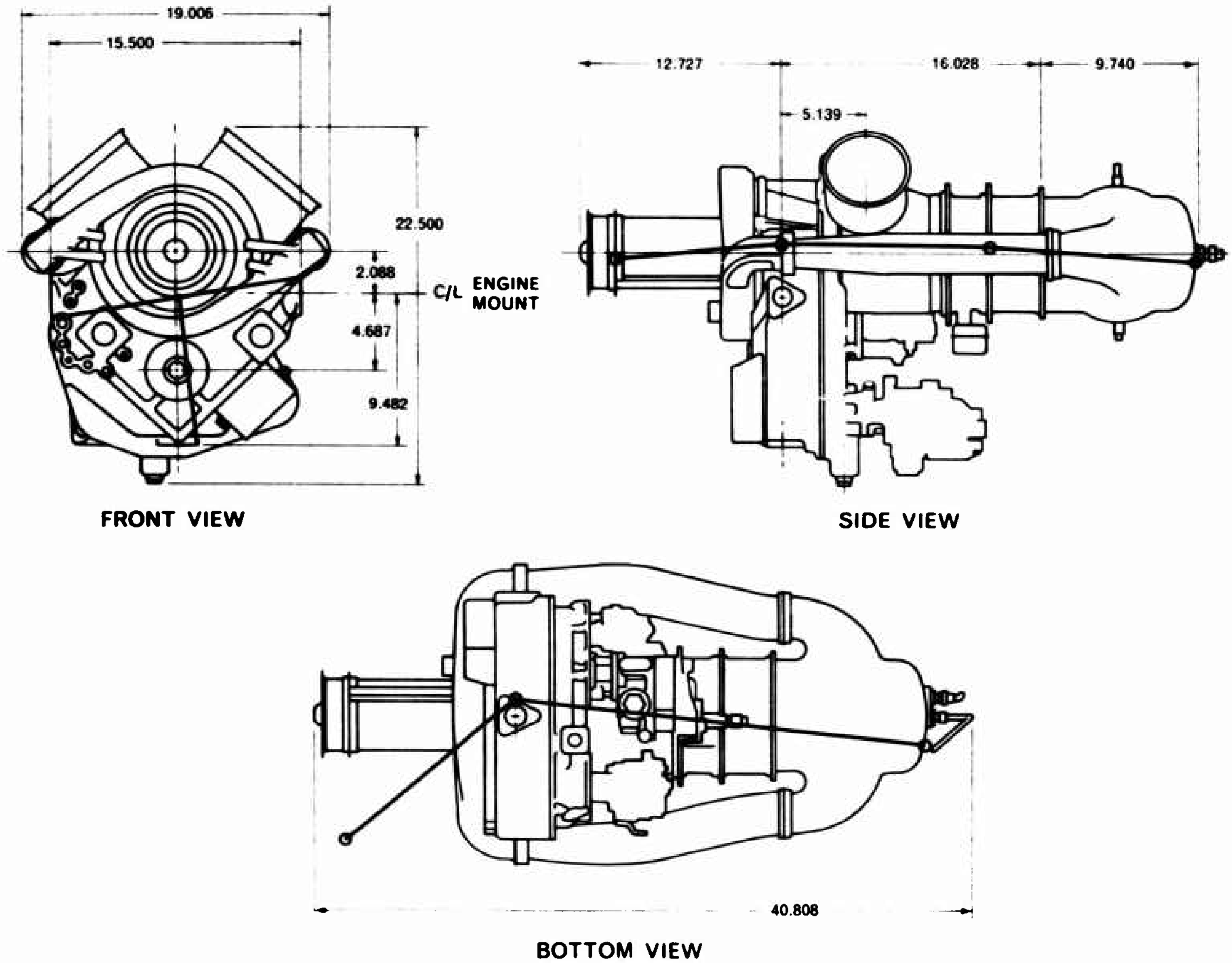

Figure 15. Engine Mode Shape at 156 Hertz.

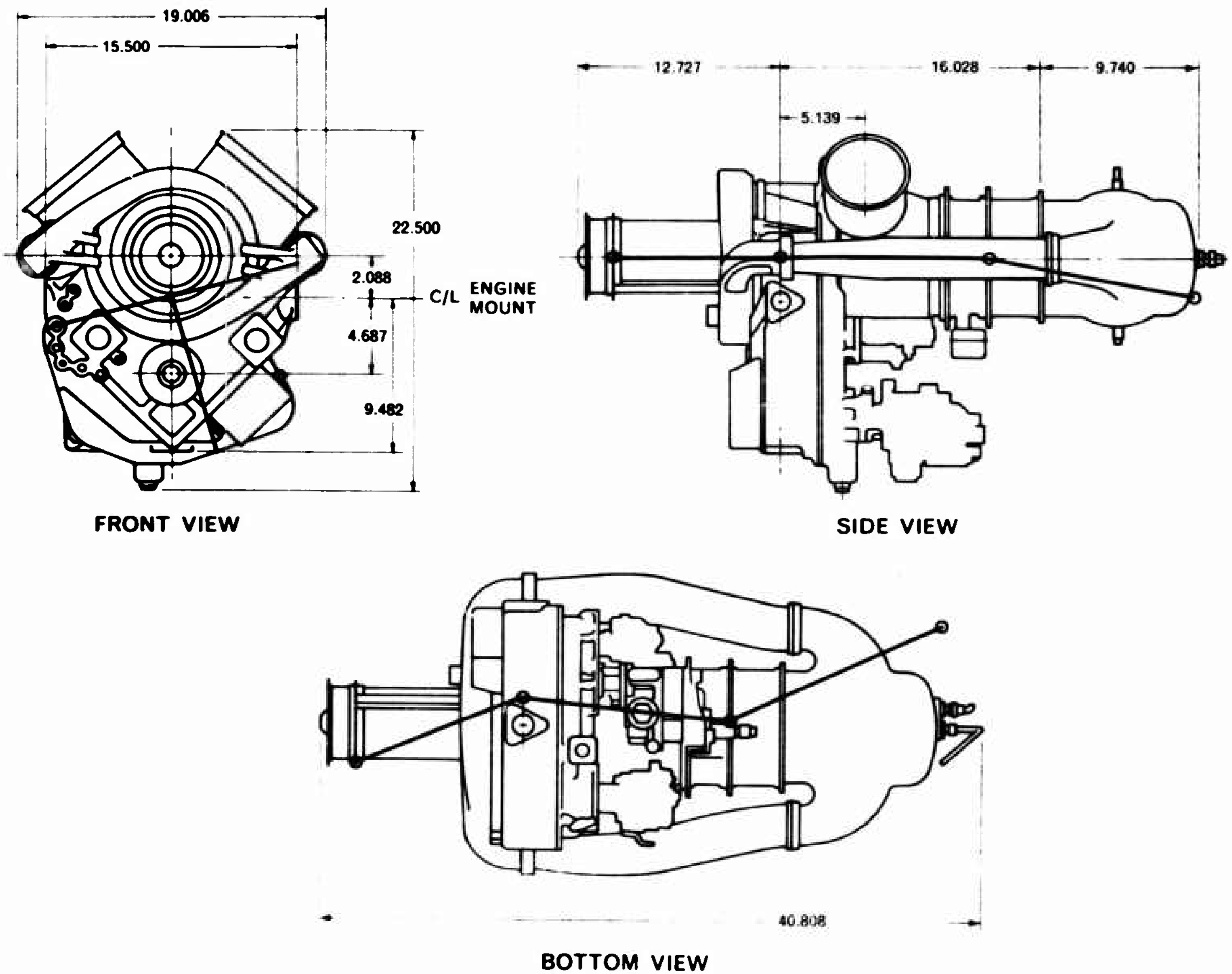

Figure 16. Engine Mode Shape at 183 Hertz.

ANALYSIS METHOD DEVELOPMENT

Three methods for studying vibration compatibility of coupled dynamic systems have been considered. Two approaches, a mobility technique and a modal synthesis technique, are thoroughly developed. Another approach, direct stiffness technique, is used as a minimal standard for judging the other approaches. These methods are developed, discussed, and compared in the following paragraphs.

MOBILITY METHOD

The application of impedance/mobility analysis techniques has been under development by electrical engineers since about 1900. A brief history of this development is presented in Reference [5]. More recently these techniques have been adopted for vibration analysis by some mechanical engineers.[6] The purpose of this section is to derive the mobility technique of analysis for application to the study of dynamic compatibility between engine and airframe for helicopter systems.

The essence of this analysis approach is to separate the complex dynamic system (a helicopter) into its component parts. The parts considered here are the helicopter airframe system (airframe, rotors, transmissions, engine mounts, etc.) and the engine (basic engine plus accessories). It will be shown later how the engine mounting system can be handled as a third component system. The dynamics of the components are described in terms of driving point and transfer mobilities and coupled at their interface points through the application of compatibility and equilibrium relationships. The driving point mobility is defined as the ratio of the response velocity at a point on a dynamic system divided by an impressed force at the same point on that system. The transfer mobility is defined as the ratio of the response velocity at a point on a dynamic system divided by an impressed force at some other point on that system. Both of these quantities can be expressed as complex numbers which vary with the sinusoidal frequency of the excitation force, thereby containing information relative to the amplitude and phase of the normalized response.

A simple problem is presented to show the equivalence of the mobility method of analysis and the classical method of analysis. An idealized model of the helicopter system is then studied to demonstrate the mobility method application. Finally, the mobility method is applied to derive a set of mobility equations describing the dynamics of the OH-6 and OH-58 helicopters.

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[5] Plunkett, R. MECHANICAL IMPEDANCE METHOS FOR MECHANICAL VIBRATIONS, compilation of papers from the ASME Annual Meeting, New York, December 2, 1958.

[6] MECHANICAL IMPEDANCE ANALYSIS UPDATE FOR THE 70's, Spectral Dynamics Corporation of San Diego.

An idealized system is analyzed by the mobility and classical methods to show their equivalence. Example 8.9 of Reference 7 is used as this system. Displacement mobilities are used throughout this example for ease of computation.

Consider the idealized spring-mass system in Figure 17. The total system I is composed of two subsystems G and H. The displacement mobilities of these subsystems are denoted by G_{ij} and H_{ki}. The first subscript refers to the station at which the response displacement is measured and the second subscript refers to the point at which the force is impressed. The problem is to determine the interface response displacement as a function of the impressed force F_1. The classical method is applied first.

The energies of this system are:

$$2T = M_1 \dot{X}_1^2 + (M_2 + M_3)\dot{X}_2^2 + M_4 \dot{X}_3^2$$

$$2V = K_1 (X_1 - X_2)^2 + K_2 (X_2 - X_3)^2$$

The virtual work of the impressed force is

$$\delta W = F_1 \delta X$$

Application of the Lagrange equations yields the following equations of motion arranged in matrix form.

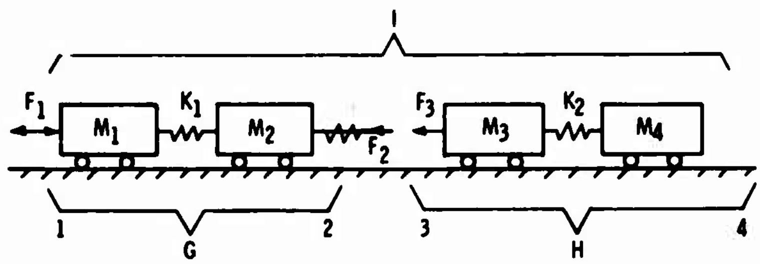

Figure 17. Idealized Spring—Mass System.

7 Church, Austin H. MECHANICAL VIBRATIONS, John Wiley and Sons, Inc., New York, 1963.

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & (m_2+m_3) & 0 \\ 0 & 0 & m_4 \end{bmatrix} \begin{Bmatrix} \ddot{X}_1 \\ \ddot{X}_2 \\ \ddot{X}_3 \end{Bmatrix} + \begin{bmatrix} K_1 & -K_1 & 0 \\ -K_1 & (K_1+K_2) & -K_2 \\ 0 & -K_2 & K_2 \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \\ X_3 \end{Bmatrix} = \begin{bmatrix} F_1 \\ 0 \\ 0 \end{bmatrix} \qquad (1)$$

For a sinusoidal impressed force

$$F_1 = F \sin \omega t$$
$$X_1 = X_1 \sin \omega t$$
$$X_2 = X_2 \sin \omega t$$
$$X_3 = X_3 \sin \omega t$$

Differentiating twice with respect to time and substituting into Equation (1) yields

$$\begin{bmatrix} (K_1 - m_1\omega^2) & -K_1 & 0 \\ -K_1 & \begin{pmatrix} (K_1+K_2) \\ -(m_2+m_3)\omega^2 \end{pmatrix} & -K_2 \\ 0 & -K_2 & (K_2 - m_4\omega^2) \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \\ X_3 \end{Bmatrix} = \begin{bmatrix} F \\ 0 \\ 0 \end{bmatrix} \qquad (2)$$

Using Cramer's Rule the solution for X_3/F (interface response) can be written as:

$$\frac{X_3}{F} = \frac{K_1 K_2}{(K_1 - m_1\omega^2)\left\{\left[(K_1+K_2) - (m_2+m_3)\omega^2\right]\left[K_2 - m_4\omega^2\right] - K_2^2\right\} - K_1^2 (K_2 - m_4\omega^2)} \qquad (3)$$

The mobility method will be considered. The responses at each point in subsystem G can be expressed using the mobilities as dynamic influence coefficients as follows:

$$\left.\begin{aligned} X_1 &= F_1 G_{11} + F_2 G_{12} \\ X_2 &= F_1 G_{21} + F_2 G_{22} \\ X_3 &= F_3 H_{33} \\ X_4 &= F_3 H_{43} \end{aligned}\right\} \qquad (4)$$

The compatibility relationship requires

$$X_2 = X_3 \tag{5}$$

and the equilibrium consideration requires

$$F_2 = -F_3 \tag{6}$$

Therefore,

$$\left.\begin{aligned} X_1 &= F_1\, G_{11} + F_2\, G_{12} \\ X_2 &= F_1\, G_{21} + F_2\, G_{22} \\ X_2 &= -F_2\, H_{33} \\ X_4 &= -F_2\, H_{43} \end{aligned}\right\} \tag{7}$$

or in matrix form

$$\begin{bmatrix} 1 & 0 & -G_{12} & 0 \\ 0 & 1 & -G_{22} & 0 \\ 0 & 1 & H_{33} & 0 \\ 0 & 0 & H_{43} & 1 \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \\ F_2 \\ X_4 \end{Bmatrix} = \begin{bmatrix} F_1\, G_{11} \\ F_1\, G_{21} \\ 0 \\ 0 \end{bmatrix} \tag{8}$$

Using Cramer's rule and solving for X_2/F, or, using (5), X_3/F_1

$$\frac{X_3}{F_1} = \frac{G_{21}\, H_{43}}{H_{33} + G_{22}} \tag{9}$$

It remains, then, to show the equivalence of Equations (9) and (3). Using the techniques of Reference 3 it can be shown that:

$$G_{22} = \frac{m_1\omega^2 - K_1}{\omega^2 \left[K_1(m_1+m_2) - m_1 m_2 \omega^2\right]} \tag{10}$$

$$G_{21} = \frac{-K_1}{\omega^2 \left[K_1(m_1+m_2) - m_1 m_2 \omega^2\right]} \tag{11}$$

$$H_{33} = \frac{m_4\omega^2 - K_2}{\omega^2 \left[K_2(m_3+m_4) - m_3m_4\omega^2\right]} \quad (12)$$

$$H_{43} = \frac{-K_2}{\omega^2 \left[K_2(m_3+m_4) - m_3m_4\omega^2\right]} \quad (13)$$

Substituting these mobilities into Equation (9) yields:

$$\frac{X_3}{F_1} = \frac{K_1 K_2}{\omega^2 \left\{(m_4\omega^2-K_2)\left[K_1(m_1+m_2) - m_1m_2\omega^2\right] + (m_1\omega^2 - K_1)\left[K_2(m_3+m_4) - m_3m_4\omega^2\right]\right\}} \quad (14)$$

After considerable algebraic manipulation, it can be shown that Equations (14) and (3) are equivalent.

At this point in the development of the mobility and application to helicopter systems, it may appear to be a laborious procedure. However, if the mobilities had been available in tabular form versus frequency at the stage of Equation (9), it would only have been necessary to perform this simple calculation at each frequency of interest.

This portion of the development has shown the equivalence of solution between the classical and mobility methods of dynamic system analysis.

Idealized Helicopter System

Consider the idealized helicopter system shown in Figure 18, which is separated into two subsystems: airframe and engine. The helicopter airframe mobilities, G_{ij}, define the velocity response at station i divided by an exciting force applied at j. Similarly, the engine mobilities are M_{ij}. Note that two potential sources of impressed excitation have been considered at the airframe: the main rotor and tail rotor. Four interface connection points are considered: three mount points and one shaft coupling point.

The engine system considerations for this simple model include the four interface points as well as a case vibration instrumentation location and an engine station for possible excitation from engine rotor unbalance. For this discussion a single degree of freedom for each point of consideration is assumed. In the general case there would be as many as six degrees of freedom at each point.

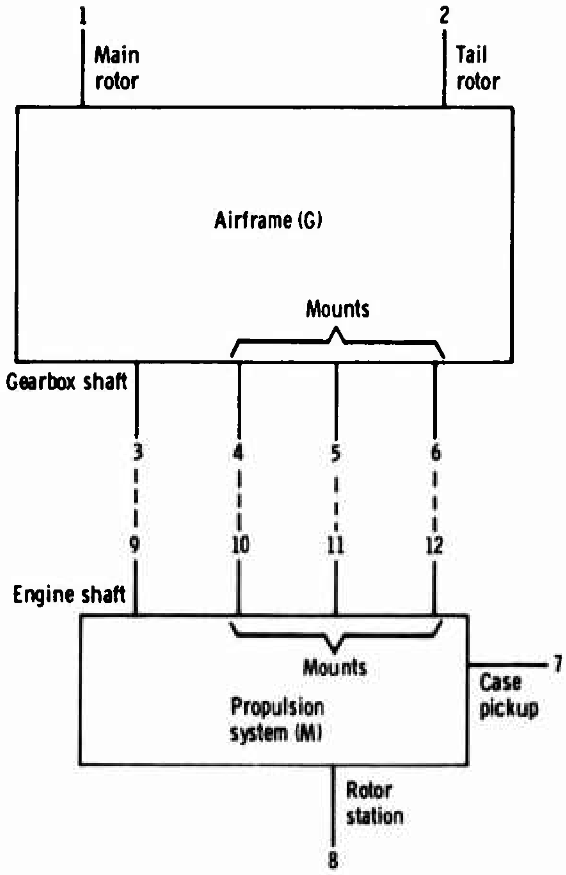

Figure 18. Idealized Helicopter System.

As before, the response, R, at any point i can be expressed in terms of the forces, impressed and interface, and the subsystem mobilities as:

Airframe

$$R_i = \sum_{j=1}^{6} G_{ij} F_j \qquad i = 1, \ldots, 6 \qquad (15)$$

Engine

$$R_i = \sum_{j=7}^{12} M_{ij} F_j \qquad i = 7, \ldots, 12 \qquad (16)$$

The dynamic coupling is effected through the application of the compatibility and equilibrium conditions. These are:

Compatibility

$$R_i = R_{i+6} \qquad i = 3, \ldots, 6 \tag{17}$$

Equation (17) states that the response on the airframe is equivalent to the response on the engine at the interface points.

Equilibrium

$$F_i = -F_{i+6} \qquad i = 3, \ldots, 6 \tag{18}$$

Equation (18) states that the forces existing at the airframe are equal in magnitude but opposite in direction to those on the engine at the interface points. Substituting Equations (17) and (18) into Equations (15) and (16) and expanding yields the following set of simultaneous linear equations.

$$\begin{aligned}
R_1 &= G_{11}F_1 + G_{12}F_2 + G_{13}F_3 + G_{14}F_4 + G_{15}F_5 + G_{16}F_6 \\
R_2 &= G_{21}F_1 + G_{22}F_2 + G_{23}F_3 + G_{24}F_4 + G_{25}F_5 + G_{26}F_6 \\
R_3 &= G_{31}F_1 + G_{32}F_2 + G_{33}F_3 + G_{34}F_4 + G_{35}F_5 + G_{36}F_6 \\
R_4 &= G_{41}F_1 + G_{42}F_2 + G_{43}F_3 + G_{44}F_4 + G_{45}F_5 + G_{46}F_6 \\
R_5 &= G_{51}F_1 + G_{52}F_2 + G_{53}F_3 + G_{54}F_4 + G_{55}F_5 + G_{56}F_6 \\
R_6 &= G_{61}F_1 + G_{62}F_2 + G_{63}F_3 + G_{64}F_4 + G_{65}F_5 + G_{66}F_6 \\
R_3 &= - M_{33}F_3 - M_{34}F_4 - M_{35}F_5 - M_{36}F_6 + M_{37}F_7 + M_{38}F_8 \\
R_4 &= - M_{43}F_3 - M_{44}F_4 - M_{45}F_5 - M_{46}F_6 + M_{47}F_7 + M_{48}F_8 \\
R_5 &= - M_{53}F_3 - M_{54}F_4 - M_{55}F_5 - M_{56}F_6 + M_{57}F_7 + M_{58}F_8 \\
R_6 &= - M_{63}F_3 - M_{64}F_4 - M_{65}F_5 - M_{66}F_6 + M_{67}F_7 + M_{68}F_8 \\
R_7 &= - M_{73}F_3 - M_{74}F_4 - M_{75}F_5 - M_{76}F_6 + M_{77}F_7 + M_{78}F_8 \\
R_8 &= - M_{83}F_3 - M_{84}F_4 - M_{85}F_5 - M_{86}F_6 + M_{87}F_7 + M_{88}F_8
\end{aligned} \tag{19}$$

where for convenience

$$M_{33} = M_{99}$$

$$M_{43} = M_{10,9}$$

$$M_{ij} = M_{it+6,\ jt+6} \qquad i = 3,6 \quad j = 3,6$$

In matrix form these become:

$$
\begin{bmatrix}
1 & & & & & & & & -G_{13} & -G_{14} & -G_{15} & -G_{16} \\
 & 1 & & & & & & & -G_{23} & -G_{24} & -G_{25} & -G_{26} \\
 & & 1 & & & & & & -G_{33} & -G_{34} & -G_{35} & -G_{36} \\
 & & & 1 & & & & & -G_{43} & -G_{44} & -G_{45} & -G_{46} \\
 & & & & 1 & & & & -G_{53} & -G_{54} & -G_{55} & -G_{56} \\
 & & & & & 1 & & & -G_{63} & -G_{64} & -G_{65} & -G_{66} \\
 & & 1 & & & & & & +M_{33} & +M_{34} & +M_{35} & +M_{36} \\
 & & & 1 & & & & & +M_{43} & +M_{44} & +M_{45} & +M_{46} \\
 & & & & 1 & & & & +M_{53} & +M_{54} & +M_{55} & +M_{56} \\
 & & & & & 1 & & & +M_{63} & +M_{64} & +M_{65} & +M_{66} \\
 & & & & & & 1 & & +M_{73} & +M_{74} & +M_{75} & +M_{76} \\
 & & & & & & & 1 & +M_{83} & +M_{84} & +M_{85} & +M_{86}
\end{bmatrix}
\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \\ R_6 \\ R_7 \\ R_8 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \end{bmatrix}
=
\begin{bmatrix}
G_{11} & G_{12} & & \\
G_{21} & G_{22} & & \\
G_{31} & G_{32} & & \\
G_{41} & G_{42} & & \\
G_{51} & G_{52} & & \\
G_{61} & G_{62} & & \\
 & & M_{37} & M_{38} \\
 & & M_{47} & M_{48} \\
 & & M_{57} & M_{58} \\
 & & M_{67} & M_{68} \\
 & & M_{77} & M_{78} \\
 & & M_{87} & M_{88}
\end{bmatrix}
\begin{bmatrix} F_1 \\ F_2 \\ F_7 \\ F_8 \end{bmatrix}
\qquad (20)
$$

These equations represent the coupled system dynamics of the helicopter in terms of the driving point and transfer mobilities of the airframe and engine. Each element of the matrix is a complex number at each discrete frequency. This system of equations can be solved for the response at any of the points considered resulting from impressed forces at any of the excitation points considered either singularly or in combination. The effects of mount stiffness and/or mass changes at the interface points can be evaulated by analytically altering either the engine or airframe system mobilities and repeating the computations. However, a more logical approach might be to model these interface changes as separate elements.

Consider the simplified helicopter model of Figure 19 with the coupling elements represented as dynamic subsystems. The number of degrees of freedom have been further reduced for simplicity. Here the airframe has one excitation point (main rotor) and is coupled to the engine through two separate mount systems, K and S. These in turn couple to the engine, which has one pickup location for measuring case vibration. The equations of motion are:

$$V_1 = M_{11}F_1 + M_{12}F_2 + M_{13}F_3 \qquad (21)$$

$$V_2 = M_{21}F_1 + M_{22}F_2 + M_{23}F_3$$

$$V_3 = M_{31}F_1 + M_{32}F_2 + M_{33}F_3$$

$$V_7 = S_{77}F_7 + S_{79}F_9 \tag{21 (cont)}$$

$$V_9 = S_{97}F_7 + S_{99}F_9$$

$$V_8 = K_{88}F_8 + K_{8,10}F_{10}$$

$$V_{10} = K_{10,8}F_8 + K_{10,10}F_{10}$$

$$V_4 = G_{44}F_4 + G_{45}F_5 + G_{40}F_6$$

$$V_5 = G_{54}F_4 + G_{55}F_5 + G_{56}F_6$$

$$V_6 = G_{64}F_4 + G_{65}F_5 + G_{66}F_6$$

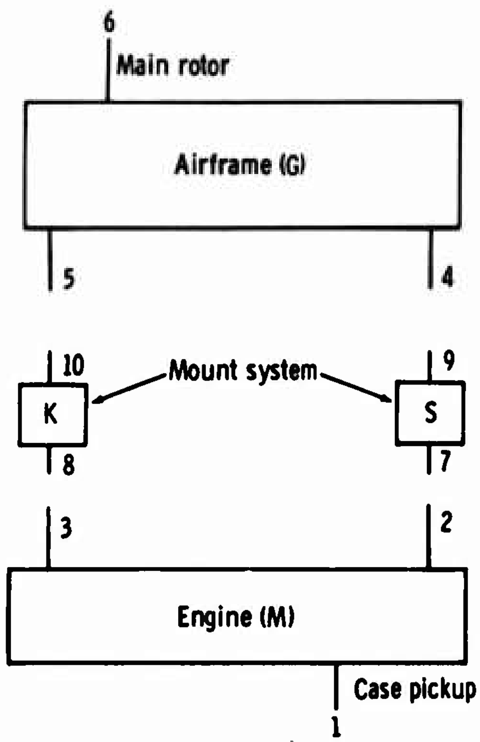

Figure 19. Simplified Helicopter Model With Coupling Elements as Subsystems.

The compatibility relationships are:

$$
\begin{aligned}
V_2 &= V_7 & \qquad V_9 &= V_4 \\
V_3 &= V_8 & \qquad V_{10} &= V_5
\end{aligned}
\tag{22}
$$

The equilibrium relationships are:

$$
\begin{aligned}
F_2 &= -F_7 & \qquad F_9 &= -F_4 \\
F_3 &= -F_8 & \qquad F_{10} &= -F_5
\end{aligned}
\tag{23}
$$

Substituting Equations (22) and (23) into Equation (21) and arranging in matrix form yields:

$$
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & -M_{12} & -M_{13} & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & -M_{22} & -M_{23} & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & -M_{32} & -M_{33} & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & S_{77} & 0 & S_{79} & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & S_{97} & 0 & S_{99} & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & K_{88} & 0 & K_{8,10} \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & K_{10,8} & 0 & K_{10,10} \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -G_{44} & -G_{45} \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -G_{54} & -G_{55} \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -G_{64} & -G_{65}
\end{bmatrix}
\begin{Bmatrix}
V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ F_2 \\ F_3 \\ F_4 \\ F_5
\end{Bmatrix}
=
\begin{bmatrix}
M_{11}F_1 \\ M_{21}F_1 \\ M_{31}F_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ G_{46}F_6 \\ G_{56}F_6 \\ G_{66}F_6
\end{bmatrix}
\tag{24}
$$

The solution matrix, Equation (24), can be evaluated at all discrete frequencies in terms of the mount mobilities. If a mount change is desired, it can be studied by merely changing those mount mobilities and recomputing.

OH-6 and OH-58 Helicopter Mobility Model

The derivation of the system equations for predicting the dynamic behavior of the OH-6 and OH-58 helicopters follows the previously discussed approach. The helicopter idealized model is shown in Figure 20. The airframe is considered to have a potential of six excitation degrees of freedom: fore and aft, lateral, and vertical at the main rotor, and fore and aft, lateral, and vertical at the tail rotor. Twelve potential interface degrees of freedom are considered: fore and aft, lateral, and vertical at the left bipod, right bipod, lower bipod, and transmission input shaft. Note that the mounting arrangement has been assigned to the airframe. The engine description is in terms of the twelve interface degrees of freedom: fore and aft, lateral, and vertical at the left mount, right mount, lower mount, and gearbox output shaft. Also included are two degrees of freedom at each of four transducer locations on the engine: fore and aft and vertical at the top gearbox, lateral and vertical at the top

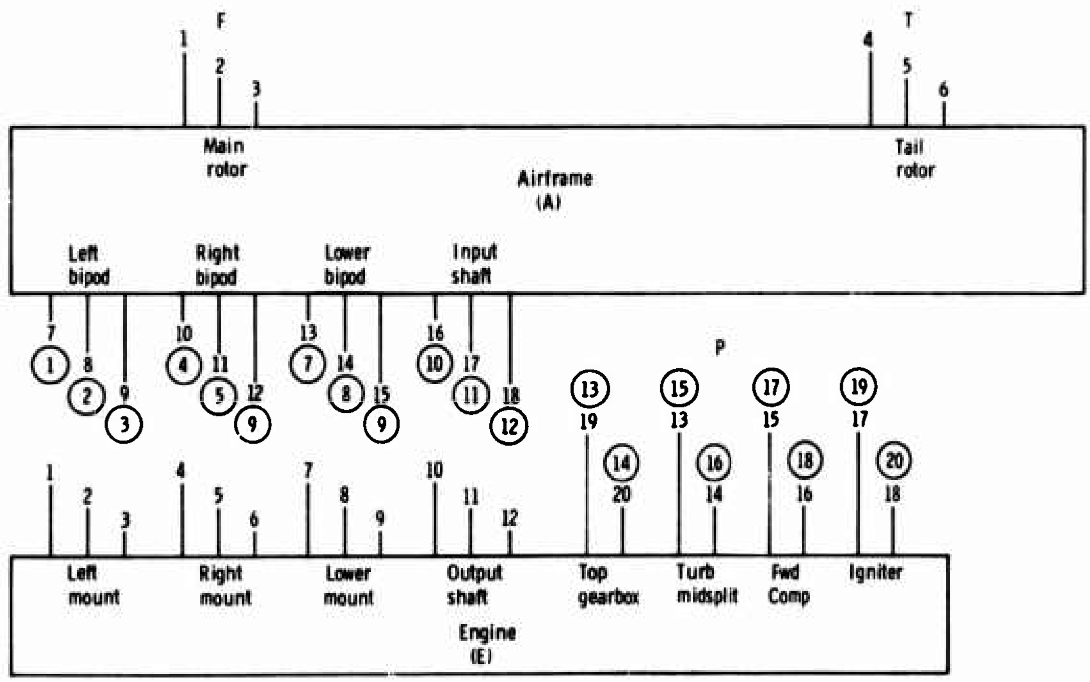

Figure 20. Helicopter Idealized Model.

turbine middle splitline, lateral and vertical at the top forward compressor, and lateral and vertical at the igniter. Potential excitation forces are considered at the turbine middle splitline to simulate loads resulting from engine rotor unbalances.

Three sets of coordinates have been considered: airframe, engine, and system. The coordinate definitions are presented in Table 6. The exciting loads are: F_X, F_Y, and F_Z for main rotor fore and aft, lateral, and vertical respectively; T_X, T_Y, and T_Z for tail rotor fore and aft, lateral, and vertical respectively; and P_Y and P_Z for turbine middle splitline lateral and vertical respectively.

TABLE 6. MOBILITY DERIVATION COORDINATE DEFINITIONS

Airframe Coordinates	Engine Coordinates	System Coordinates
1 Main rotor fore and aft	1 Left mount fore and aft	1 Left bipod fore and aft
2 Main rotor lateral	2 Left mount lateral	2 Left bipod lateral
3 Main rotor vertical	3 Left mount vertical	3 Left bipod vertical
4 Tail rotor fore and aft	4 Right mount fore and aft	4 Right bipod fore and aft
5 Tail rotor lateral	5 Right mount lateral	5 Right bipod lateral
6 Tail rotor vertical	6 Right mount vertical	6 Right bipod vertical
7 Left bipod fore and aft	7 Lower mount fore and aft	7 Lower bipod fore and aft
8 Left bipod lateral	8 Lower mount lateral	8 Lower bipod lateral
9 Left bipod vertical	9 Lower mount vertical	9 Lower bipod vertical
10 Right bipod fore and aft	10 Output shaft fore and aft	10 Output shaft fore and aft
11 Right bipod lateral	11 Output shaft lateral	11 Output shaft lateral
12 Right bipod vertical	12 Output shaft vertical	12 Output shaft vertical
13 Lower bipod fore and aft	13 Turbine middle splitline lateral	13 Top gearbox fore and aft
14 Lower bipod lateral	14 Turbine middle splitline vertical	14 Top gearbox vertical
15 Lower bipod vertical	15 Forward compressor lateral	15 Turbine middle splitline lateral
16 Input shaft fore and aft	16 Forward compressor vertical	16 Turbine middle splitline vertical
17 Input shaft lateral	17 Igniter lateral	17 Forward compressor lateral
18 Input shaft vertical	18 Igniter vertical	18 Forward compressor vertical
	19 Top gearbox fore and aft	19 Igniter lateral
	20 Top gearbox vertical	20 Igniter vertical

The equations of motion can be written in terms of the airframe (A) and engine (E) mobilities and the system coordinates as:

(25)

$$V_1 = F_X A_{7,1} + F_Y A_{7,2} + F_Z A_{7,3} + T_X A_{7,4} + T_Y A_{7,5} +$$
$$T_Z A_{7,6} + F_1 A_{7,7} + F_2 A_{7,8} + F_3 A_{7,9} + F_4 A_{7,10} +$$
$$F_5 A_{7,11} + F_6 A_{7,12} + F_7 A_{7,13} + F_8 A_{7,14} + F_9 A_{7,15} +$$
$$F_{10} A_{7,16} + F_{11} A_{7,17} + F_{12} A_{7,18}$$

⋮ ⋮ ⋮

$$V_{12} = F_X A_{18,1} + F_Y A_{18,2} + F_Z A_{18,3} + T_X A_{18,4} + T_Y A_{18,5} + T_Z A_{18,6} + F_1 A_{18,7} + F_2 A_{18,8} + F_3 A_{18,9} + F_4 A_{18,10} + F_5 A_{18,11} + F_6 A_{18,12} + F_7 A_{18,13} + F_8 A_{18,14} + F_9 A_{18,15} + F_{10} A_{18,16} + F_{11} A_{18,17} + F_{12} A_{18,18} \quad (25)\ (\text{cont})$$

$$V_1 = P_Y E_{1,13} + P_Z E_{1,14} - F_1 E_{1,1} - F_2 E_{1,2} - F_3 E_{1,3} - F_4 E_{1,4} - F_5 E_{1,5} - F_6 E_{1,6} - F_7 E_{1,7} - F_8 E_{1,8} - F_9 E_{1,9} - F_{10} E_{1,10} - F_{11} E_{1,11} - F_{12} E_{1,12}$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$V_{20} = P_Y E_{20,13} + P_Z E_{20,14} - F_1 E_{20,1} - F_2 E_{20,2} - F_3 E_{20,3} - F_4 E_{20,4} - F_5 E_{20,5} - F_6 E_{20,6} - F_7 E_{20,7} - F_8 E_{20,8} - F_9 E_{20,9} - F_{10} E_{20,10} - F_{11} E_{20,11} - F_{12} E_{20,12}$$

These equations include the compatibility and equilibrium relationships which state that the interface velocities are equal and the interface forces are equal in magnitude but opposite in direction. Equation (25) can be written in matrix notation in terms of the thirty-two independent variables V_1-V_{20} and F_1-F_{12}. These equations are shown in Table 7.

Each nonzero element of these matrices is a complex number which is frequency dependent. The total solution is effected by generating and solving the matrices at each discrete frequency of interest. The resulting answers are interface forces and velocities along with velocities at various stations on the engine.

A computer program, MOBIL, has been written to generate and solve these matrices. A listing of the program is included in Appendix C. This program was written in FORTRAN IV language for solution on the IBM 370/165 computer. Also included is an input data format sheet and a glossary of terms. The program shown was written specifically for analysis of the OH-6 and OH-58 helicopter systems. The airframe and engine mobilities are obtained from magnetic tape input. Other input are supplied as cards.

TABLE 7. HELICOPTER EQUATION IN MATRIX FORM

-1																				$A_{7,7}$	$A_{7,8}$	$A_{7,9}$	$A_{7,10}$	$A_{7,11}$	$A_{7,12}$	$A_{7,13}$	$A_{7,}$
	-1																			$A_{8,7}$	$A_{8,8}$	$A_{8,9}$	$A_{8,10}$	$A_{8,11}$	$A_{8,12}$	$A_{8,13}$	$A_{8,}$
		-1																		$A_{9,7}$	$A_{9,8}$	$A_{9,9}$	$A_{9,10}$	$A_{9,11}$	$A_{9,12}$	$A_{9,13}$	$A_{9,}$
			-1																	$A_{10,7}$	$A_{10,8}$	$A_{10,9}$	$A_{10,10}$	$A_{10,11}$	$A_{10,12}$	$A_{10,13}$	A_{1}
				-1																$A_{11,7}$	$A_{11,8}$	$A_{11,9}$	$A_{11,10}$	$A_{11,11}$	$A_{11,12}$	$A_{11,13}$	A_{1}
					-1															$A_{12,7}$	$A_{12,8}$	$A_{12,9}$	$A_{12,10}$	$A_{12,11}$	$A_{12,12}$	$A_{12,13}$	A_{1}
						-1														$A_{13,7}$	$A_{13,8}$	$A_{13,9}$	$A_{13,10}$	$A_{13,11}$	$A_{13,12}$	$A_{13,13}$	A_{1}
							-1													$A_{14,7}$	$A_{14,8}$	A_{1}	$A_{14,10}$	$A_{14,11}$	$A_{14,12}$	$A_{14,13}$	A_{1}
								-1												$A_{15,7}$	$A_{15,8}$	$A_{15,9}$	$A_{15,10}$	$A_{15,11}$	$A_{15,12}$	$A_{15,13}$	A_{1}
									-1											$A_{16,7}$	$A_{16,8}$	$A_{16,9}$	$A_{16,10}$	$A_{16,11}$	$A_{16,12}$	$A_{16,13}$	A_{1}
										-1										$A_{17,7}$	$A_{17,8}$	$A_{17,9}$	$A_{17,10}$	$A_{17,11}$	$A_{17,12}$	$A_{17,13}$	A_{1}
											-1									$A_{18,7}$	$A_{18,8}$	$A_{18,9}$	$A_{18,10}$	$A_{18,11}$	$A_{18,12}$	$A_{18,13}$	A_{1}
-1																				$-E_{1,1}$	$-E_{1,2}$	$-E_{1,3}$	$-E_{1,4}$	$-E_{1,5}$	$-E_{1,6}$	$-E_{1,7}$	$-E$
	-1																			$-E_{2,1}$	$-E_{2,2}$	$-E_{2,3}$	$-E_{2,4}$	$-E_{2,5}$	$-E_{2,6}$	$-E_{2,7}$	$-E$
		-1																		$-E_{3,1}$	$-E_{3,2}$	$-E_{3,3}$	$-E_{3,4}$	$-E_{3,5}$	$-E_{3,6}$	$-E_{3,7}$	$-E$
			-1																	$-E_{4,1}$	$-E_{4,2}$	$-E_{4,3}$	$-E_{4,4}$	$-E_{4,5}$	$-E_{4,6}$	$-E_{4,7}$	$-E$
				-1																$-E_{5,1}$	$-E_{5,2}$	$-E_{5,3}$	$-E_{5,4}$	$-E_{5,5}$	$-E_{5,6}$	$-E_{5,7}$	$-E$
					-1															$-E_{6,1}$	$-E_{6,2}$	$-E_{6,3}$	$-E_{6,4}$	$-E_{6,5}$	$-E_{6,6}$	$-E_{6,7}$	$-E$
						-1														$-E_{7,1}$	$-E_{7,2}$	$-E_{7,3}$	$-E_{7,4}$	$-E_{7,5}$	$-E_{7,6}$	$-E_{7,7}$	$-E$
							-1													$-E_{8,1}$	$-E_{8,2}$	$-E_{8,3}$	$-E_{8,4}$	$-E_{8,5}$	$-E_{8,6}$	$-E_{8,7}$	$-E$
								-1												$-E_{9,1}$	$-E_{9,2}$	$-E_{9,3}$	$-E_{9,4}$	$-E_{9,5}$	$-E_{9,6}$	$-E_{9,7}$	$-E$
									-1											$-E_{10,1}$	$-E_{10,2}$	$-E_{10,3}$	$-E_{10,4}$	$-E_{10,5}$	$-E_{10,6}$	$-E_{10,7}$	$-E$
										-1										$-E_{11,1}$	$-E_{11,2}$	$-E_{11,3}$	$-E_{11,4}$	$-E_{11,5}$	$-E_{11,6}$	$-E_{11,7}$	$-E$
											-1									$-E_{12,1}$	$-E_{12,2}$	$-E_{12,3}$	$-E_{12,4}$	$-E_{12,5}$	$-E_{12,6}$	$-E_{12,7}$	$-E$
												-1								$-E_{13,1}$	$-E_{13,2}$	$-E_{13,3}$	$-E_{13,4}$	$-E_{13,5}$	$-E_{13,6}$	$-E_{13,7}$	$-E$
													-1							$-E_{14,1}$	$-E_{14,2}$	$-E_{14,3}$	$-E_{14,4}$	$-E_{14,5}$	$-E_{14,6}$	$-E_{14,7}$	$-E$
														-1						$-E_{15,1}$	$-E_{15,2}$	$-E_{15,3}$	$-E_{15,4}$	$-E_{15,5}$	$-E_{15,6}$	$-E_{15,7}$	$-E$
															-1					$-E_{16,1}$	$-E_{16,2}$	$-E_{16,3}$	$-E_{16,4}$	$-E_{16,5}$	$-E_{16,6}$	$-E_{16,7}$	$-E$
																-1				$-E_{17,1}$	$-E_{17,2}$	$-E_{17,3}$	$-E_{17,4}$	$-E_{17,5}$	$-E_{17,6}$	$-E_{17,7}$	$-E$
																	-1			$-E_{18,1}$	$-E_{18,2}$	$-E_{18,3}$	$-E_{18,4}$	$-E_{18,5}$	$-E_{18,6}$	$-E_{18,7}$	$-E$
																		-1		$-E_{19,1}$	$-E_{19,2}$	$-E_{19,3}$	$-E_{19,4}$	$-E_{19,5}$	$-E_{19,6}$	$-E_{19,7}$	$-E$
																			-1	$-E_{20,1}$	$-E_{20,2}$	$-E_{20,3}$	$-E_{20,4}$	$-E_{20,5}$	$-E_{20,6}$	$-E_{20,7}$	$-E$

LICOPTER EQUATIONS OF MOTION IN MATRIX FORM

$_{7,10}$	$A_{7,11}$	$A_{7,12}$	$A_{7,13}$	$A_{7,14}$	$A_{7,15}$	$A_{7,16}$	$A_{7,17}$	$A_{7,18}$	V_1		$-F_X A_{7,1} - F_Y A_{7,2} - F_Z A_{7,3} - T_X A_{7,4} - T_Y A_{7,5} - T_Z A_{7,6}$
$_{8,10}$	$A_{8,11}$	$A_{8,12}$	$A_{8,13}$	$A_{8,14}$	$A_{8,15}$	$A_{8,16}$	$A_{8,17}$	$A_{8,18}$	V_2		$-F_X A_{8,1} - F_Y A_{8,2} - F_Z A_{8,3} - T_X A_{8,4} - T_Y A_{8,5} - T_Z A_{8,6}$
$_{9,10}$	$A_{9,11}$	$A_{9,12}$	$A_{9,13}$	$A_{9,14}$	$A_{9,15}$	$A_{9,16}$	$A_{9,17}$	$A_{9,18}$	V_3		$-F_X A_{9,1} - F_Y A_{9,2} - F_Z A_{9,3} - T_X A_{9,4} - T_Y A_{9,5} - T_Z A_{9,6}$
$_{10,10}$	$A_{10,11}$	$A_{10,12}$	$A_{10,13}$	$A_{10,14}$	$A_{10,15}$	$A_{10,16}$	$A_{10,17}$	$A_{10,18}$	V_4		$-F_X A_{10,1} - F_Y A_{10,2} - F_Z A_{10,3} - T_X A_{10,4} - T_Y A_{10,5} - T_Z A_{10,6}$
$_{11,10}$	$A_{11,11}$	$A_{11,12}$	$A_{11,13}$	$A_{11,14}$	$A_{11,15}$	$A_{11,16}$	$A_{11,17}$	$A_{11,18}$	V_5		$-F_X A_{11,1} - F_Y A_{11,2} - F_Z A_{11,3} - T_X A_{11,4} - T_Y A_{11,5} - T_Z A_{11,6}$
$_{12,10}$	$A_{12,11}$	$A_{12,12}$	$A_{12,13}$	$A_{12,14}$	$A_{12,15}$	$A_{12,16}$	$A_{12,17}$	$A_{12,18}$	V_6		$-F_X A_{12,1} - F_Y A_{12,2} - F_Z A_{12,3} - T_X A_{12,4} - T_Y A_{12,5} - T_Z A_{12,6}$
$_{13,10}$	$A_{13,11}$	$A_{13,12}$	$A_{13,13}$	$A_{13,14}$	$A_{13,15}$	$A_{13,16}$	$A_{13,17}$	$A_{13,18}$	V_7		$-F_X A_{13,1} - F_Y A_{13,2} - F_Z A_{13,3} - T_X A_{13,4} - T_Y A_{13,5} - T_Z A_{13,6}$
$_{14,10}$	$A_{14,11}$	$A_{14,12}$	$A_{14,13}$	$A_{14,14}$	$A_{14,15}$	$A_{14,16}$	$A_{14,17}$	$A_{14,18}$	V_8		$-F_X A_{14,1} - F_Y A_{14,2} - F_Z A_{14,3} - T_X A_{14,4} - T_Y A_{14,5} - T_Z A_{14,6}$
$_{15,10}$	$A_{15,11}$	$A_{15,12}$	$A_{15,13}$	$A_{15,14}$	$A_{15,15}$	$A_{15,16}$	$A_{15,17}$	$A_{15,18}$	V_9		$-F_X A_{15,1} - F_Y A_{15,2} - F_Z A_{15,3} - T_X A_{15,4} - T_Y A_{15,5} - T_Z A_{15,6}$
$_{16,10}$	$A_{16,11}$	$A_{16,12}$	$A_{16,13}$	$A_{16,14}$	$A_{16,15}$	$A_{[illegible],16}$	$A_{16,17}$	$A_{16,18}$	V_{10}		$-F_X A_{16,1} - F_Y A_{16,2} - F_Z A_{16,3} - T_X A_{16,4} - T_Y A_{16,5} - T_Z A_{16,6}$
$_{17,10}$	$A_{17,11}$	$A_{17,12}$	$A_{17,13}$	$A_{17,14}$	$A_{17,15}$	$A_{17,16}$	$A_{17,17}$	$A_{17,18}$	V_{11}		$-F_X A_{17,1} - F_Y A_{17,2} - F_Z A_{17,3} - T_X A_{17,4} - T_Y A_{17,5} - T_Z A_{17,6}$
$_{18,10}$	$A_{18,11}$	$A_{18,12}$	$A_{18,13}$	$A_{18,14}$	$A_{18,15}$	$A_{18,16}$	$A_{17,18}$	$A_{18,18}$	V_{12}		$-F_X A_{18,1} - F_Y A_{18,2} - F_Z A_{18,3} - T_X A_{18,4} - T_Y A_{18,5} - T_Z A_{18,6}$
$E_{1,4}$	$-E_{1,5}$	$-E_{1,6}$	$-E_{1,7}$	$-E_{1,8}$	$-E_{1,9}$	$-E_{1,10}$	$-E_{1,11}$	$-E_{1,12}$	V_{13}		$-P_Y E_{1,13} - P_Z E_{1,14}$
$E_{2,4}$	$-E_{2,5}$	$-E_{2,6}$	$-E_{2,7}$	$-E_{2,8}$	$-E_{2,9}$	$-E_{2,10}$	$-E_{2,11}$	$-E_{2,12}$	V_{14}		$-P_Y E_{2,13} - P_Z E_{2,14}$
$E_{3,4}$	$-E_{3,5}$	$-E_{3,6}$	$-E_{3,7}$	$-E_{3,8}$	$-E_{3,9}$	$-E_{3,10}$	$-E_{3,11}$	$-E_{3,12}$	V_{15}	=	$-P_Y E_{3,13} - P_Z E_{3,14}$
$E_{4,4}$	$-E_{4,5}$	$-E_{4,6}$	$-E_{4,7}$	$-E_{4,8}$	$-E_{4,9}$	$-E_{4,10}$	$-E_{4,11}$	$-E_{4,12}$	V_{16}		$-P_Y E_{4,13} - P_Z E_{4,14}$
$E_{5,4}$	$-E_{5,5}$	$-E_{5,6}$	$-E_{5,7}$	$-E_{5,8}$	$-E_{5,9}$	$-E_{5,10}$	$-E_{5,11}$	$-E_{5,12}$	V_{17}		$-P_Y E_{5,13} - P_Z E_{5,14}$
$E_{6,4}$	$-E_{6,5}$	$-E_{6,6}$	$-E_{6,7}$	$-E_{6,8}$	$-E_{6,9}$	$-E_{6,10}$	$-E_{6,11}$	$-E_{6,12}$	V_{18}		$-P_Y E_{6,13} - P_Z E_{6,14}$
$E_{7,4}$	$-E_{7,5}$	$-E_{7,6}$	$-E_{7,7}$	$-E_{7,8}$	$-E_{7,9}$	$-E_{7,10}$	$-E_{7,11}$	$-E_{7,12}$	V_{19}		$-P_Y E_{7,13} - P_Z E_{7,14}$
$E_{8,4}$	$-E_{8,5}$	$-E_{8,6}$	$-E_{8,7}$	$-E_{8,8}$	$-E_{8,9}$	$-E_{8,10}$	$-E_{8,11}$	$-E_{8,12}$	V_{20}		$-P_Y E_{8,13} - P_Z E_{8,14}$
$E_{9,4}$	$-E_{9,5}$	$-E_{9,6}$	$-E_{9,7}$	$-E_{9,8}$	$-E_{9,9}$	$-E_{9,10}$	$-E_{9,11}$	$-E_{9,12}$	F_1		$-P_Y E_{9,13} - P_Z E_{9,14}$
$E_{10,4}$	$-E_{10,5}$	$-E_{10,6}$	$-E_{10,7}$	$-E_{10,8}$	$-E_{10,9}$	$-E_{10,10}$	$-E_{10,11}$	$-E_{10,12}$	F_2		$-P_Y E_{10,13} - P_Z E_{10,14}$
$E_{11,4}$	$-E_{11,5}$	$-E_{11,6}$	$-E_{11,7}$	$-E_{11,8}$	$-E_{11,9}$	$-E_{11,10}$	$-E_{11,11}$	$-E_{11,12}$	F_3		$-P_Y E_{11,13} - P_Z E_{11,14}$
$E_{12,4}$	$-E_{12,5}$	$-E_{12,6}$	$-E_{12,7}$	$-E_{12,8}$	$-E_{12,9}$	$-E_{12,10}$	$-E_{12,11}$	$-E_{12,12}$	F_4		$-P_Y E_{12,13} - P_Z E_{12,14}$
$E_{13,4}$	$-E_{13,5}$	$-E_{13,6}$	$-E_{13,7}$	$-E_{13,8}$	$-E_{13,9}$	$-E_{13,10}$	$-E_{13,11}$	$-E_{13,12}$	F_5		$-P_Y E_{13,13} - P_Z E_{13,14}$
$E_{14,4}$	$-E_{14,5}$	$-E_{14,6}$	$-E_{14,7}$	$-E_{14,8}$	$-E_{14,9}$	$-E_{14,10}$	$-E_{14,11}$	$-E_{14,12}$	F_6		$-P_Y E_{14,13} - P_Z E_{14,14}$
$E_{15,4}$	$-E_{15,5}$	$-E_{15,6}$	$-E_{15,7}$	$-E_{15,8}$	$-E_{15,9}$	$-E_{15,10}$	$-E_{15,11}$	$-E_{15,12}$	F_7		$-P_Y E_{15,13} - P_Z E_{15,14}$
$E_{16,4}$	$-E_{16,5}$	$-E_{16,6}$	$-E_{16,7}$	$-E_{16,8}$	$-E_{16,9}$	$-E_{16,10}$	$-E_{16,11}$	$-E_{16,12}$	F_8		$-P_Y E_{16,13} - P_Z E_{16,14}$
$E_{17,4}$	$-E_{17,5}$	$-E_{17,6}$	$-E_{17,7}$	$-E_{17,8}$	$-E_{17,9}$	$-E_{17,10}$	$-E_{17,11}$	$-E_{17,12}$	F_9		$-P_Y E_{17,13} - P_Z E_{17,14}$
$E_{18,4}$	$-E_{18,5}$	$-E_{18,6}$	$-E_{18,7}$	$-E_{18,8}$	$-E_{18,9}$	$-E_{18,10}$	$-E_{18,11}$	$-E_{18,12}$	F_{10}		$-P_Y E_{18,13} - P_Z E_{18,14}$
$E_{19,4}$	$-E_{19,5}$	$-E_{19,6}$	$-E_{19,7}$	$-E_{19,8}$	$-E_{19,9}$	$-E_{19,10}$	$-E_{19,11}$	$-E_{19,12}$	F_{11}		$-P_Y E_{19,13} - P_Z E_{19,14}$
$E_{20,4}$	$-E_{20,5}$	$-E_{20,6}$	$-E_{20,7}$	$-E_{20,8}$	$-E_{20,9}$	$-E_{20,10}$	$-E_{20,11}$	$-E_{20,12}$	F_{12}		$-P_Y E_{20,13} - P_Z E_{20,14}$

Certain features of the mobility approach to system analysis can be characterized. The approach involves a frequency domain representation of the subsystems in terms of its subsystem driving point and transfer mobilities. The response calculations are performed in the frequency domain and include the true damping effects inherent in the subsystem mobilities. Although it was not developed in this discussion, it is possible to obtain the damped eigenvalues of the coupled system. This approach is amenable to the use of either test data or calculated mobilities.

There are some substantial advantages to the use of the mobility approach. The effects of the subsystem mass, stiffness, and damping are considered. If the mobility data used have been obtained from test, these subsystem parameters are the true system values. The numerical computations involved are simple solutions to simultaneous equations performed using complex arithmetic. The computation can be performed on a digital computer at relatively low cost.

Some disadvantages to the use of this approach are also present. Where complex systems are to be modeled, large volumes of mobility data are required. These data must be generated and digitized for digital computer simulation and use. Once the model has been established and the data generated, only motion at those points which were included in the model can be obtained. This requires a very accurate definition of the model at the inception. If test data are to be used, and the subsystem is nonlinear it should be obtained at the actual force levels expected so that the actual damping, stiffness, and mass effects are representative. Variations in the subsystems can only be studied by changing the input mobilities. If the subsystem under consideration has any rotating components which can cause gyroscopic effects, these effects must be present when the subsystem mobilities are generated (which is generally not feasible). An approach to adding the gyroscopic effects after the mobilities have been generated has not been developed in this study.

This portion of the Analysis Method Development section has been concerned with the development of the mobility method as applied by DDA. The approach has been shown to be valid by proving equivalence to the classical approach to system analysis. Some simple models have been discussed to demonstrate the utility of the method, and the specific application of the method to the OH-6 and OH-58 helicopter systems has been developed. A discussion of advantages and disadvantages of the mobility method was presented.

MODAL SYNTHESIS

Modal synthesis is a method for analytically determining the dynamics of a system in terms of the modal representation of its subsystems. This approach is similar to the impedance/mobility method in that it affords the study of interface requirements without altering the subsystem dynamics. The main difference is that the subsystem is represented in terms of a set of normal modes instead of mobilities. The development of the modal synthesis technique for the coupling of two dynamic subsystems is discussed.

The general approach is to form the kinetic and potential energy expressions for the subsystems and the potential energy expression for any coupling (interface) springs in terms of the subsystem uncoupled modes. The Lagrange equations are then applied to produce the coupled system modal equations of motion. Conventional means are used to solve these equations to determine the coupled system's eigenvalues and associated eigenvectors. The concept of modal structural damping is used and the virtual work of various excitation forces is developed to produce a set of forced equations of motion. Again these are solved using conventional means to generate the response deflection shape for each frequency of interest.

For each of the uncoupled modes of a subsystem, the following relationships exist:

$$\text{Kinetic Energy} = T = \sum_{i=1}^{n} 1/2\, m_i \left[\dot{h}_i(i,t)\right]^2 \tag{26}$$

where

$h(i,t) = h(t) \cdot f(i)$
$h(t)$ = time history
$f(i)$ = mode shape
m_i = ith mass element
n = number of mass elements

Equation (26) includes the assumption that the uncoupled modes are orthogonal. So,

$$T = 1/2\, \dot{h}^2(t) \sum_{i=1}^{n} m_i f^2(i) \tag{27}$$

or since $\dot{h}(t)$ represents the modal velocity, the kinetic energy for the mode becomes

$$T = 1/2 \ \mathcal{M} \ \dot{h}^2(t) \tag{28}$$

where

$$\mathcal{M} = \sum_{i=1}^{n} m_i f^2(i) \tag{29}$$

is the modal (weighted) mass.

The conservation of energy states:

$$\text{Kinetic Energy (T) + Potential Energy (V) = constant} \tag{30}$$

Then, if

$$h(t) = h_o \sin \omega_n t$$

$$\dot{h}(t) = h_o \omega_n \cos \omega_n t$$

So,

$$1/2 \ \mathcal{M} \ h_o^2 \omega_n^2 \cos^2 \omega_n t + V = \text{constant}$$

When the modal deflection is zero, the potential energy $V = 0$ and $h(t) = h_o \sin \omega_n t = 0$ and $\sin \omega_n t = 0$ and $\cos \omega_n t = \pm 1$.

For this condition

$$1/2 \ \mathcal{M} \ h_o^2 \omega_n (\pm 1)^2 + 0 = \text{constant}$$

or

$$\text{constant} = 1/2 \ \mathcal{M} \ h_o^2 \omega_n^2$$

Then

$$V = \text{constant} - T$$

$$= 1/2 \ \mathcal{M} \ h_o^2 \omega_n^2 - 1/2 \ \mathcal{M} \ h_o^2 \omega_n^2 \cos^2 \omega_n t$$

$$= 1/2 \ \mathcal{M} \ h_o^2 \omega_n^2 \sin^2 \omega_n t$$

$$= 1/2 \ \mathcal{M} \ \omega_n^2 \ h^2(t)$$

or

$$V = 1/2 \ \mathbf{K} \ h^2(t) \tag{31}$$

where $\mathbf{K} = \mathcal{M} \omega_n^2$ is the modal stiffness.

Another type of potential energy term results from consideration of the supports whether between subsystems or a support to ground. The potential energy of an inter-subsystem support has the form

$$V = 1/2 \ K_S \left[Y_1(S) - Y_2(S)\right]^2 \tag{32}$$

where

K_S = spring rate of support attaching subsystem 1 to subsystem 2 at station S.

$Y_1(S)$ = deflection of subsystem 1 at station S

$Y_2(S)$ = deflection of subsystem 2 at station S

For each subsystem the deflection at any station S can be represented as

$$Y_K \ (S, t) = \sum_{i=1}^{n2} h_{Ki}(t) \cdot f_{Ki}(S) \tag{33}$$

where n2 is the number of modes. Combining Equations (32) and (33) yields

$$V = 1/2 \ K_S \left\{ \sum_{i=1}^{n} h_{1i}(t) \ f_{1i}(S) - \sum_{i=1}^{m} h_{2i}(t) \ f_{2i}(S) \right\}^2 \tag{34}$$

where

n = No. modes for subsystem 1

m = No. modes for subsystem 2

Similarly, the potential energy of a support to ground from any subsystem K at station S is

$$V = 1/2\, K_S \left[\sum_{i=1}^{m} h_{Ki}(t)\, f_{Ki}(S) \right]^2 \qquad (35)$$

Therefore, all the energy relationships can be written as a function of the uncoupled modes.

If $\mathcal{M}_{ij}$ and $\mathbf{K}_{ij}$ represent the modal masses and stiffnesses for the jth mode of the ith subsystem, the total kinetic energy becomes

$$T_{total} = 1/2 \sum_{i=1}^{n1} \sum_{j=1}^{n2(i)} \mathcal{M}_{ij}\, \dot{h}_{ij}^2(t) \qquad (36)$$

where

n1 = number of subsystems

n2(i) = number of modes in each subsystem

The total potential energy becomes

$$\begin{aligned} V_{total} = {} & 1/2 \sum_{i=1}^{n1} \sum_{j=1}^{n2(i)} \mathbf{K}_{ij}\, h_{ij}^2(t) \\ & + 1/2\, K_P \left[\sum_{i=1}^{n2(K)} h_{Ki}(t)\, f_{Ki}(P) - \sum_{i=1}^{n2(L)} h_{Li}(t)\, f_{Li}(P) \right]^2 \\ & + 1/2\, K_Q \left[\sum_{i=1}^{n2(f)} h_{fi}(t)\, f_{fi}(Q) - \sum_{i=1}^{n2(g)} h_{gi}(t)\, f_{gi}(P) \right]^2 \\ & + 1/2\, K_S \left[\sum_{i=1}^{n2(V)} h_{Vi}(t)\, f_{VI}(S) \right]^2 \end{aligned} \qquad (37)$$

where K_P represents the rate of a spring attached at station P from the Kth subsystem to the Lth subsystem and K_Q is the rate of a spring attached at station Q from the fth subsystem to the gth subsystem. K_S is the spring rate of a support from ground to station S on the Vth subsystem. Specifically for the OH-58 and OH-6 helicopters, there are only two subsystems. Therefore,

$$T = 1/2 \sum_{i=1}^{n1} M_{Hi} \dot{h}_{Hi}^{2}(t) + 1/2 \sum_{i=1}^{n2} M_{Ei} \dot{h}_{Ei}^{2}(t) \tag{38}$$

$$\begin{aligned} V = {} & 1/2 \sum_{i=1}^{n1} K_{Hi} h_{Hi}^{2}(t) + 1/2 \sum_{i=1}^{n2} K_{Ei} h_{Ei}^{2}(t) \\ & + 1/2 \sum_{P=P(1)}^{P(NC)} K_P \left[\sum_{i=1}^{n1} h_{Hi}(t) f_{Hi}(P) - \sum_{i=1}^{n2} h_{Ei}(t) f_{Ei}(P) \right]^2 \\ & + 1/2 \sum_{S=S(1)}^{S(NGH)} K_S \left[\sum_{i=1}^{n1} h_{Hi}(t) f_{Hi}(S) \right]^2 \\ & + 1/2 \sum_{Q=Q(1)}^{Q(NGE)} K_Q \left[\sum_{i=1}^{n1} h_{Ei}(t) f_{Ei}(Q) \right]^2 \end{aligned} \tag{39}$$

where

NC = number of coupling springs
NGH = number of helicopter springs to ground
NGE = number of engine springs to ground
n1 = number of helicopter modes
n2 = number of engine modes

Lagrange's equations of free motion can be written in terms of modal coordinates[8] as

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{h}_{Ki}}\right) + \frac{\partial V}{\partial h_{Ki}} = 0 \tag{40}$$

[8] Scanlan, R. H., and Rosenbaum, R. AIRCRAFT VIBRATION AND FLUTTER, The MacMillan Company, New York, 1951.

where h_{Kj} is the motion of the ith mode of the Kth subsystem. Then, the ith equation in the helicopter set is:

$$\mathcal{M}_{Hi}\,\ddot{h}_{Hi}(t) + \mathbf{K}_{Hi}\,h_{Hi}(t)$$

$$+ \sum_{P=P(1)}^{P(NC)} K_P\,f_{Hi}(P)\left[\sum_{i=1}^{n1} h_{Hi}(t)\,f_{Hi}(P) - \sum_{i=1}^{n2} h_{Ei}(t)\,f_{Ei}(P)\right] \tag{41}$$

$$+ \sum_{S=S(1)}^{S(NGH)} K_S\,f_{Hi}(S)\sum_{i=1}^{n1} h_{Hi}(t)\,f_{Hi}(S) = 0$$

Similarly, the ith equation in the engine set is:

$$\mathcal{M}_{Ei}\,\ddot{h}_{Ei}(t) + \mathbf{K}_{Ei}\,h_{Ei}(t)$$

$$- \sum_{P=P(1)}^{P(NC)} K_P\,f_{Ei}(P)\left[\sum_{i=1}^{n1} h_{Hi}(t)\,f_{Hi}(P) - \sum_{i=1}^{n2} h_{Ei}(t)\,f_{Ei}(P)\right] \tag{42}$$

$$+ \sum_{Q=Q(1)}^{Q(NGE)} K_Q\,f_{Ei}(Q)\sum_{i=1}^{n1} h_{Ei}(t)\,f_{Ei}(Q) = 0$$

In this manner the modal equations of motion are developed. These are:

$$\left[M\right]\left\{\ddot{h}\right\} + \left[K\right]\left\{h\right\} = 0 \tag{43}$$

The solution of Equation (43) for the eigenvalues and associated eigenvectors was determined using a conventional matrix power procedure.[9,10] The results of this eigenvalue solution are the coupled system critical speeds. The accompanying eigenvectors are the subsystem modal participation factors. If the elements of the eigenvector are h_{HI}^* and h_{Ei}^* for the helicopter and engine respectively, the real space deflections of each subsystem are defined as:

$$\delta_H(k) = \sum_{i=1}^{n1} h_{Hi}^{*}\,f_{Hi}(k) \qquad \delta_E(k) = \sum_{i=1}^{n2} h_{Ei}^{*}\,f_{Ei}(k) \tag{44}$$

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9 Wilkinson, J. H. THE ALGEBRAIC EIGENVALUE PROBLEM, Clarendon Press, Oxford, 1965.

10 Crandall, S. H. ENGINEERING ANALYSIS, McGraw-Hill Book Company, New York, 1956.

where $\delta_H(k)$ and $\delta_E(k)$ are the deflections at the kth station for the helicopter and engine respectively.

At this point in the discussion only the free vibration problem has been presented. The forced vibration problem can be solved if we include the effects of the forcing function and system damping.

For aircraft structures a simplified concept is often used. It is assumed that the damping force is proportional to the elastic restoring force in magnitude, and directly opposes the velocity of motion. For small damping and harmonic oscillation, the stiffness values are modified by a factor (1+jg), where g is called the structural damping factor and is of the order 0.02-0.08 for metal aircraft structures (Reference 8) and j denotes a 90-degree phase shift from displacement. Therefore, each individual spring stiffness in the formulation (i.e., coupling and springs to ground) becomes:

$$\text{Dynamic Stiffness} = (1+jg)\,K \tag{45}$$

where K is the stiffness of a single spring. The system damping is incorporated as modal structural damping as

$$\text{Dynamic modal stiffness} = (1+jg)\,\mathbf{K} \tag{46}$$

for each mode. There it is assumed that each mode of a subsystem has the same structural damping. A more general formulation could include a separate damping value for each mode. The potential energy of the coupled system then alters Equation (39) to be:

$$\begin{aligned} V = {} & 1/2 \sum_{i=1}^{n1} (1+jg_H)\mathbf{K}_{Hi}\, h_{Hi}^2(t) + 1/2 \sum_{i=1}^{n2} (1+jg_E)\mathbf{K}_{Ei}\, h_{Ei}^2(t) \\ & + 1/2 \sum_{P=P(1)}^{P(NC)} (1+jg(P))\, K_P \left[\sum_{i=1}^{n1} h_{Hi}(t)\, f_{Hi}(P) - \sum_{i=1}^{n2} h_{Ei}(t)\, f_{Ei}(P) \right]^2 \\ & + 1/2 \sum_{S=S(1)}^{S(NGH)} (1+jg(S))\, K_S \left[\sum_{i=1}^{n1} h_{Hi}(t)\, f_{Hi}(S) \right]^2 \\ & + 1/2 \sum_{Q=Q(1)}^{Q(NGE)} (1+jg(Q))\, K_Q \left[\sum_{i=1}^{n2} h_{Ei}(t)\, f_{Ei}(Q) \right]^2 \end{aligned} \tag{47}$$

The virtual work done by an excitation force F at station R on subsystem K for the ith mode is

$$\delta \text{Work} = F(R) \qquad \delta h_{Ki}\, f_{Ki}(R) \tag{48}$$

The ith generalized force is

$$Q_{Ki} = \frac{\delta \text{Work}}{\delta h_{Ki}} = F(R)\, f_{Ki}(R) \tag{49}$$

For the combined system the Lagrange equations of forced motion are:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{h}_{Ki}}\right) + \frac{\partial V}{\partial h_{Ki}} = Q_{Ki} \tag{50}$$

Then the ith equation of motion for the helicopter is:

$$\mathcal{M}_{Hi}\, \ddot{h}_{Hi}(t) + (1+jg)\mathcal{K}_{Hi}\, h_{Hi}(t) \tag{51}$$

$$+ \sum_{P=P(1)}^{P(NC)} (1+jg(P))\, K_P\, f_{Hi}(P) \left[\sum_{i=1}^{n1} h_{Hi}(t)\, f_{Hi}(P) - \sum_{i=1}^{n2} h_{Ei}(t)\, f_{Ei}(P)\right]$$

$$+ \sum_{S=S(1)}^{S(NGH)} (1+jg(S))\, K_S\, f_{Hi}(S) \sum_{i=1}^{n1} h_{Hi}(t)\, f_{Hi}(S) = \sum_{R=R(1)}^{R(NFH)} F(R)\, f_{Hi}(R)$$

where NFH is the number of forces applied to the helicopter.

The ith equation of motion for the engine is:

$$\mathcal{M}_{Ei}\, \ddot{h}_{Ei}(t) + (1+ig)\mathcal{K}_{Ei}\, h_{Ei}(t) \tag{52}$$

$$- \sum_{P=P(1)}^{P(NC)} (1+jg(P))\, K_P\, f_{Ei}(P) \left[\sum_{i=1}^{n1} h_{Hi}(t)\, f_{Hi}(P) - \sum_{i=1}^{n2} h_{Ei}(t)\, f_{Ei}(P)\right]$$

$$+ \sum_{Q=Q(1)}^{Q(NGE)} (1+jg(Q))\, K_Q\, f_{Ei}(Q) \sum_{i=1}^{n1} h_{Ei}(t) f_{Ei}(Q) = \sum_{T=T(1)}^{T(NFE)} F(T)\, f_{Ei}(T)$$

where NFE is the number of forces applied to the engine. In this manner the modal equations of forced vibrations are developed

$$[M] \{\ddot{h}\} + [K_c] \{h\} = \{Q\} \tag{53}$$

where K_c indicates a complex stiffness matrix.

These equations are in complex form in terms of the complex modal deflections h.

The Q's are sinusoidal complex forces to provide the capability of preserving the phase between forces. These forces can be expressed as rotating vectors as

$$Q = Q_o e^{j\omega t} \tag{54}$$

The modal deflections are of the form

$$h = h_o e^{j(\omega t - \phi)} = h_o e^{j\omega t} e^{-j\phi} \tag{55}$$

where ϕ is the phase lag angle with respect to the force.

Substituting Equations (54) and (55) into Equation (53) yields

$$-\omega^2 [M] \{h_c\} + [K_c] \{h_c\} = \{Q_o\}$$

where $h_c = h_o e^{-j\phi}$ = complex modal deflection

or

$$\Big[[K_c] - [M] \omega^2\Big] \{h_c\} = \{Q_o\} \tag{56}$$

This is a set of linear complex algebraic equations in terms of the modal responses h_c. Solutions are of the form $a + b_j$, which indicates the modal amplitude of response and the phase relationship with respect to the exciting forces. The real space deflections can easily be determined using Equation (44).

A computer program, MODSYN, has been written to generate and solve the equations derived here. A listing of the computer program is included in Appendix D. The program is written in FORTRAN IV language for the IBM 370/165 computer. Also included with the listing is an input data format sheet and glossary of terms.

One consideration which has not been discussed at this point is the inclusion of gyroscopic effects in the modal synthesis analysis. In general these effects can be significant, not only in coupling off-axis rotation but also in changing the natural frequency of some system modes. Gyroscopic effects were not included in this modal synthesis presentation since they were found to have little effect upon the system modes and responses within the frequency range of interest. What is discussed here is a suggested approach to including these effects.

The gyroscopic terms in the equations of motion are generally included as part of the kinetic energy as:[11]

$$T = 1/2\, I_P\, (2\Omega\, \dot{\theta}\, \psi) \tag{57}$$

where

I_P = polar moment of inertia

Ω = rotor speed

$\dot{\theta}$ = pitching velocity

ψ = yaw rotation

or, in terms of uncoupled modes of the kth subsystem and for one inertia per subsystem

$$T = I_P(k)\Omega \sum_{i=1}^{NM(k)} \dot{h}_i(t)\, f_{Ki}(A) \sum_{j=1}^{NM(k)} h_j(t)\, f_{Kj}(B) \tag{58}$$

where

A = pitch displacement of I_P

B = yaw displacement of I_P

NM(k) = number of modes per subsystem

Then,

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{h}_i(t)}\right) = I_P(k)\Omega\, f_{Ki}(A) \sum_{j=1}^{NM(k)} \dot{h}_j(t)\, f_{Kj}(B) \tag{59}$$

[11] Myklestad, N. O. FUNDAMENTALS OF VIBRATION ANALYSIS, McGraw-Hill, New York, 1956.

There then appears an additive term on the left-hand side of the differential equations of motion, Equations (43) and (53), $[I]\{\dot{h}\}$ where the elements of the matrix $[I]$ are

$$I_{ij} = \sum_{k=1}^{NSYS} \sum_{l=1}^{NiP(k)} I_{P_l}(k)\,\Omega\, f_{ki}(A)\, f_{kj}(B) \tag{60}$$

where

NSYS = number of subsystems

NiP(k) = number of inertias per subsystem

By this means the gyroscopic effects of the main and/or tail rotors and the engine gas generator and power turbine rotors can be included. This requires that significant inertias be supplied along with the rotations at the inertia stations of each mode. It should be pointed out that after inclusion of Equation (60) in Equation (43) a determinantal solution for the eigenvalues is required.

The modal synthesis technique of analysis is basically a computational tool for coupled system study in terms of a finite set of the subsystem uncoupled modes. This approach is amenable to eigenvalue and forced response calculation.

There are certain advantages which can be enjoyed using this approach. Since the subsystems are described as a finite set of uncoupled modes, the size of the eigenvalue problem and the forced response problem are reduced, and computations can be effected in relatively short time and low cost on a digital computer. Also there is a low volume of input data required in the analysis. Although it has not been applied in this analysis, it has been shown that gyroscopic effects can be included in this approach.

There are also disadvantages associated with the use of the modal synthesis technique. Since the subsystems are represented in terms of a finite set of uncoupled modes, these modes must be generated by some means and the finite number must be sufficiently large to accurately model the coupled system for the frequency range of interest. These modes can be generated from test but their orthogonality, a necessary condition in Equation (26), would be suspect. A more often used approach is to develop and exercise a spring-mass model of the subsystem and correlate the resulting modes with those of an accompanying test. It is also necessary to input modal damping to the analysis. Subsystem parameters cannot be varied without regenerating the subsystem modes. This does not imply that coupling flexibilities cannot readily be varied.

The modal synthesis technique for coupled system dynamic analysis has been presented. The technique has been applied to the OH-6 and OH-58 helicopters for the eigenvalue and forced response solutions. A computer program, generated for the modal synthesis solution for the coupled system dynamics of two subsystems has been presented. A discussion of the features, advantages, and disadvantages of this method of analysis completed the development.

DIRECT STIFFNESS

The direct stiffness approach to dynamic analysis is perhaps the most widely used technique available for dynamic systems. In general this approach involves the generation of mass and stiffness matrices by considering the real properties (geometry, material modulii, temperatures, etc.) of the dynamic system. Examples are the Myklestad Method (Reference 9) for beam analysis and the various finite element analyses such as those included in NASTRAN.[12,13] They all have one thing in common, the dynamic system is modeled on an elemental basis.

The direct stiffness approach can be a subset of the mobility and modal approaches. If the mobilities are generated analytically, they can be generated from an elemental model of the particular subsystem. Similarly, the uncoupled modes of the subsystems for a modal synthesis approach can be generated using a direct stiffness model. It is the intent here to consider the direct stiffness approach as applied to the entire helicopter system, not the airframe and engine separately. This discussion is limited to total system modeling of the helicopter.

For many years the helicopter has been modeled and analyzed using direct stiffness methods. By this approach the fuselage structure could be described in terms of elemental beams, skins, and stringers, thereby, yielding a sophisticated model of the fuselage. As is generally the case, the powerplant is treated as a rigid body having the proper mass distribution and connected to the fuselage at the correct mounting points. However, engine case flexibilities and engine rotor/case interactions are almost never considered simultaneously with the fuselage. Potential vibration problems involving helicopter excitation and engine response

[12] Butler, T. G., and Michel, D. NASTRAN, A SUMMARY OF THE FUNCTIONS AND CAPABILITIES OF THE NASA STRUCTURAL ANALYSIS COMPUTER SYSTEM, NASA SP-260, 1971.

[13] McCormick, C. W. NASTRAN BEGINNER'S GUIDE, MS 139-1, prepared for NASA Langley Research Center, Hampton, Virginia, by the MacNeal-Schwendler Corporation.

(and vice versa) can be overlooked. In addition, potential coupled helicopter shafting and engine rotor/case vibration problems cannot be detected. These considerations cannot reasonably be included with the fuselage or the model would become too unwieldy. For this reason, substructuring techniques have been developed.

There are some very specific advantages which make the direct stiffness method attractive. Solutions to the eigenvalue and forced response problems are performed in real space (a configuration space where the coordinates are in real dimension, pounds, inches, seconds, etc) thereby, having direct correspondence with the model. Another advantage of having real space coordinates is the ease by which gyroscopic effects can be incorporated. Since the system is composed of elemental representation, structural or mass changes within the system can easily be studied without complicating the solution.

There are also some inherent disadvantages to the use of a direct stiffness technique. In order to include significant aspects of the design the model becomes large. Therefore, the solution for the eigenvalues and/or the forced response requires long, expensive computer runs. Often times very large problems, which likely occur with helicopter systems, require a large amount of computer core space to accommodate their solution. Since computer space and time are at a premium, slow turnaround of solutions is common. Because of the complexity of the model itself, long lead time and a large manpower is required for the definition.

The direct stiffness method of analysis for dynamic systems has been used for many years. Derivation and application approaches are well documented in the literature and were not presented. Rather, this has been a discourse on the possible application of this method while citing some advantages and disadvantages to be used in a comparative analysis with other methods.

ANALYSIS METHOD COMPARISON

Three methods of analysis for helicopter dynamic systems have been developed. The features, advantages, and disadvantages of each method have been presented. This section discusses a comparison of these methods of helicopter analysis with respect to:

- Ability of method to include results of shake test data
- Versatility and complexity of use
- Completeness
- Applicability as a specification method

Each method includes the ability to assimilate the results of shake test data, but only the mobility method can rely exclusively on these data. If the airframe and engine subsystem shake tests are directed toward generating the necessary driving point and transfer mobilities, these shake test data can be used as the actual input to the analysis. If the mobilities are to be generated by a direct stiffness subsystem analytical model (NASTRAN), the modeling can be adjusted to check with the shake test data. The modal synthesis and direct stiffness methods cannot use shake test data directly but, similar to the mobility method, can use test data to correlate with the model.

These methods can be ranked according to their versatility in the following order:

1. Stiffness
2. Modal
3. Mobility

Once the models have been generated for each method, changes in the airframe and/or engine can readily be made in the stiffness model. Without generating new subsystem modal descriptions, only the airframe/engine coupling flexibilities can be altered in the modal model. If the mobility model has not been formulated to treat the airframe/engine coupling elements as subsystems, no changes to the mobility model can be evaluated without regenerating the subsystem mobilities.

If shake test data are available for each subsystem, the mobility method is the least complex approach to use. However, if analytical mobilities and uncoupled modes must be used, the methods are equally complex since the subsystem inputs to the mobility and modal synthesis methods must be generated from some type of stiffness method model.

If accurate test data are available, the mobility method is the most complete. Actual subsystem masses, stiffnesses, and damping are represented. If test data are not available, each method is equivalent, since again the direct stiffness method is used to generate data for the other models.

As a specification method, the direct stiffness approach would be least suitable. To require this method as a specification would require a large amount of detailed mass-elastic data be made available. It would also put an unreasonable burden on the user to have the capability to utilize this information. For example, the engine and airframe manufacturers might be required to supply NASTRAN data decks describing the mass-elastic model of their respective subsystems. This would imply that the party having system responsibility is prepared to bear the cost and has the expertise to operate NASTRAN. It would appear more likely that the less costly mobility and/or modal methods could be specified as an analysis method. If the mobility method were specified, subsystem mobilities would also be required in the specification. These could be either analytical or experimental in nature. A definition of the content and format of these mobilities would need formulation. Similarly, subsystem uncoupled modes and the use of a modal synthesis technique could be specified.

This has been a general discussion covering three methods of analysis of coupled dynamic systems. A comparison has been made with the intent of using one or more of these approaches as an analysis method specification.

METHOD VERIFICATION

The previous sections of this report were related to data collection, review, and analysis and development of methods of coupled system dynamic analysis. This section discusses the validation of these methods by correlation with the collected test data for the OH-58 and OH-6 helicopters. The two helicopter systems will be discussed separately. A discussion of the analysis of the OH-58, using the mobility and modal synthesis methods and the subsequent comparison with test data is followed by a discussion of the OH-6, using the modal synthesis method and a comparison with test data. Sufficient funds were not available to perform the mobility analysis using CH-6 test data.

OH-58 ANALYSIS

The mobility method and modal synthesis technique have been applied to the analysis of the OH-58 helicopter. These analyses are discussed in the following pages and the results are compared with collected test data.

Mobility Analysis

As discussed earlier, computer program MOBIL (Appendix C) has been written to apply the mobility method to the helicopter/engine compatibility analysis. Required inputs to this analysis are the helicopter airframe and engine mobilities. The specific mobilities for each subsystem are a function of the excitation points, interface points, and points at which coupled system response are desired.

Reference 3 notes the predominant excitations as being associated with main and tail rotor frequencies for the OH-58 airframe, and gas generator and power turbine frequencies for the T63-A-5 engine. Therefore, the excitation points which must be accommodated are the main and tail rotors for the airframe and the compressor front and turbine middle splitlines for the engine.

The airframe and engine connect at three mount points and an output shaft. The airframe interfaces with three bipods for the mounting and a stub shaft, which is the input to the main transmission. The engine interfaces with the bipods at two side mount pads and one lower mount pad on the engine gearbox and interfaces with the stub shaft at the engine gearbox output shaft. These interface points must be represented in the mobilities.

3 ENGINE INSTALLATION VIBRATION SURVEY OF THE MODEL 206A-1 HELICOPTER, Bell Report 206-099-179, 1969.

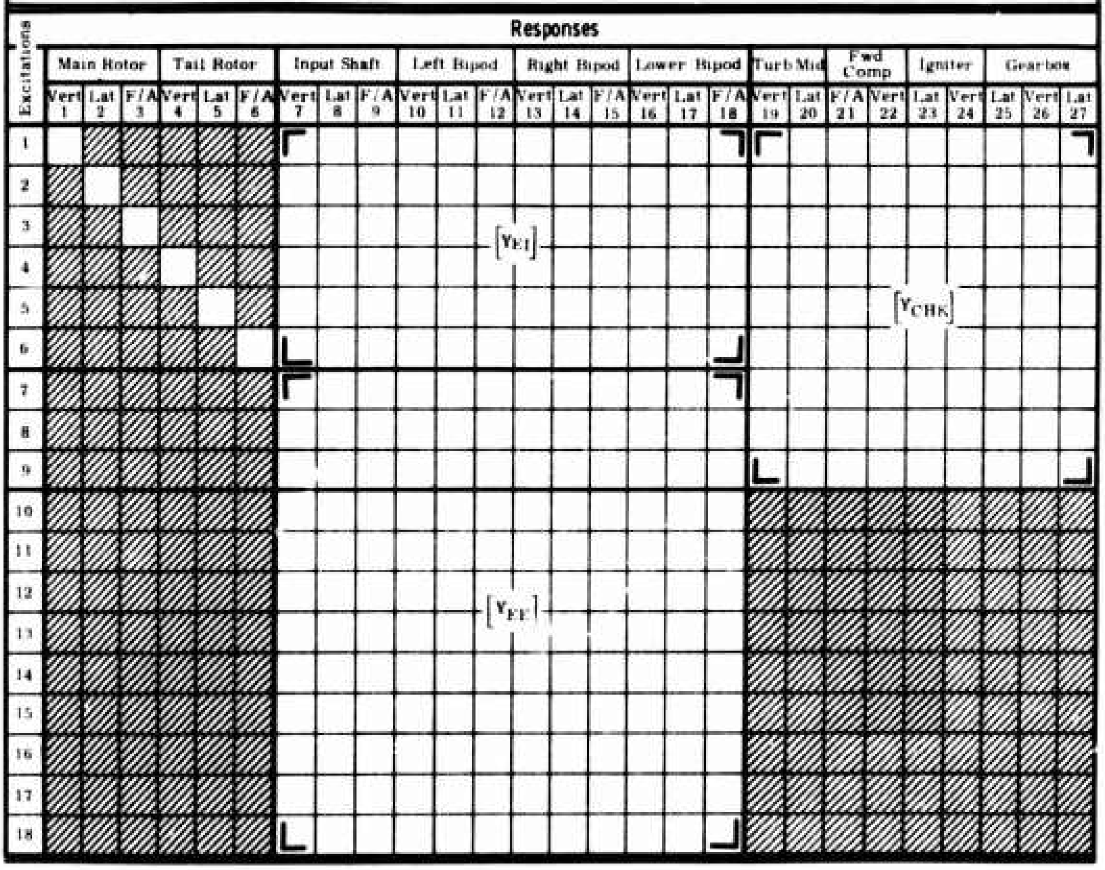
The points of coupled response interest for this study occur on the engine. These points are the locations where vibration measurements were recorded in the vibration survey reported in Reference[3]. The locations, called out on the DDA (Detroit Diesel Allison) installation drawing (P/N 6850000), are:

- Turbine middle splitline—lateral and vertical
- Forward compressor—lateral and vertical
- Igniter—lateral and vertical
- Top gearbox—fore and aft, and vertical

These locations must be represented in the engine mobilities.

The required airframe mobilities are those driving point and transfer mobilities represented as the elements of the matrix shown in Table 8.

TABLE 8. OH-58 AIRFRAME MOBILITIES



These mobilities were generated in a laboratory shake test by Bell Helicopter under authorization of Contract DAAJ02-73-C-0017 and subsequently supplied to DDA. The official delivery of these data was made in the form of analog plots of mobility amplitude and phase versus frequency from 5 to 200 Hz. The plots are not included in this report but are included in the final report of the Bell contract.[14] These data were also digitized by Bell at the following discrete frequencies:

- Main rotor 1/rev (5.9 Hz) and ±10%
- Main rotor 2/rev (11.8 Hz) and ±10%
- Main rotor 4/rev (23.6 Hz) and ±10%
- Main rotor 6/rev (35.4 Hz) and ±10%
- Main rotor 8/rev (47.2 Hz) and ±10%
- Tail rotor 1/rev (43.8 Hz) and ±10%
- Tail rotor 2/rev (87.6 Hz) and ±10%
- Input driveshaft 1/rev (103.0 Hz) and ±10%
- Input driveshaft at -10% of 2/rev (185.4 Hz)
- 200 Hz

A magnetic tape of these digitized frequencies and mobilities was supplied to DDA and is catalogued at the DDA Data Center as Generation Data Set C877 (AO2400).

The required engine mobilities are those driving point and transfer mobilities represented as the elements of the matrix shown in Table 9. These mobilities were generated as part of this contract and were discussed earlier in this report. A digital tape of the mobilities at the previously mentioned OH-58 discrete excitation frequencies was generated and is catalogued at the DDA Data Center as Generation Data Set C878(AO2918). Computer program MOBIL was written to read these tapes as part of the input data.

The only other input data required in the computerized analysis are the input forces. For the mobility checks, single forces of 100 lb were used at the main and tail rotors in the fore and aft, lateral, and vertical directions. Forces to be used in the flight simulation analysis were supplied by Bell and are presented in Figures 21 through 24. The specific data used in the flight simulation at 90, 110, and 130 kn are shown in Table 10.

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14 White, James A., OH-58A PROPULSION SYSTEM VIBRATION INVESTIGATION, Bell Helicopter Co., USAAMRDL-TR-74-47, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, August 1974.

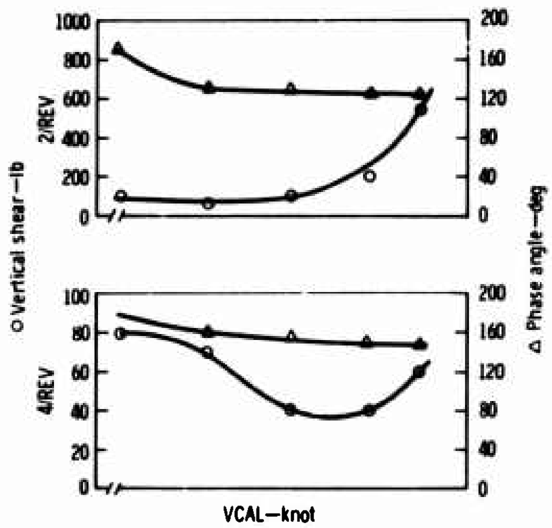

Figure 21. Main Rotor Vertical Hub Shears at 2/Rev and 4/Rev.

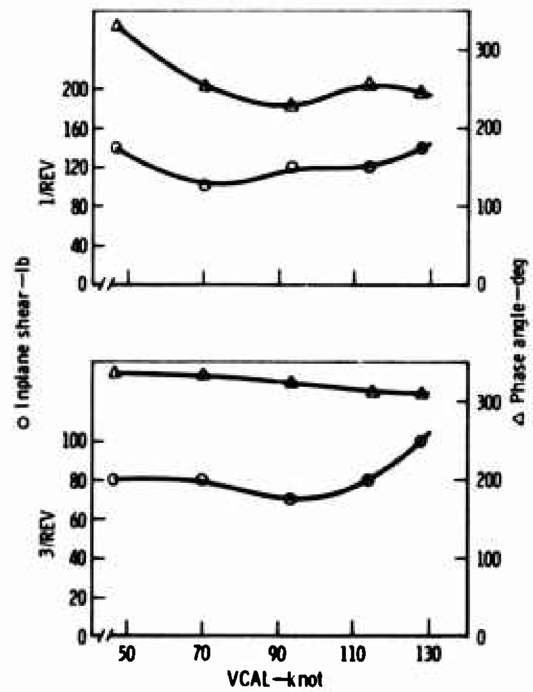

Figure 23. Main Rotor Inplane Hub Shears at 1/Rev and 3/Rev.

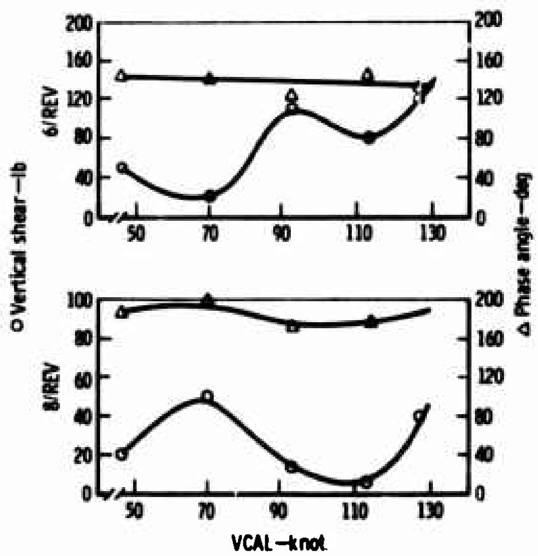

Figure 22. Main Rotor Vertical Hub Shears at 6/Rev and 8/Rev.

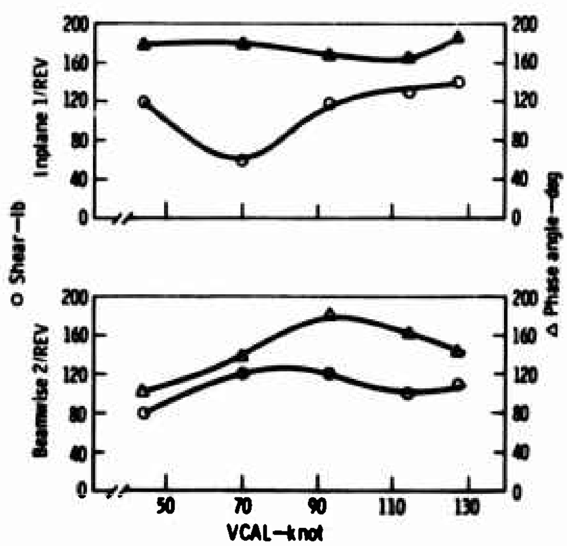

Figure 24. Tail Rotor Hub Shears.

TABLE 9. T63-A-5 ENGINE MOBILITIES

Excitations	Responses																	
	Left mount			Right mount			Lower mount			Output shaft			Turbine midsplit		Fwd compressor		Igniter	
	X 1	Y 2	Z 3	X 4	Y 5	Z 6	X 7	Y 8	Z 9	X 10	Y 11	Z 12	Y 13	Z 14	Y 15	Z 16	Y 17	Z 18
1	158 3638 3945	158 3946 4246	158 4247 4543	158 4544 4843	158 4844 5142	158 5143 5441	158 5442 5743	158 5744 6044	158 6045 6346	158 6347 6648	158 6649 6947	158 6948 7250	158 7251 7543	158 7544 7842	158 7843 8142	158 8143 8446	158 8447 8743	158 8744 9047
2	136 5050 5315	136 5581 5846	136 5359 5580	136 618 922	136 923 1224	136 1225 1529	136 1530 1832	136 1834 2139	136 2142 2445	136 2446 2746	136 2747 3060	136 3061 3354	136 3355 3636	136 3637 3898	136 3899 4191	136 4192 4472	136 5 311	136 312 617
3	151 1492 1793	151 1193 1491	151 2424 2718	151 2094 2393	151 2719 3016	151 1794 2093	151 3017 3303	151 3304 3604	151 6001 6299	151 3605 3899	151 3900 4195	151 4196 4498	151 4801 5095	151 4499 4800	151 896 1192	151 307 601	151 5395 5697	151 5096 5394
4	159 4557 4853	159 4854 5148	159 4260 4556	159 5739 6043	159 5443 5738	159 5149 5442	159 3965 4259	159 3666 3964	159 3358 3665	159 3048 3357	159 2741 3047	159 2438 2740	159 2137 2437	159 1834 2136	159 1532 1833	159 1228 1531	159 922 1227	159 616 921
5	162 333 636	162 637 936	162 937 1234	162 1235 1536	155 5 304	162 1537 1837	155 2696 2993	155 2994 3286	155 3287 3581	162 1838 2141	162 2142 2444	162 2445 2750	155 1800 2097	155 1503 1799	155 305 610	155 611 906	155 2101 2397	155 2398 2695
6	152 1231 1531	152 932 1230	152 1532 1829	152 1830 2129	152 2429 2729	152 2130 2428	152 310 612	152 613 931	152 5 309	152 2730 3025	152 5533 5827	152 5828 6122	152 3026 3321	152 3322 3623	152 3624 4038	152 4039 4336	152 4337 4637	152 4638 4935
7	157 6699 7001	157 7002 7300	157 7301 7606	158 1512 1809	158 2117 2425	158 1810 2116	517 6083 6390	157 6391 6698	158 3329 3637	158 2426 2724	158 2725 3027	158 3028 3328	157 7607 7905	157 7906 8206	157 8207 8503	158 5 306	158 307 609	158 610 910
8	142 11342 11662	142 11966 12267	142 11663 11965	142 6163 6464	142 6767 7066	142 6465 6766	142 7682 7985	142 7067 7369	142 7370 7681	142 7986 8290	142 8291 8604	142 8605 8911	142 8912 9213	142 9214 9514	142 9515 9816	142 9817 10122	142 10123 10431	142 10432 10733
9	121 1260 1571	121 1879 2184	121 1572 1878	121 5 313	121 341 643	120 1745 2049	120 319 623	121 644 952	120 5 318	130 620 922	130 315 619	130 5 314	121 3395 3696	121 3697 3998	121 953 1259	117 313 609	121 2787 3098	121 3099 3394
10	157 1203 1500	157 1802 2099	157 1501 1801	157 2698 3004	157 2399 2697	157 2100 2398	157 309 606	157 607 905	157 906 1202	157 5 308	157 5481 5781	157 5782 6082	157 3005 3308	157 3309 3610	157 3660 3958	157 3959 4256	157 4257 4568	157 4569 4875
11	138 1532 1837	138 2144 2461	138 1838 2143	138 917 1222	138 307 611	138 612 916	136 6178 6489	136 5848 6177	138 1223 1531	138 3692 3992	138 3993 4294	138 3386 3691	136 7402 7635	138 5 306	136 7095 7401	136 6792 7094	138 2462 2768	138 2769 3079
12	130 2135 2434	130 3942 4241	130 2435 2730	130 1832 2134	130 1527 1831	130 1226 1526	130 4242 4541	130 4542 4843	130 4844 5142	130 5143 5441	130 5442 5741	130 923 1225	134 5 308	130 3639 3941	130 3031 3338	130 2731 3030	134 309 613	134 614 921
13	143 325 618	143 5 324	143 619 921	143 922 1221	143 1222 1518	143 1519 1813	143 1814 2109	143 2110 2406	143 2407 2703	143 2704 2999	143 3000 3295	143 3296 3590	143 3591 3889	143 3890 4186	143 4187 4484	143 4775 5073	143 5074 5369	143 5370 5665
14	143 6267 6566	143 6567 6865	143 6866 7162	143 7462 7759	143 7760 8057	143 8058 8357	143 8358 8658	143 8659 8962	143 8963 9260	143 9261 9557	143 9558 9856	143 9857 10153	143 10154 10452	143 10453 10753	144 171 462	144 463 758	144 759 1054	144 1055 1346
15	142 4326 4630	142 4935 5243	142 4631 4934	142 5856 6162	142 5244 5549	142 5550 5855	142 918 1220	142 1221 1533	142 1534 1841	142 4020 4325	142 3377 3687	142 3688 4019	142 310 615	142 616 917	142 5 309	142 2450 2753	142 2754 3068	142 3069 3376
16	164 5 307	164 308 609	145 5 301	144 6677 6972	144 6377 6676	144 6079 6376	144 5782 6078	144 5484 5781	144 5187 5483	144 4890 5186	144 4597 4889	144 4301 4596	144 4008 4300	144 3712 4007	144 3419 3711	144 3121 3418	144 2826 3120	144 2530 2825

TABLE 9. T63-A-5 ENGINE MOBILITIES

Responses													
Lower mount			Output shaft			Turbine midsplit		Fwd compressor		Igniter		Top gearbox	
X 7	Y 8	Z 9	X 10	Y 11	Z 12	Y 13	Z 14	Y 15	Z 16	Y 17	Z 18	X 19	Z 20
58	158	158	158	158	158	158	158	158	158	158	158	158	158
442	5744	6045	6347	6649	6948	7251	7544	7843	8143	8447	8744	9048	9349
743	6044	6346	6648	6947	7250	·7543	7842	8142	8446	8743	9047	9348	9647
136	136	136	136	136	136	136	136	136	136	136	136	136	136
1530	1834	2142	2446	2747	3061	3355	3637	3899	4192	5	312	4473	4774
1832	2139	2445	2746	3060	3354	3636	3898	4191	4472	311	617	4773	5049
151	151	151	151	151	151	151	151	151	151	151	151	151	151
3017	3304	6001	3605	3900	4196	4801	4499	896	307	5395	5096	5698	5
3303	3604	6299	3899	4195	4498	5095	4800	1192	601	5697	5394	6000	306
159	159	159	159	159	159	159	159	159	159	159	159	159	159
3965	3666	3358	3048	2741	2438	2137	1834	1532	1[illegible]28	922	616	317	5
4259	3964	3665	3357	3047	2740	2437	2136	1833	1531	1227	921	615	316
155	155	155	162	162	162	155	155	155	155	155	155	155	155
2696	2994	3287	1838	2142	2445	1800	1503	305	611	2101	2398	1204	907
2993	3286	3581	2141	2444	2750	2097	1799	610	906	2397	2695	1502	1203
152	152	152	152	152	152	152	152	152	152	152	152	152	152
310	613	5	2730	5533	5828	3026	3322	3624	4039	4337	4638	4936	5235
612	931	309	3025	5827	6122	3321	3623	4038	4336	4637	4935	5234	5532
517	157	158	158	158	158	157	157	157	158	158	158	158	158
6083	6391	3329	2426	2725	3028	7607	7906	8207	5	307	610	911	1212
6390	6698	3637	2724	3027	3328	7905	8206	8503	306	609	910	1211	1511
142	142	142	142	142	142	142	142	142	142	142	142	142	142
7682	7067	7370	7986	8291	8605	8912	9214	9515	9817	10123	10432	10734	11040
7985	7369	7681	8290	8604	8911	9213	9514	9816	10122	10431	10733	11039	11341
120	121	120	130	130	130	121	121	121	117	121	121	121	121
319	644	5	620	315	5	3395	3697	953	313	2787	3099	2185	2485
623	952	318	922	619	314	3696	3998	1259	609	3098	3394	2484	2786
157	157	157	157	157	157	157	157	157	157	157	157	157	157
309	607	906	5	5481	5782	3005	3309	3660	3959	4257	4569	4876	5178
606	905	1202	308	5781	6082	3308	3610	3958	4256	4568	4875	5177	5480
136	136	138	138	138	138	136	138	136	136	138	138	136	138
6178	5848	1223	3692	3993	3386	7402	5	7095	6792	2462	2769	6490	3080
6489	6177	1531	3992	4294	3691	7635	306	7401	7094	2768	3079	6791	3385
130	130	130	130	130	130	134	130	130	130	134	134	134	134
4242	4542	4844	5143	5442	923	5	3639	3031	2731	309	614	922	1222
4541	4843	5142	5441	5741	1225	308	3941	3338	3030	613	921	1221	1523
143	143	143	143	143	143	143	143	143	143	143	143	143	143
1814	2110	2407	2704	3000	3296	3591	3890	4187	4775	5074	5370	5666	5963
2109	2406	2703	2999	3295	3590	3889	4186	4484	5073	5369	5665	5962	6266
143	143	143	143	143	143	143	143	144	144	144	144	144	144
8358	8659	8963	9261	9558	9857	10154	10453	171	463	759	1055	1347	1641
8658	8962	9260	9557	9856	10153	10452	10753	462	758	1054	1346	1640	1934
142	142	142	142	142	142	142	142	142	142	142	142	142	142
918	1221	1534	4020	3377	3688	310	616	5	2450	2754	3069	2148	1842
1220	1533	1841	4325	3687	4019	615	917	309	2753	3068	3376	2449	2147
144	144	144	144	144	144	144	144	144	144	144	144	164	144
5782	5484	5187	4890	4597	4301	4008	3712	3419	3121	2826	2530	610	1935
6078	5781	5483	5186	4889	4596	4300	4007	3711	3418	3120	2825	909	2232

TABLE 10. OH-58 FLIGHT SIMULATION EXCITAT

Freq	Comment	Forces (lb) Main Rotor Fore and Aft	Main Rotor Lateral	Main Rotor Vertical	Fore an
				90 Knots	
11.8	MR 2/Rev	-8.611-64.505 j	64.505-8.611 j	-55.4 + 70.9 j	-
23.6	MR 4/Rev	28.67-20.075 j	20.075 + 28.67 j	-39.877 + 18.595 j	-
35.4	MR 6/Rev	-	-	-79.668 + 66.85 j	-
47.2	MR 8/Rev	-	-	-18.0	-
87.6	TR 2/Rev	-	-	-	-54.164 +
				110 Knots	
11.8	MR 2/Rev	5.995-82.897 j	82.897 + 5.995 j	-99.923 + 137.533 j	-
23.6	MR 4/Rev	26.516-26.516 j	26.516 + 26.516 j	25.872-26.45 j	-
35.4	MR 6/Rev	-	-	77.892-18.244 j	-
47.2	MR 8/Rev	-	-	-5.0	-
87.6	TR 2/Rev	-	-	-	-62.482 +
				130 Knots	
11.8	MR 2/Rev	-41.119-116.018 j	116.018-41.119 j	-363.475-538.874 j	-
23.6	MR 4/Rev	-4.619-52.798 j	52.798-4.619 j	-55.971 + 34.975 j	-
35.4	MR 6/Rev	-	-	-100.707 + 116.065 j	-
47.2	MR 8/Rev	-	-	-47.271-8.335 j	-
87.6	TR 2/Rev	-	-	-	-67.288-1

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' SIMULATION EXCITATIONS

Forces (lb)			
	Tail Rotor		
ertical	Fore and Aft	Lateral	Vertical
nots			
+ 70.9 j	-	-	-
7 + 18.595 j	-	-	-
8 + 66.85 j	-	-	-
18.0	-	-	-
-	-54.164 + 9.55 j	-124.0	-9.55-54.164 j
nots			
3 + 137.533 j	-	-	-
-26.45 j	-	-	-
-18.244 j	-	-	-
-5.0	-	-	-
-	-62.482 + 17.916 j	-98.481 + 17.365 j	-17.916-62.482 j
nots			
75-538.874 j	-	-	-
1 + 34.975 j	-	-	-
07 + 116.065 j	-	-	-
1-8.335 j	-	-	-
-	-67.288-19.295 j	-84.265 + 70.706 j	19.295-67.288 j

Initial computations were made to generate the coupled system mobilities for comparison with the laboratory shake test data supplied by Bell. Calculations were made with 100-lb excitations as follows:

- Main rotor fore and aft, lateral, and vertical for the case where engine and airframe are coupled by a pinned connection at the transmission input shaft (option=2)
- Main rotor vertical for the case where the engine and airframe are rigidly connected at the transmission input shaft (option=1)
- Main rotor vertical for the case where the engine and airframe are uncoupled at the transmission input shaft (option=0)

Calculations were performed at the aforementioned digitized frequencies. The +10% points were included to prevent missing a potential peak response because of off-design operation of the helicopter and/or data scatter. No significant differences between the discrete excitation frequencies and the ±10% values were noted. Therefore, only the results of the discrete frequencies are tabulated. Results are presented in Tables 11 through 50 for comparison with shake test results supplied by Bell for discrete frequencies through drive shaft 1/rev.

TABLE 11. OH-58 TRANSFER MOBILITIES FOR FORE & AFT FORCE AT MAIN ROTOR (FREQUENCY = 5.9 HZ; OPTION = 2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00148	-136.4	0.0550	58.9
Splitline	(Vertical)	0.00836	90.3	0.0476	-129.7
Forward	(Lateral)	0.00186	70.5	0.0778	-95.6
Compressor	(Vertical)	0.01003	78.6	0.3596	47.9
Igniter	(Lateral)	0.00087	103.4	0.1535	48.1
	(Vertical)	0.00869	76.6	0.2768	-143.1
Top	(Fore & Aft)	0.00733	-63.9	0.0275	-79.1
Gearbox	(Vertical)	0.01337	88.2	0.0568	47.2

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TABLE 12. OH-58 TRANSFER MOBILITIES FOR FORE & AFT FORCE AT MAIN ROTOR (FREQUENCY=11.8 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00015	91.8	0.1828	172.1
Splitline	(Vertical)	0.00184	51.7	0.0075	-59.0
Forward	(Lateral)	0.00004	2.5	0.2719	0.3
Compressor	(Vertical)	0.00147	56.8	0.0631	45.9
Igniter	(Lateral)	0.00059	-104.5	0.0434	41.4
	(Vertical)	0.00248	49.2	0.0612	-148.4
Top	(Fore & Aft)	0.00110	-15.2	0.1229	4.6
Gearbox	(Vertical)	0.00147	62.9	0.0084	139.6

TABLE 13. OH-58 TRANSFER MOBILITIES FOR FORE & AFT FORCE AT MAIN ROTOR (FREQUENCY=23.6 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00014	73.0	0.0007	141.5
Splitline	(Vertical)	0.00061	84.7	0.0026	-99.0
Forward	(Lateral)	0.00006	-113.6	0.0009	-37.1
Compressor	(Vertical)	0.00010	-126.3	0.0049	83.2
Igniter	(Lateral)	0.00031	-115.6	0.0033	80.8
	(Vertical)	0.00142	83.2	0.0047	-101.5
Top	(Fore & Aft)	0.00057	88.2	0.0004	-46.5
Gearbox	(Vertical)	0.00004	144.5	0.0002	176.5

TABLE 14. OH-58 TRANSFER MOBILITIES FOR FORE & AFT FORCE AT MAIN ROTOR (FREQUENCY=35.4 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00036	-113.6	0.0017	85.1
Splitline	(Vertical)	0.00120	-111.0	0.0031	-116.0
Forward	(Lateral)	0.00004	119.7	0.0013	-87.9
Compressor	(Vertical)	0.00168	33.0	0.0081	48.1
Igniter	(Lateral)	0.00074	17.2	0.0045	51.0
	(Vertical)	0.00327	-118.6	0.0067	-128.6
Top	(Fore & Aft)	0.00134	-155.2	0.0004	-52.3
Gearbox	(Vertical)	0.00063	11.2	0.0005	41.0

TABLE 15. OH-58 TRANSFER MOBILITIES FOR FORE & AFT FORCE AT MAIN ROTOR (FREQUENCY=43.8 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00015	-59.8	0.0084	-3.1
Splitline	(Vertical)	0.00073	89.2	0.0017	-55.7
Forward	(Lateral)	0.00009	9.1	0.0046	179.3
Compressor	(Vertical)	0.00039	-19.3	0.0064	134.1
Igniter	(Lateral)	0.00019	-151.1	0.0037	131.4
	(Vertical)	0.00177	108.0	0.0055	-53.1
Top	(Fore & Aft)	0.00036	113.6	0.0004	-126.0
Gearbox	(Vertical)	0.00028	-28.4	0.0004	158.4

TABLE 16. OH-58 TRANSFER MOBILITIES FOR FORE & AFT FORCE AT MAIN ROTOR (FREQUENCY=47.2 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00020	167.8	0.0017	-175.9
Splitline	(Vertical)	0.00112	127.3	0.0010	-9.3
Forward	(Lateral)	0.00014	-83.7	0.0014	6.6
Compressor	(Vertical)	0.00067	-65.9	0.0045	-138.5
Igniter	(Lateral)	0.00050	14.2	0.0027	-132.9
	(Vertical)	0.00287	118.1	0.0037	41.3
Top	(Fore & Aft)	0.00015	41.1	0.0003	36.1
Gearbox	(Vertical)	0.00031	-46.1	0.0003	-155.6

TABLE 17. OH-58 TRANSFER MOBILITIES FOR FORE & AFT FORCE AT MAIN ROTOR (FREQUENCY=87.6 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00003	46.1	0.0012	9.0
Splitline	(Vertical)	0.00016	-165.8	0.0040	-63.6
Forward	(Lateral)	0.00009	-81.6	0.0022	133.5
Compressor	(Vertical)	0.00018	-158.2	0.0082	116.4
Igniter	(Lateral)	0.00011	160.7	0.0009	-9.5
	(Vertical)	0.00002	14.2	0.0022	-81.9
Top	(Fore & Aft)	0.00019	-10.6	0.0014	118.2
Gearbox	(Vertical)	0.00014	-153.6	0.0024	126.4

TABLE 18. OH-58 TRANSFER MOBILITIES FOR FORE & AFT FORCE AT MAIN ROTOR (FREQUENCY=103.0 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00006	-52.7	0.0008	-93.3
Splitline	(Vertical)	0.00020	123.2	0.0021	4.9
Forward	(Lateral)	0.00003	-41.6	0.0013	161.4
Compressor	(Vertical)	0.00014	-56.3	0.0038	166.9
Igniter	(Lateral)	0.00009	171.9	0.0015	170.3
	(Vertical)	0.00066	109.5	0.0026	-12.3
Top	(Fore & Aft)	0.00011	-23.8	0.0005	-168.8
Gearbox	(Vertical)	0.00004	-105.5	0.0003	-8.0

TABLE 19. OH-58 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR (FREQUENCY=5.9 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.04113	12.2	0.1346	-139.8
Splitline	(Vertical)	0.00238	-158.2	0.0176	-14.0
Forward	(Lateral)	0.03086	-166.3	0.1150	58.3
Compressor	(Vertical)	0.00343	48.2	0.1999	171.4
Igniter	(Lateral)	0.03609	180.0	0.0918	170.1
	(Vertical)	0.00753	16.2	0.1569	-22.3
Top	(Fore & Aft)	0.00261	-27.4	0.0343	99.1
Gearbox	(Vertical)	0.00814	-159.7	0.0320	178.8

TABLE 20. OH-58 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR (FREQUENCY=11.8 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00411	-74.0	0.0165	31.3
Splitline	(Vertical)	0.00037	110.5	0.0004	81.3
Forward	(Lateral)	0.00218	77.6	0.0229	-147.3
Compressor	(Vertical)	0.00007	-84.7	0.0067	-108.8
Igniter	(Lateral)	0.00372	82.1	0.0051	-105.4
	(Vertical)	0.00052	-77.1	0.0070	61.5
Top	(Fore & Aft)	0.00036	-88.2	0.0097	-146.0
Gearbox	(Vertical)	0.00086	107.0	0.0005	-1.7

TABLE 21. OH-58 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR (FREQUENCY=23.6 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00267	-89.2	0.0069	-156.8
Splitline	(Vertical)	0.00040	94.3	0.0031	24.1
Forward	(Lateral)	0.00184	56.3	0.0099	27.2
Compressor	(Vertical)	0.00007	-85.2	0.0090	-148.2
Igniter	(Lateral)	0.00429	63.9	0.0037	-141.5
	(Vertical)	0.00019	-120.7	0.0072	32.7
Top	(Fore & Aft)	0.00048	-111.5	0.0047	28.4
Gearbox	(Vertical)	0.00063	83.2	0.0013	-152.4

TABLE 22. OH-58 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR (FREQUENCY=35.4 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00228	80.1	0.0044	-82.6
Splitline	(Vertical)	0.00031	150.6	0.0015	-37.0
Forward	(Lateral)	0.00057	-1.0	0.0020	94.4
Compressor	(Vertical)	0.00017	49.2	0.0085	120.5
Igniter	(Lateral)	0.00441	-128.3	0.0053	123.8
	(Vertical)	0.00112	103.9	0.0074	-58.5
Top	(Fore & Aft)	0.00076	69.0	0.0002	-98.7
Gearbox	(Vertical)	0.00005	124.7	0.0005	124.9

TABLE 23. OH-58 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR (FREQUENCY=43.8 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00051	-19.8	0.0028	107.5
Splitline	(Vertical)	0.00006	144.5	0.0008	5.8
Forward	(Lateral)	0.00026	-64.4	0.0019	-64.5
Compressor	(Vertical)	0.00015	15.2	0.0042	176.4
Igniter	(Lateral)	0.00124	133.9	0.0024	175.3
	(Vertical)	0.00006	-139.4	0.0036	-9.7
Top	(Fore & Aft)	0.00024	-36.0	0.0005	-39.4
Gearbox	(Vertical)	0.00013	-39.5	0.0003	-175.2

TABLE 24. OH-58 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR (FREQUENCY=47.2 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00009	39.0	0.0015	-70.9
Splitline	(Vertical)	0.00022	-162.3	0.0014	38.2
Forward	(Lateral)	0.00028	-76.1	0.0009	109.1
Compressor	(Vertical)	0.00014	-42.1	0.0034	-156.0
Igniter	(Lateral)	0.00032	122.7	0.0012	-168.3
	(Vertical)	0.00050	164.3	0.0022	15.8
Top	(Fore & Aft)	0.00012	-9.1	0.0002	-132.6
Gearbox	(Vertical)	0.00018	-93.3	0.0004	-150.6

TABLE 25. OH-58 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR (FREQUENCY=87.6 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00010	-65.9	0.0028	95.0
Splitline	(Vertical)	0.00004	130.3	0.0091	17.9
Forward	(Lateral)	0.00002	94.8	0.0050	-139.6
Compressor	(Vertical)	0.00008	156.2	0.0178	-162.2
Igniter	(Lateral)	0.00009	101.4	0.0023	71.1
	(Vertical)	0.00020	-86.2	0.0046	-4.5
Top	(Fore & Aft)	0.00003	-137.4	0.0032	-157.2
Gearbox	(Vertical)	0.00025	111.0	0.0055	-150.8

TABLE 26. OH-58 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR (FREQUENCY=103.0 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00005	-158.2	0.0004	-142.7
Splitline	(Vertical)	0.00005	65.9	0.0009	-9.5
Forward	(Lateral)	0.00006	158.2	0.0005	129.5
Compressor	(Vertical)	0.00004	-115.6	0.0017	165.7
Igniter	(Lateral)	0.00010	-22.8	0.0006	141.1
	(Vertical)	0.00016	55.3	0.0010	-32.1
Top	(Fore & Aft)	0.00003	-49.2	0.0002	144.8
Gearbox	(Vertical)	0.00001	131.8	0.0002	-106.4

TABLE 27. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=5.9 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00075	-40.6	0.0112	103.1
Splitline	(Vertical)	0.00327	-72.5	0.0097	-75.8
Forward	(Lateral)	0.00033	-146.5	0.0112	-59.2
Compressor	(Vertical)	0.00184	-76.6	0.0664	121.0
Igniter	(Lateral)	0.00046	101.4	0.0316	129.0
	(Vertical)	0.00340	-70.5	0.0534	-67.6
Top	(Fore & Aft)	0.00068	61.4	0.0027	-55.9
Gearbox	(Vertical)	0.00311	-69.5	0.0097	114.0

TABLE 28. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=11.8 HZ OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00050	-12.2	0.2688	0.0
Splitline	(Vertical)	0.01147	-31.4	0.0054	134.3
Forward	(Lateral)	0.00034	-153.6	0.4136	-169.7
Compressor	(Vertical)	0.00619	-11.2	0.1067	-117.4
Igniter	(Lateral)	0.00232	-132.3	0.0678	-122.4
	(Vertical)	0.01395	-23.8	0.1018	47.1
Top	(Fore & Aft)	0.00522	-29.9	0.1903	-164.2
Gearbox	(Vertical)	0.00849	10.6	0.0154	-38.8

TABLE 29. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=23.6 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00171	-120.7	0.0079	90.6
Splitline	(Vertical)	0.01257	-96.3	0.0130	47.5
Forward	(Lateral)	0.00093	95.3	0.0065	-68.0
Compressor	(Vertical)	0.00724	69.5	0.0245	-137.0
Igniter	(Lateral)	0.00522	50.7	0.0146	-141.3
	(Vertical)	0.02322	-101.4	0.0214	33.4
Top	(Fore & Aft)	0.00858	-102.9	0.0027	-53.6
Gearbox	(Vertical)	0.00221	59.3	0.0014	-85.6

TABLE 30. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=35.4 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00092	-127.3	0.0019	-39.7
Splitline	(Vertical)	0.00204	-72.5	0.0080	52.2
Forward	(Lateral)	0.00017	82.1	0.0022	127.6
Compressor	(Vertical)	0.00392	41.6	0.0248	-132.5
Igniter	(Lateral)	0.00163	-22.8	0.0142	-127.9
	(Vertical)	0.00597	-97.4	0.0206	50.7
Top	(Fore & Aft)	0.00298	-156.7	0.0011	142.6
Gearbox	(Vertical)	0.00181	12.7	0.0015	-134.0

TABLE 31. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=43.8 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.0024	-55.8	0.0747	133.7
Splitline	(Vertical)	0.0041	88.2	0.0080	47.6
Forward	(Lateral)	0.0013	-15.7	0.0412	-37.2
Compressor	(Vertical)	0.0040	-33.5	0.0406	-113.4
Igniter	(Lateral)	0.0045	131.3	0.0239	-118.5
	(Vertical)	0.0098	105.0	0.0374	56.4
Top	(Fore & Aft)	0.0030	90.8	0.0065	28.9
Gearbox	(Vertical)	0.0025	-45.6	0.0026	-72.4

TABLE 32. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=47.2 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0015	-164.3	0.0121	58.6
Splitline	(Vertical)	0.0066	107.0	0.0108	127.2
Forward	(Lateral)	0.00186	-123.2	0.0073	-139.0
Compressor	(Vertical)	0.0054	-56.8	0.0408	-39.6
Igniter	(Lateral)	0.0048	8.6	0.0179	-30.6
	(Vertical)	0.0165	114.1	0.0270	141.2
Top	(Fore & Aft)	0.0013	22.3	0.0010	-129.4
Gearbox	(Vertical)	0.0028	-99.4	0.0053	-51.6

TABLE 33. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=87.6 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0002	59.3	0.0205	-56.0
Splitline	(Vertical)	0.0020	154.6	0.0542	-126.6
Forward	(Lateral)	0.0013	-24.3	0.0375	74.2
Compressor	(Vertical)	0.0032	-164.3	0.1146	58.7
Igniter	(Lateral)	0.0021	154.1	0.0135	-85.2
	(Vertical)	0.0009	100.4	2.78	-131.6
Top	(Fore & Aft)	0.0031	-35.0	0.0217	54.7
Gearbox	(Vertical)	0.0021	167.8	0.0357	64.2

TABLE 34. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=103.0 HZ; OPTION=2)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.0002	-123.7	0.0031	-19.6
Splitline	(Vertical)	0.0009	14.7	0.0090	107.5
Forward	(Lateral)	0.0003	-135.9	0.0047	-98.5
Compressor	(Vertical)	0.0014	-168.3	0.0112	-87.6
Igniter	(Lateral)	0.0008	69.0	0.0056	-93.8
	(Vertical)	0.0052	-14.2	0.0093	86.7
Top	(Fore & Aft)	0.0006	-119.2	0.0022	70.7
Gearbox	(Vertical)	0.0013	147.0	0.0022	72.9

TABLE 35. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=5.9 HZ; OPTION=1)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00075	-40.6	0.0060	72.4
Splitline	(Vertical)	0.00327	-72.5	0.0082	-80.3
Forward	(Lateral)	0.00033	-146.5	0.0099	-96.2
Compressor	(Vertical)	0.00184	-76.6	0.0033	74.8
Igniter	(Lateral)	0.00046	101.4	0.0013	-141.8
	(Vertical)	0.00340	-70.5	0.0028	-64.7
Top	(Fore & Aft)	0.00068	61.4	0.0053	-83.6
Gearbox	(Vertical)	0.00311	-69.5	0.0009	-15.4

TABLE 36. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=11.8 HZ; OPTION=1)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00050	-12.2	0.1255	-85.1
Splitline	(Vertical)	0.01147	-31.4	0.0136	171.8
Forward	(Lateral)	0.00034	-153.6	0.1762	105.3
Compressor	(Vertical)	0.00619	-11.2	0.0219	-64.3
Igniter	(Lateral)	0.00232	-132.3	0.0328	98.1
	(Vertical)	0.01395	-23.8	0.0118	-106.7
Top	(Fore & Aft)	0.00522	-29.9	0.0742	112.2
Gearbox	(Vertical)	0.00849	10.6	0.0211	-82.0

TABLE 37. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=23.6 HZ; OPTION=1)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00171	-120.7	0.0595	41.9
Splitline	(Vertical)	0.01257	-96.3	0.0150	74.6
Forward	(Lateral)	0.00093	95.3	0.0808	-137.4
Compressor	(Vertical)	0.00724	69.5	0.0072	-35.2
Igniter	(Lateral)	0.00522	50.7	0.0185	-129.6
	(Vertical)	0.02322	-101.4	0.0093	52.0
Top	(Fore & Aft)	0.00858	-102.9	0.0373	-137.1
Gearbox	(Vertical)	0.00221	59.3	0.0104	31.0

TABLE 38. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=35.4 HZ; OPTION=1)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00092	-127.3	0.0005	-130.5
Splitline	(Vertical)	0.00204	-72.5	0.0022	-41.7
Forward	(Lateral)	0.00017	82.1	0.0004	-165.0
Compressor	(Vertical)	0.00392	41.6	0.0011	157.2
Igniter	(Lateral)	0.00163	-22.8	0.0001	168.4
	(Vertical)	0.00597	-97.4	0.0007	-60.6
Top	(Fore & Aft)	0.00298	-156.7	0.0008	-153.2
Gearbox	(Vertical)	0.00181	12.7	0.0002	-130.1

TABLE 39. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=43.8 HZ; OPTION=1)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0024	-55.8	0.0066	-126.6
Splitline	(Vertical)	0.0041	88.2	0.0053	-77.9
Forward	(Lateral)	0.0013	-15.7	0.0090	68.5
Compressor	(Vertical)	0.0040	-33.5	0.0038	41.5
Igniter	(Lateral)	0.0045	131.3	0.0020	87.2
	(Vertical)	0.0098	105.0	0.0018	-73.2
Top	(Fore & Aft)	0.0030	90.8	0.0048	82.8
Gearbox	(Vertical)	0.0025	-45.6	0.0016	-15.9

TABLE 40. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=47.2 HZ; OPTION=1)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0015	-164.3	0.0060	36.0
Splitline	(Vertical)	0.0066	107.0	0.0141	110.6
Forward	(Lateral)	0.0019	-123.2	0.0085	-136.8
Compressor	(Vertical)	0.0054	-56.8	0.0140	-73.7
Igniter	(Lateral)	0.0048	8.6	0.0034	75.8
	(Vertical)	0.0165	114.1	0.0018	108.2
Top	(Fore & Aft)	0.0013	22.3	0.0059	-94.2
Gearbox	(Vertical)	0.0028	-99.4	0.0041	-75.5

TABLE 41. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=87.6 HZ; OPTION=1)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0002	59.3	0.0086	-2.9
Splitline	(Vertical)	0.0020	154.6	3.41	-124.3
Forward	(Lateral)	0.0013	-24.3	0.0200	61.8
Compressor	(Vertical)	0.0032	-164.3	0.0744	61.6
Igniter	(Lateral)	0.0021	154.1	0.0196	-109.3
	(Vertical)	0.0009	100.4	0.0066	-131.2
Top	(Fore & Aft)	0.0031	-35.0	0.0131	43.3
Gearbox	(Vertical)	0.0021	167.8	0.0303	63.3

TABLE 42. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=103.0 HZ; OPTION=1)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.0002	-123.7	0.0007	32.2
Splitline	(Vertical)	0.0009	14.7	0.0017	121.1
Forward	(Lateral)	0.0003	-135.9	0.0011	-77.0
Compressor	(Vertical)	0.0014	-168.3	0.0031	94.5
Igniter	(Lateral)	0.0008	69.0	0.0006	-84.0
	(Vertical)	0.0052	-14.2	0.0002	129.0
Top	(Fore & Aft)	0.0006	-119.2	0.0009	-67.7
Gearbox	(Vertical)	0.0013	147.0	0.0014	96.6

TABLE 43. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=5.9 HZ; OPTION=0)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00075	-40.6	0.0061	74.7
Splitline	(Vertical)	0.00327	-72.5	0.0086	-80.7
Forward	(Lateral)	0.00033	-146.5	0.0098	-95.4
Compressor	(Vertical)	0.00184	-76.6	0.0046	84.6
Igniter	(Lateral)	0.00046	101.4	0.0012	-176.4
	(Vertical)	0.00340	-70.5	0.0040	-70.9
Top	(Fore & Aft)	0.00068	61.4	0.0051	-82.9
Gearbox	(Vertical)	0.0031	-69.5	0.0003	-8.3

TABLE 44. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=11.8 HZ; OPTION=0)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00050	-12.2	0.0936	-85.3
Splitline	(Vertical)	0.01147	-31.4	0.0153	-173.1
Forward	(Lateral)	0.00034	-153.6	0.1299	107.7
Compressor	(Vertical)	0.00619	-11.2	0.0230	-59.0
Igniter	(Lateral)	0.00232	-132.3	0.0340	92.8
	(Vertical)	0.01395	-23.8	0.0147	-114.8
Top	(Fore & Aft)	0.00522	-29.9	0.0536	117.8
Gearbox	(Vertical)	0.00849	10.6	0.0208	-82.8

TABLE 45. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=23.6 HZ; OPTION=0)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00171	-120.7	0.0881	-36.6
Splitline	(Vertical)	0.01257	-96.3	0.0244	-1.5
Forward	(Lateral)	0.00093	95.3	0.1316	143.8
Compressor	(Vertical)	0.00724	69.5	0.0133	-104.8
Igniter	(Lateral)	0.00522	50.7	0.0365	153.2
	(Vertical)	0.02322	-101.4	0.0211	-22.6
Top	(Fore & Aft)	0.00858	-102.9	0.0622	144.1
Gearbox	(Vertical)	0.00221	59.3	0.0204	-44.0

TABLE 46. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=35.4 HZ; OPTION=0)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00092	-127.3	0.0006	-135.9
Splitline	(Vertical)	0.00204	-72.5	0.0023	-38.8
Forward	(Lateral)	0.00017	82.1	0.0004	-166.8
Compressor	(Vertical)	0.00392	41.6	0.0015	156.0
Igniter	(Lateral)	0.00163	-22.8	0.0003	157.0
	(Vertical)	0.00597	-97.4	0.0010	-49.7
Top	(Fore & Aft)	0.00298	-156.7	0.0008	-153.1
Gearbox	(Vertical)	0.00181	12.7	0.0002	-132.8

TABLE 47. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=43.8 HZ; OPTION=0)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.0024	-55.8	0.0055	-126.1
Splitline	(Vertical)	0.0041	88.2	0.0056	-76.0
Forward	(Lateral)	0.0013	-15.7	0.0084	69.7
Compressor	(Vertical)	0.0040	-33.5	0.0041	57.4
Igniter	(Lateral)	0.0045	131.3	0.0025	95.8
	(Vertical)	0.0098	105.0	0.0027	-68.3
Top	(Fore & Aft)	0.0030	90.8	0.0047	83.2
Gearbox	(Vertical)	0.0025	-45.6	0.0016	-14.1

TABLE 48. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=47.2 HZ; OPTION=0)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.0015	-164.3	0.0060	26.3
Splitline	(Vertical)	0.0066	107.0	0.0152	117.3
Forward	(Lateral)	0.0019	-123.2	0.0087	-136.1
Compressor	(Vertical)	0.0054	-56.8	0.0161	-66.9
Igniter	(Lateral)	0.0048	8.6	0.0027	62.1
	(Vertical)	0.0165	114.1	0.0036	119.2
Top	(Fore & Aft)	0.0013	22.3	0.0061	-88.5
Gearbox	(Vertical)	0.0028	-99.4	0.0042	-71.6

TABLE 49. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=87.6 HZ; OPTION=0)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.0002	59.3	0.0082	-14.2
Splitline	(Vertical)	0.0020	154.6	0.0344	-126.4
Forward	(Lateral)	0.0013	-24.3	0.0211	62.7
Compressor	(Vertical)	0.0032	-164.3	0.0750	60.1
Igniter	(Lateral)	0.0021	154.1	0.0176	-106.6
	(Vertical)	0.0009	100.4	0.0089	-133.6
Top	(Fore & Aft)	0.0031	-35.0	0.0135	43.7
Gearbox	(Vertical)	0.0021	167.8	0.0293	62.9

TABLE 50. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=103.0 HZ; OPTION = 0)

Location		Shake Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.0002	-123.7	0.0007	25.7
Splitline	(Vertical)	0.0009	14.7	0.0018	123.1
Forward	(Lateral)	0.0003	-135.9	0.0011	-74.8
Compressor	(Vertical)	0.0014	-168.3	0.0029	89.5
Igniter	(Lateral)	0.0008	69.0	0.0006	-79.9
	(Vertical)	0.0052	-14.2	0.0003	133.2
Top	(Fore & Aft)	0.0006	-119.2	0.0009	-66.6
Gearbox	(Vertical)	0.0013	147.0	0.0013	95.3

Comparison of these analysis results with the shake test data shows a relatively poor correlation. Some transfer mobilities are not even of the same order of magnitude as the test data for any option. A decision as to which option best represents the actual simulation cannot be determined.

Further computations were made in an effort to determine the source for these discrepancies. Some selected coupled transfer mobilities were computed, using subsystem mobilities with all off-axis mobility terms set to zero (i.e., fore and aft forces create only fore and aft responses, etc). The results are tabulated opposite the shake test data in Tables 51 through 58 for vertical excitations at the main rotor. These results, although different, show no better correlation than before, and no indication was determined as to where the source of variation occurs.

TABLE 51. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=5.9 HZ; OPTION=2; ALL OFF-AXIS TERMS ZERO)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00075	-40.6	0.1070	-56.7
Splitline	(Vertical)	0.00327	-72.5	0.0015	-72.6
Forward	(Lateral)	0.00033	-146.5	0.1960	142.4
Compressor	(Vertical)	0.00184	-76.6	0.0160	-65.9
Igniter	(Lateral)	0.00046	101.4	0.0160	-67.0
	(Vertical)	0.00340	-70.5	0.0510	120.7
Top	(Fore & Aft)	0.00068	61.4	0.1370	138.3
Gearbox	(Vertical)	0.00311	-69.5	0.0020	-71.6

TABLE 52. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY = 11.8 HZ; OPTION = 2; ALL OFF-AXIS TERMS ZERO)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00050	-12.2	0.3940	71.3
Splitline	(Vertical)	0.01147	-31.4	0.0060	-109.4
Forward	(Lateral)	0.00034	-153.6	0.4160	-102.0
Compressor	(Vertical)	0.00619	-11.2	0.0466	47.9
Igniter	(Lateral)	0.00232	-132.3	0.0320	46.8
	(Vertical)	0.01395	-23.8	0.0648	-123.7
Top	(Fore & Aft)	0.00522	-29.9	0.2110	-101.6
Gearbox	(Vertical)	0.00849	10.6	0.0027	24.8

TABLE 53. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=23.6 HZ; OPTION=2; ALL OFF-AXIS TERMS ZERO)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00171	-120.7	0.0055	161.4
Splitline	(Vertical)	0.01257	-96.3	0.0128	49.5
Forward	(Lateral)	0.00093	95.3	0.0045	-18.3
Compressor	(Vertical)	0.00724	69.5	0.0243	-130.0
Igniter	(Lateral)	0.00522	50.7	0.0177	-127.4
	(Vertical)	0.02322	-101.4	0.0253	48.9
Top	(Fore & Aft)	0.00858	-102.9	0.0019	-25.4
Gearbox	(Vertical)	0.00221	59.3	0.0016	48.1

TABLE 54. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=35.4 HZ; OPTION=2; ALL OFF-AXIS TERMS ZERO)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00092	-127.3	0.0775	-63.3
Splitline	(Vertical)	0.00204	-72.5	0.0068	67.8
Forward	(Lateral)	0.00017	82.1	0.0639	116.3
Compressor	(Vertical)	0.00392	41.6	0.0234	-108.4
Igniter	(Lateral)	0.00163	-22.8	0.0157	-102.9
	(Vertical)	0.00597	-97.4	0.0208	71.6
Top	(Fore & Aft)	0.00298	-156.7	0.0258	118.3
Gearbox	(Vertical)	0.00181	12.7	0.0001	-83.5

TABLE 55. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY = 43.8 HZ; OPTION = 2; ALL OFF-AXIS TERMS ZERO)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle Splitline	(Lateral)	0.0024	-55.8	0.0651	113.4
	(Vertical)	0.0041	88.2	0.0205	151.0
Forward Compressor	(Lateral)	0.0013	-15.7	0.0591	-61.1
	(Vertical)	0.0040	-33.5	0.0742	-24.9
Igniter	(Lateral)	0.0045	131.3	0.0480	-25.0
	(Vertical)	0.0098	105.0	0.0594	158.5
Top Gearbox	(Fore & Aft)	0.0030	90.8	0.0282	-55.5
	(Vertical)	0.0025	-45.6	0.0009	11.1

TABLE 56. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=47.2 HZ; OPTION=2; ALL OFF-AXIS TERMS ZERO)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle Splitline	(Lateral)	0.0015	-164.3	0.0624	143.3
	(Vertical)	0.0066	107.0	0.0298	130.6
Forward Compressor	(Lateral)	0.00186	-123.2	0.0479	-34.2
	(Vertical)	0.0054	-56.8	0.0841	-48.7
Igniter	(Lateral)	0.0048	8.6	0.0528	-51.1
	(Vertical)	0.0165	114.1	0.0686	126.7
Top Gearbox	(Fore & Aft)	0.0013	22.3	0.0194	-34.2
	(Vertical)	0.0028	-99.4	0.0010	141.3

TABLE 57. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=87.6 HZ; OPTION=2; ALL OFF-AXIS TERMS ZERO)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0002	59.3	0.0002	-151.5
Splitline	(Vertical)	0.0020	154.6	0.0018	20.1
Forward	(Lateral)	0.0013	-24.3	0.0002	-109.2
Compressor	(Vertical)	0.0032	-164.3	0.0058	-159.1
Igniter	(Lateral)	0.0021	154.1	0.0023	-164.8
	(Vertical)	0.0009	100.4	0.0039	20.2
Top	(Fore & Aft)	0.0031	-35.0	0.0002	-123.3
Gearbox	(Vertical)	0.0021	167.8	0.0001	-158.0

TABLE 58. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=103.0 HZ; OPTION=2; ALL OFF-AXIS TERMS ZERO)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0002	-123.7	0.0006	-141.5
Splitline	(Vertical)	0.0009	14.7	0.0013	-172.5
Forward	(Lateral)	0.0003	-135.9	0.0014	-64.8
Compressor	(Vertical)	0.0014	-168.3	0.0039	-63.8
Igniter	(Lateral)	0.0008	69.0	0.0010	-47.1
	(Vertical)	0.0052	-14.2	0.0014	144.8
Top	(Fore & Aft)	0.0006	-119.2	0.0008	-80.9
Gearbox	(Vertical)	0.0013	147.0	0.0006	-141.5

Computations were then made to predict responses which occurred during flights documented in Reference 3. The results are tabulated for comparison with the measured flight data in Reference 12 when such data are available. These tabulations are shown in Tables 59 through 73.

Also included in the tabulations are the predicted flight responses, using the coupled system transfer mobilities derived from the shake test data. The results show, notably, that the responses using mobility test data vary from the measured flight data by as much as factors of 10 in some locations and conditions while fair correlation is evidenced for others. However, no clear pattern occurs. This variation may be caused by errors in the flight data, shake data, or excitation forces; all three of these factors are possibilities for error. As expected from the poor mobility correlation, the correlation between measured flight responses and those predicted using the mobility analysis is poor.

TABLE 59. OH-58 FLIGHT TEST DATA—90 KN; 3100 FT ALT; FREQUENCY = 11.8 HZ (MR 2/REV)

Location		Flight Test		Mobility Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine	Y	-	-	0.227	-82.7	32.76	109.1
Midsplit	Z	-	-	0.964	92.4	0.82	-128.0
Forward	Y	-	-	0.139	57.0	49.29	-60.6
Compressor	Z	-	-	0.465	112.7	11.93	-8.9
Igniter	Y	-	-	0.332	44.3	7.79	-15.4
	Z	-	-	1.081	100.5	11.52	155.4
Top	X	-	-	0.387	104.4	22.41	-55.1
Gearbox	Z	-	-	0.714	134.9	1.80	75.3

TABLE 60. OH-58 FLIGHT TEST DATA—90 KN; 3100 FT ALT; FREQUENCY = 23.6 HZ (MR 4/REV)

Location		Flight Test		Mobility Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine	Y	-	-	0.095	12.7	0.19	100.3
Midsplit	Z	-	-	0.213	67.5	0.84	-167.8
Forward	Y	-	-	0.018	-137.9	0.23	-92.4
Compressor	Z	-	-	0.407	-178.4	2.58	7.5
Igniter	Y	-	-	0.169	117.2	1.48	12.1
	Z	-	-	0.621	42.6	2.14	-169.3
Top	X	-	-	0.310	-16.7	0.12	-77.4
Gearbox	Z	-	-	0.188	152.7	0.16	6.0

TABLE 61. OH-58 FLIGHT TEST DATA—90 KN; 3100 FT ALT; FREQUENCY = 35.4 HZ (MR 6/ REV)

Location		Flight Test		Mobility Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine	Y	-	-	0.144	-2.8	0.57	-110.6
Midsplit	Z	-	-	0.574	59.7	0.60	-162.6
Forward	Y	-	-	0.044	152.7	0.60	83.2
Compressor	Z	-	-	0.321	-135.4	1.13	6.9
Igniter	Y	-	-	0.290	174.7	0.72	8.4
	Z	-	-	1.068	53.0	1.04	179.9
Top	X	-	-	0.392	49.8	0.27	90.5
Gearbox	Z	-	-	0.105	-158.2	0.02	61.0

TABLE 62. OH-58 FLIGHT TEST DATA—90 KN; 3100 FT ALT; FREQUENCY = 47.2 HZ (MR 8/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	-	-	0.027	105.7	0.22	-31.4
Midsplit	Z	-	-	0.119	17.0	0.19	37.2
Forward	Y	-	-	0.033	146.8	0.13	131.0
Compressor	Z	-	-	0.010	-146.8	0.73	-129.6
Igniter	Y	-	-	0.087	-81.4	0.32	-120.6
	Z	-	-	0.298	24.1	0.49	51.2
Top	X	-	-	0.024	-67.7	0.02	140.6
Gearbox	Z	-	-	0.051	170.6	0.10	-141.6

TABLE 63. OH-58 FLIGHT TEST DATA—90 KN; 3100 FT ALT; FREQUENCY = 87.6 HZ (TR 2/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	-	-	0.044	109.6	19.56	84.9
Midsplit	Z	-	-	1.679	69.0	4.69	-40.9
Forward	Y	-	-	0.159	117.5	16.78	-86.5
Compressor	Z	-	-	0.113	-68.9	5.50	12.9
Igniter	Y	-	-	0.328	-64.5	4.11	-113.8
	Z	-	-	0.644	58.5	5.91	123.2
Top	X	-	-	0.208	-161.7	5.83	-105.5
Gearbox	Z	-	-	0.007	175.7	2.95	66.7

TABLE 64. OH-58 FLIGHT TEST DATA—110 KN; 3100 FT ALT; FREQUENCY = 11.8 HZ (MR 2/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	0.68	-	0.260	-68.5	58.42	115.0
Midsplit	Z	0.20	-	1.886	91.3	1.39	-118.4
Forward	Y	0.58	-	0.168	62.3	88.48	-54.8
Compressor	Z	0.23	-	0.950	110.6	21.84	-3.1
Igniter	Y	0.84	-	0.455	36.9	14.17	-9.1
	Z	0.15	-	2.178	98.5	21.02	161.3
Top	X	0.26	-	0.770	98.1	40.37	-49.3
Gearbox	Z	0.23	-	1.396	133.6	3.23	79.6

TABLE 65. OH-58 FLIGHT TEST DATA—110 KN; 3100 FT ALT; FREQUENCY = 23.6 HZ (MR 4/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	0.25	-	0.084	-79.9	0.11	-4.3
Midsplit	Z	0.075	-	0.445	-143.9	0.45	8.4
Forward	Y	0.11	-	0.093	85.9	0.10	77.8
Compressor	Z	0.095	-	0.265	23.6	0.85	-168.8
Igniter	Y	0.35	-	0.210	52.0	0.45	-180.0
	Z	0.15	-	0.809	-146.9	0.68	-0.1
Top	X	0.095	-	0.299	-146.0	0.07	58.8
Gearbox	Z	0.05	-	0.076	31.4	0.09	-124.4

TABLE 66. OH-58 FLIGHT TEST DATA—110 KN; 3100 FT ALT; FREQUENCY = 35.4 HZ (MR 6/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	0.22	-	0.073	-140.5	0.15	-52.8
Midsplit	Z	0.295	-	0.164	-85.7	0.64	39.0
Forward	Y	0.14	-	0.0140	69.0	0.17	114.4
Compressor	Z	0.355	-	0.313	28.4	1.99	-145.7
Igniter	Y	0.55	-	0.131	-36.0	1.14	-141.1
	Z	0.66	-	0.478	-110.5	1.64	37.5
Top	X	0.30	-	0.238	-169.9	0.09	129.4
Gearbox	Z	0.045	-	0.145	-0.5	0.12	-147.2

TABLE 67. OH-58 FLIGHT TEST DATA—110 KN; 3100 FT ALT; FREQUENCY=47.2 HZ (MR 8/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	0.03	-	0.007	105.7	0.06	-31.4
Midsplit	Z	0.03	-	0.033	17.0	0.05	37.2
Forward	Y	0.02	-	0.009	146.8	0.04	131.0
Compressor	Z	0.135	-	0.027	-146.8	0.20	-129.0
Igniter	Y	0.07	-	0.024	-81.4	0.09	-120.6
	Z	0.10	-	0.083	24.1	0.13	51.2
Top	X	0.07	-	0.007	-67.7	0.01	140.6
Gearbox	Z	0.05	-	0.014	170.6	0.03	-141.6

TABLE 68. OH-58 FLIGHT TEST DATA—110 KN; 3100 FT ALT; FREQUENCY = 87.6 HZ (TR 2/REV)

Location		Flight Test		Mobility Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine	Y	0.03	-	0.027	109.5	15.63	76.3
Midsplit	Z	0.015	-	1.410	57.7	2.70	-38.6
Forward	Y	0.035	-	0.172	123.4	14.16	-94.6
Compressor	Z	0.02	-	0.119	-76.9	5.67	-24.8
Igniter	Y	0.04	-	0.308	-57.9	3.32	-129.1
	Z	0.04	-	0.617	50.2	5.41	110.8
Top	X	0.04	-	0.244	-171.6	5.10	-112.1
Gearbox	Z	0.02	-	0.028	172.9	2.03	37.2

TABLE 69. OH-58 FLIGHT TEST DATA—130 KN; 3100 FT ALT; FREQUENCY = 11.8 HZ (MR 2/REV); OPTION = 2

Location		Flight Test		Mobility Test		Mobility Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine	Y	0.90	-	0.248	-123.0	185.97	117.3
Midsplit	Z	0.515	-	7.305	91.7	3.88	-114.1
Forward	Y	0.78	-	0.351	18.7	284.18	-52.3
Compressor	Z	0.37	-	3.839	112.3	71.81	0.3
Igniter	Y	1.16	-	1.660	7.9	45.87	-5.4
	Z	0.49	-	8.72	99.6	68.76	164.6
Top	X	0.275	-	3.248	95.9	130.28	-46.6
Gearbox	Z	0.33	-	5.412	133.9	10.60	80.3

TABLE 70. OH-58 FLIGHT TEST DATA—130 KN; 3100 FT ALT; FREQUENCY = 23.6 HZ (MR 4/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	0.21	-	0.134	-43.6	0.80	-138.1
Midsplit	Z	0.16	-	0.862	50.6	0.82	-170.0
Forward	Y	0.10	-	0.038	36.7	0.79	47.9
Compressor	Z	0.175	-	0.481	-142.9	1.42	1.0
Igniter	Y	0.34	-	0.241	157.5	0.96	-2.3
	Z	0.32	-	1.563	44.2	1.33	170.6
Top	X	0.175	-	0.561	41.8	0.33	52.7
Gearbox	Z	0.08	-	0.126	-164.9	0.07	105.3

TABLE 71. OH-58 FLIGHT TEST DATA—130 KN; 3100 FT ALT; FREQUENCY = 35.4 HZ (MR 6/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	0.07	-	0.141	3.7	0.28	91.3
Midsplit	Z	0.27	-	0.314	58.4	1.24	-176.8
Forward	Y	0.10	-	0.027	-146.9	0.33	-101.4
Compressor	Z	0.37	-	0.602	172.5	3.82	-1.6
Igniter	Y	0.27	-	0.251	108.1	2.18	3.0
	Z	0.65	-	0.917	33.6	3.16	-178.4
Top	X	0.17	-	0.457	-25.7	0.17	-86.5
Gearbox	Z	0.04	-	0.278	143.6	0.23	-3.0

TABLE 72. OH-58 FLIGHT TEST DATA—130 KN: 3100 FT ALT; FREQUENCY = 47.2 HZ (MR 8/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	0.01	-	0.072	-174.3	0.58	48.6
Midsplit	Z	0.05	-	0.318	97.0	0.52	117.2
Forward	Y	0.03	-	0.089	-133.2	0.35	-149.0
Compressor	Z	0.12	-	0.261	-66.8	1.96	-49.6
Igniter	Y	0.04	-	0.232	-1.4	0.86	-40.6
	Z	0.13	-	0.794	104.1	1.30	131.2
Top	X	0.09	-	0.064	12.3	0.05	-139.4
Gearbox	Z	0.05	-	0.136	-109.4	0.25	-61.6

TABLE 73. OH-58 FLIGHT TEST DATA—130 KN; 3100 FT ALT; FREQUENCY = 87.6 HZ (TR 2/REV)

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Mobility Test Amplitude (in./sec/lb)	Mobility Test Phase (degrees)	Mobility Analysis Amplitude (in./sec/lb)	Mobility Analysis Phase (degrees)
Turbine	Y	0.02	-	0.040	21.4	15.85	43.4
Midsplit	Z	0.02	-	1.582	35.7	4.05	-159.5
Forward	Y	0.03	-	0.105	177.5	13.57	-111.7
Compressor	Z	0.01	-	0.117	-61.4	12.99	-30.9
Igniter	Y	0.04	-	0.072	-16.1	3.73	-157.0
	Z	0.06	-	0.573	50.7	7.37	133.8
Top	X	0.02	-	0.290	-145.6	4.25	-133.3
Gearbox	Z	0.02	-	0.068	-125.4	4.93	6.4

There is speculation that the test procedure used in testing the bipod interface points may have caused some error in the data. The bipods were tested in the fore and aft, lateral, and vertical directions, although their plane of orientation is not so aligned. Therefore, forces along the coordinate axes might become biased by the "soft" directions and could have produced erroneous results. The suggestion has been made that more accurate testing could be accomplished by securing the bipods together by light, rigid links similar to the fixity they would have when the engine is attached. This approach would quite obviously change the airframe mobilities and thus change the coupled system mobilities. It is not clear whether forcing this bipod coupling during testing is equivalent to mathematically performing the coupling through the engine mobilities. Before altering the test procedure in the suggested manner, this question must be resolved.

Analysis of the test mobilities shows the matrices to be nonsymmetric. Table 74 shows a comparison of some selected mobilities for the engine and airframe to indicate the degree to which the off-diagonal terms of the mobility matrices are unequal. These considerable deviations indicate the extreme nonlinearities in the subsystems. Although the nonsymmetry does not create problems with the solution scheme used, it is a source of potential error and needs further study.

TABLE 74. SYMMETRY COMPARISON FOR AIRFRAME AND ENGINE TEST MOBILITIES

Element	Amplitude	Phase	Element	Amplitude	Phase	Amplitude Deviation
Engine						
1/4	0.0047	-89.2	4/1	0.0111	-89.1	2.36
2/4	0.0203	116.9	4/2	0.0344	91.3	1.69
3/4	0.0010	-99.8	4/3	0.0017	-95.7	1.70
Airframe Y_{EE} Matrix						
4/7	0.0315	91.9	7/4	0.0204	91.3	0.65
4/8	0.0368	91.4	8/4	0.0579	84.6	1.57
4/9	0.0012	83.2	9/4	0.0070	143.5	5.83

The analysis of the OH-58 helicopter has been presented, using the mobility technique in conjunction with laboratory shake test data for both the engine and airframe. The results compare poorly with coupled system shake and flight data. Potential areas of error have been discussed.

Modal Synthesis Analysis

The OH-58 helicopter was also analyzed using the previously described modal synthesis technique. This technique, automated as program MODSYN (Appendix D), requires input subsystem descriptions in terms of uncoupled modes. The subsystems are coupled through point stiffnesses, and solutions to the coupled system dynamics problems are determined.

The subsystem description of the OH-58 airframe was accomplished by Bell Helicopter and subsequently transmitted to DDA in terms of uncoupled modes. Results of a NASTRAN analysis of the OH-58 airframe for a 2-D model were provided. Details of this analysis are provided in Reference 14. The specific information required here includes:

- Normalized mode shapes
- Generalized masses
- Generalized stiffness

The data were prepared for input to MODSYN and are listed in Table 75. Definition of the coordinates of the airframe which are represented in the mode shapes is given in Table 76. The first 20 airframe modes, through 52 Hz, were used because of program space limitations at the time of the analysis. (The program was later enlarged to accommodate more modes.) Therefore, calculations must be limited to below 50 Hz, which covers all main rotor excitations.

TABLE 75. OH-58 AIRFRAME INPUT TO MODSYN

OH-58 GENERALIZED MASS								
1.349801	.5679669	4.758002	3.668324	1.929529	.2602376	.8058739	MH	1
.1156369	.2885643	.1168187	.4147482	.004662938	.00639987	.6386055	MH	2
.02335675	.2906427	.2538396	.2337462	.01561724	.01123283		MH	3
OH-58 GENERALIZED STIFFNESS								
0.0	0.0	0.0	0.0	0.0	0.0	673.4766	HSTIFF	1
218.1284	725.5632	353.2124	2142.048	38.907	140.0786	14468.07	HSTIFF	2
619.5295	9738.906	13742.45	19818.73	1637.947	1239.930		HSTIFF	3
OH-58 FREQUENCIES								
0.0	0.0	0.0	0.0	0.0	0.0	4.600954	OMEGH	1
6.912388	7.980620	8.751491	11.43780	14.53799	23.4617	23.95570	OMEGH	2
25.92059	29.13368	37.03162	46.34315	51.54282	52.87787		OMEGH	3
OH-58 MODE SHAPE FOR MODE 1								
.028572	-.446915	-.205163	-.0010085	-.446915	.0279733	-.007006	FH	11
-.305808	-.088595	.0042734	-.41414	-.051705	.0875258	-1.0	FH	2
-.02762	.013748	-.071034	-.52475	.011252	-.4765	-.034297	FH	3
-.085108	-.013584	.187678	-.03017	-.172350	-.060956	-.016642	FH	4
-.143153	-.201503	-.0027457	-.120609	-.3372	.092252	-.65674	FH	5
-.46342	-.064973	.39652	-.447195				FH	6
OH-58 MODE SHAPE FOR MODE 2								
-.014156	-.093397	.1263	-.021896	-.093397	.176996	.022407	FH	21
-.062713	.151648	.0004684	-.087675	.079896	-.16146	-.21599	FH	22
.0330502	-.01796	.004937	1.0	-.013105	-.101897	.046036	FH	23
.174322	-.0096807	-.38572	.067469	-.0347439	.097888	.04115	FH	24
-.023046	.37126	.01412[illegible]1	-.01298	.6352	-.19918	-.12088	FH	25
1.10107	.106626	.1075346	1.06951				FH	26
OH-58 MODE SHAPE FOR MODE 3								
.0274597	-.0087058	.739704	.026506	-.0087058	.750762	.0078131	FH	31
-.0020124	.74523	.0182145	-.0066688	.779251	.0949865	-.0341438	FH	32
.80146	.026951	.00341945	.343027	.0246497	-.0093993	.795303	FH	33
-.06421	.0154624	1.0	-.01355	.0046795	.77072	-.001073	FH	34
.0042263	.641114	.0117417	.0035208	.51598	.11085	-.24894	FH	35
.310444	-.034135	.02528	.325411				FH	36
OH-58 MODE SHAPE FOR MODE 4								
-.0241196	.613683	-.0113983	.024184	.61368	-.0121748	.00002346	FH	41
.613213	-.0117866	.00002823	.066535	-.11771	.00006343	.701104	FH	42
-.0117608	.00003224	.0002681	-.011971	.00003118	.68999	-.011763	FH	43
-.00000956	1.0	-.0116698	.000013667	.651559	-.0117748	.000019389	FH	44
.4542	-.0118343	.00002526	.263668	-.0118916	.021184	-.054728	FH	45
-.012327	.0211177	-.035457	-.0123206				FH	46
OH-58 MODE SHAPE FOR MODE 5								
.600522	.00301999	-.127155	.602163	.0030198	-.130323	.55982	FH	51
.0011027	-.12874	.582348	.0039054	-.055052	.74867	.012734	FH	52
-.006937	.60127	-.0178198	-1.0	.596288	.0053807	-.020275	FH	53
.403798	.007098	.42314	.051354	.0002865	-.073528	.54057	FH	54
-.00518	-.35428	.568326	-.010381	-.62534	.78464	-.011325	FH	55
-1.08243	.47056	-.02505	-1.05				FH	56
OH-58 MODE SHAPE FOR MODE 6								
-.033517	-.13216	.0058987	.0301479	-.13216	-.001703	-.0011926	FH	61
-.136763	.0020988	-.0014594	-.06589	.001226	-.003432	-.0028320	FH	62
.0006555	-.001683	-.94034	.012413	-.0016247	-.03208	.00081374	FH	63
.00065569	.358099	-.0044394	-.0006443	-.090656	.00144469	-.0009645	FH	64
-.348175	.00477	-.001293	-.59657	.00798	.0239618	-.99536	FH	65
.010055	.0276766	-1.0	.009671				FH	66
OH-58 MODE SHAPE FOR MODE 7								

TABLE 75—Continued

.17356	-.0033256	-.0084372	.173553	.00098233	-.008087	.15144	FH	71
-.0009522	.00094047	.211957	.000004688	.167667	-.86939	.0020036	FH	72
-.068447	.23402	-.0005898	-.99528	.15317	.0001316	.0021072	FH	73
.09225	-.000455	.172923	.136357	-.0007187	.0148611	.151875	FH	74
-.0008319	-.119449	.177007	-.0009135	-.364566	.59805	-.003195	FH	75
-1.15629	-.023268	.0017154	-1.091643				FH	76
	OH-58 MODE SHAPE FOR MODE 8							
.013808	-.25298	-.054972	-.016451	-.25293	.0573265	-.1072828	FH	81
-.178277	.0012286	-.0014562	-.053934	.00008566	.0013889	.163092	FH	82
.0006266	-.000401	-.333728	-.0028155	-.001335	-.056324	.0003878	FH	83
.00000619	-.25936	-.0030681	-.0007485	-.127115	.0008189	-.0008783	FH	84
-.065954	.0024473	-.0008554	-.101752	.00217615	.021899	-1.0	FH	85
.0557797	.016837	.113647	.0563016				FH	86
	OH-58 MODE SHAPE FOR MODE 9							
.1319686	.0046274	-.132297	.130905	-.0028806	-.131434	.1094697	FH	91
.0015016	-.141126	.152782	.0008949	-.0204808	-.104903	.00040273	FH	92
-.066368	-.029532	-.0184984	.988721	.143095	.00033666	-.0446133	FH	93
.00003664	-.008905	.342184	.076207	.001222	-.0974468	.084786	FH	94
.0037567	-.240597	.068052	.0001501	-.074919	-.71589	-.039185	FH	95
1.293982	.468073	-.023852	1.171766				FH	96
	OH-58 MODE SHAPE FOR MODE 10							
.0088994	.316412	.04118486	-.0104208	.31648	-.039033	-.00062967	FH	101
.262344	.00117196	-.0009735	.124998	.00028146	.00061574	-.096674	FH	102
.00053557	.00083713	-.546999	-.0122301	-.0009259	.105415	.00040013	FH	103
.00018157	-.158877	-.0027104	-.0003917	.193625	.00084701	-.0004238	FH	104
.243606	.0016835	-.0001948	.0996131	-.0007137	.0752106	-1.0	FH	105
-.0373201	.064384	-.87378	-.036203				FH	106
	OH-58 MODE SHAPE FOR MODE 11							
-.099571	-.002464	.128507	-.099561	.0050751	.128089	-.08343	FH	111
.009902	.133748	-.106558	.0005445	.0066703	.019944	-.0003089	FH	112
.08913	-.0265596	-.0006159	-.2584	-.101895	.00053794	.0783128	FH	113
-.0049814	.0001017	-.176816	-.061444	.00072865	.104431	-.070213	FH	114
.00065118	.214109	-.068551	.0002942	.195949	.2896965	-.0006698	FH	115
-.39847	-.25421	-.0004199	-.342323				FH	116
	OH-58 MODE SHAPE FOR MODE 12							
-.0001035	.0017852	.00094046	.00008759	.00178745	-.0009132	-.00000874	FH	121
.00002438	.00001641	-.00001258	-.0005691	.000006226	.000001777	-.00025807	FH	122
.000008359	-.00005565	.055771	.00057051	-.00001226	-.00016472	.000007112	FH	123
-.00000506	.0137835	-.00002327	-.00000709	-.00097546	.000013116	-.00005549	FH	124
.00336537	.000012659	-.00000560	.0219311	.00002822	-.033006	-1.0	FH	125
.014896	-.0012723	.202281	.0146868				FH	126
	OH-58 MODE SHAPE FOR MODE 13							
-.0033889	-.0037867	-.0001638	.00417909	-.0037639	.00037419	.0002448	FH	131
-.0011787	.00022093	.00019744	.035257	.0001428	-.00000030	-.0085526	FH	132
.00003882	.00002037	-.017682	.0028874	.00017359	.0430398	.00008343	FH	133
-.0000523	-.0251741	-.00000494	.00017957	.0053257	.00024006	.00028278	FH	134
-.0362736	-.000481	.0003314	-.074974	-.0007124	-.0156665	.146946	FH	135
.0327715	-.0141278	1.0	.0326127				FH	136
	OH-58 MODE SHAPE FOR MODE 14							
-.44599	.0093192	-.10375	-.44445	-.011146	-.1036	-.274954	FH	141
-.0003012	-.230867	-.22913	.0058051	-.184215	.0038115	-.001529	FH	142
-.10046	-.22298	.00244547	-.368684	-.202376	.0074853	-.117658	FH	143
.0129783	-.0053273	.0426024	-.198589	.0010254	-.25803	-.305944	FH	144
-.0073467	.578101	-.369175	-.014634	1.16913	1.251894	-.0193499	FH	145
-1.024032	-1.291293	.0774064	-.7615117				FH	146
	OH-58 MODE SHAPE FOR MODE 15							

TABLE 75—Continued

.0118767	.077644	.0050916	-.013562	.0776663	-.005304	-.0005873	FH	151
.046744	-.0002914	-.0005244	-.143103	-.0001131	-.00000817	.032249	FH	152
.00005934	-.0009203	-.115998	.0013539	-.0004716	-.174105	.00001859	FH	153
.0001938	.0623939	-.0004784	-.0004573	.0225968	-.0003457	-.0006273	FH	154
.109435	.0007846	-.0006508	.1351122	.0001303	.0226125	.276911	FH	155
.0350211	.0258806	1.0	.0346837				FH	156
OH-58 MODE SHAPE FOR MODE 16								
.0441898	-.167681	-.010752	-.0520972	-.167250	.010456	-.003093	FH	161
-.113435	-.0008852	-.002592	.3994837	-.00047797	-.00009019	-.0764579	FH	162
.00049265	-.0055602	-.366084	.0060905	-.0022816	.0435607	.0002944	FH	163
.0013632	.3190255	-.0045181	-.0026932	-.186428	-.0009105	-.0032448	FH	164
.4073018	.0018734	-.0029323	.809249	-.0083619	.118986	.735744	FH	165
.1209699	.177735	1.0	.1149073				FH	166
OH-58 MODE SHAPE FOR MODE 17								
-.20465	-.049636	-.0369715	-.194192	.0282575	-.038446	-.201424	FH	171
-.0050975	-.052288	-.173714	-.0049435	.0293257	-.011128	.00037006	FH	172
.0990966	-.2252128	.0208152	.0612303	-.1514088	-.0023947	.0849289	FH	173
.062723	-.013743	-.522014	-.194979	.0015969	-.036999	-.165457	FH	174
-.02419	-.146811	-.113901	-.012688	-.793789	-1.59713	.0170948	FH	175
.6843892	.7818499	-.0618792	.4388162				FH	176
OH-58 MODE SHAPE FOR MODE 18								
-.2260359	-.29927	.202274	-.1748092	.1489694	.1781884	-.0570377	FH	181
-.0188863	.1926222	-.1392949	-.0077642	-.119433	.0147582	.00021928	FH	182
-.104275	-.0145223	.0198904	.0408069	-.136638	-.0013538	-.113847	FH	183
-.0230204	-.0205856	.4839633	.01919806	-.0035997	.0408958	-.0096316	FH	184
-.033502	.3218292	.0683858	.03154669	-.053123	-1.502911	.0588504	FH	185
.7517812	1.102813	-.0862379	.4828023				FH	186
OH-58 MODE SHAPE FOR MODE 19								
.3030366	.9285405	-.214623	-.334649	1.0	.2370737	-.0033843	FH	191
.0590674	.0048464	-.0053873	.0204926	-.0031858	.00024218	-.0001955	FH	192
-.0017672	.0016534	.0095041	-.004942	-.0049551	.0013277	-.00214	FH	193
-.0001785	-.0001610	.00260102	-.0013467	.01725836	[illegible]052403	-.0004286	FH	194
.032398	.00276376	.00238364	-.110948	-.01883[illegible]	[illegible]520557	-.0658637	FH	195
-.0387138	-.0193171	.0454178	-.0420932				FH	196
OH-58 MODE SHAPE FOR MODE 20								
-.0328185	-1.0	.255965	-.3015366	.9191473	.2353776	.00188915	FH	201
-.00022697	.000282516	.0023585	-.00009058	.00018808	.00002375	.000000143	FH	202
-.0005446	.0036769	-.0004283	.00047426	.0021409	-.00000489	-.0003445	FH	203
.0007557	.0040687	-.0037146	.0014956	-.000126	-.0005032	.0029978	FH	204
.0018966	-.0093996	.00211316	-.0021091	.0048289	.029979	-.0022503	FH	205
-.0134366	-.0180056	.00191137	-.0084833				FH	206

TABLE 76. DEFINITION OF COORDINATES REPRESENTED IN OH-58 AIRFRAME MODE SHAPES

Node No.	Coord No.	Description
		Left Bipod
206	1	Fore and aft
	2	Lateral
	3	Vertical
		Right Bipod
209	4	Fore and aft
	5	Lateral
	6	Vertical
		Lower Bipod
203	7	Fore and aft
	8	Lateral
	9	Vertical
		Transmission Input
323	10	Fore and aft.
	11	Lateral
	12	Vertical
		Main Rotor
321	13	Fore and aft
	14	Lateral
	15	Vertical
		Tail Rotor
428	16	Fore and aft
	17	Lateral
	18	Vertical
		Main Rotor Hub
312	19	Fore and aft
	20	Lateral
	21	Vertical
		Nose
401	22	Fore and aft
	23	Lateral
	24	Vertical
		Center of Fuselage
419	25	Fore and aft
	26	Lateral
	27	Vertical
		Tail Boom Base
422	28	Fore and aft
	29	Lateral
	30	Vertical
		Center of Tail Boom
425	31	Fore and aft
	32	Lateral
	33	Vertical
		Top Tail Fin
602	34	Fore and aft
	35	Lateral
	36	Vertical
		Bottom Tail Fin
604	37	Fore and aft
	38	Lateral
	39	Vertical

The T63-A-5 engine was modeled at DDA and correlated with the engine laboratory shake test data. A conventional beam element rotor/case analysis program already in use at DDA was used to develop a mass-elastic representation of the engine. Table 77 is a listing of the pitch plane representation showing weights, geometry, and material properties as well as subsystem coupling elements. The resulting mode shapes, masses, and stiffnesses for the first eight free-free modes are shown in Tables 78 through 85. These modes include the six rigid body modes and the first two flexible engine modes for the pitch and yaw planes. A comparison of these flexible modes with those determined during test are shown in Figures 25 and 26. The data were prepared for input to MODSYN and are included as Table 86. Definition of the coordinates represented in the mode shapes is presented in Table 87.

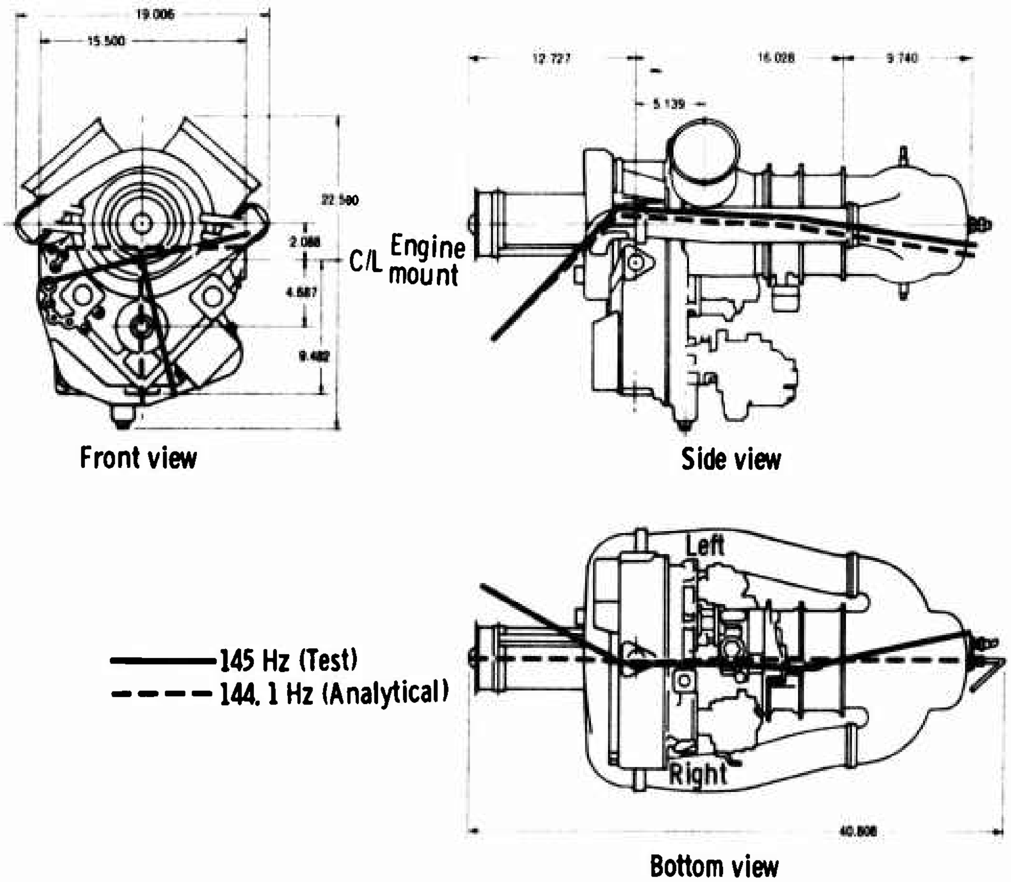


Figure 25. Correlation of Analytical and Test Modes for First Flexible Engine Mode.

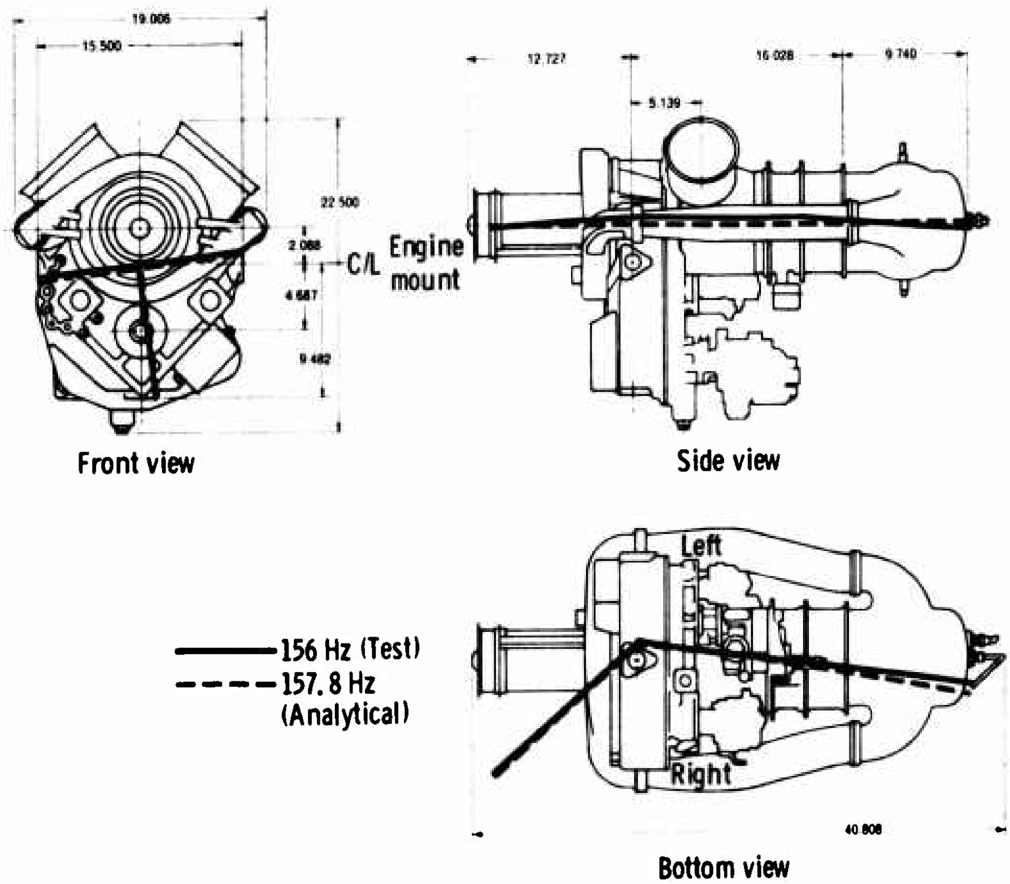


Figure 26. Correlation of Analytical and Test Modes for Second Flexible Mode.

TABLE 77. T63-A-5 IDEALIZED MODEL FOR OBTAINING ENGINE MODE SHAPES

Main Case

Modulus of Elasticity—30,000,000 psi	Material Density—0.2820 lb/in.^{3}
Shear Modulus—12,000,000 psi	Speed Ratio—0.0
Y Position—0.0	Z Position—0.0

Axial Station (in.)	OD (in.)	ID (in.)	Weight (lb)	Polar Moment	
-0.450	4.600	4.520	5.294	9.339	MAIN CYL
1.110	4.520	4.420	0.680	3.216	MAIN CYL
2.760	4.520	4.420	0.680	3.216	MAIN CYL
4.490	4.520	4.420	0.680	3.216	MAIN CYL
6.170	4.520	4.420	0.680	3.216	MAIN CYL
7.090	4.520	4.420	0.0	0.0	MAIN CYL
7.690	4.740	4.440	0.0	0.0	MAIN CYL
8.090	5.260	4.910	2.517	17.014	MAIN CONE
S = 1,000,000 (in.-lb/rad) Pitch = 820,000 (deg) Yaw					
8.880	13.000	12.000	0.001	0.001	MAIN CYL
9.070	13.000	12.000	0.0	0.0	MAIN CYL
9.080	4.140	3.840	0.0	0.0	MAIN CYL
9.400	4.060	3.840	0.0	0.0	MAIN CONE
9.530	4.060	3.200	0.0	0.0	MAIN CYL
9.570	3.500	3.200	0.024	0.0	MAIN CYL
9.640	13.000	12.000	4.988	17.890	MAIN CYL
10.500	13.000	12.000	12.877	288.200	MAIN CYL
11.200	13.000	12.000	12.877	288.200	MAIN CYL
11.530	13.000	12.000	17.846	0.0	MAIN CYL
12.450	13.000	12.000	23.699	576.500	MAIN CYL
13.980	13.000	12.000	23.443	576.500	MAIN CYL
14.500	9.140	9.020	0.0	0.0	MAIN CYL
15.450	9.140	9.020	3.349	27.800	MAIN CYL
16.450	9.140	9.020	3.200	80.000	MAIN CYL
16.451	10.140	10.000	0.0	64.000	MAIN CYL
19.450	7.720	7.600	4.000	64.000	MAIN CONE
21.000	7.400	7.280	5.713	30.000	MAIN CYL
21.630	7.320	7.000	7.010	21.000	MAIN CYL
21.910	7.320	7.000	0.0	0.0	MAIN CYL
22.700	7.320	7.000	3.000	20.000	MAIN CYL
23.500	7.000	6.900	2.900	20.000	MAIN CYL
25.600	7.200	7.100	8.239	57.000	MAIN CYL
27.000	7.240	7.140	3.000	37.000	MAIN CYL
30.000	7.240	7.140	3.112	37.000	MAIN CYL
33.000	7.240	7.140	3.112	37.000	MAIN CYL
36.000	7.240	7.140	3.112	37.000	MAIN CYL

WEIGHT = 156.034 IXX = 6.003 IYY = 24.101 IZZ = 24.101
C.G. LOCATION = 15.216 0.0 0.0

TABLE 78. T63-A-5 FREE-FREE MODE 1

Location	Coordinates X	Coordinates Y	Coordinates Z	Mode Shape X	Mode Shape Y	Mode Shape Z
Left Mount	11.2	7.75	-4.6875	-0.3053	0.02321	0.0
Right Mount	11.2	-7.75	-4.6875	0.3053	0.02321	0.0
Bottom Mount	11.2	0.0	12.0155	0.0	0.02321	0.0
Output Shaft	11.2	0.0	-7.375	0.0	0.02321	0.0
Turbine Mid-Splitline	23.5	0.0	4.25	-	0.50767	0.0
Fwd Compressor	-0.45	0.0	2.7	-	-0.43565	0.0
Igniter	36.0	0.0	0.0	-	1.0	0.0
Top Gearbox	11.2	0.0	4.62	0.0	-	0.0

Frequency, 0.35; Modal Mass, 0.05068016; Modal Stiffness, 0.2409089.

TABLE 79. T63-A-5 FREE-FREE MODE 2

Location	Coordinates X	Coordinates Y	Coordinates Z	Mode Shape X	Mode Shape Y	Mode Shape Z
Left Mount	11.2	7.75	-4.6875	0.1846	0.0	0.02321
Right Mount	11.2	-7.75	-4.6375	0.1846	0.0	0.02321
Bottom Mount	11.2	0.0	12.0155	0.4733	0.0	0.02321
Output Shaft	11.2	0.0	-7.375	0.2905	0.0	0.02321
Turbine Mid-Splitline	23.5	0.0	4.25	-	0.0	0.50767
Fwd Compressor	-0.45	0.0	2.7	-	0.0	-0.18198
Igniter	36.0	0.0	0.0	-	0.0	1.0
Top Gearbox	11.2	0.0	4.62	-0.18198	-	0.02321

Frequency, 0.40; Modal Mass, 0.05068016; Modal Stiffness, 0.3212115.

TABLE 80. T63-A-5 FREE-FREE MODE 3

Location	Coordinates X	Coordinates Y	Coordinates Z	Mode Shape X	Mode Shape Y	Mode Shape Z
Left Mount	11.2	7.75	-4.6875	0.0	0.0	7.75
Right Mount	11.2	-7.75	-4.6875	0.0	0.0	-7.75
Bottom Mount	11.2	0.0	12.0155	0.0	12.0155	0.0
Output Shaft	11.2	0.0	-7.375	0.0	7.375	0.0
Turbine Mid-Splitline	23.5	0.0	4.25	-	-4.25	0.0
Fwd Compressor	-0.45	0.0	2.7	-	-2.7	0.0
Igniter	36.0	0.0	0.0	-	0.0	0.0
Top Gearbox	11.2	0.0	4.62	0.0	-	0.0

Frequency, 0.65; Modal Mass, 6.002852; Modal Stiffness, 10.0543

TABLE 81. T63-A-5 FREE-FREE MODE 4

Location	Coordinates X	Coordinates Y	Coordinates Z	Mode Shape X	Mode Shape Y	Mode Shape Z
Left Mount	11.2	7.75	-4.6875	1.0	0.0	0.0
Right Mount	11.2	-7.75	-4.6875	1.0	0.0	0.0
Bottom Mount	11.2	0.0	12.0155	1.0	0.0	0.0
Output Shaft	11.2	0.0	-7.375	1.0	0.0	0.0
Turbine Mid-Splitline	23.5	0.0	4.25	-	0.0	0.0
Fwd Compressor	-0.45	0.0	2.7	-	0.0	0.0
Igniter	36.0	0.0	0.0	-	0.0	0.0
Top Gearbox	11.2	0.0	4.62	1.0	-	0.0

Frequency, 0.79; Modal Mass, 0.404025; Modal Stiffness, 10.00544.

TABLE 82. T63-A-5 FREE-FREE MODE 5

Location	Coordinates X	Coordinates Y	Coordinates Z	Mode Shape X	Mode Shape Y	Mode Shape Z
Left Mount	11.2	7.75	-4.6875	0.2708	0.59289	0.0
Right Mount	11.2	-7.75	-4.6875	-0.2708	0.59289	0.0
Bottom Mount	11.2	0.0	12.0155	0.0	0.59289	0.0
Output Shaft	11.2	0.0	-7.375	0.0	0.59289	0.0
Turbine Mid-Splitline	23.5	0.0	4.25	-	0.16313	0.0
Fwd Compressor	-0.45	0.0	2.7	-	1.0	0.0
Igniter	36.0	0.0	0.0	-	-0.27361	0.0
Top Gearbox	11.2	0.0	4.62	0.0	-	0.0

Frequency, 1.11; Modal Mass, 0.1121773; Modal Stiffness, 5.458884.

TABLE 83. T63-A-5 FREE-FREE MODE 6

Location	Coordinates X	Coordinates Y	Coordinates Z	Mode Shape X	Mode Shape Y	Mode Shape Z
Left Mount	11.2	7.75	-4.6875	-0.16378	0.0	0.59287
Right Mount	11.2	-7.75	-4.6875	-0.16378	0.0	0.59287
Bottom Mount	11.2	0.0	12.0155	-0.41982	0.0	0.59287
Output Shaft	11.2	0.0	-7.375	-0.25768	0.0	0.59287
Turbine Mid-Splitline	23.5	0.0	4.25	-	0.0	0.16313
Fwd Compressor	-0.45	0.0	2.7	-	0.0	1.000
Igniter	36.0	0.0	0.0	-	0.0	-0.27360
Top Gearbox	11.2	0.0	4.62	0.1614	-	0.59287

Frequency, 1.28; Modal Mass, 0.1121703; Modal Stiffness, 7.278037.

TABLE 84. T63-A-5 FREE-FREE MODE 7

Location	Coordinates X	Coordinates Y	Coordinates Z	Mode Shape X	Mode Shape Y	Mode Shape Z
Left Mount	11.2	7.75	-4.6875	0.0576	0.0	-0.10924
Right Mount	11.2	-7.75	-4.6875	0.0576	0.0	-0.10924
Bottom Mount	11.2	0.0	12.0155	0.1475	0.0	-0.10924
Output Shaft	11.2	0.0	-7.375	0.0905	0.0	-0.10924
Turbine Mid-Splitline	23.5	0.0	4.25	-	0.0	0.05702
Fwd Compressor	-0.45	0.0	2.7	-	0.0	1.000
Igniter	36.0	0.0	0.0	-	0.0	0.25393
Top Gearbox	11.2	0.0	4.62	-0.0567	-	-0.10924

Frequency, 144.1; Modal Mass, 0.02059351; Modal Stiffness, 16,880.82.

TABLE 85. T63-A-5 FREE-FREE MODE 8

Location	Coordinates X	Coordinates Y	Coordinates Z	Mode Shape X	Mode Shape Y	Mode Shape Z
Left Mount	11.2	7.75	-4.6875	-0.09253	-0.10892	0.0
Right Mount	11.2	-7.75	-4.6875	0.09253	-0.10892	0.0
Bottom Mount	11.2	0.0	12.0155	0.0	-0.10892	0.0
Output Shaft	11.2	0.0	-7.375	0.0	-0.10892	0.0
Turbine Mid-Splitline	23.5	0.0	4.25	-	0.05622	0.0
Fwd Compressor	-0.45	0.0	2.7	-	1.0	0.0
Igniter	36.0	0.0	0.0	-	0.25810	0.0
Top Gearbox	11.2	0.0	4.62	0.0	-	0.0

Frequency, 157.867; Modal Mass, 0.02058931; Modal Stiffness, 20,257.61.

TABLE 86. T63-A-5 INPUT TO MODSYN FOR OH-58 ANALYSIS

```
           T63-A-5 GENERALIZED MASS
.05068016 .05068016 6.002852  .404025   .1121773  .1121703  .02059351   ME      1
.02058931                                                               ME      2
           T63-A-5 GENERALIZED STIFFNESS
0.0       0.0       0.0       0.0       0.0       0.0       16880.82    ESTIFF  1
20257.61                                                                ESTIFF  2
           T63-A-5 FREQUENCIES
0.0       0.0       0.0       0.0       0.0       0.0       144.1       OMEGE   1
157.9                                                                   OMEGE   2
           T63-A-5 MODE SHAPE FOR MODE 1
-.3053    -.02321   0.0       .3053     -.02321   0.0       0.0         FE     11
-.02321   0.0       0.0       -.02321   0.0       -.50767   0.0         FE     12
.43565    0.0       1.0       0.0       0.0       0.0                   FE     13
           T63-A-5 MODE SHAPE FOR MODE 2
.1846     0.0       .02321    .1846     0.0       .02321    .4733       FE     21
0.0       .02321    .2905     0.0       .02321    0.0       .50767      FE     22
0.0       -.43565   0.0       1.0       -.18198   .02321                FE     23
           T63-A-5 MODE SHAPE FOR MODE 3
0.0       0.0       .6450     0.0       0.0       -.6450    0.0         FE     31
-1.0      0.0       0.0       -.6138    0.0       .3537     0.0         FE     32
.2247     0.0       0.0       0.0       0.0       0.0                   FE     33
           T63-A-5 MODE SHAPE FOR MODE 4
1.0       0.0       0.0       1.0       0.0       0.0       1.0         FE     41
0.0       0.0       1.0       0.0       0.0       0.0       0.0         FE     42
0.0       0.0       0.0       0.0       1.0       0.0                   FE     43
           T63-A-5 MODE SHAPE FOR MODE 5
.2708     -.5929    0.0       -.2708    -.5929    0.0       0.0         FE     51
-.5929    0.0       0.0       -.5929    0.0       -.16313   0.0         FE     52
-1.0      0.0       .2736     0.0       0.0       0.0                   FE     53
           T63-A-5 MODE SHAPE FOR MODE 6
-.1638    0.0       .5929     -.1638    0.0       .5929     -.4198      FE     61
0.0       .5929     -.2577    0.0       .5929     0.0       .1631       FE     62
0.0       1.0       0.0       -.2736    .1614     .5929                 FE     63
           T63-A-5 MODE SHAPE FOR MODE 7
.0576     0.0       -.1092    .0576     0.0       -.1094    .1475       FE     71
0.0       -.1094    .0905     0.0       -.1092    0.0       .05702      FE     72
0.0       1.0       0.0       .2539     -.0567    -.1092                FE     73
           T63-A-5 MODE SHAPE FOR MODE 8
-.09253   .10892    0.0       .09253    .10892    0.0       0.0         FE     81
.10892    0.0       0.0       .10892    0.0       -.05622   0.0         FE     82
-1.0      0.0       -.2581    0.0       0.0       0.0                   FE     83
```

```
C     MAINLINE
C     THIS PROGRAM ACCEPTS THE MODAL DESCRIPTION OF TWO SUB-SYSTEMS AND
C     COUPLES THEM TOGETHER THROUGH COUPLING SPRINGS TO PRODUCE THE
C     COUPLED SYSTEM DYNAMICS
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/DATA/IN,IOUT,OPTION,ISTFH,ISTFE,N
     1   ,    N1,N2,NH,NE,NC,NGH,NGE
     2   ,    NFORH,NFORE
      COMMON/SET/FH(59,60),FE(20,60),IRATEH(20),IRATEE(20),IHGRND(20),
     1         IEGRND(20),OMEGH(59),OMEGE(20),MH(59),ME(20)
     2        ,KC(20),KGH(20),KGE(20)
      COMMON/TRIG/IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IFREQ,IVEL
```

TABLE 87. DEFINITION OF T63-A-5 ENGINE MODE SHAPE COORDINATES	
Coordinate No.	Description
	Left Mount
1	Fore and aft
2	Lateral
3	Vertical
	Right Mount
4	Fore and aft
5	Lateral
6	Vertical
	Lower Mount
7	Fore and aft
8	Lateral
9	Vertical
	Output Shaft
10	Fore and aft
11	Lateral
12	Vertical
	Turbine Mid-splitline
13	Lateral
14	Vertical
	Forward Compressor
15	Lateral
16	Vertical
	Igniter
17	Lateral
18	Vertical
	Top Gearbox
19	Fore and aft
20	Vertical

Coupling of the engine and airframe was accomplished through the use of stiff springs at the interface points. A stiffness of 10^8 lb/in. was selected as being sufficiently large to force compatibility, but not too large to create numerical errors in the solution.

Structural damping is used in the forced vibration portion of the modal synthesis analysis. For this model a modal damping value of 0.05 was used as being representative of airframe modes.

Coupled system transfer mobilities were generated for comparison with test data. These results are shown in Tables 88 through 95 for vertical forces at the main rotor, using options 2 (pinned fixity at input shaft) and 0 (uncoupled at input shaft), respectively. The data show remarkable agreement between calculated and test data. Most mobilities are of the correct order of magnitude, although they may occasionally differ by as much as a factor of ten. The phase correlation is reasonable.

Some small variation is seen between options. Where the mobilities are relatively large, the pinned option appears to contain higher mobilities. However, these differences are small and do not warrant further consideration. The pinned condition was used in further studies.

TABLE 88. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=5.9 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Modal Analysis Amplitude (in./sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00075	-40.6	0.00007	85.5
Splitline	(Vertical)	0.00327	-72.5	0.0028	90.3
Forward	(Lateral)	0.00033	-146.5	0.000009	0.8
Compressor	(Vertical)	0.00184	-76.6	0.0034	90.4
Igniter	(Lateral)	0.00046	101.4	0.00009	-99.0
	(Vertical)	0.00340	-70.5	0.00258	90.3
Top	(Fore & Aft)	0.00068	61.4	0.00043	88.7
Gearbox	(Vertical)	0.00311	-69.5	0.00312	90.4

TABLE 89. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=11.8 HZ; OPTION=2)

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Modal Analysis Amplitude (in./sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.00050	-12.2	0.00021	83.6
Splitline	(Vertical)	0.01147	-31.4	0.00216	89.0
Forward	(Lateral)	0.00034	-153.6	0.00045	84.3
Compressor	(Vertical)	0.00619	-11.2	0.00069	97.6
Igniter	(Lateral)	0.00232	-132.3	0.00026	-97.2
	(Vertical)	0.01395	-23.8	0.00294	88.0
Top	(Fore & Aft)	0.00522	-29.9	0.00032	-97.5
Gearbox	(Vertical)	0.00849	10.6	0.00140	91.2

TABLE 90. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=23.6 HZ; OPTION=2)

Location		Shake Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00171	-120.7	0.00059	-88.7
Splitline	(Vertical)	0.01257	-96.3	0.000246	-78.9
Forward	(Lateral)	0.00093	95.3	0.00117	-96.8
Compressor	(Vertical)	0.00724	69.5	0.00287	92.5
Igniter	(Lateral)	0.00522	50.7	0.00085	92.2
	(Vertical)	0.02322	-101.4	0.00182	-85.6
Top	(Fore & Aft)	0.00858	-102.9	0.00223	88.7
Gearbox	(Vertical)	0.00221	59.3	0.00131	91.9

TABLE 91. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=35.4 HZ; OPTION=2)

Location		Shake Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00092	-127.3	0.000093	125.3
Splitline	(Vertical)	0.00204	-72.5	0.00079	96.9
Forward	(Lateral)	0.00017	82.1	0.000196	117.2
Compressor	(Vertical)	0.00392	41.6	0.000814.	83.8
Igniter	(Lateral)	0.00163	-22.8	0.000153	-56.8
	(Vertical)	0.00597	-97.4	0.00083	102.8
Top	(Fore & Aft)	0.00298	-156.7	0.00217	-78.8
Gearbox	(Vertical)	0.00181	12.7	0.00076	90.4

TABLE 92. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=5.9 HZ; OPTION=0)

Location		Shake Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00075	-40.6	0.00077	-75.1
Splitline	(Vertical)	0.00327	-72.5	0.00283	90.5
Forward	(Lateral)	0.00033	-146.5	0.00074	-73.5
Compressor	(Vertical)	0.00184	-76.6	0.00336	92.7
Igniter	(Lateral)	0.00046	101.4	0.00134	104.6
	(Vertical)	0.00340	-70.5	0.00256	89.0
Top	(Fore & Aft)	0.00068	61.4	0.00035	-64.7
Gearbox	(Vertical)	0.00311	-69.5	0.00310	91.7

TABLE 93. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT AT MAIN ROTOR (FREQUENCY=11.8 HZ; OPTION=0)

Location		Shake Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00050	-12.2	0.00008	158.5
Splitline	(Vertical)	0.01147	-31.4	0.0057	107.8
Forward	(Lateral)	0.00034	-153.6	0.00013	-74.1
Compressor	(Vertical)	0.00619	-11.2	0.0041	106.6
Igniter	(Lateral)	0.00232	-132.3	0.00026	-39.5
	(Vertical)	0.01395	-23.8	0.0065	108.2
Top	(Fore & Aft)	0.00522	-29.9	0.0040	-66.8
Gearbox	(Vertical)	0.00849	10.6	0.0049	107.3

TABLE 94. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=23.6 HZ; OPTION=0)

Location		Shake Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00171	-120.7	0.00022	-105.0
Splitline	(Vertical)	0.01257	-96.3	0.00201	87.9
Forward	(Lateral)	0.00093	95.3	0.00002	-78.1
Compressor	(Vertical)	0.00724	69.5	0.00065	95.2
Igniter	(Lateral)	0.00522	50.7	0.00040	74.5
	(Vertical)	0.02322	-101.4	0.00274	87.0
Top	(Fore & Aft)	0.00858	-102.9	0.00132	-93.8
Gearbox	(Vertical)	0.00221	59.3	0.00129	89.8

TABLE 95. OH-58 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR (FREQUENCY=35.4 HZ; OPTION=0)

Location		Shake Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.00092	-127.3	0.00080	127.2
Splitline	(Vertical)	0.00204	-72.5	0.0044	27.1
Forward	(Lateral)	0.00017	82.1	0.00048	-66.4
Compressor	(Vertical)	0.00392	41.6	0.0032	137.0
Igniter	(Lateral)	0.00163	-22.8	0.0015	-53.8
	(Vertical)	0.00597	-97.4	0.0074	16.0
Top	(Fore & Aft)	0.00298	-156.7	0.0057	123.9
Gearbox	(Vertical)	0.00181	12.7	0.0021	68.5

Computations were made for the flight conditions mentioned earlier. These results are shown in Tables 96 through 107. Again, it can be noticed that the analytical results are of the right order of magnitude but generally high. These trends during the design phase would generate a conservative design philosophy with respect to airframe-induced engine vibration.

TABLE 96. OH-58 FLIGHT TEST DATA—90 KN; 3100 FT ALT; FREQUENCY=11.8 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	-	-	0.729	-113.0
Splitline	(Vertical)	-	-	0.599	-164.0
Forward	(Lateral)	-	-	0.603	-122.9
Compressor	(Vertical)	-	-	0.174	-59.2
Igniter	(Lateral)	-	-	1.347	68.9
	(Vertical)	-	-	0.940	-169.9
Top	(Fore & Aft)	-	-	0.421	-9.7
Gearbox	(Vertical)	-	-	0.281	-146.8

TABLE 97. OH-58 FLIGHT TEST DATA—90 KN; 3100 FT ALT; FREQUENCY =23.6 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	-	-	0.0190	-50.6
Splitline	(Vertical)	-	-	0.1021	-79.8
Forward	(Lateral)	-	-	0.0353	0.4
Compressor	(Vertical)	-	-	0.1589	-163.0
Igniter	(Lateral)	-	-	0.0349	119.4
	(Vertical)	-	-	0.1662	-51.3
Top	(Fore & Aft)	-	-	0.0588	115.6
Gearbox	(Vertical)	-	-	0.0979	-132.9

TABLE 98. OH-58 FLIGHT TEST DATA—90 KN, 3100 FT ALT; FREQUENCY-35.4 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	-	-	0.0097	-94.8
Splitline	(Vertical)	-	-	0.0825	-123.1
Forward	(Lateral)	-	-	0.0204	-102.8
Compressor	(Vertical)	-	-	0.0845	-136.2
Igniter	(Lateral)	-	-	0.0159	83.1
	(Vertical)	-	-	0.0871	-117.2
Top	(Fore & Aft)	-	-	0.2262	61.2
Gearbox	(Vertical)	-	-	0.0791	-129.6

TABLE 99. OH-58 FLIGHT TEST DATA—90 KN; 3100 FT ALT; FREQUENCY=47.2 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	-	-	0.0063	155.6
Splitline	(Vertical)	-	-	0.0043	21.9
Forward	(Lateral)	-	-	0.0039	160.6
Compressor	(Vertical)	-	-	0.0181	-6.4
Igniter	(Lateral)	-	-	0.0105	-25.2
	(Vertical)	-	-	0.0039	122.1
Top	(Fore & Aft)	-	-	0.0090	-174.2
Gearbox	(Vertical)	-	-	0.0099	-0.6

TABLE 100. OH-58 FLIGHT TEST DATA—110 KN; 3100 FT ALT; FREQUENCY=11.8 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.68	-	0.922	-101.9
Splitline	(Vertical)	0.20	-	0.899	-155.4
Forward	(Lateral)	0.58	-	0.773	-113.2
Compressor	(Vertical)	0.23	-	0.208	-58.8
Igniter	(Lateral)	0.84	-	1.701	80.2
	(Vertical)	0.15	-	1.387	-159.9
Top	(Fore & Aft)	0.26	-	0.559	2.1
Gearbox	(Vertical)	0.23	-	0.437	-141.5

TABLE 101. OH-58 FLIGHT TEST DATA—110 KN; 3100 FT ALT; FREQUENCY-23.6 HZ; OPTION=2

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Modal Analysis Amplitude (in./sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.22	-	0.007	111.9
Splitline	(Vertical)	0.295	-	0.063	83.7
Forward	(Lateral)	0.14	-	0.016	104.0
Compressor	(Vertical)	0.355	-	0.065	70.6
Igniter	(Lateral)	0.55	-	0.012	-70.2
	(Vertical)	0.66	-	0.067	89.7
Top	(Fore & Aft)	0.30	-	0.174	-92.0
Gearbox	(Vertical)	0.045	-	0.061	77.2

TABLE 102. OH-58 FLIGHT TEST DATA—110 KN; 3100 FT ALT; FREQUENCY=35.4 HZ; OPTION=2

Location		Flight Test Amplitude (in./sec/lb)	Flight Test Phase (degrees)	Modal Analysis Amplitude (in./sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.25	-	0.060	-110.0
Splitline	(Vertical)	0.075	-	0.128	-94.3
Forward	(Lateral)	0.11	-	0.081	-114.5
Compressor	(Vertical)	0.095	-	0.173	97.8
Igniter	(Lateral)	0.35	-	0.097	71.5
	(Vertical)	0.15	-	0.281	-90.5
Top	(Fore & Aft)	0.095	-	0.228	62.4
Gearbox	(Vertical)	0.05	-	0.029	124.8

TABLE 103. OH-58 FLIGHT TEST DATA—110 KN; 3100 FT ALT; FREQUENCY=47.2 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.03	-	0.0016	157.0
Splitline	(Vertical)	0.03	-	0.0012	18.9
Forward	(Lateral)	0.02	-	0.0011	161.9
Compressor	(Vertical)	0.135	-	0.0050	-5.7
Igniter	(Lateral)	0.07	-	0.0028	-23.8
	(Vertical)	0.10	-	0.0009	120.0
Top	(Fore & Aft)	0.07	-	0.0025	-174.5
Gearbox	(Vertical)	0.05	-	0.0028	-0.5

TABLE 104. OH-58 FLIGHT TEST DATA—130 KN; 3100 FT ALT; FREQUENCY=11.8 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.90	-	1.056	-73.6
Splitline	(Vertical)	0.515	-	0.756	-124.0
Forward	(Lateral)	0.78	-	0.824	-68.0
Compressor	(Vertical)	0.37	-	0.951	-142.5
Igniter	(Lateral)	1.16	-	1.967	105.2
	(Vertical)	0.49	-	0.702	-111.1
Top	(Fore & Aft)	0.275	-	0.621	-159.1
Gearbox	(Vertical)	0.33	-	0.841	-134.5

TABLE 105. OH-58 FLIGHT TEST DATA—130 KN; 3100 FT ALT; FREQUENCY=23.6 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.21	-	0.029	175.9
Splitline	(Vertical)	0.16	-	0.156	-145.1
Forward	(Lateral)	0.10	-	0.0165	98.5
Compressor	(Vertical)	0.175	-	0.083	163.2
Igniter	(Lateral)	0.34	-	0.055	4.4
	(Vertical)	0.32	-	0.214	-136.4
Top	(Fore & Aft)	0.175	-	0.124	-18.8
Gearbox	(Vertical)	0.08	-	0.106	-162.8

TABLE 106. OH-58 FLIGHT TEST DATA—130 KN; 3100 FT ALT; FREQUENCY=35.4 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.07	-	0.0144	-103.9
Splitline	(Vertical)	0.27	-	0.1218	-132.2
Forward	(Lateral)	0.10	-	0.0301	-111.9
Compressor	(Vertical)	0.37	-	0.1249	-145.3
Igniter	(Lateral)	0.27	-	0.0235	74.0
	(Vertical)	0.65	-	0.1286	-126.2
Top	(Fore & Aft)	0.17	-	0.3341	52.1
Gearbox	(Vertical)	0.04	-	0.1168	-138.7

Location		Flight Test		Modal Analysis	
		Amplitude (in. /sec/lb)	Phase (degrees)	Amplitude (in. /sec/lb)	Phase (degrees)
Turbine Middle Splitline	(Lateral)	0.01	-	0.0158	77.0
	(Vertical)	0.05	-	0.0117	-61.1
Forward Compressor	(Lateral)	0.03	-	0.0100	81.9
	(Vertical)	0.12	-	0.048	-85.8
Igniter	(Lateral)	0.04	-	0.0264	-103.8
	(Vertical)	0.13	-	0.0091	40.1
Top Gearbox	(Fore & Aft)	0.09	-	0.0244	105.5
	(Vertical)	0.05	-	0.0266	-80.5

TABLE 107. OH-58 FLIGHT TEST DATA—130 KN; 3100 FT ALT; FREQUENCY=47.2 HZ; OPTION=2

The modal synthesis approach presented here is not sensitive to potential errors in the subsystem mobilities. It does require subsystem modeling to generate the subsystem uncoupled modes. Using the assumed, representative values of modal damping, reasonably good correlation resulted.

Two methods of analysis, mobility and modal synthesis, have been used in the coupled system study of the OH-58 helicopter. Test mobilities were exclusively used in the mobility analysis. Poor correlation resulted and potential error sources were discussed. Subsystem uncoupled modes, derived from direct stiffness models of the airframe and engine, were coupled in the modal synthesis approach. Correlation results were sufficiently good for design purposes. However, note that good correlation results for the mobility analysis—similar to those obtained in the modal synthesis analysis—could be expected if the component mobilities were generated analytically. This point was not proven during the course of this study.

OH-6 ANALYSIS

The modal synthesis technique has been applied to the coupled engine/airframe analysis of the OH-6 helicopter. The mobility approach, using airframe and engine test data, was not applied since digitized airframe mobilities were not available and the available funds did not permit performing this digitizing task. The modal synthesis analysis is discussed and results are compared with the collected test data.

Computer program MODSYN was used to perform the analysis.

The OH-6 airframe free-free mode shapes, masses, and stiffnesses were generated from a NASTRAN simulation by The Mac Neal-Schwendler Corporation as a subcontractor to Hughes Helicopter and were subsequently transmitted to DDA on magnetic tape. The tape has been catalogued at the DDA Data Center as Generation Data Set C908 (AO4142). Details of the NASTRAN simulation are provided in the final report of Contract DAAJ02-73-C-0016.[15] The data were prepared for input to MODSYN and are listed in Table 108. Definition of the coordinates of the airframe—which are represented in the mode shapes—is given in Table 109. MODSYN was altered at this junction to accommodate more airframe modes. A total of 59 airframe modes, through 106 Hz, were used in the coupled system analysis.

The engine data used in the OH-6 analysis are essentially those used in the OH-58 analysis except that a coordinate transformation is required. Five coordinate systems had to be accommodated in this analysis. The airframe mode shapes are in terms of airframe coordinates except at the bipod interface points. There is a separate coordinate system for each of the three bipods caused, primarily, by the fact that they are each oriented in different planes skewed from the pitch, yaw, and roll planes of the airframe. In addition, the engine has an installed attitude of 47 deg, nose up, in airframe coordinates. Consequently, the engine mode shapes were transformed as follows:

- Left mount in left bipod coordinates
- Right mount in right bipod coordinates
- Lower mount in lower bipod coordinates
- Output shaft in airframe coordinates
- Other engine locations in engine coordinates

15 Sullivan, R. J., Head, R. E., Korkosz, G. J., Neff, J. R., Sotis, S. J., and Gockel, M. A., OH-6A PROPULSION SYSTEM VIBRATION INVESTIGATION, Hughes Helicopters, USAAMRDL-TR-74-85, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1975.

TABLE 108. OH-6 AIRFRAME INPUT TO MODSYN

OH-6 GENERALIZED MASS

3.32118	3.33707	3.33771	0.55813	0.20450	0.15784	0.05074	
0.12450	0.12061	0.01434	0.03975	0.02731	0.10439	0.01155	
0.16484	0.04144	0.05849	0.05914	0.02071	0.19960	0.02563	
0.00454	0.00177	0.00071	0.00533	0.00263	0.10137	0.00323	
0.03027	0.11828	0.03583	0.01159	0.00106	0.00103	0.04031	
0.02380	0.01243	0.02026	0.01110	0.00587	0.08177	0.02570	
0.02038	0.00167	0.00490	0.03076	0.00251	0.03119	0.02485	
0.05421	0.03107	0.01462	0.00187	0.08188	0.13846	0.03222	
0.22454	0.03863	0.07725					MH 9

OH-6 GENERALIZED STIFFNESS

0.0	0.0	0.0	0.0	0.0	0.0	130.3	
382.3	660.0	121.1	363.7	285.1	1391.6	161.3	
2573.6	783.4	1495.7	1638.9	600.3	5836.6	820.2	
152.7	78.2	34.0	256.1	133.9	5351.6	172.0	
1843.0	8962.4	2840.5	945.3	92.0	89.7	3720.7	
2403.1	1421.3	2591.7	1475.7	787.2	12149.3	4049.1	
3226.3	269.8	803.1	5582.1	485.0	6428.7	5709.8	
12832.0	8217.1	4499.3	579.0	26098.9	49412.1	12237.8	
88936.1	16894.2	34558.1					HSTIFF 9

OH-6 FREQUENCIES

0.0	0.0	0.0	0.0	0.0	0.0	8.066	OMEGH 1
8.82	11.77	14.63	15.22	16.26	18.37	18.80	OMEGH 2
19.88	21.88	25.45	26.49	27.09	27.21	28.47	OMEGH 3
29.19	33.49	34.76	34.87	35.94	36.57	36.71	OMEGH 4
39.27	43.81	44.81	45.45	46.89	47.05	48.35	OMEGH 5
50.57	53.81	56.92	58.03	58.30	61.35	63.17	OMEGH 6
63.32	63.95	64.43	67.8	69.95	72.25	76.28	OMEGH 7
77.43	81.85	88.28	88.62	89.85	95.08	98.08	OMEGH 8
100.16	105.25	106.45					OMEGH 9

OH-6 MODE SHAPE FOR MODE 1

0.31259	0.80329	-0.50697	0.31259	-0.80329	-0.50697	-0.00000
-0.81098	-0.58507	1.00000	-0.00000	0.00000	1.00000	0.0
-0.00000	0.0	-0.00000	0.0	1.00000	-0.00000	0.00000
1.00000	-0.00000	0.00000	1.00000	-0.00000	0.00000	1.00000
-0.00000	0.00000	-0.00000	0.00000	1.00000	-0.00000	0.00000
1.00000	0.00000	-0.00000	0.00000	-0.00000	0.00000	-0.00000

OH-6 MODE SHAPE FOR MODE 2

0.32836	-0.59219	-0.73586	-0.32836	-0.59219	0.73586	1.00000
-0.00000	0.00000	-0.00000	1.00000	0.00000	-0.00000	1.00000
0.00000	-0.00000	0.00000	-0.00000	0.00000	1.00000	0.00000
-0.00000	1.00000	0.00000	-0.00000	1.00000	0.00000	0.00000
1.00000	0.00000	1.00000	0.00000	-0.00000	1.00000	0.00000
0.00000	1.00000	-0.00000	1.00000	-0.00000	1.00000	0.00000

OH-6 MODE SHAPE FOR MODF 3

-0.89133	0.06355	-0.44888	-0.89133	-0.06355	-0.44888	0.00000
-0.58507	0.81098	-0.00000	0.00000	1.00000	-0.00000	-0.00000
1.00000	0.00000	-0.00000	0.00000	-0.00000	0.00000	1.00000
-0.00000	0.00000	1.00000	-0.00000	0.00000	1.00000	0.00000
0.00000	1.00000	0.00000	1.00000	-0.00000	0.00000	1.00000
0.00000	-0.00000	1.00000	-0.00000	1.00000	-0.00000	1.00000

OH-6 MODE SHAPE FOR MODE 4

0.08601	0.01547	0.07757	-0.08047	0.01587	-0.07477	0.05914
0.00182	-0.00252	-0.00000	-0.22193	-0.00311	-0.00000	-0.70495
-0.00311	0.01386	0.00000	0.00000	-0.00001	-0.30606	-0.16385

TABLE 108—Continued

0.00004	-0.69376	0.83243	0.00000	-1.00000	-0.00311	-0.00000
0.07526	-0.00311	-0.31752	-0.00311	0.00000	-0.44858	-0.00311
-0.00000	0.22705	-0.00311	0.64347	-0.48951	0.64347	0.48329

OH-6 MODE SHAPE FOR MODE 5

0.16239	-0.00001	0.07328	0.15980	0.00050	0.07091	0.00092
0.09824	-0.09885	0.08059	-0.00346	-0.08091	0.25693	-0.01098
-0.00099	0.00022	0.00506	0.00000	0.11137	-0.00477	-0.92363
0.25283	-0.01081	-0.90154	0.36456	-0.01558	-1.00000	-0.02776
0.00117	-0.96208	-0.00495	-0.60768	0.16340	-0.00699	-0.19058
-0.08306	0.00354	0.27884	0.01002	0.33927	0.01002	0.35442

OH-6 MODE SHAPE FOR MODE 6

0.08429	-0.07298	-0.14312	-0.08068	-0.07352	0.14431	0.14794
0.00078	-0.00132	0.00099	0.05467	-0.00105	0.00246	-0.08861
-0.00038	0.00173	0.00004	0.00554	0.06171	0.90981	-0.02879
-0.31117	0.85421	0.09676	0.00362	0.90358	-0.00925	0.00009
1.00000	-0.00891	0.58573	-0.00573	0.00181	0.13982	-0.00200
-0.00036	-0.25784	0.00194	-0.27434	-0.05998	-0.27434	0.06501

OH-6 MODE SHAPE FOR MODE 7

0.07074	-0.06433	-0.07155	-0.00899	-0.04007	0.10252	0.08744
0.02350	-0.02065	-0.01673	0.05771	-0.03474	0.04327	0.06180
-0.00905	-0.00125	0.00197	0.00194	-0.08010	-0.36930	0.03452
0.44929	-0.64039	0.71755	-0.10955	-1.00000	0.15573	0.06476
-0.23613	0.13738	-0.00207	0.00992	0.00267	0.10732	-0.03124
-0.01056	-0.13341	0.03292	-0.20998	0.06647	-0.19631	0.04007

OH-6 MODE SHAPE FOR MODE 8

0.11533	-0.01990	0.11247	0.16226	0.08300	0.01225	-0.05489
0.09810	-0.09438	-0.09889	-0.03373	-0.16882	0.21607	-0.01580
-0.03516	0.00021	0.01057	-0.00147	0.09041	0.27273	0.71054
-0.81945	0.13477	1.00000	-0.68906	0.18038	0.96453	0.39420
0.38962	0.84734	0.00902	0.11177	0.01161	-0.05134	-0.13508
-0.03087	0.07771	0.15378	0.06472	0.27634	0.14471	0.23705

OH-6 MODE SHAPE FOR MODE 9

-0.02656	0.02998	0.06878	0.04202	0.04049	-0.06210	-0.07816
0.00622	-0.00521	-0.01719	-0.04911	-0.01569	0.01798	0.04091
-0.00097	-0.00202	0.00124	-0.00216	0.02926	0.01017	0.18331
-0.28638	0.28233	-0.48863	-0.10625	0.55672	0.13784	0.04678
-0.16514	0.11830	-0.09568	0.03057	-0.00433	-0.05634	-0.00640
0.00069	0.04580	0.01047	0.17656	-0.29688	0.19080	0.34167

OH-6 MODE SHAPE FOR MODE 10

-0.00888	0.02636	0.01133	-0.00215	-0.00185	-0.02059	-0.02116
-0.01012	0.00291	0.04146	-0.00684	0.02729	-0.02090	0.00947
0.00036	-0.00042	-0.00219	-0.00046	0.04494	0.17123	-0.30142
-0.24494	-0.37733	1.00000	0.15573	-0.68236	-0.21777	-0.04350
0.55200	-0.18580	0.02695	-0.07389	0.01884	-0.01293	0.00226
-0.00165	0.02009	-0.01022	0.10356	-0.10123	-0.02014	-0.07124

OH-6 MODE SHAPE FOR MODE 11

-0.00353	0.00728	-0.00339	-0.00250	-0.00257	-0.00915	-0.00382
-0.00528	-0.00155	0.02640	-0.00038	0.01483	-0.03516	0.00046
-0.00779	-0.00002	-0.00260	-0.00004	0.01095	0.03326	-0.06556
0.00355	-0.06695	0.17306	0.07075	-0.12961	-0.06305	-0.01894
0.10284	-0.04904	0.00816	-0.00445	0.00621	-0.00218	0.00463
0.01022	0.00419	-0.03384	-0.86662	0.99201	0.88597	1.00000

OH-6 MODE SHAPE FOR MODE 12

-0.00093	-0.00330	-0.00092	0.00160	-0.00177	0.00155	-0.00589
0.00080	0.00002	-0.00112	-0.02386	-0.00065	-0.00010	0.05888
-0.00010	-0.00321	0.00002	-0.00003	-0.00444	-0.00414	0.00648

TABLE 108—Continued

0.04662	0.00642	-0.01747	-0.00038	0.00044	0.00433	-0.00076
-0.01327	0.00421	0.00827	0.00268	-0.00078	0.00711	-0.00015
0.00005	-0.03080	0.00079	0.75582	-0.99984	0.75516	1.00000
OH-6 MODE SHAPE FOR MODE 13						
0.06135	-0.04387	0.04632	0.06602	0.04010	0.03421	-0.00309
0.16240	0.04670	0.11495	-0.04177	0.13807	-0.29557	0.04411
0.01823	-0.00274	-0.02222	-0.00166	0.04028	-0.06588	0.01060
-1.00000	-0.02442	-0.10306	-0.25271	0.24899	0.08031	0.08992
-0.08330	0.02511	-0.11216	-0.07976	0.00171	-0.02998	-0.05654
0.08679	-0.02155	0.28743	-0.04102	0.15158	-0.13892	0.00613
OH-6 MODE SHAPE FOR MODE 14						
-0.01342	0.01378	0.00007	-0.00974	-0.01742	-0.01374	-0.00365
-0.02377	-0.00388	0.00015	-0.04599	-0.00539	0.03210	0.04587
0.00022	-0.00292	0.00216	-0.00191	0.04816	-0.05586	-0.02598
-1.00000	-0.04707	-0.06085	-0.11234	0.22355	0.00491	0.04191
-0.04892	-0.02017	-0.11464	-0.03358	0.00532	-0.03320	0.00618
-0.00517	-0.02296	-0.03563	-0.11121	0.06539	-0.06839	-0.07171
OH-6 MODE SHAPE FOR MODE 15						
0.08584	0.16388	-0.05249	0.08555	-0.17545	-0.03427	0.01026
-0.12757	-0.09813	0.78076	0.01438	0.35900	-0.17933	-0.01544
-0.08013	0.00100	-0.03380	0.00066	0.26467	-0.07692	0.44364
0.00894	0.24468	-0.33480	-1.00000	0.37985	0.80318	0.89332
-0.30809	0.57323	0.00062	-0.31116	0.33688	0.01788	-0.07361
-0.09540	-0.00193	-0.10621	0.17989	-0.14194	-0.14788	-0.07367
OH-6 MODE SHAPE FOR MODE 16						
0.00147	-0.01744	-0.08000	-0.01637	-0.03488	0.07900	0.07986
-0.00136	0.00494	-0.00897	0.26947	0.00113	0.00494	-0.15821
0.00557	0.01295	0.00070	0.01112	-0.00934	-0.13657	-0.01611
-1.00000	-0.12120	-0.06668	-0.25156	0.12137	0.04970	0.06174
-0.22427	-0.01333	0.05269	-0.04762	-0.00219	0.16212	-0.00010
0.00585	-0.00062	-0.00223	0.27585	-0.46510	0.31578	0.46720
OH-6 MODE SHAPE FOR MODE 17						
-0.05505	0.05402	-0.00759	0.05767	0.06091	0.00654	0.00158
-0.00218	-0.00241	0.00526	-0.16301	0.00016	-0.00013	0.04299
-0.00246	-0.00453	-0.00017	-0.01494	0.01370	0.03802	0.00057
0.17857	0.02368	0.03403	0.16965	-0.00529	-0.05481	-0.03710
0.07720	-0.00638	-0.05699	0.02218	-0.00177	-0.07984	0.00233
-0.00144	0.00250	-0.00018	0.66841	-0.47423	0.64189	0.48019
OH-6 MODE SHAPE FOR MODE 18						
-0.04302	0.04913	-0.00303	-0.04250	-0.04600	-0.00597	-0.00220
0.01035	-0.01536	-0.00081	-0.00988	-0.02429	-0.00530	0.00352
-0.01745	-0.00039	-0.00094	-0.00052	-0.01040	0.00803	0.00227
0.10511	0.01550	-0.01379	-0.47652	-0.07927	0.17668	0.09522
0.01044	0.03622	0.01508	-0.07343	0.00552	-0.00198	-0.02436
-0.01019	0.00206	0.06725	0.26555	-0.79207	-0.21812	-0.83020
OH-6 MODE SHAPE FOR MODE 19						
0.01473	-0.00422	0.01216	0.01476	0.00608	0.01028	-0.00136
0.00923	0.00369	0.00757	-0.00652	0.00786	0.00007	0.00236
0.00231	-0.00028	-0.00011	-0.00012	-0.00726	0.00523	-0.00365
0.06007	0.00777	-0.00847	-0.32696	-0.05620	0.11691	0.05797
0.00910	0.01799	0.00952	-0.04458	0.00271	-0.00158	-0.01110
-0.01082	0.00103	0.01411	-0.95710	0.23438	1.00000	0.19873
OH-6 MODE SHAPE FOR MODE 20						
0.01411	-0.01596	-0.03978	-0.01660	-0.01215	0.04277	0.04963
0.00131	-0.00004	0.00738	0.21172	0.00535	-0.00135	-0.13959
0.00074	0.01946	-0.00032	-0.08943	-0.01340	-0.01286	-0.00480

TABLE 108—Continued

-0.05928	-0.01322	-0.00428	-0.03316	-0.00540	0.00315	-0.01065
-0.02859	-0.00827	0.02917	0.00169	-0.00761	0.05264	0.00111
0.00050	-0.03574	0.00249	-1.00000	-0.81550	-0.92995	0.82230

OH-6 MODE SHAPE FOR MODE 21

0.01845	-0.01973	-0.01191	-0.02682	-0.02844	0.01313	0.01323
0.00121	0.00447	-0.00473	0.06316	0.00320	0.00189	-0.01736
0.00429	0.00271	0.00045	-0.00997	-0.01922	-0.01714	-0.01936
-0.05232	-0.00762	-0.03647	-0.39739	-0.05340	0.12697	0.04430
-0.03086	-0.00170	0.04781	-0.02982	-0.00301	0.03709	0.00020
0.00312	-0.03317	-0.00565	1.00000	0.92055	0.91910	-0.89879

OH-6 MODE SHAPE FOR MODE 22

-0.00986	0.01445	0.00488	-0.00728	-0.00567	-0.00073	-0.00377
0.00538	0.01092	-0.01377	-0.01742	0.00591	0.00400	0.00482
0.01015	-0.00068	0.00109	0.00023	-0.02060	0.01725	-0.05657
0.09974	0.00042	-0.01289	-1.00000	-0.19293	0.32167	0.09997
0.05188	-0.01022	0.01883	-0.07365	-0.00462	-0.00630	-0.00143
0.00622	0.00563	-0.01135	-0.00617	-0.04148	-0.12670	0.08364

OH-6 MODE SHAPE FOR MODE 23

0.00575	-0.02477	0.00791	0.00552	0.02493	0.00837	0.00011
0.03757	0.01719	0.08327	-0.00234	0.10160	0.00946	0.00000
0.01407	-0.00003	0.00176	0.00001	-0.00601	0.00004	-0.00211
0.00537	-0.00145	0.00133	0.04255	0.00062	-0.02023	-0.01347
0.00006	-0.00527	0.00112	-0.00661	-0.00479	0.00022	-0.00583
-0.00162	0.00017	-0.01202	0.01153	-0.00071	-0.01061	-0.00159

OH-6 MODE SHAPE FOR MODE 24

-0.00184	0.00142	0.00180	0.00068	-0.00091	-0.00259	-0.00159
-0.00153	-0.00032	0.00050	0.01480	-0.00002	0.00027	-0.00005
-0.00061	0.00005	0.00005	0.00003	0.00129	-0.00379	0.00051
0.00360	-0.00155	-0.00490	-0.00234	-0.00294	0.00124	0.00016
-0.00682	0.00022	-0.00986	0.00041	0.00026	-0.00360	0.00050
0.00011	-0.00093	0.00091	-0.00440	-0.00387	-0.00074	0.00131

OH-6 MODE SHAPE FOR MODE 25

-0.03982	0.05555	-0.01880	-0.04155	-0.05761	-0.01699	0.00044
-0.07923	-0.01311	0.04463	-0.00328	0.01332	0.01731	0.00011
-0.03020	-0.00003	0.00273	0.00001	-0.00877	0.00234	-0.01957
-0.00133	-0.00598	0.03099	-0.10500	-0.03088	0.02106	-0.03260
0.01169	-0.02722	0.00544	0.01543	-0.00556	0.00376	0.03384
0.00668	0.00124	0.04167	-0.11015	-0.07474	0.10204	-0.07192

OH-6 MODE SHAPE FOR MODE 26

-0.00234	-0.01809	0.00291	-0.00245	0.01854	0.00437	0.00036
0.01842	0.01167	0.06298	-0.00558	0.06865	0.00713	0.00014
0.00677	-0.00008	0.00121	0.00004	-0.00467	-0.00288	0.01584
0.00503	0.00507	-0.00284	0.07592	0.02152	-0.01684	-0.00119
-0.01329	0.01494	0.00097	0.00108	-0.00226	0.00130	0.00250
-0.00214	0.00039	-0.01034	-0.01058	-0.01156	0.01518	-0.01579

OH-6 MODE SHAPE FOR MODE 27

0.06194	-0.11875	0.01402	-0.06276	-0.10534	-0.01173	0.01321
0.00834	0.00604	0.04325	0.09751	0.04728	0.00441	0.00036
0.00314	0.00110	0.00090	0.00042	0.00147	0.00066	-0.00230
0.00401	0.02934	-0.05169	0.03124	0.04266	-0.00396	0.00299
0.04058	0.00950	-0.00208	0.00222	0.00018	-0.00539	0.00056
-0.00045	0.00102	-0.00088	-0.45032	-0.35552	-0.43709	0.33937

OH-6 MODE SHAPE FOR MODE 28

0.01125	-0.00214	0.00170	0.01024	0.00181	0.00097	-0.00009
-0.00131	-0.01183	-0.13037	-0.00063	-0.13339	-0.01537	0.00034
-0.00067	-0.00004	-0.00305	0.00003	0.00651	0.00080	-0.00589

TABLE 108—Continued

-0.00434	-0.00211	0.00083	-0.00767	-0.00418	-0.00042	0.01812
0.00510	-0.00032	-0.00091	-0.01252	0.00592	-0.00150	-0.00913
-0.00261	-0.00023	-0.01679	0.04102	0.03985	-0.04441	0.04484
OH-6 MODE SHAPE FOR MODE 29						
0.05823	-0.00827	-0.06468	-0.06072	-0.00089	0.06677	0.03919
-0.00292	-0.00347	-0.01060	-0.46749	-0.01662	-0.00137	0.03100
-0.00148	-0.00879	-0.00066	-0.00451	-0.10743	-0.12017	0.02991
-0.35476	-0.05323	-0.10790	0.16760	0.05214	-0.06088	0.00078
-0.41639	0.01386	0.35835	0.01261	-0.01187	0.12672	0.00182
0.00059	0.06723	-0.00069	-0.07442	0.01978	-0.09157	0.00033
OH-6 MODE SHAPE FOR MODE 30						
-0.00253	0.11061	-0.01822	-0.00355	0.16106	0.01565	0.02255
-0.01067	-0.00619	0.01391	-1.00000	0.00221	0.00013	-0.02626
-0.00592	0.00469	-0.00048	0.01072	0.09410	0.08307	-0.07587
0.27368	0.11191	-0.09366	-0.15456	0.01516	0.04883	-0.12291
0.58303	-0.06161	-0.37418	0.03752	-0.00892	-0.19159	0.00647
0.00182	-0.06989	0.00102	0.84345	-0.00621	0.97604	-0.15523
OH-6 MODE SHAPE FOR MODE 31						
-0.00334	-0.01443	-0.00256	0.00146	-0.02949	0.00189	0.00417
-0.00066	0.00030	-0.00275	-0.02892	-0.00253	0.00006	-0.00252
0.00038	0.00063	-0.00000	0.00080	0.01554	0.01230	-0.00907
0.03912	0.01611	-0.01144	-0.01315	0.00500	0.00527	-0.00517
0.08677	-0.00289	-0.05402	0.00038	0.00085	-0.02393	0.00010
0.00047	-0.00132	-0.00059	-1.00000	0.30063	-0.02514	-0.39836
OH-6 MODE SHAPE FOR MODE 32						
-0.00319	0.08223	0.00054	-0.00316	-0.08785	-0.00084	-0.00067
0.02911	0.01468	-0.08393	0.01487	-0.06287	-0.00151	0.00053
0.02362	-0.00014	-0.00084	-0.00020	0.00781	-0.00244	0.01171
-0.00441	0.00074	0.00223	0.05260	0.01723	-0.00987	0.09117
-0.01912	0.04309	0.00602	-0.03364	0.01227	-0.00019	-0.00971
0.00060	0.00078	-0.01343	-0.72031	-1.00000	0.74476	-0.98850
OH-6 MODE SHAPE FOR MODE 33						
-0.00267	0.98363	0.00110	-0.00261	-1.00000	0.00055	-0.00024
-0.00113	0.00154	-0.00559	0.00256	-0.00185	0.00001	0.00011
0.00200	-0.00003	0.00017	-0.00002	-0.00262	-0.00070	0.00592
0.00545	0.00183	-0.00036	0.03199	0.00766	-0.00900	0.02172
-0.00622	0.01459	0.00101	-0.01524	-0.00039	-0.00074	-0.00599
0.00040	0.00008	-0.00082	0.01101	0.01846	-0.00754	0.01821
OH-6 MODE SHAPE FOR MODE 34						
0.00049	-1.00000	0.00171	-0.00054	-0.98020	-0.00172	-0.00184
-0.00001	0.00003	-0.00012	0.00218	-0.00011	0.00001	0.00004
0.00000	-0.00003	0.00000	-0.00004	0.00006	0.00007	0.00021
0.00015	-0.00035	0.00085	-0.00002	-0.00014	0.00001	0.00023
-0.00083	0.00009	-0.00006	-0.00008	0.00004	0.00050	0.00004
0.00001	0.00046	-0.00001	0.00522	-0.00012	0.00435	0.00131
OH-6 MODE SHAPE FOR MODE 35						
-0.02318	-0.02956	-0.04024	0.03968	-0.51622	0.04069	0.04853
0.00687	-0.00647	0.01851	-1.00000	0.01036	-0.00113	-0.03938
-0.00296	0.01010	-0.00095	0.00298	0.00738	0.01358	0.01772
0.03475	-0.06799	0.14953	-0.09951	-0.04901	0.02451	-0.12534
-0.12797	-0.06663	-0.04192	0.04355	-0.00988	0.06878	0.00345
-0.00311	-0.03945	0.00515	-0.27841	-0.08734	-0.19791	-0.04175
OH-6 MODE SHAPE FOR MODE 36						
-0.08233	-0.72109	0.00890	-0.05802	0.74537	0.01491	0.00712
0.00534	0.07360	-0.26494	-0.10505	-0.19543	0.00932	-0.00516
0.06257	0.00121	0.00449	-0.00033	-0.01949	-0.01364	0.14765

TABLE 108—Continued

0.10401	-0.00048	0.07443	0.65590	0.18021	-0.17648	1.00000
-0.27162	0.52968	0.02565	-0.40202	0.04440	-0.00117	-0.03783
0.01625	-0.00548	-0.01834	0.13230	0.28321	-0.14202	0.27548

OH-6 MODE SHAPE FOR MODE 37

-0.04505	0.06959	-0.05238	0.05791	-0.00584	0.04886	0.07678
-0.00053	-0.00581	0.02082	-0.02588	0.01578	-0.00064	-0.00498
-0.00620	-0.00018	-0.00015	-0.00221	-0.00689	0.00127	0.13374
0.03330	-0.28586	0.58083	-0.11022	0.13718	0.03849	-0.07374
-1.00000	-0.04290	0.01825	0.03337	0.00002	0.04404	0.00453
-0.00157	-0.01138	0.00240	0.00932	0.03911	0.01598	-0.06763

OH-6 MODE SHAPE FOR MODE 38

0.01546	0.18333	-0.02621	0.01782	-0.21885	0.01391	0.02229
0.10464	0.05515	-0.16573	0.03638	-0.16809	0.01046	-0.00020
0.04463	-0.00049	-0.00066	-0.00027	0.06707	0.01613	-0.10204
-0.08488	0.05409	-0.13449	-0.41124	-0.17834	0.13973	-1.00000
0.46456	-0.50836	-0.06778	0.28059	0.01952	0.02872	0.07441
-0.00826	-0.00247	-0.05645	-0.00806	0.09685	-0.09397	0.14549

OH-6 MODE SHAPE FOR MODE 39

0.00437	0.05819	-0.03266	0.01197	-0.06451	0.03010	0.03869
0.06020	0.02938	-0.08123	-0.01568	-0.07103	0.00371	-0.00089
0.02465	-0.00049	0.00022	-0.00124	0.05023	0.01744	-0.10943
-0.04396	0.23455	-0.46385	-0.03179	-0.40454	0.00903	-0.09301
1.00000	-0.05936	-0.07958	0.04470	0.01641	0.03043	0.02393
-0.01226	0.00277	0.05579	0.03164	0.09336	0.00772	0.01562

OH-6 MODE SHAPE FOR MODE 40

0.01615	0.06696	0.02658	-0.00103	-0.04382	-0.03088	-0.03760
0.04327	0.02113	-0.05800	0.03814	-0.05206	0.00284	0.00108
0.01726	0.00024	0.00015	0.00131	-0.00634	-0.01422	0.08609
0.00147	-0.26599	0.51255	-0.14361	0.44261	0.05748	-0.08493
-1.00000	-0.05372	0.06294	0.05876	0.01232	-0.03067	0.02270
-0.00731	0.00295	0.02144	0.05396	0.04975	0.03360	0.02998

OH-6 MODE SHAPE FOR MODE 41

-0.02290	-0.38028	-0.16925	-0.03875	-0.19897	0.19521	0.22170
-0.04070	-0.01473	0.02481	0.92511	0.01298	0.00057	0.03422
-0.00215	-0.01583	-0.00245	0.00562	0.02852	0.03024	0.06276
0.41138	-0.22755	0.54364	0.05303	1.00000	-0.01332	-0.60903
0.10410	-0.22199	-0.34536	-0.11768	-0.04620	-0.04456	-0.04042
0.00765	-0.02858	0.00427	-0.09298	0.09256	0.01973	-0.06611

OH-6 MODE SHAPE FOR MODE 42

-0.01372	-0.02329	-0.01372	0.00406	-0.00112	0.01379	0.00102
-0.00144	-0.00117	0.00081	-0.01854	0.00050	0.00009	-0.00104
0.00065	0.00047	-0.00028	0.00003	0.01653	0.00006	0.00002
0.09595	-0.08796	0.18195	-0.03494	0.46379	0.01704	-0.17835
0.09598	-0.07729	-0.06905	-0.01152	-0.00194	0.00462	-0.00512
-0.00029	-0.00927	0.00832	-0.96024	-0.86932	-0.77832	1.00000

OH-6 MODE SHAPE FOR MODE 43

-0.03041	-0.04314	-0.00406	-0.03379	0.06019	-0.01455	-0.00539
-0.00925	-0.01432	0.02399	-0.02505	0.01999	-0.00032	-0.00067
-0.00274	0.00033	-0.00160	-0.00023	-0.01220	-0.00157	0.00949
0.00248	0.00636	-0.00571	-0.01164	0.01387	0.01293	-0.60463
-0.02468	-0.26561	0.00578	-0.00570	-0.00510	0.00436	-0.01848
0.00182	0.00195	-0.00462	-0.84833	0.73468	1.00000	0.57479

OH-6 MODE SHAPE FOR MODE 44

0.00197	-0.02157	0.00468	-0.01096	0.03795	0.00254	-0.00311
-0.01512	-0.00378	0.00465	-0.04390	0.00117	0.00052	-0.00064
0.00039	0.00027	-0.00073	-0.00066	-0.00565	-0.00307	0.01204

TABLE 108—Continued

0.06377	-0.03488	0.08423	-0.02488	0.31226	0.02655	-1.00000
0.09067	-0.43836	-0.03501	-0.02903	-0.00377	0.01343	-0.01971
0.00220	0.00319	-0.00005	0.06238	-0.00726	-0.01457	-0.05770
OH-6 MODE SHAPE FOR MODE 45						
0.02353	0.02523	-0.01324	-0.01705	-0.02181	0.00775	0.00809
0.01098	0.00277	-0.00230	-0.08539	0.00195	-0.00087	0.00087
-0.00143	-0.00043	0.00089	-0.00199	0.05854	-0.00132	-0.05039
0.16031	-0.15334	0.28493	-0.06486	0.85828	0.00776	1.00000
0.55439	0.43699	-0.13281	0.01780	0.00203	0.02950	0.01630
-0.00142	0.00575	-0.00117	0.01592	0.06558	0.06168	-0.02832
OH-6 MODE SHAPE FOR MODE 46						
-0.01888	-0.00904	-0.00610	0.01767	-0.01077	0.00682	-0.00426
0.00051	-0.00013	0.00081	0.00747	0.00005	0.00014	-0.00227
-0.00000	0.00104	-0.00012	0.00123	-0.00454	-0.00974	-0.01785
0.01834	-0.02649	0.03451	-0.01017	0.25379	0.00122	0.05625
0.22172	0.02485	0.00830	0.00002	-0.00225	-0.00044	0.00088
0.00005	0.00287	0.00025	-0.75119	0.99929	-0.75045	-1.00000
OH-6 MODE SHAPE FOR MODE 47						
-0.00800	0.00631	0.00044	0.00822	0.00203	-0.00054	0.00162
0.00129	-0.00000	0.00125	0.01577	0.00057	0.00004	-0.00280
-0.00036	0.00098	-0.00003	0.00147	-0.02018	-0.04089	-0.06052
0.01492	-0.05822	0.03959	-0.03762	0.75035	0.01024	0.02071
1.00000	0.00353	0.06165	0.00093	-0.00066	0.00314	0.00190
-0.00010	0.00206	-0.00036	0.03833	-0.01945	0.04051	0.01965
OH-6 MODE SHAPE FOR MODE 48						
0.01474	-0.03338	-0.03880	-0.03220	-0.03116	0.04865	0.04071
-0.00057	-0.00254	0.01909	-0.48735	0.01005	0.00211	-0.00604
-0.00039	-0.00177	-0.00168	0.00467	0.01615	0.05175	0.05195
0.07672	0.03904	0.01372	0.06881	-0.67229	-0.03812	0.28320
-1.00000	0.14857	-0.12096	0.00238	-0.02326	0.01150	-0.00044
0.00149	0.01918	-0.00282	0.05209	-0.01217	0.05254	0.00173
OH-6 MODE SHAPE FOR MODE 49						
0.02037	0.04037	-0.02080	-0.07143	0.03557	0.04793	0.02292
0.01108	-0.00220	0.20094	0.21065	0.16700	0.00777	-0.01318
0.00620	0.00730	-0.00626	0.00186	0.02017	0.06886	0.03792
0.24410	0.02036	0.07070	0.10820	-0.64829	-0.07800	0.59240
-1.00000	0.31370	-0.23046	0.02398	-0.05889	0.18097	0.00333
0.00412	0.04238	-0.01170	0.11555	-0.00521	0.11302	-0.01902
OH-6 MODE SHAPE FOR MODE 50						
-0.05179	0.00891	0.03584	0.00627	-0.03173	-0.01997	-0.02614
0.08612	0.03964	0.86959	-0.09222	0.79120	-0.00032	0.00658
0.04234	-0.00357	-0.00211	-0.00129	-0.07737	-0.04051	-0.02501
-0.05724	-0.02287	-0.02996	0.01913	0.31487	-0.02380	0.15741
0.62485	0.07807	0.13747	0.01340	-0.01402	-0.08796	0.03004
0.00083	-0.02416	-0.00571	-0.04474	-0.00881	-0.07924	0.00369
OH-6 MODE SHAPE FOR MODE 51						
-0.06597	-0.02262	0.04852	-0.02477	0.04367	-0.00410	-0.03038
-0.18702	-0.09485	-0.07337	-0.03285	-0.02609	0.05598	0.00322
0.00111	-0.00148	-0.04004	-0.00081	-0.17334	-0.02840	-0.00940
0.16005	-0.05335	0.03085	0.13535	-0.05537	-0.13380	1.00000
0.60343	0.53630	0.07645	0.13148	-0.12825	-0.00782	-0.04709
0.00921	-0.01131	-0.01856	0.00807	-0.02162	-0.05695	-0.01032
OH-6 MODE SHAPE FOR MODE 52						
-0.00940	0.01888	0.04311	-0.00084	-0.00684	-0.03794	-0.06405
0.04272	0.00814	-0.00153	0.03795	-0.00749	0.00252	-0.00580
-0.00343	0.00184	-0.00123	0.00048	-0.01062	0.03921	-0.10009

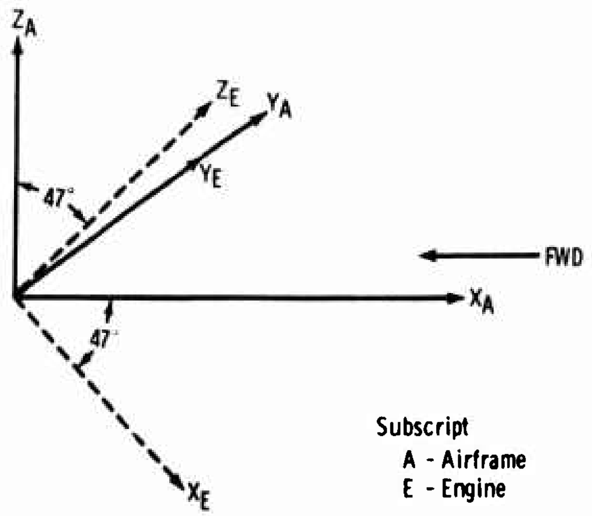
TABLE 108 — Continued

0.03374	0.11964	-0.17403	-0.02529	0.58250	-0.01931	0.05040
-1.00000	-0.00137	0.00559	-0.00749	-0.00005	0.01176	0.02443
0.00048	-0.07020	0.00883	-0.02573	-0.00282	-0.02604	-0.00003
OH-6 MODE SHAPE FOR MODE 53						
0.00109	-0.00167	-0.00960	0.00092	-0.00913	0.00666	0.01473
-0.00087	-0.00154	0.00086	-0.00362	0.00619	0.00207	0.00044
0.00018	0.00004	-0.00135	-0.00009	-0.00594	0.03867	-0.10607
0.00156	0.12642	-0.18914	-0.04689	0.63701	-0.00812	0.01975
-1.00000	-0.02328	0.01198	-0.00707	0.00311	-0.01479	0.00863
-0.00068	0.00756	-0.00106	0.00556	0.00206	0.00354	0.00052
OH-6 MODE SHAPE FOR MODE 54						
-0.20836	0.20756	0.11349	-0.13131	-0.15650	0.03436	-0.06435
1.00000	0.23563	-0.03265	-0.01370	-0.32073	-0.01536	0.00153
-0.05180	-0.00089	0.01821	-0.00089	-0.32176	-0.00188	-0.01053
0.67119	0.07504	-0.14410	0.58375	0.34754	-0.37584	0.83276
-0.18762	0.53762	0.08800	-0.08164	-0.12493	0.04758	0.35649
0.01664	-0.00551	-0.02916	-0.10247	-0.06607	0.05794	-0.04951
OH-6 MODE SHAPE FOR MODE 55						
-0.16024	0.07736	-0.04014	-0.18670	-0.08456	-0.02909	0.01740
0.57322	0.15028	-0.00803	-0.00273	0.05106	0.07546	0.00069
0.03318	-0.00041	-0.03590	0.00012	0.15889	-0.02343	0.12210
-0.36318	-0.06106	0.13607	-0.02167	-0.32988	0.13736	-1.00000
0.47021	-0.52423	-0.03286	-0.24177	0.18933	0.00727	0.43196
-0.02643	-0.01525	0.08979	0.12533	0.08360	-0.09674	0.07253
OH-6 MODE SHAPE FOR MODE 56						
-0.00086	0.12241	-0.02798	-0.02093	-0.17042	0.02757	0.02141
0.59293	0.09112	0.00386	0.02065	0.04175	0.02032	-0.00355
-0.03434	0.00347	-0.01093	-0.00003	0.10430	-0.03650	0.13497
-0.44766	-0.06830	0.14084	0.06395	-0.27742	0.10201	-1.00000
0.50849	-0.51568	0.01406	-0.31638	0.14670	-0.09927	0.36403
0.00193	0.03193	-0.03604	-0.02039	-0.00148	0.03533	-0.00777
OH-6 MODE SHAPE FOR MODE 57						
-0.13907	-0.25195	-0.08442	0.01831	0.01007	0.11154	-0.12380
-0.34777	-0.04636	0.00326	0.23593	-0.07702	-0.00707	-0.03724
0.01629	0.03528	0.00538	-0.00146	-0.35896	-0.08140	-0.03838
-0.39806	-0.09540	0.02212	-0.04564	0.12623	-0.06613	0.93153
0.57157	0.52171	0.34573	0.32669	-0.14380	-0.58314	-0.30273
0.04716	0.19129	-0.03195	0.02020	-0.01221	-0.00958	-0.02567
OH-6 MODE SHAPE FOR MODE 58						
0.04363	0.09655	0.00090	0.14758	0.01018	-0.01614	-0.06491
0.05244	0.03912	-0.00713	0.00464	0.02126	0.01449	-0.00114
0.00172	-0.00236	-0.00616	0.00051	0.12614	0.03615	0.01417
1.00000	0.10331	-0.16081	0.23151	0.05994	-0.13061	-0.15082
-0.16459	-0.08335	-0.10709	-0.11640	0.01289	0.20788	0.05105
-0.04636	0.07126	0.00576	-0.04024	0.02027	-0.04571	0.04659
OH-6 MODE SHAPE FOR MODE 59						
0.22859	0.00218	0.00621	0.17580	-0.13567	0.01502	0.00170
-0.02742	0.06631	-0.00735	0.03881	0.00987	0.02240	-0.00443
0.00169	0.00867	-0.00886	-0.00070	-0.09977	-0.04549	0.07651
1.00000	-0.04814	0.03305	0.56722	-0.41171	-0.27810	-0.03550
0.29609	0.05533	0.15527	-0.16031	-0.05198	-0.29837	0.01609
-0.12660	-0.07269	0.06974	0.05939	0.08029	0.03570	0.04915

TABLE 109. DEFINITION OF OH-6 AIRFRAME MODE SHAPE COORDINATES

Node No.	Coordinate No.	Description
		Left Bipod
13311	1	Fore and aft
	2	Lateral
	3	Vertical
		Right Bipod
13310	4	Fore and aft
	5	Lateral
	6	Vertical
		Lower Bipod
12232	7	Fore and aft
	8	Lateral
	9	Vertical
		Transmission Input
11400	10	Fore and aft
	11	Lateral
	12	Vertical
		Main Rotor
10800	13	Fore and aft
	14	Lateral
	15	Vertical
	16	Roll
	17	Pitch
	18	Yaw
		Tail Rotor
28524	19	Fore and aft
	20	Lateral
	21	Vertical
		Tail Fin Tip
28523	22	Fore and aft
	23	Lateral
	24	Vertical
		Tail Fin Tip
28512	25	Fore and aft
	26	Lateral
	27	Vertical
		Tail Fin Tip
28516	28	Fore and aft
	29	Lateral
	30	Vertical
		Fuselage/Tail
22500	31	Lateral
	32	Vertical
		Fuselage
13600	33	Fore and aft
	34	Lateral
	35	Vertical
		Fuselage Nose
4100	36	Fore and aft
	37	Lateral
	38	Vertical
		Left Landing Gear Front
3137	39	Lateral
	40	Vertical
		Right Landing Gear Front
3136	41	Lateral
	42	Vertical

The direction vectors of the interface points for the NASTRAN simulation of the airframe in terms of airframe coordinates are shown in Figure 27. Also shown are the direction vectors of the engine coordinate axes. The transformed engine mode shapes were obtained by dotting the engine displacements into the respective direction vectors for the interface points. For instance, the left mount displacement in the 1 direction in the left bipod coordinates is determined by dotting the left mount vector displacement into a unit vector in the 1 direction. Similarly, all other deflections were obtained. The transformed engine mode shapes are shown in Table 110.



	Coord	Description	Unit vector
Left bipod	3	Bisector	$-0.5006\bar{i} - 0.7153\bar{j} - 0.4876\bar{k}$
	2	Normal to plane	$-0.7746\bar{i} + 0.6216\bar{j} - 0.1165\bar{k}$
	1	Perpendicular	$-0.3864\bar{i} - 0.3194\bar{j} + 0.8653\bar{k}$
Right bipod	3	Bisector	$-0.5006\bar{i} + 0.7153\bar{j} - 0.4876\bar{k}$
	2	Normal to plane	$0.7746\bar{i} + 0.6216\bar{j} + 0.1165\bar{k}$
	1	Perpendicular	$-0.3864\bar{i} + 0.3194\bar{j} + 0.8653\bar{k}$
Lower bipod	3	Bisector	$-0.8716\bar{i} + 0.4896\bar{k}$
	2	Normal to plane	$-0.4896\bar{i} - 0.8716\bar{k}$
	1	Perpendicular	$+1.0\bar{j}$
Engine	X_E	Fore and Aft	$0.7313\bar{i} - 0.6820\bar{k}$
	Y_E	Lateral	$+1.0\bar{j}$
	Z_E	Vertical	$0.6820\bar{i} + 0.7313\bar{k}$

Figure 27. Unit Vectors for Bipods and Engine in Airframe Coordinates.

TABLE 110. T63-A-5 INPUT TO MODSYN FOR OH-6 ANALYSIS

```
          T63-A-5 GENERALIZED MASS
.05068016 .05068016 6.002852  .404025    .1121773  .1121703  .02059351   ME      1
.02058931                                                                ME      2
          T63-A-5 GENERALIZED STIFFNESS
0.0       0.0       0.0       0.0        0.0       0.0       16880.82    ESTIFF  1
20257.61                                                                 ESTIFF  2
          T63-A-5 FREQUENCIES
0.0       0.0       0.0       0.0        0.0       0.0       144.1       OMEGE   1
157.9                                                                    OMEGE   2
          T63-A-5 MODE SHAPE FOR MODE 1
 0.27385   0.13425  -0.00634  -0.27385   0.13425  -0.02683  -0.02321     FE     13
 0.0       0.0       0.0      -0.02321   0.0      -0.50767   0.0         FE     13
 0.43565   0.0       1.00000   0.0       0.0       0.0       0.0         FE     13
          T63-A-5 MODE SHAPE FOR MODE 2
-0.15253  -0.10414  -0.02240  -0.15253   0.10414  -0.02238   0.0         FE     23
-0.13438  -0.46520   0.22830   0.0      -0.18115   0.0       0.50767     FE     23
 0.0      -0.43565   0.0       1.00000  -0.18198   0.02321   0.0         FE     23
          T63-A-5 MODE SHAPE FOR MODE 3
 0.23820  -0.39571  -0.45021  -0.23820  -0.39571   0.45021  -1.00000     FE     33
 0.0       0.0       0.0      -0.61380   0.0       0.35370   0.0         FE     33
 0.22470   0.0       0.0       0.0       0.0       0.0       0.0         FE     33
          T63-A-5 MODE SHAPE FOR MODE 4
-0.87270  -0.48700  -0.03360  -0.87270   0.48700  -0.03350   0.0         FE     43
-0.23630  -0.97130   0.73140   0.0      -0.68200   0.0       0.0         FE     43
 0.0       0.0       0.0       0.0       1.00000   0.0       0.0         FE     43
          T63-A-5 MODE SHAPE FOR MODE 5
-0.04695  -0.50043  -0.43320   0.04695  -0.50043  -0.41503  -0.59290     FE     53
 0.0       0.0       0.0      -0.59290   0.0      -0.16313   0.0         FE     53
-1.00000   0.0       0.27360   0.0       0.0       0.0       0.0         FE     53
          T63-A-5 MODE SHAPE FOR MODE 6
 0.36191  -0.28397  -0.40834   0.36191   0.28397  -0.40836   0.0         FE     63
-0.47668   0.26771   0.21588   0.0       0.60940   0.0       0.16310     FE     63
 0.0       1.00000   0.0      -0.27360   0.16140   0.59290   0.0         FE     63
          T63-A-5 MODE SHAPE FOR MODE 7
-0.09060   0.03894   0.07429  -0.09067  -0.03907   0.07443   0.0         FE     73
 0.07141  -0.11743  -0.00828   0.0      -0.14159   0.0       0.05702     FE     73
 0.0       1.00000   0.0       0.25390  -0.05670  -0.10920   0.0         FE     73
          T63-A-5 MODE SHAPE FOR MODE 8
 0.04596   0.11277   0.08102  -0.04596   0.11277   0.07481   0.10892     FE     83
 0.0       0.0       0.0       0.10892   0.0      -0.05622   0.0         FE     83
-1.00000   0.0      -0.25810   0.0       0.0       0.0       0.0         FE     83
```

Initial computations were performed to generate a limited number of coupled system transfer mobilities for correlation with the OH-6 helicopter shake test data generated at Hughes and reported in Reference 14. Specifically, transfer mobilities, defined by excitations at the main rotor in the fore and aft, lateral, and vertical directions, were computed for excitation frequencies through 100 Hz. The results of these computations are shown in Tables 111 through 122. Also included for comparison in these tables are results of the laboratory shake test performed at Hughes. All the transducer locations were not instrumented in the test because, when the vibration survey was performed for this helicopter system (1964), these locations were not required instrumentation points. These points tabulated as less than (LT) some given value, were below the plotting range of the curves supplied by Hughes. Predicted transfer mobilities in most cases show reasonable amplitude agreement with laboratory shake test data.

TABLE 111. OH-6 TRANSFER MOBILITIES FOR FORE AND AFT FORCE AT MAIN ROTOR—FREQUENCY=8 HZ; OPTION=2

Location		Shake Test		Modal Analysis	
		Amplitude (in. /sec/lb)	Phase (degrees)	Amplitude (in. /sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.003	90	0.0050	-78.9
Splitline	(Vertical)	0.005	90	0.0081	-99.4
Forward	(Lateral)	0.0009	90	0.0176	-78.9
Compressor	(Vertical)	0.005	90	0.0086	-44.8
Igniter	(Lateral)	-	-	0.0050	101.0
	(Vertical)	-	-	0.0104	-119.7
Top	(Fore & Aft)	0.001	-90	0.0056	-28.7
Gearbox	(Vertical)	-	-	0.0074	-70.5

TABLE 112. OH-6 TRANSFER MOBILITIES FOR FORE AND AFT FORCE AT MAIN ROTOR—FREQUENCY=32 HZ; OPTION=2

Location		Shake Test		Modal Analysis	
		Amplitude (in. /sec/lb)	Phase (degrees)	Amplitude (in. /sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.0017	90	0.0005	89.7
Splitline	(Vertical)	0.0018	0	0.0058	-60.4
Forward	(Lateral)	0.006	-70	0.00213	-75.5
Compressor	(Vertical)	0.0025	190	0.0045	115.1
Igniter	(Lateral)	-	-	0.00138	-85.7
	(Vertical)	-	-	0.0110	-61.3
Top	(Fore & Aft)	0.0021	10	0.0089	111.4
Gearbox	(Vertical)	-	-	0.00065	-46.1

TABLE 113. OH-6 TRANSFER MOBILITIES FOR FORE AND AFT FORCE AT MAIN ROTOR—FREQUENCY=50 HZ; OPTION=2

Location		Shake Test		Modal Analysis	
		Amplitude (in. /sec/lb)	Phase (degrees)	Amplitude (in. /sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	LT 0.0003	0	0.00016	82.0
Splitline	(Vertical)	LT 0.0003	20	0.00059	-45.5
Forward	(Lateral)	LT 0.0003	180	0.00020	-108.2
Compressor	(Vertical)	0.0012	160	0.00076	-107.0
Igniter	(Lateral)	-	-	0.00036	-100.9
	(Vertical)	-	-	0.00080	-23.8
Top	(Fore & Aft)	LT 0.0003	180	0.00065	95.0
Gearbox	(Vertical)	-	-	0.00054	-78.7

TABLE 114. OH-6 TRANSFER MOBILITIES FOR FORE AND AFT FORCE AT MAIN ROTOR—FREQUENCY=100 HZ; OPTION=2

Location		Shake Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.0008	180	0.00033	118.4
Splitline	(Vertical)	0.0008	180	0.00069	20.7
Forward	(Lateral)	0.0028	180	0.00220	-62.5
Compressor	(Vertical)	0.009	90	0.00461	-165.4
Igniter	(Lateral)	-	-	0.00098	-63.2
	(Vertical)	-	-	0.00198	20.1
Top	(Fore & Aft)	0.0001	0	0.00077	-22.6
Gearbox	(Vertical)	-	-	0.00063	-162.1

TABLE 115. OH-6 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR—FREQUENCY=8 HZ; OPTION=2

Location		Shake Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.003	270	0.00742	85.6
Splitline	(Vertical)	LT 0.0003	270	0.00243	94.3
Forward	(Lateral)	0.005	90	0.00895	-79.1
Compressor	(Vertical)	LT 0.0003	90	0.00629	-68.6
Igniter	(Lateral)	-	-	0.0141	-92.5
	(Vertical)	-	-	0.00688	102.3
Top	(Fore & Aft)	LT 0.0003	-90	0.00562	-72.4
Gearbox	(Vertical)	-	-	0.00211	-59.1

TABLE 116. OH-6 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR—FREQUENCY=32 HZ; OPTION=2

Location		Shake Test Amplitude (in. /sec/lb)	Shake Test Phase (degrees)	Modal Analysis Amplitude (in. /sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.02	270	0.000368	-144.5
Splitline	(Vertical)	0.006	270	0.00129	-85.9
Forward	(Lateral)	0.02	70	0.00171	-81.8
Compressor	(Vertical)	0.002	180	0.00033	-104.6
Igniter	(Lateral)	-	-	0.000567	1.9
	(Vertical)	-	-	0.00182	-84.3
Top	(Fore & Aft)	0.002	-90	0.00048	105.5
Gearbox	(Vertical)	-	-	0.00078	-89.6

TABLE 117. OH-6 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR—FREQUENCY=50 HZ; OPTION=2

Location		Shake Test Amplitude (in. /sec/lb)	Shake Test Phase (degrees)	Modal Analysis Amplitude (in. /sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	LT 0.0003	180	0.00018	1.5
Splitline	(Vertical)	0.0012	180	0.00105	-104.4
Forward	(Lateral)	LT 0.0003	230	0.00102	-98.5
Compressor	(Vertical)	LT 0.0003	270	0.000213	-40.6
Igniter	(Lateral)	-	-	0.00036	174.5
	(Vertical)	-	-	0.00158	-107.5
Top	(Fore & Aft)	0.0006	0	0.000110	65.6
Gearbox	(Vertical)	-	-	0.00054	-95.5

TABLE 118. OH-6 TRANSFER MOBILITIES FOR LATERAL FORCE AT MAIN ROTOR—FREQUENCY=100 HZ; OPTION=2

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Modal Analysis Amplitude (in./sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0008	180	0.000141	-90.3
Splitline	(Vertical)	LT 0 0003	180	0.000139	108.3
Forward	(Lateral)	0.0023	0	0.00131	103.6
Compressor	(Vertical)	0.0015	90	0.00051	115.8
Igniter	(Lateral)	-	-	0.000462	94.0
	(Vertical)	-	-	0.000125	98.3
Top	(Fore & Aft)	LT 0.0003	-90	0.00005	102.3
Gearbox	(Vertical)	-	-	0.00016	116.0

TABLE 119. OH-6 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR—FREQUENCY=8 HZ; OPTION=2

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Modal Analysis Amplitude (in./sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0007	90	0.00117	-50.0
Splitline	(Vertical)	0.002	90	0.00207	90.6
Forward	(Lateral)	LT 0.0003	90	0.00407	-48.0
Compressor	(Vertical)	0.002	90	0.00521	-53.7
Igniter	(Lateral)	-	-	0.00118	127.3
	(Vertical)	-	-	0.00558	107.0
Top	(Fore & Aft)	0.002	90	0.00472	-62.7
Gearbox	(Vertical)	-	-	0.00193	-36.1

TABLE 120. OH-6 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR—FREQUENCY=32 HZ; OPTION=2

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Modal Analysis Amplitude (in./sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0026	0	0.00021	-51.2
Splitline	(Vertical)	0.0012	0	0.00785	103.1
Forward	(Lateral)	0.0013	30	0.00049	153.6
Compressor	(Vertical)	0.0035	90	0.00441	-69.9
Igniter	(Lateral)	-	-	0.00042	144.4
	(Vertical)	-	-	0.01416	104.1
Top	(Fore & Aft)	0.004	270	0.00765	-70.8
Gearbox	(Vertical)	-	-	0.00167	94.3

TABLE 121. OH-6 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR—FREQUENCY=50 HZ; OPTION=2

Location		Shake Test Amplitude (in./sec/lb)	Shake Test Phase (degrees)	Modal Analysis Amplitude (in./sec/lb)	Modal Analysis Phase (degrees)
Turbine Middle	(Lateral)	0.0023	-90	0.00033	-113.7
Splitline	(Vertical)	0.0065	-90	0.00339	34.5
Forward	(Lateral)	LT 0.0003	90	0.00039	-140.6
Compressor	(Vertical)	0.0065	90	0.00565	-108.0
Igniter	(Lateral)	-	-	0.00029	76.8
	(Vertical)	-	-	0.00731	46.6
Top	(Fore & Aft)	0.001	50	0.00127	-103.7
Gearbox	(Vertical)	-	-	0.00155	-67.6

TABLE 122. OH-6 TRANSFER MOBILITIES FOR VERTICAL FORCE AT MAIN ROTOR—FREQUENCY=100 HZ; OPTION=2

Location		Shake Test		Modal Analysis	
		Amplitude (in./sec/lb)	Phase (degrees)	Amplitude (in./sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	LT 0.0003	90	0.00011	152.3
Splitline	(Vertical)	0.00046	90	0.00103	-71.8
Forward	(Lateral)	0.0011	220	0.00061	41.3
Compressor	(Vertical)	0.05	220	0.00365	129.9
Igniter	(Lateral)	-	-	0.00026	-5.9
	(Vertical)	-	-	0.00228	-63.9
Top	(Fore & Aft)	LT 0.0003	90	0.00033	-10.6
Gearbox	(Vertical)	-	-	0.00039	164.8

Further computations were made to predict engine installed responses during OH-6 flight operation and to compare these predictions with measured flight responses. The only flight condition for which engine vibration data are available occurs at an altitude of 5000 ft and a velocity of 126 kn. This condition is documented in Reference 2. The major excitation forces for the flight condition were supplied by Hughes. They are:

- Main Rotor—32 Hz (4/rev)
  - Vertical—69 lb at 231 deg
  - Longitudinal—61 lb at 106 deg
  - Lateral—66 lb at 330 deg

- Tail rotor—100 Hz (2/rev)
  - Vertical—3 lb
  - Longitudinal—8 lb
  - Lateral—50 lb

Results of computations performed with these excitation forces and frequencies are shown in Tables 123 and 124 in comparison with flight test results taken from Reference 2. Variations by as much as a factor. of 2 are seen for the main rotor excitations. However, note that similar vibration levels are seen on the engine, but at different locations. The correlation at tail rotor excitation frequency is low. However, this frequency coincides with the output shaft frequency, so the output shaft excited responses (which were not computed) could magnify the response. One possible source of variation in measured and predicted responses lies in the fact that the excitation forces are difficult to accurately determine.

TABLE 123. OH-6 FLIGHT TEST DATA—126 KN; 5000 FT ALT; FREQUENCY=32 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in. /sec/lb)	Phase (degrees)	Amplitude (in. /sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	-	-	0.0783	-171.5
Splitline	(Vertical)	0.5	-	0.7830	1.8
Forward	(Lateral)	0.7	-	0.1186	-6.7
Compressor	(Vertical)	1.2	-	0.5910	-165.2
Igniter	(Lateral)	-	-	0.1632	8.2
	(Vertical)	-	-	1.4790	4.3
Top	(Fore & Aft)	0.65	-	1.0410	-168.0
Gearbox	(Vertical)	-	-	0.1180	-31.1

Although the mobility analysis, using engine and airframe test data, was not applied to the OH-6 helicopter, some comments can be made with respect to the test approach. As pointed out earlier, one possibility of error in the OH-58 mobility analysis might be caused by inaccurate airframe data resulting from the method of testing the bipod interface points. The suggestion was made that better data might result from tying the bipods together with a rigid link to simulate the engine fixity. The test approach at Hughes was to shake and measure along three mutually perpendicular axes defined as:

- Perpendicular bisector of the bipods in the bipod plane
- Normal to the bipod bisector in the plane of the bipod
- Normal to the bipod plane

In this way, the force was always aligned in a stiff direction. Whether or not this difference in testing approach would improve the data, and thereby improve the analysis, was not determined in this study.

Analyses of the OH-58 and OH-6 helicopter systems have been presented. Application of the mobility method of dynamic system analysis to the OH-58 was thoroughly discussed. The resulting poor correlation of the computed mobilities, using subsystem descriptions in terms of test generated mobilities, with test data showed:

- Effect of input shaft fixity could not be determined
- Effect of neglecting all off-axis mobilities did not improve correlation.
- Evaluation of mobilities at ±10% points showed little variation from the center frequency point

TABLE 124. OH-6 FLIGHT TEST DATA—126 KN; 5000 FT ALT; FREQUENCY=100 HZ; OPTION=2

Location		Flight Test		Modal Analysis	
		Amplitude (in. /sec/lb)	Phase (degrees)	Amplitude (in. /sec/lb)	Phase (degrees)
Turbine Middle	(Lateral)	0.6	-	0.0077	-55.2
Splitline	(Vertical)	0.4	-	0.0174	-149.8
Forward	(Lateral)	0.6	-	0.0424	126.3
Compressor	(Vertical)	0.9	-	0.1130	16.0
Igniter	(Lateral)	-	-	0.0214	124.3
	(Vertical)	-	-	0.0488	-154.4
Top	(Fore & Aft)	-	-	0.0195	154.1
Gearbox	(Vertical)	-	-	0.0154	15.5

Poor flight correlation also was evidenced, even when using the coupled system mobilities generated from test. Potential sources of error could be:

- Inaccurate treatment of bipods during test
- Nonlinear characteristics of subsystems

Application of the modal synthesis technique of analysis, using analytically generated subsystem modes, resulted in fair correlation with test data both with coupled system mobilities and with flight data. This correlation existed to the extent that the results could reasonably be used for initial design purposes. The pinned fixity showed higher response than does the uncoupled fixity of the transmission input shaft with the engine output shaft. A more favorable correlation might be expected of the mobility method if computed subsystem mobilities were used instead of test mobilities. Application of the modal synthesis method of analysis to the OH-6 helicopter showed results similar to that of the OH-58 when the same analysis approach is used. However, the use of five different coordinate systems created an unnecessary complication and should be avoided if possible.

CONCLUSIONS

Certain conclusions can be drawn from the results generated during this study program. These conclusions relate to the review of available flight data, acquisition of supplementary shake test data, and simulation of the OH-58 and OH-6 helicopters.

The conclusions drawn from the results of this study follow.

1. The available flight test information is insufficient for fully determining the vibratory environment of the T63-A-5 engine for the OH-58 and OH-6 installations. However, sufficient data are available for evaluating an analysis methodology for a level flight condition.

2. Generation of free-free engine and airframe shake test data in terms of drive point and transfer mobilities provides an excellent means of recording subsystem resonances, mode shapes, and damping.

3. The mobility method of analysis, using subsystem mobilities generated by shake testing, did not show acceptable correlation with either coupled system test mobilities or flight test data.

4. The modal synthesis method of analysis, using analytically generated subsystem uncoupled modes, showed reasonable correlation with shake and flight test data.

5. The use of multiple coordinate systems for the definition of OH-6 airframe mobilities and uncoupled modes was found to be an unnecessary complication when coupling the engine and airframe.

RECOMMENDATIONS

Recommendations presented in this section are for the fulfillment of the primary objective of establishing a common language for engine/airframe lateral vibration specification and analysis to be used in future helicopter programs. Some of the recommendations presented herein relate to the acquisition of flight and shake test data on existing hardware. Others relate to the suggested method of analysis for future helicopter systems and the form and content of data required for use in the initial design phase by the airframe and engine manufacturers. A final recommendation refers to the further development of the mobility method of analysis.

TEST DATA ACQUISITION

A complete matrix of flight test data for straight and level cruise and full autorotational landing should be obtained for future study programs to fully define the vibratory environment of the engine.

A digital record of subsystem shake test mobilities should be made to facilitate their intended use.

Shake test procedures for testing airframe interface points (i.e., bipods and input shafting) should be standardized.

ANALYTICAL METHOD AND REQUIRED DATA

The modal synthesis method of coupled system analysis should be specified as a required analysis methodology.

Engine uncoupled mode description should be specified as an engine requirement for use in the modal synthesis analysis.

Potential engine vibratory excitation characterization should be specified as an engine requirement.

Airframe uncoupled mode description should be specified as an airframe requirement for use in the modal synthesis analysis.

Potential airframe induced vibratory excitations should be defined and required as an airframe specification.

All subsystem mobilities, responses, excitations, etc., should be presented in terms of the single, standardized coordinate system defined by positive translation aft, right, and up with positive rotations about these axes following the right-hand rule.

The mobility method of analysis should be further evaluated for the case where the subsystem mobilities are analytically generated, and, thereby:

- Investigate the possibility of reducing the subsystem data requirements to a few predominant mobilities
- Conceivably specifying mobility amplitude restrictions on the subsystems

As an example, a specification which includes these recommendations is presented in Appendix E.

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APPENDIX A

COMPILATION OF VIBRATION DATA CONTAINED IN BELL REPORT 206-099-179, ENGINE INSTALLATION VIBRATION SURVEY OF MODEL 206A-1 HELICOPTER

AIRCRAFT MISSIONS

FLIGHT SPECTRUM

Vibration measurements will be made during ground and flight conditions at the gross weight, center of gravity locations, rotor rotational speeds, and altitudes indicated in Table A. 1. and listed below.

Normal Conditions

I. Ground Conditions

A. Main Rotor RPM increase from 0-103% N_{II} RPM at flat pitch (normal start)

B. Normal shutdown with rapid deceleration of rotor by use of collective

II. Power on Maneuvers, IGE, at 103% N_{II} RPM except as noted

A. 360° clearing turn to left and right, hover

B. Longitudinal cyclic control reversal, hover

C. Lateral cyclic control reversal, hover

D. Rudder control reversal, hover

E. Steady hovering 101% and 103% N_{II} RPM

F. Sideward flight to left, IGE, at maximum speed

G. Sideward flight to right, IGE, at maximum speed

H. Rearward flight, IGE, at maximum speed

I. Jump takeoff

J. Normal flare and landing

K. Autorotation landing approach with rapid power recovery IGE

L. Full autorotation landing, from normal approach speed

M. Normal acceleration from hover to 70 MPH

III. Forward Flight, Power On, at 101% and 103% N_{II} RPM

A. Stabilized level flight airspeed sweeps from 0.2 V_H to V_H

B. Airspeed of V_{ne} and 111% V_{ne}

IV. Power on Maneuvers, at 103% N_{II} RPM

A. Climb at takeoff power

(L)

B. Climb at maximum continuous power

C. Left and right turns at .5 V_H, and .9 V_H with a load factor of 1.35 to 1.5 g.

D. Cyclic pullups at .6 V_H and .9 V_H, load factor of 1.45 to 1.55 g

E. Longitudinal cyclic control reversal at V_H

F. Lateral cyclic control reversal at V_H

G. Rudder control reversal at V_H

H. Normal deceleration from V_H to 70 MPH

I. Partial power descent (normal approach to landing)

V. Power Transition Maneuvers, at 354 Rotor RPM

A. Transition from stabilized power-on level flight at 0.5 V_H and 0.9 V_H to stabilized autorotation

B. Transition from stabilized autorotation to stabilized power-on level flight at 0.5 V_H and 0.7 V_H.

VI. Stabilized Autorotation at 330, 354 and 390 rotor RPM at 0.5 V_H and 0.7 V_H (A)

VII. Autorotative Maneuvers (to be entered at 354 Rotor RPM)

A. Stabilized left and right turns at 0.5 V_H and 0.7 V_H

B. Longitudinal cyclic control reversal at 70 MPH

C. Lateral cyclic control reversal at 70 MPH

D. Rudder control reversal at 70 MPH

E. Cyclic pullup at 0.8 V_H load factor of 1.45 to 1.55 g.

TABLE A.1

SCHEDULE OF REPRESENTATIVE CONDITIONS TO BE EXECUTED FOR THE MODEL 206A-1 ENGINE INSTALLATION VIBRATION SURVEY

Gross weight → Center of Gravity → Density Altitude, H_D ↓	2530 lb Neutral	2760 lb Fwd	 Aft	3000 lb Fwd	 Aft
Ground	I				
In Ground Effect	II	II	II	II	II
3000 Feet	III through VII	III through VII	III through VIII	III through VII	III through VII

INSTRUMENTATION

The data shown here were taken from Bell Helicopter report 206-099-179.

The instrumentation listed below will be used in conjunction with airborne magnetic tape recorders to acquire data during the engine vibration survey.

Item	Transducer	Location	Plane	Frequency Range for Unattenuated Output, Hz
1	Accelerometer	Front Compressor	Vertical	10 to 2000
2	Accelerometer	Front Compressor	Lateral	10 to 2000
3	Accelerometer	Accessory Gear-box, Left Side	Vertical	10 to 2000 (A)
4	Accelerometer	Accessory Gear-box, Bottom	Lateral	10 to 2000 (A)
5	Accelerometer	Accessory Gear-box, Right Side	Longi-tudinal	10 to 2000
6	Accelerometer	Turbine Mid Splitline	Vertical	10 to 2000
7	Accelerometer	Turbine Mid Splitline	Lateral	10 to 2000
8	Accelerometer	Fuel Nozzle	Vertical	10 to 2000
9	Accelerometer	Fuel Nozzle	Lateral	10 to 2000
10	Pressure	Engine Torque		DC to 100
11	Tachometer	N_1 Speed		DC to 11
12	Accelerometer	Helicopter CG	Vertical	DC to 50
13	Capstan Servo Reference Tone (Track 7)			
14	Voice Monitor (Track 13)			
15	IRIG "B" Time Code (Track 14)			

The airborne data acquisition system conformed to the proposal in Part I. The individual components are identified below.

ACCELEROMETERS (Locations are shown in Figures A. 1 and A. 2)

ENGINE VERTICAL AND LATERAL

Kistler Piezoelectric Model 808A
Frequency Response: 2 to 7000 Hz
Maximum Acceleration: ±10,000g
Maximum Temperature: 500°F

ENGINE FORE AND AFT

C. E. C. Low Impedance Piezoelectric Model 4-280-0001
Frequency Response: 2 to 6000 Hz
Maximum Acceleration: ±200g
Maximum Temperature: 200°F

CENTER OF GRAVITY

Statham Strain Gage Model A5-5-350
Natural Frequency: 190 Hz
Maximum Acceleration: ±5g

CHARGE AMPLIFIERS

Endevco Model 2640M12
Adjustable Charge Gain
Frequency Response: 2 Hz to 80,000 Hz

Kistler Model 533B
Adjustable Charge Gain
Frequency Response: 3 Hz to 20,000 Hz

All engine accelerometers were used with Endevco charge amplifiers except for the following items:

1. Turbine-midsplit lateral and vertical charge amplifiers (A506, A507) were changed to Kistler type (Serial No. 608, 609). These were checked against the Endevco charge amplifiers for frequency response and it was determined that recalibration was not necessary.

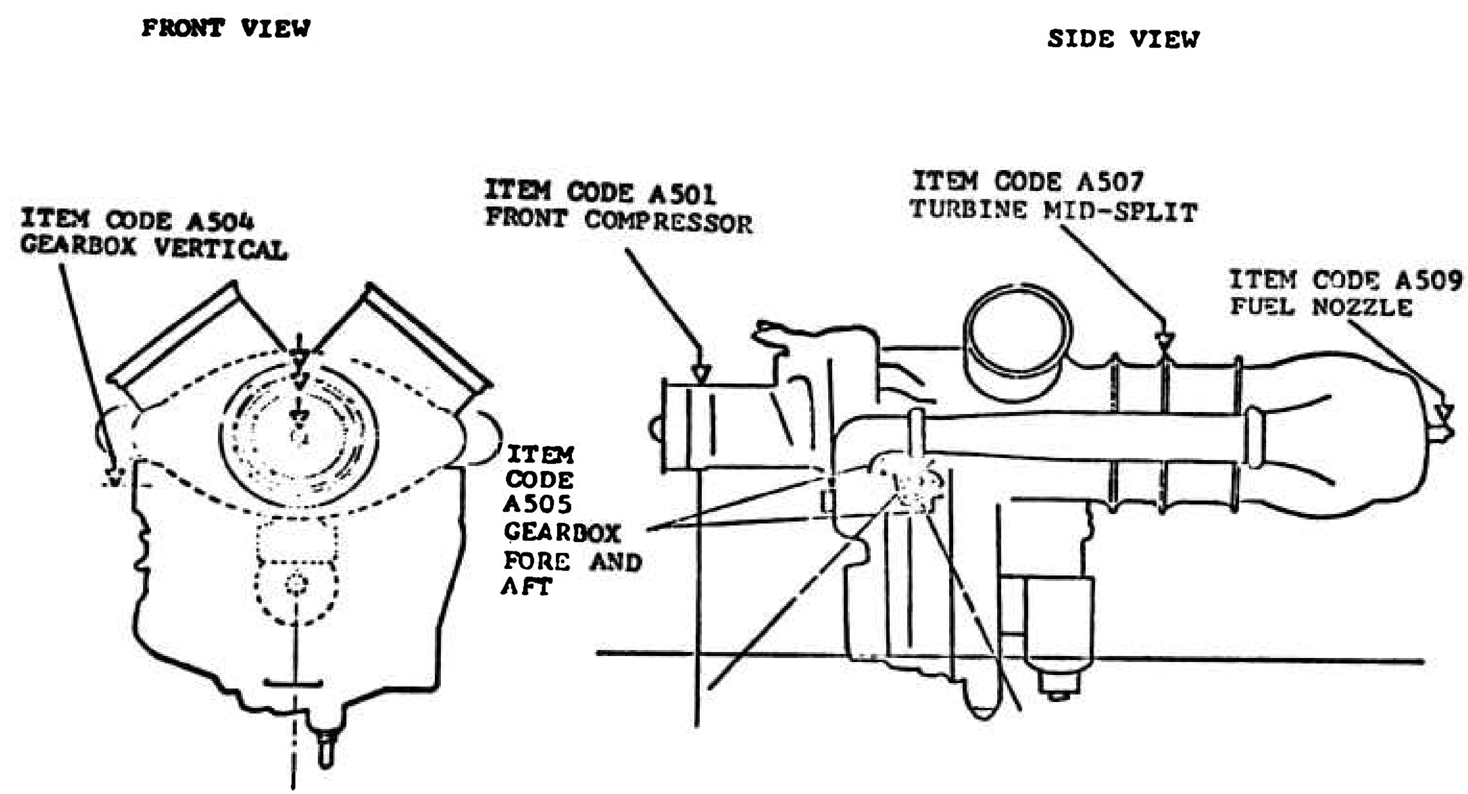

Figure A. 1. Vertical and Fore and Aft Vibration Transducer Locations.

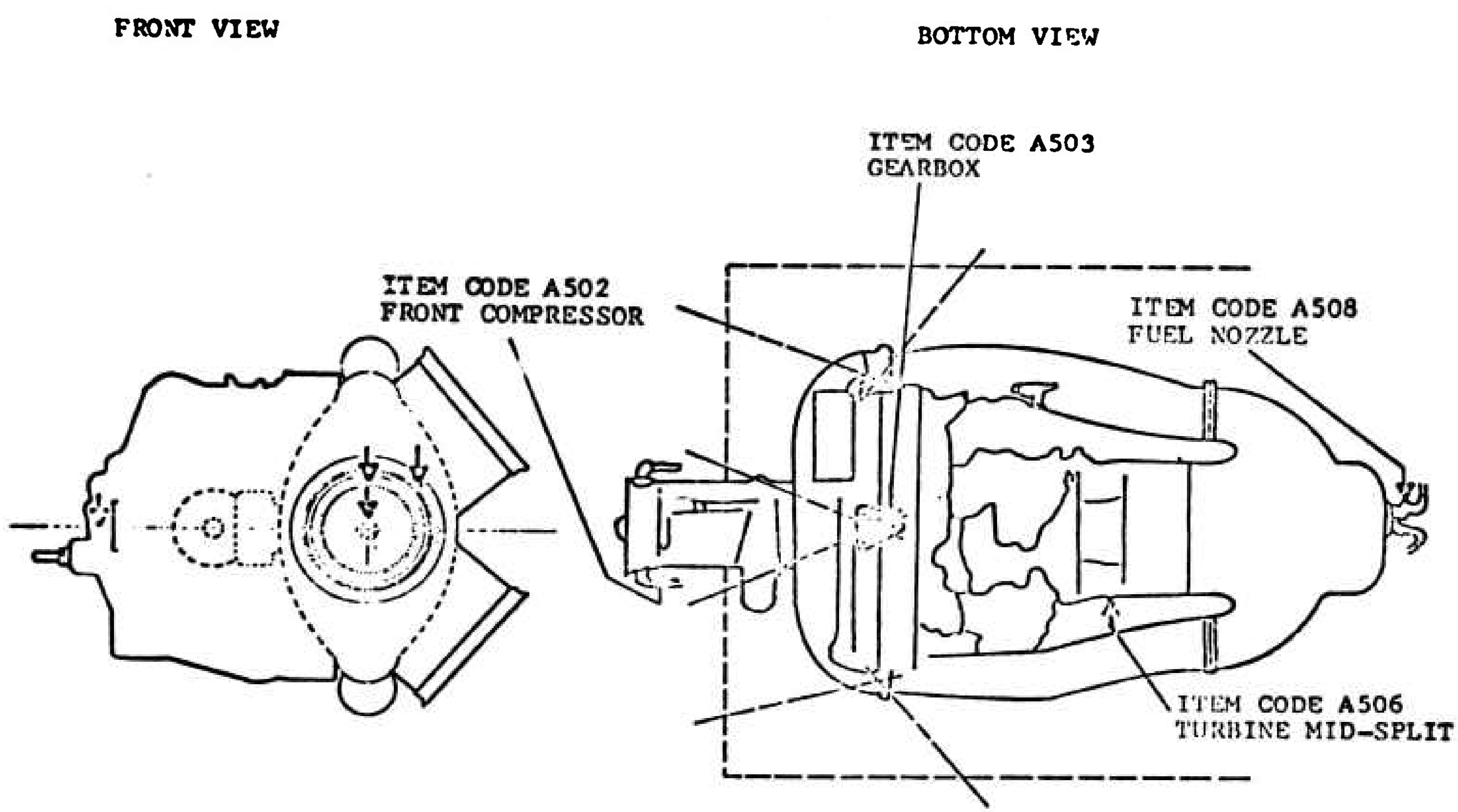

Figure A. 2. Lateral Vibration Transducer Locations.

2. The gearbox fore and aft accelerometer had a built-in cathode follower so no external charge amplifier was required.

The integrators were designed and built by Bell Helicopter to convert the acceleration signal to a velocity signal.

Frequence Response: Flat from 40 Hz to 2000 Hz
Down 3 db at 10 Hz

The complex velocity signal is attenuated by 0.637 to provide complex average velocity signal as specified in Part I.

SIGNAL CONDITIONING

Included in each circuit is a passive network which permits the recording of automatic in-flight calibration. It does not affect the data signal.

RECORD ELECTRONICS AND TAP DECK

The function of converting the transducer signal to a frequency modulated signal for recording is performed by the tape deck unit.

Ampex Model AR-200
Tape Speed Used: 15 inches per second
Frequency Response: D. C. to 5000 Hz
Signal-to-Noise Ratio: 43db

FORM OF VIBRATION DATA

The vibration data contined within the report are of the following type and content.

1. Analog traces of the vibration transducers at the V_h and V_{ne} flight conditions are included as plots and are recorded on magnetic tape.

2. Time histories for all flight phases and all transducers are presented as plots of overall vibration versus a dual abscissa - airspeed and time (sec/cm).

3. Frequency analysis plots of vibration amplitude versus discrete frequency are included for V_h and V_{ne} and four gross weight-CG combinations for all transducers.

4. Mode shapes are shown for the engine for peak discrete frequency responses for V_h and V_{ne}.

5. Tables are included for identifying the points in the mission where the engine vibration limits were violated and the relative percent of the mission spent at this violated condition.

MODE SHAPES

The response mode shapes of the engine occurring for V_h and V_{ne} at high response discrete frequency excitations has been included as plots in the report. Further data, for other flight conditions, was not included. Phase and amplitude data for these other conditions are not available in the report.

GENERAL APPRAISAL

The data contained within this report appear adequate for defining the environmental vibratory characteristics of the engine for the OH-58/T63 helicopter system. Sources of excitation are available from the discrete frequency analysis of the measured response. Since this was an engine vibration survey, no data are included relative to the helicopter airframe response.

E. Strain Gages

Type HT100-2A Used on Front Diffuser Plate Top & Side Rib

Type MH-06-125AC-350 Used to Complete Full Bridges At Center of Each Aircraft To Engine Strut

The frequency ranges of the instrumentation was not contained in the report.

FORM OF VIBRATION DATA

The basic data contained in this report are in the form of oscillograms for all conditions recorded. Some of these are random clips and should not be used for phasing. The tapes recorded during the survey are not available. Selected data points have been analyzed and are presented in the report as plots of vibration velocity versus discrete frequency. Tables show the maximum overall velocity encountered for each mission phase at all transducers recorded. Included in these tables is an assessment of the effect of main and tail rotor unbalance on the vibration.

MODE SHAPES

No information relative to the response mode shapes is available in the report.

GENERAL APPRAISAL

The data contained within this report provides only minimal information toward defining the OH-6A/T63 in-flight vibratory environment. Only engine vibration is provided. The sketchy frequency analysis plots do provide the discrete frequency of the predominant sources in the overall vibration. The response modes are not defined.

APPENDIX B

COMPILATION OF VIBRATION DATA CONTAINED IN DDA REPORT 64B19, INSTALLATION SURVEY OF YT63-A-5 ENGINE INSTALLED IN HUGHES OH-6A AIRCRAFT

AIRCRAFT MISSION

Conditions				
Horse-power	LAS MPH	Alt. Ft.	Bal. Cond.	Maneuver
100	---	GRD	B	Tie Down Ground Run
100	---	GRD	U	Tie Down Ground Run
134	---	GRD	B	Tie Down Ground Run
134	---	GRD	U	" " " "
200	0	5000	B	Hover
134	44	5000	B	Straight Flight
134	87	5000	B	Straight Flight
227	120	5000	B	Straight Flight
224	126	5000	B	Straight Flight
---	---	100	B	Sideward Flight-Right
---	---	100	B	Sideward Flight-Left
---	0-10	100	B	Pedal Turn-Right
---	0-10	100	B	Pedal Turn-Left
---	---	GRD	B	Eng. Start to 100% N_2 RPM
---	---	GRD	U	" " " " " "
---	---	GRD	B	Stabilized 100% N_2 RPM
---	---	GRD	U	Stabilized 100% N_2 RPM

INSTRUMENTATION

A. Portable Lockheed Four Channel FM Tape Recorder Type 4-11

B. Signal Switching Box with Dana Amplifier P/N T-165062

C. B & F Strain Gage Signal Conditioning Box P/N T-163790

D. MB Vibration Pickups Types 122 & 126 Everywhere Exept a CEC Type 4-106 On Exhaust Extension Lateral

APPENDIX C

DESCRIPTION OF MOBIL

```
C THIS PROGRAM (MOB58) COMPUTES THE TOTAL SYSTEM MOBILITIES AND RESPONSE     MAIN
C FOR THE OH58/T63 HELICOPTER - INPUT DATA ARE THE ENGINE AND AIRFRAME       MAIN
C COMPONENT MOBILITIES GENERATED BY TESTING                                  MAIN
C                                                                            MAIN
C                                                                            MAIN
      COMMON/XMAIN/IN,IOUT,FORCE(10),ICCN,ISET,IOMEG,ITYPE,OMEGA(26),IO1MAIN  10
     1       ,IDATA
      COMPLEX *8 FORCE                                                   MAIN  11
      DEFINE FILE 2(30,5000,L,ISET)                                      MAIN  20
      DEFINE FILE 1(30,5000,L,ICON)                                      MAIN  30
      IN=5
      IO1=0
  100 READ(IN,2) IOMEG
    2 FORMAT(20I4)
      IDATA=0
      IO3=IOMEG+2
      IOMEG=IOMEG-1
      ICON=1                                                             MAIN  40
      ISET=1                                                             MAIN  41
    1 CALL MOBIN1                                                        MAIN  50
      IF((IOMEG.LT.IO3) .AND. (IO1. NE. 0)) GO TO 10
      CALL MOBIN2                                                        MAIN  60
   10 IOMEG=IOMEG+1                                                      MAIN  80
      CALL MOBST1                                                        MAIN  90
      IF(IDATA.EQ.1) GO TO 100
      CALL MOBST2                                                        MAIN 100
      CALL MOBSOL                                                        MAIN 110
    6 CALL MOBOUT                                                        MAIN 130
      IO1=1
      IF(IOMEG.LT.IO3) GO TO 10
      GO TO 100
      END                                                                MAIN 150
```

```
      BLOCK DATA                                                         BLOCK   1
      COMMON/XMAIN/IN,IOUT,FORCE(10),ICON,ISET,IOMEG,ITYPE,OMEGA(26),IO1BLOCK   2
     1       ,IDATA
      COMPLEX *8 FORCE                                                   BLOCK  2A
      DATA OMEGA/5.3,5.9,6.5,10.6,11.8,13.0,21.2,23.6,26.0,31.8,35.4,    BLOCK   3
     1          39.0,39.4,42.4,43.8,47.2,48.2,52.0,78.8,87.6,92.7,96.4 ,BLOCK   4
     2         103.0,113.3,185.4,200.0/                                  BLOCK   5
      END                                                                BLOCK   6
```

```
      SUBROUTINE MOBINI
C
C THIS SUBROUTINE READS THE OH58 TEST DATA CN TAPE BELL58 AND THE T63
C TEST DATA ON TAPE DDAT63 - WRITES THEM ON DISK - RETURNS
C BELL58 IS UNIT 9 -- DCAT63 IS UNIT 8
      COMMON/XMAIN/IN,IOUT,FORCE(10),ICON,ISET,IOMEG,ITYPE,OMEGA(26),IO1
     1      ,ICATA
      CCMPLEX *8 FORCE
      INTEGER*4 OPTION
      REAL*4 FR1
      DIMENSION TITLE(19)
      COMPLEX*16 YEE1(12,12),YEI1(12,9),YCK(8,9),YIE2(8,12),YEE2(12,12)
      IN=5
      IOUT=6
      READ(IN,10) ITYPE,TITLE
   10 FORMAT(I4,19A4)
      WRITE(IOUT,20) ITYPE,TITLE
   20 FORMAT(1H1,I4,19A4)
      READ(IN,11) (FORCE(I),I=1,3)
   11 FORMAT(7E10.3)
      READ(IN,11) (FORCE(I),I=4,6)
      READ(IN,11) (FORCE(I),I=7,9)
      READ(IN,11)  FORCE(10)
      WRITE(IOUT,12)
   12 FORMAT(1H0,30(1H*),' AIRFRAME FORCES ',30(1H*),/,11HOMAIN ROTOR,/)
      WRITE(IOUT,13)(FORCE(I),I=1,3)
   13 FORMAT(1H0,5X,12HFORE AND AFT,12X,7HLATERAL,15X,8HVERTICAL,/,
     1    3(2X,F8.2,2X,F8.2,2X))
      WRITE(IOUT,14)
   14 FORMAT('OTAIL ROTOR',/)
      WRITE(IOUT,13)(FORCE(I),I=4,6)
      WRITE(IOUT,15)
   15 FORMAT(1H0,31(1H*),' ENGINE FORCES ',31(1H*),/,17HOTURBINE MIDSPLI
     1T,/)
      WRITE(IOUT,16)(FORCE(I),I=7,8)
   16 FORMAT(1H0,29X,7HLATERAL,15X,8HVERTICAL,/,20X,2(2X,F8.2,2X,F8.2,
     1 2X ))
      WRITE(IOUT,17)
   17 FORMAT(1H0,'FORWARD COMPRESSOR',/)
      WRITE(IOUT,16)(FORCE(I),I=9,10)
      IF(IO1.NE.0) RETURN
   18 READ(9,END=19) OPTION,FR1,YEE1,YEI1,YCK,YIE2,YEE2
      IF((OPTION.NE.ITYPE).AND.(ITYPE.NE.0)) GO TO 18
      IF((ITYPE.EQ.0).AND.(OPTION.EQ.2)) GO TO 19
      WRITE(1'ICON) OPTION,FR1,YEE1,YEI1
      GO TO 18
   19 CONTINUE
      ICON=1
      RETURN
      END
```

```
      SUBROUTINE MOBIN2
      COMMON/XMAIN/IN,IOUT,FORCE(10),ICCN,ISET,IOMEG,ITYPE,OMEGA(26),IO1
     1        ,ICATA
      COMPLEX *8 FORCE
      DIMENSION FREQ(26),GAIN(26,16,20),PHASE(26,16,20)
      DO 400 I=1,26
      DO 400 J=1,16
      DO 400 K=1,20
      GAIN(I,J,K)=0.0
      PHASE(I,J,K )=0.0
  400 CONTINUE
      REWIND 8
      READ (8) FREQ,GAIN,PHASE
      DO 1 I=1,26
      WRITE(2'ISET) ((GAIN(I,IR,IC),PHASE(I,IR,IC),IR=1,16),IC=1,20),I
    1 CONTINUE
      ISET=1
      RETURN
      END
```

```
      SUBROUTINE MOBST1
C
C     THIS SUBROUTINE SETS UP THE H AND E MATRICES
C
      COMMON/XMAIN/IN,IOUT,FORCE(10),ICCN,ISET,ICMEG,ITYPE,OMEGA(26),I01
     1      ,IDATA
      CCMMCN/XSET/H(18,18),E(16,20)
      COMPLEX *8 FORCE
      INTEGER*4 OPTION
      COMPLEX*8 H,E
      COMPLEX*16 YEE1(12,12),YEI1(12,9)
      COMPLEX*16 ZERO
      DIMENSION GAIN(18,20),PHASE(18,20)
      ZERO=DCMPLX(0.D0,0.D0)
      H(1,1)=CMPLX(0.0,0.0)
      CALL MVC(H(2,1),5144,H)
   18 READ(1'ICON) OPTION,FR1,YEE1,YEI1
      IF(FR1.EQ.OMEGA(IOMEG)) GO TO 19
      IF(ICON.LE.27) GO TO 18
      WRITE(IOUT,21)
   21 FORMAT( 1H0,10X,'WE ARE OUT OF HELICOPTER DATA')
      IDATA=1
      RETURN
   19 CCNTINUE
      IF(ITYPE.NE.0) GO TO 5
      DO 4 I=1,12
      YEE1(10,I)=ZERO
      YEE1(11,I)=ZERO
      YEE1(12,I)=ZERO
      YEE1(I,10)=ZERO
      YEE1(I,11)=ZERO
      YEE1(I,12)=ZERO
      IF(I.GT.6) GO TO 4
      YEI1(10,I)=ZERO
      YEI1(11,I)=ZERO
      YEI1(12,I)=ZERO
    4 CONTINUE
    5 CONTINUE
      RAD=0.0174533
      DO 1 IR=7,18
      DO 1 IC=1,6
      I=IR-6
    1 H(IR,IC)=YEI1(I,IC)
      DO 3 IR=7,18
      DO 3 IC=7,18
      I=IR-6
      J=IC-6
    3 H(IR,IC)=YEE1(I,J )
  100 READ(2'ISET) ((GAIN(IR,IC),PHASE(IR,IC),IR=1,16),IC=1,20),I
      IF(ISET.LE. 27) GO TO 30
      WRITE(IOUT,29)
   29 FORMAT(1H0,10X,'WE ARE OUT OF ENGINE CATA')
      IDATA=1
      RETURN
   30 CONTINUE
      IF(I.NE.IOMEG) GO TO 100
      DO 2 IR=1,16
      DO 2 IC=1,20
      ANG=PHASE(IR,IC)*RAD
    2 E(IR,IC)=GAIN(IR,IC)*CMPLX(COS(ANG),SIN(ANG))
      RETURN
      END
```

```
      SUBROUTINE MOBST2
      COMMON/MATRIX/A,B
      COMMON/XMAIN/IN,IOUT,FORCE(10),ICON,ISET,IOMEG,ITYPE,OMEGA(26),IOI
     1       ,IDATA
      COMMON/XSET/H(18,18),E(16,20)
      COMPLEX *8 FORCE
      COMPLEX *8 B(32),A(32,33),H,E,ZERC,CNE
      COMPLEX *8 FX,FY,FZ,TX,TY,TZ,PY,PZ
      ZERO=CMPLX(0.0,0.0)
      ONE =CMPLX(1.0,0.0)
      DO 1 I=1,32
      B(I)=ZERO
      DO 1 J=1,33
    1 A(I,J)=ZERO
      DO 2 I=1,12
      DO 2 J=21,32
      K=I+6
      L=J-14
    2 A(I,J)=H(K,L)
      DO 3 I=13,32
      DO 3 J=21,32
      K=I-12
      L=J-20
    3 A(I,J)=-E(L,K)
      DO 4 I=1,12
    4 A(I,I)=-CNE
      DO 5 I=1,20
    5 A(I+12,I)=-ONE
      FX=FORCE(1)
      FY=FORCE(2)
      FZ=FORCE(3)
      TX=FORCE(4)
      TY=FORCE(5)
      TZ=FORCE(6)
      DO 6 I=1,12
      J=I+6
    6 B(I)=-FX*H(J,1)-FY*H(J,2)-FZ*H(J,3)-TX*H(J,4)-TY*H(J,5)-TY*H(J,6)
      PY=FORCE(7)
      PZ=FORCE(8)
      DO 7 I=13,32
      J=I-12
    7 B(I)=-PY*E(13,J)-PZ*E(14,J)
      IF(ITYPE.NE.0) GO TO 33
      DO 31 I=1,32
      A(22,I)=ZERO
      A(23,I)=ZERO
      A(24,I)=ZERO
   31 CONTINUE
      B(22)=ZERO
      B(23)=ZERO
      B(24)=ZERO
      A(22,30)=ONE
      A(23,31)=ONE
      A(24,32)=ONE
   33 CONTINUE
C
C          STILL NEED TO TAKE CARE OF THE OTHER FORCES
C
      RETURN
      END
```

```
      SUBROUTINE MOBSOL                                                 SOL   10
C                                                                         SOL
C     THIS ROUTINE SOLVES AX=B                                            SOL
C                                                                         SOL
      COMMON/MATRIX/A,B                                                 SOL   20
      COMMON/XMAIN/IN,IOUT,FORCE(10),ICON,ISET,IOMEG,ITYPE,OMEGA(26)    SOL   30
      COMMON/SOLVE/RESP(32),THETA(32)                                   SOL   40
      COMPLEX *8 FORCE                                                  SOL   41
      COMPLEX *8 B(32),A(32,33)                                         SOL   50
      N=32                                                              SOL   60
      M=32                                                              SOL   70
      CALL CSMEQ(N,M,A,B)                                               SOL   80
      RAD=57.29578                                                      SOL   90
      DO 1 I=1,32                                                       SOL  100
      RESP(I)=CABS(B(I))                                                SOL  110
      XREAL=REAL(B(I))                                                  SOL  120
      XIMAG=AIMAG(B(I))                                                 SOL  130
      THETA(I)=0.0
      IF(XIMAG+XREAL.EQ.0.0) GO TO 1
      THETA(I)=ATAN2(XIMAG,XREAL)*RAD                                   SOL  140
    1 CONTINUE
      RETURN                                                            SOL  150
      END                                                               SOL  160
```

```
      SUBROUTINE MOBOUT
C
C     THIS SUBROUTINE PRINTS OUT THE RESPCNSES (FORCES AND VELOCITIES)
C     RESULTING FROM THE INPUT FORCES
C
      COMMON/XMAIN/IN,IOUT,FORCE(10),ICCN,ISET,IOMEG,ITYPE,OMEGA(26)
      COMMON/SOLVF/RESP(32),THETA(32)
      CCMPLEX *8 FORCE
      WRITE(IOUT,2)
      WRITE(IOUT,1) OMEGA(ICMEG)
    1 FORMAT(1H0,20X,'RESPONSE AT A FREQUENCY OF',F6.1,' HERTZ',//)
    2 FORMAT(1H1,33(1H*),' RESPONSES ',33(1H*),/)
      WRITE(IOUT,3)
    3 FORMAT(1H0,' INTERFACE VELOCITIES',/,9X,'LEFT BIPOD',/)
      WRITE(IOUT,4)
    4 FORMAT(7X,12HFORE AND AFT,16X,7HLATERAL,19X,8HVERTICAL,/,6X,4HAMP.
     1      ,5X,5HPHASE,12X,4HAMP.,5X,5HPHASE,12X,4HAMP.,5X,5HPHASE,/)
      WRITE(IOUT,5)  ((RESP(I),THETA(I)),I=1,3)
    5 FORMAT(4X,F7.2,4X,F6.1, 9X,F7.2,4X,F6.1, 9X,F7.2,4X,F6.1,/)
      WRITE(IOUT,6)
    6 FCRMAT(1H0,8X,'RIGHT BIPOD',/)
      WRITE(IOUT,4)
      WRITE(IOUT,5) ((RESP(I),THETA(I)),I=4,6)
      WRITE(IOUT,7)
    7 FORMAT(1H0,8X,'LOWER BIPOD',/)
      WRITE(IOUT,4)
      WRITE(IOUT,5) ((RESP(I),THETA(I)),I=7,9)
      WRITE(IOUT,8)
    8 FORMAT(1H0,8X,'INPUT SHAFT',/)
      WRITE(IOUT,4)
      WRITE(IOUT,5) ((RESP(I),THETA(I)),I=10,12)
      WRITE(IOUT,9)
    9 FORMAT(1H0,' ENGINE VELOCITIES',/,9X,'TOP GEARBOX',/,7X,12HFORE AN
     1D AFT,16X,8HVERTICAL,/)
      WRITE(IOUT,10)
   10 FORMAT(6X,4HAMP.,5X,5HPHASE,12X,4HAMP.,5X,5HPHASE,/)
      WRITE(IOUT,50)((RESP(I),THETA(I)),I=13,14)
      WRITE(IOUT,11)
   11 FORMAT(1H0,8X,'TURBINE MIDSPLIT',/)
      WRITE(IOUT,12)
   12 FORMAT(6X,7HLATERAL,19X,8HVERTICAL,/)
      WRITE(IOUT,10)
      WRITE(IOUT,50)((RESP(I),THETA(I)),I=15,16)
      WRITE(IOUT,13)
   13 FORMAT(1H0,8X,'FORWARD COMPRESSOR',/)
   50 FORMAT(5X,F6.2,4X,F6.1,10X,F6.2,4X,F6.1,/)
      WRITE(IOUT,12)
      WRITE(IOUT,10)
      WRITE(IOUT,50)((RESP(I),THETA(I)),I=17,18)
      WRITE(IOUT,14)
```

```
14 FORMAT(1H0,8X,'IGNITER',/)
   WRITE(IOUT,12)
   WRITF(IOUT,10)
   WRITE(IOUT,50)((RESP(I),THETA(I)),I=19,20)
   WRITE(IOUT,15)
15 FORMAT(1H0,' INTERFACE FORCES (LB)',/,9X,'LEFT BIPOD',/)
   WRITE(IOUT,4)
   WRITE(IOUT,5) ((RESP(I),THETA(I)),I=21,23)
   WRITE(IOUT,6)
   WRITE(IOUT,4)
   WRITE(IOUT,5) ((RESP(I),THETA(I)),I=24,26)
   WRITE(IOUT,7)
   WRITE(IOUT,4)
   WRITE(IOUT,5) ((RESP(I),THETA(I)),I=27,29)
   WRITE(IOUT,8)
   WRITE(IOUT,4)
   WRITE(IOUT,5) ((RESP(I),THETA(I)),I=30,32)
   RETURN
   END
```

```
C       SOLUTION OF COMPLEX SIMULTANEOUS EQUATIONS  AX B                CSMQ  10
      SUBROUTINE CSMEQ N,M,A,B                                          CSMQ  20
      COMMON /UTIL/ C,AMAX,LC 310 ,I,K,L,IMAX,JMAX,J,M1                 CSMQ  30
      COMPLEX A M,M ,B 2 ,C,CRTHM4                                      CSMQ  40
      M1 N&1                                                            CSMQ  60
      DO 5 I 1,N                                                        CSMQ  70
      LC I  I                                                           CSMQ  80
    5 A I,M1  B I                                                       CSMQ  90
      DO 30 K 2,N                                                       CSMQ 100
      L K-1                                                             CSMQ 110
      M2 M1-L                                                           CSMQ 115
      AMAX 0.                                                           CSMQ 120
      DO 15 I L,N                                                       CSMQ 130
      DO 15 J L,N                                                       CSMQ 140
      IF  CABS A I,J  -AMAX  15,15,12                                   CSMQ 150
   12 IMAX I                                                            CSMQ 160
      JMAX J                                                            CSMQ 170
      AMAX CABS A I,J                                                   CSMQ 180
   15 CONTINUE                                                          CSMQ 190
      IF  AMAX  38,38,17                                                CSMQ 200
   17 J LC L                                                            CSMQ 210
      LC L  LC JMAX                                                     CSMQ 220
      LC JMAX  J                                                        CSMQ 230
      DO 20 J L,M1                                                      CSMQ 240
      C A L,J                                                           CSMQ 250
      A L,J  A IMAX,J                                                   CSMQ 260
   20 A IMAX,J  C                                                       CSMQ 270
      DO 25 I 1,N                                                       CSMQ 280
      C A I,L                                                           CSMQ 290
      A I,L  A I,JMAX                                                   CSMQ 300
   25 A I,JMAX  C                                                       CSMQ 310
      DO 30 I K,N                                                       CSMQ 320
      C A I,L /A L,L                                                    CSMQ 330
   30 CALL CROP A 1,K ,C,I,L,M2,M                                       CSMQ 350
      IF  CEBS A N,N    31,38,31                                        CSMQ 355
   31 K N                                                               CSMQ 360
   32 J LC K                                                            CSMQ 370
      B J  A K,K&1 /A K,K                                               CSMQ 380
      L K-1                                                             CSMQ 390
      DO 36 I 1,L                                                       CSMQ 400
   36 A I,K  CRTHM4 A I,K&1 ,A I,K ,B J                                 CSMQ 410
      K L                                                               CSMQ 420
      IF  K  40,40,32                                                   CSMQ 430
   38 WRITE  6,39                                                       CSMQ 433
  238 WRITE  6,39                                                       CSMQ 433
   39 FORMAT  1HO10X COMPLEX MATRIX IS SINGULAR                         CSMQ 437
   40 RETURN                                                            CSMQ 440
      END                                                               CSMQ 450
```

```
COMPLEX FUNCTION CRTHM1 A,D
COMPLEX A,B,C,CRTHM2,CRTHM3,CRTHM4,CRTHM5,CRTHM6,CRTHM7
CRTHM1 CMPLX REAL A *D,AIMAG A *D
RETURN
ENTRY CRTHM2 A,D
CRTHM2 CMPLX -AIMAG A *D,REAL A *D
RETURN
ENTRY CRTHM3 A,B,C
CRTHM3 A&B*C
RETURN
ENTRY CRTHM4 A,B,C
CRTHM4 A-B*C
RETURN
ENTRY CRTHM5 A,B,C
CRTHM5 A*B*C
RETURN
ENTRY CRTHM6 A,B
CRTHM6 A*B
RETURN
ENTRY CRTHM7 A,B,D
CRTHM7 A&CMPLX REAL B *D,AIMAG B *D
RETURN
ENTRY CEBS A
CEBS REAL A **2&AIMAG A **2
RETURN
ENTRY CMPRE A,B
IF  CABS B .GT.CABS A   A B
RETURN
END
```

SECURITY MARKINGS - ☒ UNCLASSIFIED ☐ CONFIDENTIAL ☐ SECRET ☐ RESTRICTED DATA ☐ AEC CONTRACT ☐ DOD CONTRACT ☐ AUTOMATIC DOWNGRADING STAMP

PROGRAM NO. ______

PROGRAMMER NAME W.H. PARKER

DEPT. 8892

SHEET 1 OF 1

DATE 2/22/74

PROGRAM NAME MOBILITY ANALYSIS

iOMEG					
iTYPE	TITLE				
M.R. X_R	X_i	M.R. Y_R	Y_i	M.R. Z_R	Z_i
T.R. X_R	X_i	T.R. Y_R	Y_i	T.R. Z_R	Z_i
TURB. Y_R	Y_i	TURB. Z_R	Z_i	COMPR. Y_R	Y_i
COMPR. Z_R	Z_i				

M.R. - MAIN ROTOR
T.R. - TAIL ROTOR
TURB. - TURBINE MIDDLE SPLITLINE
COMPR. - FORWARD COMPRESSOR
X - FORE & AFT
Y - LATERAL
Z - VERTICAL
R - REAL
i - IMAGINARY

iOMEG - CENTER FREQUENCY OF INTEREST NUMBER
iTYPE - RUN CODE

APPENDIX D

DESCRIPTION OF MODSYN

```
C     MAINLINE
C     THIS PROGRAM ACCEPTS THE MODAL DESCRIPTION OF TWO SUB-SYSTEMS AND
C     COUPLES THEM TOGETHER THROUGH COUPLING SPRINGS TO PRODUCE THE
C     COUPLED SYSTEM DYNAMICS
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/DATA/IN,IOUT,OPTION,ISTFH,ISTFE,N
     1   ,     N1,N2,NH,NE,NC,NGH,NGE
     2   ,     NFORH,NFORE
      COMMCN/SET/FH(59,60),FE(20,60),IRATEH(20),IRATEE(20),IHGRND(20),
     1            IEGRND(20),OMEGH(59),OMEGE(20),MH(59),ME(20)
     2           ,KC(20),KGH(20),KGE(20)
      COMMON/TRIG/IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IFREQ,IVEL
      COMMON/DAMP/GKC(20),GKGH(20),GKGE(20),GHMODE,GEMODE,HZLOW,HZHI
     1    ,IFORH(20),IFORE(20),FORH(20),FORE(20)
      COMPLEX*8 GKC,GKGH,GKGE,GHMODE,GEMODE,FORH,FCRE
      INTEGER*4 OPTION
      REAL*4 MH,ME
      REAL*4 KC,KGH,KGE
      REAL *8 FREQ(99)
      IFREQ=0
      IPAS=1
    3 CALL MAINE(FREQ,NMODE,IPAS)
      IF(IFREQ.EQ.1) GO TO 2
      IPAS=2
      CALL MAINE(FREQ,NMODE,IPAS)
    2 IF(NFROH+NFORE .EQ. 0) GO TO 1
      CALL MAINR(FREQ,NMODE)
      IPAS=3
      IF(IFREQ.EQ.1) GO TO 3
    1 IPAS=1
      GO TO 3
      END
```

```
      SUBROUTINE MAINE(XREQ,NM    ,IPAS)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/DATA/IN,IOUT,OPTION,ISTFH,ISTFE,N
     1    ,     N1,N2,NH,NE,NC,NGH,NGE
     2    ,     NFORH,NFORE
      COMMON/SOLV/MASS(99),STIFF(99,99),FREQ(99),SHAPE(99,99),NMODE
      REAL*8 MASS,XREQ(99)
      INTEGER*4 OPTION
      IF(IPAS.NE.1) GO TO 2
      CALL ZERO
      CALL MODIN
      CALL MVC(XREQ,792,FREQ)
      NM=NMODE
      RETURN
    2 IF(IPAS.NE.3) GO TO 3
      CALL MODIN
      CALL MVC(XREQ,792,FREQ)
      NM=NMODE
      RETURN
    3 CONTINUE
      CALL MODSET
      CALL DEIGV(N,NMODE,MASS,STIFF,FREQ,SHAPE,99)
      CALL TRANS
      CALL MODOUT
      CALL MVC(XREQ,792,FREQ)
      NM=NMODE
      RETURN
      END
```

```
      SUBROUTINE ZERO
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/SET/FH(59,60),FE(20,60),IRATEH(20),IRATEE(20),IHGRND(20),
     1            IEGRND(20),OMEGH(59),CMEGE(20),MH(59),ME(20)
     2           ,KC(20),KGH(20),KGE(20)
      COMMON/SOLV/MASS(99),STIFF(99,99),FREQ(99),SHAPE(99,99),NMODE
      COMMON/DAMP/GKC(20),GKGH(20),GKGE(20),GHMODE,GEMODE,HZLOW,HZHI
     1    ,IFORH(20),IFORE(20),FORH(20),FORE(20)
      COMPLEX*8 GKC,GKGH,GKGE,GHMODE,GEMODE,FORH,FORE
      REAL*4 MH,ME,KC,KGH,KGE
      REAL*8 MASS
      FH(1,1)=0.0
      MASS(1)=0.0
      CALL MVC(FH(2,1),39420,FH)
      CALL MVC(MASS(2),158392,MASS)
      GKC(1)=0.0
      CALL MVC(GKC(2),984,GKC)
      RETURN
      END
```

```
      SUBRCUTINE MODIN
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/DATA/IN,IOUT,OPTION,ISTFH,ISTFE,N
     1    ,     N1,N2,NH,NE,NC,NGH,NGE
     2    ,     NFORH,NFORE
      CCMMON/SET/FH(59,60),FE(20,60),IRATEH(20),IRATEE(20),IHGRND(20),
     1             IEGRND(20),OMEGH(59),CMEGE(20),MH(59),ME(20)
     2 ,KC(20),KGH(20),KGE(20)
      COMMON/TRIG/IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IFREQ,IVEL
      COMMON/SOLV/MASS(99),STIFF(99,99),FREQ(99),SHAPE(99,99),NMODE
      COMMON/DAMP/GKC(20),GKGH(20),GKGE(20),GHMODE,GEMODE,HZLOW,HZHI
     1     ,IFORH(20),IFORE(20),FORH(20),FORE(20)
      COMPLEX*8 GKC,GKGH,GKGE,GHMODE,GEMODE,FORH,FORE
      INTEGER*4 OPTION
      REAL*8 MASS
      REAL*4 XHMODE,XEMODE,XKC(20),XKGH(20),XKGE(20)
      REAL*4 MH,ME
      REAL*4 KC,KGH,KGE
      DIMENSION TITLE(19)
      IN=5
      ICUT=6
      IF(IFREQ.EQ.1) GO TO 330
      READ(IN,3) IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES
      NAMELIST/INPUT1/ IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IRTRAN
      WRITE(IOUT,INPUT1)
      READ(IN,1) NMODE,OPTION,TITLE
    1 FORMAT(2I2,19A4)
      IF(NMODE.GT.99) WRITE(IOUT,3830) NMODE
 3830 FORMAT(1H0,10X,'NMODE IS TOC BIG, NMODE=',I10)
      WRITE(IOUT,2) NMODE,OPTION,TITLE
    2 FORMAT(1H1,2I2,19A4,//)
      READ(IN,3) N1,NH,N2,NE,NC,NGH,NGE,ISTFH,ISTFE,NFORH,NFORE
     1       ,IVEL,IFREQ
    3 FORMAT(20I4)
      IF(N1.GT.59.OR.N2.GT.20) WRITE(IOUT,3831) N1,N2
 3831 FORMAT(1H0,'TOO MANY MODES, N1=',I10,'N2=',I10)
      IF(NH.GT.59.OR.NE.GT.59) WRITE(IOUT,3832) NH,NE
 3832 FORMAT(1H0,'TOO MANY COORDINATES,NH=',I10,'NE=',I10)
      N=N1+N2
      READ(IN,3)(IRATEH(I),I=1,NC)
      READ(IN,3)(IRATEE(I),I=1,NC)
      READ(IN,3)(IHGRND(I),I=1,NGH)
      READ(IN,3)(IEGRND(I),I=1,NGE)
      READ(IN,4)(MH(I),I=1,N1)
      IF(ISTFH .EQ. 1) READ(IN,4) (FH(I,60),I=1,N1)
      READ(IN,4)(OMEGH(I),I=1,N1)
      DO 10 I=1,N1
      READ(IN,4) (FH(I,J),J=1,NH)
```

```
   10 CONTINUE
      READ(IN,4)(ME(I),I=1,N2)
      IF(ISTFE .EQ. 1) READ(IN,4) (FE(I,60),I=1,N2)
      READ(IN,4)(OMEGE(I),I=1,N2)
      DO 11 I=1,N2
      READ(IN,4) (FE(I,J),J=1,NE)
   11 CONTINUE
    4 FORMAT(7E10.3)
      READ(IN,4) (KC(I),I=1,NC)
      READ(IN,4) (KGH(I),I=1,NGH)
      READ(IN,4) (KGE(I),I=1,NGE)
      NAMELIST/INPT/ N1,N2,NH,NE,NC,NGH,NGE,ISTFH,ISTFE,IRATEE,IRATEH,
     1 IHGRND,IEGRND,MH,OMEGH,ME,OMEGE,KC,KGH,KGE  ,IVEL,IFREQ
      IF(IIN.NE.1) GO TO 444
      WRITE(IOUT,INPT)
      DO 1235 I=1,N1
      WRITE(IOUT,1234) (FH(I,J),J=1,NH)
 1234 FORMAT(1H0,5E19.6)
 1235 CONTINUE
      DO 2235 I=1,N2
      WRITE(IOUT,2234) (FE(I,J),J=1,NE)
 2234 FORMAT(1H0,5E19.6)
 2235 CONTINUE
  444 CONTINUE
      TWOPI=6.28318
      DO 5 I=1,N1
    5 OMEGH(I)=OMEGH(I)*TWOPI
      DO 6 I=1,N2
    6 OMEGE(I)=OMEGE(I)*TWOPI
      IF((NFORH+NFORE).EQ.0) RETURN
      READ(IN,14) (FORH(I),I=1,NFORH)
      READ(IN,14) (FORE(I),I=1,NFORE)
   14 FORMAT(6E10.3)
      READ(IN,3)(IFORH(I),I=1,NFORH)
      READ(IN,3)(IFORE(I),I=1,NFORE)
      READ(IN,4 )XHMODE,XEMODE ,HZLOW,HZHI
      READ(IN,4 )(XKC(I),I=1,NC)
      READ(IN,4 )(XKGH(I),I=1,NGH)
      READ(IN,4 )(XKGE(I),I=1,NGE)
      GHMODE=CMPLX(0.0,XHMODE)
      GEMODE=CMPLX(0.0,XEMODE)
      DO 40 I=1,NC
   40 GKC(I)=CMPLX(0.0,XKC(I))
      DO 41 I=1,NGH
   41 GKGH(I)=CMPLX(0.0,XKGH(I))
      DO 42 I=1,NGE
   42 GKGE(I)=CMPLX(0.0,XKGE(I))
      NAMELIST/RESIN/NFORH,NFORE,FORH,FORE,IFORH,IFORE,GHMODE,GEMODE,
     1 GKC,GKGH,GKGE,HZLOW,HZHI
      WRITE(IOUT,RESIN)
      RETURN
  330 CONTINUE
      READ(IN,4) FREQ(1)
      READ(IN,4) (FORH(I),I=1,NFORH)
      READ(IN,4) (FORE(I),I=1,NFORE)
      RETURN
      END
```

```
      SUBROUTINE MODSET
C
C     THIS SUBROUTINE SETS UP THE MASS AND STIFF MATRICES
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/DATA/IN,IOUT,OPTION,ISTFH,ISTFE,N
     1   ,     N1,N2,NH,NE,NC,NGH,NGE
     2   ,     NFORH,NFORE
      COMMON/SOLV/MASS(99),STIFF(99,99),FREQ(99),SHAPE(99,99),NMODE
      COMMON/SET/FH(59,60),FE(20,60),IRATEH(20),IRATEE(20),IHGRND(20),
     1          IEGRND(20),OMEGH(59),OMEGE(20),MH(59),ME(20)
     2 ,KC(20),KGH(20),KGE(20)
      COMMON/TRIG/IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IFREQ,IVEL
      REAL*4 MH,ME
      REAL*4 KC,KGH,KGE
      REAL*8 MASS
      INTEGER*4 OPTION
      NAMELIST/SET1/ N1,N2,NH,NE,NC,NGH,NGE,ISTFH,ISTFE,IRATEE,IRATEH,
     1 IHGRND,IEGRND,MH,OMEGH,ME,OMEGE,KC,KGH,KGE
      IF(ISET.NE.1) GO TO 444
      WRITE(IOUT,SET1)
  444 CONTINUE
      IFRST=N1+1
      ILAST=N1+N2
      ERA1=1.0
      ERA2=1.0
      ERA3=1.0
      ERA4=1.0
      IF(ISTFH.NE.1) ERA2=0.0
      IF(ISTFH.EQ.1) ERA1=0.0
      IF(ISTFE.NE.1) ERA4=0.0
      IF(ISTFE.EQ.1) ERA3=0.0
      DO 1 I=1,N1
      MASS(I)=MH(I)
      STIFF(I,I)=MH(I)*OMEGH(I)**2*ERA1+FH(I,60)*ERA2
      DO 2 J=1,N1
      DO 3 K=1,NC
      ICH=IRATEH(K)
    3 STIFF(I,J)=STIFF(I,J)+KC(K)*FH(I,ICH)*FH(J,ICH)
      DO 4 K=1,NGH
      IGH=IHGRND(K)
    4 STIFF(I,J)=STIFF(I,J)+KGH(K)*FH(I,IGH)*FH(J,IGH)
    2 CONTINUE
      DO 5 J=IFRST,ILAST
      L=J-N1
      DO 6 K=1,NC
      ICE=IRATEE(K)
      ICH=IRATEH(K)
```

```
 6 STIFF(I,J)=STIFF(I,J)-KC(K)*FH(I,ICH)*FE(L,ICE)
 5 CONTINUE
 1 CCNTINUE
   DO 7 I=IFRST,ILAST
   LL=I-N1
   MASS(I)=ME(LL)
   STIFF(I,I)=ME(LL)*OMEGE(LL)**2*ERA3+FE(LL,60)*ERA4
   DO 8 J=1,N1
   DO 9 K=1,NC
   ICH=IRATEH(K)
   ICE=IRATEE(K)
 9 STIFF(I,J)=STIFF(I,J)-KC(K)*FE(LL,ICE)*FH(J,ICH)
 8 CONTINUE
   DO 10 J=IFRST,ILAST
   L=J-N1
   DC 11 K=1,NC
   ICE=IRATEE(K)
11 STIFF(I,J)=STIFF(I,J)+KC(K)*FE(LL,ICE)*FE(L,ICE)
   DO 12 K=1,NGE
   IGE=IEGRND(K)
12 STIFF(I,J)=STIFF(I,J)+KGE(K)*FE(LL,IGE)*FE(L,IGE)
10 CCNTINUE
 7 CONTINUE
   RETURN
   END
```

```
      SUBROUTINE TRANS
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/DATA/IN,IOUT,OPTION,ISTFH,ISTFE,N
     1    ,     N1,N2,NH,NE,NC,NGH,NGE
     2    ,     NFORH,NFORE
      COMMON/SOLV/MASS(99),STIFF(99,99),FREQ(99),SHAPE(99,99),NMODE
      COMMON/OUT/ YH(60,60),YE(20,60)
      COMMON/SET/FH(59,60),FE(20,60),IRATEH(20),IRATEE(20),IHGRND(20),
     1          IEGRND(20),OMEGH(59),CMEGE(20),MH(59),ME(20)
     2          ,KC(20),KGH(20),KGE(20)
      COMMON/TRIG/IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IFREQ,IVEL
      REAL*4 MH,ME
      INTEGER*4 OPTION
      REAL*8 MASS
      IF(ITRANS.NE.1) GO TO 444
      DO 443 J=1,NMODE
  443 WRITE(IOUT,1234) (SHAPE(I,J),I=1,N)
      WRITE(IOUT,1234) (FREQ(J),J=1,NMODE)
 1234 FORMAT(1H0,5E20.6)
  444 CONTINUE
      DO 7 J=1,60
      DO 7 I=1,NMODE
      YH(I,J)=0.0
      YE(I,J)=0.0
    7 CONTINUE
      DO 8 INM=1,NMODE
      DO 8 KSTAT=1,NH
      DO 8 I=1,N1
      YH(INM,KSTAT)=YH(INM,KSTAT)+SHAPE(I,INM)*FH(I   ,KSTAT)
    8 CONTINUE
      DO 9 INM=1,NMODE
      DO 9 KSTAT=1,NE
      DO 9 I=1,N2
      NP1=N1+I
      YE(INM,KSTAT)=YE(INM,KSTAT)+SHAPE(NP1,INM)*FE(I,KSTAT)
    9 CONTINUE
C
C        RENORMALIZE THE MODES
C
      DO 13 J=1,NMODE
      ERA1=1.E-20
      DO 11 I=1,NH
      ERA2=DABS(YH(J,I))
      IF(ERA2.GT.ERA1) ERA1=ERA2
   11 CONTINUE
      DO 110 I=1,NE
      ERA2=DABS(YE(J,I))
      IF(ERA2.GT.ERA1) ERA1=ERA2
```

```
110 CONTINUE
    DO 12 I=1,NH
 12 YH(J,I)=YH(J,I)/ERA1
    DO 120 I=1,NE
120 YE(J,I)=YE(J,I)/ERA1
 13 CONTINUE
    RETURN
    END
    SUBROUTINE MODOUT
    IMPLICIT REAL*8 (A-H,O-Z)
    COMMON/DATA/IN,IOUT,OPTION,ISTFH,ISTFE,N
   1    ,     N1,N2,NH,NE,NC,NGH,NGE
   2    ,     NFORH,NFORE
    COMMON/SOLV/MASS(99),STIFF(99,99),FREQ(99),SHAPE(99,99),NMODE.
    COMMON/OUT/ YH(60,60),YE(20,60)
    COMMON/TRIG/IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IFREQ,IVEL
    REAL*8 MASS
    REAL*8 YH,YE
    INTEGER*4 OPTION
    NMAX=MAX0(NH,NE)
    WRITE(IOUT,1)
  1 FORMAT(1H1,9X,'COUPLED SYSTEM FREQUENCIES AND MODES',//)
    DO 10 K=1,NMODE
    WRITE(IOUT,2) FREQ(K),K
  2 FORMAT(1H0,9X,F8.3,' HERTZ',20X,'MODE',I3,/)
    WRITE(IOUT,3)
  3 FORMAT(1H0, 7X,'HELICOPTER',12X,'ENGINE',/)
    WRITE(IOUT,4) (I,YH(K,I),YE(K,I),I=1,NMAX)
  4 FORMAT(1H0,I3,4X,F12.8,8X,F12.8)
    WRITE(IOUT,5)
  5 FORMAT(1H1)
 10 CONTINUE
    RETURN
    END
```

```
    SUBROUTINE MAINR(FREQ,NMODE)
    REAL*8 FREQ(99)
    CALL RESSET
    CALL MODREP(FREQ,NMODE)
    RETURN
    END
```

```
      SUBROUTINE RESSET
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/SET/FH(59,60),FE(20,60),IRATEH(20),IRATEE(20),IHGRND(20),
     1           IEGRND(20),OMEGH(59),OMEGE(20),MH(59),ME(20)
     2          ,KC(20),KGH(20),KGE(20)
      COMMON/DATA/IN,IOUT,OPTION,ISTFH,ISTFE,N
     1   ,     N1,N2,NH,NE,NC,NGH,NGE
     2   ,     NFORH,NFORE
      COMMON/TRIG/IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IFREQ,IVEL
      COMMON/MODRES/KCPL(99,99),MASS(99),QC(99)
      COMMON/DAMP/GKC(20),GKGH(20),GKGE(20),GHMODE,GEMODE,HZLOW,HZHI
     1    ,IFORH(20),IFORE(20),FORH(20),FORE(20)
      INTEGER*4 OPTION
      COMPLEX*16 KCPL,QC
      COMPLEX*8 GKC,GKGH,GKGE,GHMODE,GEMODE,FORH,FORE
      REAL*8 MASS
      REAL*4 MH,ME,KC,KGH,KGE
      KCPL(1,1)=DCMPLX(0.D0,0.D0)
      CALL MVC(KCPL(2,1),159176,KCPL)
      IFRST=N1+1
      ILAST=N1+N2
      ERA1=1.0
      ERA2=1.0
      ERA3=1.0
      ERA4=1.0
      IF(ISTFH.NE.1) ERA2=0.0
      IF(ISTFH.EQ.1) ERA1=0.0
      IF(ISTFE.NE.1) ERA4=0.0
      IF(ISTFE.EQ.1) ERA3=0.0
      DO 1 I=1,N1
      MASS(I)=MH(I)
      KCPL(I,I)=(MH(I)*OMEGH(I)**2*ERA1+FH(I,60)*ERA2)*(1.+GHMODE)
      DO 2 J=1,N1
      DO 3 K=1,NC
      ICH=IRATEH(K)
    3 KCPL(I,J)=KCPL(I,J)+(1.+GKC(K))*KC(K)*FH(I,ICH)*FH(J,ICH)
      DO 4 K=1,NGH
      IGH=IHGRND(K)
    4 KCPL(I,J)=KCPL(I,J)+(1.+GKGH(K))*KGH(K)*FH(I,IGH)*FH(J,IGH)
    2 CONTINUE
      DO 5 J=IFRST,ILAST
      L=J-N1
      DO 6 K=1,NC
      ICE=IRATEE(K)
      ICH=IRATEH(K)
    6 KCPL(I,J)=KCPL(I,J)-(1.+GKC(K))*KC(K)*FH(I,ICH)*FE(L,ICE)
    5 CONTINUE
    1 CONTINUE
      DO 7 I=IFRST,ILAST
      LL=I-N1
      MASS(I)=ME(LL)
      KCPL(I,I)=(ME(LL)*OMEGE(LL)**2*ERA3+FE(LL,60)*ERA4)*(1.+GEMODE)
      DO 8 J=1,N1
      DO 9 K=1,NC
      ICH=IRATEH(K)
      ICE=IRATEE(K)
    9 KCPL(I,J)=KCPL(I,J)-(1.+GKC(K))*KC(K)*FE(LL,ICE)*FH(J,ICH)
    8 CONTINUE
      DO 10 J=IFRST,ILAST
      L=J-N1
      DO 11 K=1,NC
      ICE=IRATEE(K)
```

```
   11 KCPL(I,J)=KCPL(I,J)+(1.+GKC(K))*FE(LL,ICE)*FE(L,ICE)*KC(K)
      DO 12 K=1,NGE
      IGE=IEGRND(K)
   12 KCPL(I,J)=KCPL(I,J)+(1.+GKGE(K))*FE(LL,IGE)*FE(L,IGE)*KGE(K)
   10 CONTINUE
    7 CONTINUE
      DO 13 I=1,N1
      QC(I)=0.0
      DO 13 K=1,NFORH
      IFCH=IFORH(K)
   13 QC(I)=FH(I,IFCH)*FORH(K)+QC(I)
      DO 14 I=IFRST,ILAST
      QC(I)=0.0
      DO 14 K=1,NFORE
      IFCE=IFORE(K)
   14 QC(I)=FE(I,IFCE)*FORE(K)+QC(I)
      IF(IRSET.NE.1) RETURN
      WRITE(IOUT,1234) (MASS(I),I=1,N)
      WRITE(IOUT,1235) (J,(QC(I),I=1,N))
      DO 1236 J=1,N
      WRITE(IOUT,1235)(J,(KCPL(J,I),I=1,N))
 1236 CONTINUE
 1234 FORMAT(1H0,(/  ,6E20.8))
 1235 FORMAT(1H0,I5,/,(6E20.8))
      RETURN
      END
```

```
      SUBROUTINE MODREP(FREQ,NMODE)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/DATA/IN,IOUT,OPTION,ISTFH,ISTFE,N
     1    ,     N1,N2,NH,NE,NC,NGH,NGE
     2    ,     NFORH,NFORE
      COMMON/TRIG/IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IFREQ,IVEL
      COMMON/SET/FH(59,60),FE(20,60),IRATEH(20),IRATEE(20),IHGRND(20),
     1           IEGRND(20),OMEGH(59),CMEGE(20),MH(59),ME(20)
     2          ,KC(20),KGH(20),KGE(20)
      CCMMCN/MODRES/KCPL(99,99),MASS(99),QC(99)
      COMMON/DAMP/GKC(20),GKGH(20),GKGE(20),GHMODE,GEMODE,HZLOW,HZHI
     1    ,IFORH(20),IFORE(20),FORH(20),FORE(20)
      INTEGER*4 OPTION
      REAL*8 FREQ(99)
      CCMPLEX*8 DYN(99,100),B(99),YH(60),YE(60)
      COMPLEX*16 KCPL,QC
      REAL*4 AHR(60),AHI(60),ANGH(60),AER(60),AEI(60),ANGE(60),AHTOT(60)
     1      ,AETOT(60)
      REAL*8 MASS
      COMPLEX*8 GKC,GKGH,GKGE,GHMODE,GEMODE,FORH,FORE
      REAL*4 MH,ME,KC,KGH,KGE,ERA
      DIMENSICN PER(7)
      REAL*4 X(201),Y(201)
      DATA PER/.92,.95,.98,1.0,1.02,1.05,1.08/
      B(1)    =CMPLX(0.0,0.0)
      CALL MVC(B(2),312,B)
      TWOPI=6.28318531
      DOM=(HZHI-HZLOW)/9.0*TWOPI
      IF(FREQ(1).EQ.0.0) FREQ(1)=HZLOW
      ISAVE=1
      IF(IFREQ.EQ.1) GO TO 401
      DO 1 I=1,10
      XK=I-1
    1 X(I)=TWOPI*HZLOW+XK*DOM
      ISAVE=10
      DO 2 I=1,NMODE
      IF(FREQ(I)-HZHI) 3,3,4
    3 DO 5 J=1,7
      ISAVE=ISAVE+1
    5 X(ISAVE)=PER(J)*FREQ(I)*TWOPI
    2 CONTINUE
    4 CONTINUE
      CALL SORT(X,Y,ISAVE)
  401 IF(IFREQ.EQ.1) X(1)=FREQ(1)*TWOPI
      DO 6 INR=1,ISAVE
      DYN(1,1)=CMPLX(0.0,0.0)
      CALL MVC(DYN(2,1),79192,DYN)
      DO 7 J=1,N
```

```
      ERA=-MASS(J  )*X(INR)**2
      DYN(J,J)=CMPLX(ERA,0.0)
      DO 7 K=1,N
    7 DYN(J,K)=DYN(J,K)+KCPL(J,K)
      DO 8 J=1,N
    8 B(J)=QC(J)
      IF(IRRES.LT.1.OR.IRRES.GT.5) GO TO 2222
      IRRES=IRRES+1
      WRITE(IOUT,12) X(INR)
      WRITE(IOUT,1235)  INR,(B(I),I=1,N)
      DO 1236 J=1,N
      WRITE(IOUT,1235)(J,(DYN(J,I),I=1,N))
 1235 FORMAT(1H0,I5,/,(6E20.8))
 1236 CONTINUE
 2222 CONTINUE
      CALL CSMEQ(N,99,DYN,B)
      DO 17 J=1,60
      YH(J)=DCMPLX(0.D0,0.D0)
   17 YE(J)=DCMPLX(0.D0,0.D0)
      DO 181 KSTAT=1,NH
      DO 18 I=1,N1
      YH(KSTAT)=YH(KSTAT)+B(I)     *FH(I,KSTAT)
   18 CONTINUE
      IF(IVEL.EQ.1) YH(KSTAT)=CMPLX(0.0,-1.0)*YH(KSTAT)*X(INR)
      AHR(KSTAT)=REAL(YH(KSTAT))
      AHI(KSTAT)=AIMAG(YH(KSTAT))
      ANGH(KSTAT)=0.0
      IF(AHR(KSTAT)+AHI(KSTAT).EQ.0.0) GO TO 28
      ANGH(KSTAT)=ATAN2(AHI(KSTAT),AHR(KSTAT))*360./TWOPI
   28 AHTOT(KSTAT)=CABS(YH(KSTAT))
  181 CONTINUE
      DO 191 KSTAT=1,NE
      DO 19 I=1,N2
      NP1=N1+I
      YE(KSTAT)=YE(KSTAT)+B(NP1)     *FE(I,KSTAT)
   19 CONTINUE
      IF(IVEL.EQ.1) YE(KSTAT)=CMPLX(0.0,-1.0)*YE(KSTAT)*X(INR)
      AER(KSTAT)=REAL(YE(KSTAT))
      AEI(KSTAT)=AIMAG(YE(KSTAT))
      ANGE(KSTAT)=0.0
      IF(AER(KSTAT)+AEI(KSTAT).EQ.0.0) GO TO 29
      ANGE(KSTAT)=ATAN2(AEI(KSTAT),AER(KSTAT))*360./TWOPI
   29 AETOT(KSTAT)=CABS(YE(KSTAT))
  191 CONTINUE
      NMAX=MAX0(NH,NE)
      IF(IVEL.EQ.1) WRITE(IOUT,11 )
   11 FORMAT(1H1,9X,'COUPLED SYSTEM RESPONSE     (VELOCITIES)',//)
      IF(IVEL.NE.1) WRITE(IOUT,110)
  110 FORMAT(1H1,9X,'COUPLED SYSTEM RESPONSE     (DISPLACEMENTS)',//)
      X(INR)=X(INR)/TWOPI
      WRITE(IOUT,12) X(INR)
   12 FORMAT(1H0,9X,F8.3,' HERTZ',/)
      WRITE(IOUT,13)
   13 FORMAT(1H0,34X,'HELICOPTER',//,8X,'REAL',13X,   'IMAGINARY',13X,
     1       'PHASE',15X,'TOTAL',//)
      WRITE(IOUT,30) (I,AHR(I),AHI(I),ANGH(I),AHTOT(I),I=1,NH)
   30 FORMAT(1X,I2,E16.9,4X,E16.9,9X,F6.1,9X,E16.9,/)
      WRITE(IOUT,14)
   14 FORMAT(1H0,36X,'ENGINE',     //,8X,'REAL',13X,   'IMAGINARY',13X,
     1       'PHASE',15X,'TOTAL',//)
      WRITE(IOUT,30) (I,AER(I),AEI(I),ANGE(I),AETOT(I),I=1,NE)
    6 CONTINUE
      RETURN
      END
```

```
C       EIGENVALUE AND EIGENVECTOR CALC.
      SUBROUTINE DEIGV (N,NMODE,AM,C,FR,Y,M)
      COMMON/TRIG/IIN,ISET,IEIGV,ITRANS,IIOUT,IRSET,IRRES,IRTRAN,IROUT
      COMMON /UTIL/ YG(70),YT(70),YTY(20)
      DIMENSION AM(2),FR(2),C(M,M),Y(M,2)
      DOUBLE PRECISION EIGVL,EVA,AK,YG,B,EV,YT,B1,C,YTY,AM,FR,Y
      IF( IEIGV.NE.1) GO TO 444
      WRITE(6,1235) N,NMODE,M,(AM  (I),I=1,N)
 1235 FORMAT(3I10,/,(1H0,5E20.7))
      DO 1236 I=1,N
      WRITE(6,1237) I,(C(I,J),J=1,N)
 1237 FORMAT(1H0,I5,/,(6E20.8))
 1236 CONTINUE
  444 CONTINUE
      CALL DINV(N,M,C,IBAD)
      DO 5 I=1,N
      DO 5 J=I,N
      C(I,J)=.5D0*(C(I,J)+C(J,I))*DSQRT(AM(I)*AM(J))
    5 C(J,I)=C(I,J)
      DO 55 K=1,NMODE
      EIGVL=1.D-20
      EVA=0.D0
      ICN=0
      AK=.05D0
      DO 10 I=1,N
   10 YG(I)=1.D0
      KL=K-1
      IF (KL) 13,13,30
   13 EIGVL=0.D0
      B=0.D0
      B1=0.
      EV=AK*EVA
      CALL DMVMLT(YT,C,YG,N,M)
      DO 20 I=1,N
      IF (DABS(B1).LT.DABS(YT(I)))B1=YT(I)
      YT(I)=YT(I)-EV*YG(I)
      EIGVL=EIGVL+YT(I)*YG(I)
   20 B=B+YG(I)*YG(I)
      EIGVL=EIGVL/B+EV
      DO 23 I=1,N
   23 YG(I)=YT(I)/B1
      AK=AK+AK
      IF (AK.GT.(.3+.02*FLOAT(ICN))) AK=.05D0
      ICN=ICN+1
      IF (KL) 40,40,30
   30 DO 35 I=1,KL
      B=0.D0
      DO 32 J=1,N
```

```
 32 B=B+Y(J,I)*YG(J)                                                     DGV  370
    B=B/YTY(I)                                                           DGV  380
    DO 35 J=1,N                                                          DGV  390
 35 YG(J)=YG(J)-B*Y(J,I)                                                 DGV  400
 40 IF (DABS(EIGVL-EVA)-.0000000100*EVA) 45,45,41                        DGV  410
 41 EVA=EIGVL                                                            DGV  420
    IF (ICN-60) 13,13,45                                                 DGV  430
 45 YTY(K)=0.D0                                                          DGV  450
    IF(ICN.GT. 60) WRITE(6,102) K,EIGVL,EVA
102 FORMAT(85X,'DID NOT CONVERGE FOR MODE',I3,/,45X,'EIGVL=',E20.10 ,
  1              5X,'EVA=',E20.10)
    FR(K)=.159155/DSQRT(DABS(EIGVL))                                     DGV  460
    IF (EIGVL.LT.0.) WRITE (6,101) K,ICN                                 DGV  462
    DO 55 I=1,N                                                          DGV  470
    Y(I,K)=YG(I)                                                         DGV  480
 55 YTY(K)=YTY(K)+YG(I)**2                                               DGV  490
    DO 65 K=1,NMODE                                                      DGV  500
    B=0.                                                                 DGV  510
    DO 60 I=1,N                                                          DGV  520
    Y(I,K)=Y(I,K)/DSQRT(AM(I))                                           DGV  530
 60 IF (DABS(B).LT.DABS(Y(I,K))) B=Y(I,K)                                DGV  54
    DO 65 I=1,N                                                          DGV  550
 65 Y(I,K)=Y(I,K)/B                                                      DGV  560
    RETURN                                                               DGV  562
101 FORMAT (85X'NEG. EIGVL. FOR MODE =',I3,1H,I3,'ITER')                 DGV
    END                                                                  DGV  570
```

```
C       SOLUTION OF COMPLEX SIMULTANEOUS EQUATIONS  AX B
      SUBROUTINE CSMEQ N,M,A,B
      COMMON /UTIL/ C,AMAX,LC 310 ,I,K,L,IMAX,JMAX,J,M1
      COMPLEX A M,M ,B 2 ,C,CRTHM4
      M1 N&1
      DO 5 I 1,N
      LC I  I
    5 A I,M1  B I
      DO 30 K 2,N
      L K-1
      M2 M1-L
      AMAX 0.
      DO 15 I L,N
      DO 15 J L,N
      IF  CABS A I,J  -AMAX  15,15,12
   12 IMAX I
      JMAX J
      AMAX CABS A I,J
   15 CONTINUE
      IF  AMAX  38,38,17
   17 J LC L
      LC L  LC JMAX
      LC JMAX  J
      DO 20 J L,M1
      C A L,J
      A L,J  A IMAX,J
   20 A IMAX,J  C
      DO 25 I 1,N
      C A I,L
      A I,L  A I,JMAX
   25 A I,JMAX  C
      DO 30 I K,N
      C A I,L /A L,L
   30 CALL CROP A L,K ,C,I,L,M2,M
      IF  CEBS A N,N    31,38,31
   31 K N
   32 J LC K
      B J  A K,K&1 /A K,K
      L K-1
      DO 36 I 1,L
   36 A I,K  CRTHM4 A I,K&1 ,A I,K ,B J
      K L
      IF  K  40,40,32
   38 WRITE  6,39
  238 WRITE  6,39
   39 FORMAT  1H010X COMPLEX MATRIX IS SINGULAR
   40 RETURN
      END
```

```
COMPLEX FUNCTION CRTHM1 A,D
COMPLEX A,B,C,CRTHM2,CRTHM3,CRTHM4,CRTHM5,CRTHM6,CRTHM7
CRTHM1 CMPLX REAL A *D,AIMAG A *D
RETURN
ENTRY CRTHM2 A,D
CRTHM2 CMPLX -AIMAG A *D,REAL A *D
RETURN
ENTRY CRTHM3 A,B,C
CRTHM3 A&B*C
RETURN
ENTRY CRTHM4 A,B,C
CRTHM4 A-B*C
RETURN
ENTRY CRTHM5 A,B,C
CRTHM5 A*B*C
RETURN
ENTRY CRTHM6 A,B
CRTHM6 A*B
RETURN
ENTRY CRTHM7 A,B,D
CRTHM7 A&CMPLX REAL B *D,AIMAG B *D
RETURN
ENTRY CEBS A
CEBS REAL A **2&AIMAG A **2
RETURN
ENTRY CMPRE A,B
IF CABS B .GT.CABS A   A B
RETURN
END
```

PROGRAM NAME MCDSYN

SHEET 1 OF 3

DATE

iiN	iSET	iEiGV	iMINUS	iiOUT	iRSET	iRRES	PRINTS						
TITLE													
NI	NN	N2	NE	NC	NGN	NGE	iSTFN	iSTFE	NWGN	NWGE	iVEL	iFREQ	INTEGERS

iRATEN(i) i=1,NC (20i4)

iRATEE(i) i=1,NC (20i4)

iNGEND(i) i=1,NGN (20i4)

iEGEND(i) i=1,NGE (20i4)

MN(i) i=1,Ni (7E10.3)

iF (iSTFN = 1) FN(i,60) i=1,NI (OTHERWISE SKIP) (7E10.3)

OMEGN(i) i=1,NI (7E10.3)

(FN(i,j), j=1,NN) DO i=1,NI (7E10.3)

ME(i) i=1,N2 (7E10.3)

PROGRAM NAME ________ SHEET 2 OF 3
DATE ________

IF (ISTFE = 1) FE(I,60) I=1,N2 (OTHERWISE SKIP) (7E10.3)

OMEGE (I) I=1,N2 (7E10.3)

(FE(I,J), J=1,NE) DO I=1,N2 (7E10.3)

KC(I) I=1,NC (7E10.3)

KGN(I) I=1,NGN (7E10.3)

KGE(I) I=1,NGE (7E10.3)

PROCEED FURTHER ONLY IF (NFORN+NFORE ≠ 0)

FORN(I) I=1, NFORN (6E10.3)

FORE(I) I=1, NFORE (6E10.3)

IFORN(I) I=1, NFORN (20I4)

IFORE (I) I=1, NFORE (20I4)

XNMODE	XEMODE	HZLOW	HZHI

PROGRAM NAME ________ SHEET 3 OF 3
DATE ________

XKC(I) I=1,NC (7E10.3)

XKGN(I) I=1,NGN (7E10.3)

XKGE(I) I=1,NGE (7E10.3)

IF RESPONSE IS DESIRED AT INDIVIDUAL FREQUENCIES

PROCEED FURTHER

FREQ

FORN(I) I=1, NFORN (7E10.3)

FORE(I) I=1, NFORE (7E10.3)

MH(i)	Modal mass for helicopter mode i
ME(i)	Modal mass for engine mode i
N1	No. helicopter modes
N2	No. engine modes
OMEGH(i)	Frequency for helicopter mode i
OMEGE(i)	Frequency for engine mode i
FH(i, j)	Helicopter mode shape for mode i
FE(i, j)	Engine mode shape for mode i
NH	No. helicopter mass stations
NE	No. engine mass stations
NC	No. coupling springs
iRATEH	Helicopter location of coupling spring
iRATEE	Engine location of coupling spring
iHGRND	Helicopter location of ground spring
iEGRND	Engine location of ground spring
KC	Rate of coupling spring
KGH	Rate of helicopter ground spring
KGE	Rate of engine ground spring
NGH	Number of helicopter ground springs
NGE	Number of engine ground springs
iSTFH	1 for stiffness read in for helicopter
iSTFE	1 for stiffness read in for engine
FORH	Force at helicopter
FORE	Force at engine
iFORH	Helicopter location of force
iFORE	Engine location of force
NFORH	No. of helicopter forces
NFORE	No. of engine forces
XHMODE	Helicopter modal structural damping
XEMODE	Engine modal structural damping
XKC	Coupling structural damping
XKGH	Helicopter-to-ground structural damping
XKGE	Engine-to-ground structural damping
OPTION	0 - Engine output shaft not connected
	1 - Engine output shaft is rigid
	2 - Engine output shaft is pinned
FH(i, 60)	Modal stiffness for helicopter mode i
FE(i, 60)	Modal stiffness for engine mode i
HZLOW	Lower frequency of interest (Hz)
HZHi	Highest frequency of interest (Hz)
FREQ	Frequency at which response is desired (Hz)

APPENDIX E

EXAMPLE OF SPECIFICATION TO SATISFY ENGINE/AIRFRAME COMPATIBILITY

METHOD OF ANALYSIS

The contractor having system responsibility (CHSR) shall perform a dynamic analysis of the helicopter system. A modal synthesis method of analysis shall be employed to determine coupled engine/airframe vibratory responses resulting from engine and airframe vibratory excitations. These responses shall be compared with installed vibratory limits for critical components (i.e., engine, avionics, etc) and modifications shall be implemented by the CHSR to attenuate excessive vibration.

DATA REQUIREMENTS

Engine

The engine manufacturer shall:

1. Perform an analysis to determine the engine uncoupled modes and associated generalized masses and stiffnesses. These data shall be made available to the CHSR.

2. Determine the engine generated excitations (frequency and amplitude) and provide them to the CHSR.

3. Perform an engine free-free laboratory shake test to correlate and modify the analytical data generated in step 1.

Airframe

The airframe manufacturer shall:

1. Perform an analysis to determine the airframe uncoupled modes and associated generalized masses and stiffnesses. These data shall be made available to the CHSR.

2. Determine the airframe generated excitations (frequency and amplitude) and provide them to the CHSR.

3. Perform an airframe free-free laboratory shake test to correlate and modify the analytical data generated in step 1.

LIST OF SYMBOLS

A_{ij}	Mobilities for subsystem A
E_{ij}	Mobilities for subsystem E
F	Force
f	Applied sinusoidal force for mobility development
G_{ij}	Mobilities for subsystem G
g	Structural damping
H_{ij}	Mobilities for subsystem H
h	Mode shape participation factor
I_P	Mass polar moment of inertia
K_{ij}	Mobilities for subsystem K
K	Spring stiffness
$\mathcal{K}$	Generalized stiffness
M_{ij}	Mobilities for subsystem M
$\mathcal{M}$	Generalized mass
m	Elemental mass
Q	Generalized force
R	Response
S_{ij}	Mobilities for subsystem S
T	Kinetic energy
V	Potential energy
V_H	Maximum horizontal flight speed at full power
V_{NE}	Flight velocity not to exceed (90% of maximum demonstrated)

W Work

X Translational displacement

Y Deflection

θ Pitch rotation

ψ Yaw rotation

Ω Rotor rotational speed

ω Frequency