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ENGINE/AIRFRAME/DRIVE TRAIN DYNAMIC INTERFACE DOCUMENTATION

LEVEL II

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Old Windsor Road
Bloomfield, Conn. 06002

June 1978

Final Report

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Prepared for

APPLIED TECHNOLOGY LABORATORY
U. S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report provides the details of a program that is part of a larger effort designed to provide a complete report of past and present engine/airframe/drive train dynamic interface problems. The problems of vibration-related interface compatibility in engine/drive system installations are usually complicated by the inherent coupling of the three major multi-degree-of-freedom systems: engine, airframe, and drive train. The result of this effort is a report documenting dynamic interface problems associated with the UH-2 A/B, UH-2 Twin, HH-43B, and the K-16B Tilt Wing Research Vehicle. The ultimate benefit will be the accumulation of data that will eventually lead to a solution of generic problems of this type. This report is one of five reports resulting from engine/airframe/drive train interface documentation efforts funded by the Applied Technology Laboratory. The related reports and their final report numbers are: Boeing-Vertol, USARTL-TR-78-11; Hughes Helicopters, USARTL-TR-78-12; Sikorsky Aircraft, USARTL-TR-78-13; Kaman Aerospace, USARTL-TR-78-14; and Bell Helicopter, USARTL-TR-78-15.

Mr. Allen C. Royal, Propulsion Technical Area, Technology Applications Division, served as project engineer for this effort.

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An historical review of Kaman Aerospace Corporation helicopter development effort was conducted. Information pertaining to instances of engine/airframe/drive train incompatibility was extracted from the resulting review data. The details of each incompatibility problem and its solution are presented and discussed. These problems were found to be associated with normally occurring rotor and drive system vibratory excitations and resonance amplified rotor and drive system vibratory excitations.

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20. ABSTRACT (Cont'd)

It is concluded that the type of incompatibility problems encountered in helicopter development programs can be expected in the future. For the most part, these problems, and their solutions, are an intrinsic part of the development process, and they will not be eliminated through the application of increasingly more sophisticated and complex analytical design tools. It is recommended that research in this area be directed towards improved dynamic testing methods which will enable more rapid, efficient determination of the exact nature of future incompatibility problems, once they are encountered.

SUMMARY

An historical review of Kaman Aerospace Corporation helicopter development effort was conducted. Information pertaining to instances of engine/airframe/drive train incompatibility was extracted from the resulting review data. The details of each incompatibility problem and its solution are presented and discussed. These problems were found to be associated with normally occurring rotor and drive system vibratory excitations and resonance amplified rotor and drive system vibratory excitations. A summary of these problems is given in Table 1.

It is concluded that the type of incompatibility problems encountered in past helicopter development programs can be expected in the future. For the most part, these problems and their solutions are an intrinsic part of the development process, and they will not be eliminated through the application of increasingly more sophisticated and complex analytical design tools. It is recommended that research in this area be directed toward improved dynamic testing methods which will enable more rapid, efficient determination of the exact nature of future incompatibility problems once they are encountered.

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1.0 INTRODUCTION

A helicopter consists of a multitude of individual components, all of which must function together properly in order to obtain optimum performance from the total vehicle. To assure this, considerable design effort is expended in the performance of systems integration studies of one sort or another. Despite this effort, however, major incompatibilities are often discovered during vehicle testing. This has been particularly true, at least in the experience of Kaman Aerospace Corporation (KAC), with regard to dynamic incompatibility among the various elements of the drive system and between the airframe and the drive system. This type of incompatibility, which is characterized by excessive vibration in one or more of the drive system components or in the airframe structure supporting the drive system, caused delays in the development of several KAC helicopters.

The existence of a general engine/airframe/drive train dynamic compatibility problem has long been accepted as a "fact of life" by most knowledgeable helicopter engineers. Documentation of specific problems in this area, however, is sparse, and this scarcity of definite data has tended to retard the development of methods for preventing the recurrence of such problems. The present study, which includes parallel efforts by KAC and other helicopter producers, represents an attempt to overcome this lack of data.

The study documented by this report consisted of three technical tasks. In Task 1.0, a survey of KAC helicopter development programs was performed and, from this survey, detailed accounts of special engine/airframe/drive train dynamic incompatibility problems were extracted. These data were evaluated in Task 2.0 in an attempt to ascertain the probability of past problems recurring in future helicopter development programs. The final technical task, Task 3.0, involved formulation of recommendations directed toward minimizing the extent of future dynamic interfacing efforts.

2.0 HISTORICAL REVIEW

The major task of the present program involved performance of an historical review of Kaman experience pertinent to the attainment of dynamic compatibility among the engine, airframe and drive train subsystems. This review was performed in a systematic manner by tracing the development of each distinct Kaman helicopter model through a separate survey of available internal data. This approach served to pinpoint and isolate in time possible instances of pertinent dynamic compatibility problems, which were then more thoroughly researched.

In keeping with the probable use of the study data, historical review efforts were limited to turbine powered vehicles only. Kaman has been involved in the development of several turbine powered vehicles, including the Navy UH-2 and UH-2 twin-engine helicopters, the Air Force HH-43 helicopter series and the Army/Navy K-16 tilt-wing research vehicles. Historical surveys of the development programs for each of these vehicles were performed. Descriptions of these vehicles and brief synopses of their respective development histories are given in the following paragraphs.

UH-2 (SINGLE-ENGINE) HELICOPTER

The requirements for a class HU ship-based helicopter were set forth in type specification TS-136, which was issued 27 March 1956. This specification did not specify engine type, but did permit a variety of reciprocating and turbine engines, including the T53 and T58-GE-2 turboprop engines. A time between overhaul (TBO) of 500 hours was required for all drive system components. Paragraph 1.1.3a calls for "Minimum vibration at hover and low speed." No requirement for engine vibration limits is included in the TS nor in the General Specification, SD-24-G.

Kaman's response to TS-136 was submitted 15 August 1956. Two new vehicles were proposed: the K-19, A Synchropter, and the K-20, A Single Main Rotor/Tail Rotor vehicle. Both vehicles were proposed with single T58-GE-2 engines which were mounted in an identical manner. This mounting arrangement was developed in coordination with General Electric. The engine-transmission shaft used gear-type couplings for misalignment. The main transmission had a 23.08/1 ratio and used a spur gear input stage, then a spiral bevel and finally a planet system. A sprag-type overrunning clutch at the engine input shaft was proposed. A segmented tail rotor drive shaft (TRDS), with common segments, was proposed.

Buaer Contract number Noa(s) 57-625C was awarded January 1957, for the development of Kaman Model K-20 helicopter.

Qualification testing of the UH-2 (Figure 1) required numerous component, rig and vehicle tests. Of primary interest to the engine/airframe/drive train interfacing study were the drive system endurance test, the turbine power plant installation test (TPIT), the tiedown endurance test, the vehicle shake testing and the initial vehicle flight testing.

Figure 1. UH-2 A/B Helicopter.

Initial evaluation of the engine/drive train compatibility was obtained during the TPIT program, which began in January of 1959. This program involved testing of a complete (less tail rotor and tail rotor drive train) HU-2K dynamic system. This was installed on a simple structural framework. The TPIT program, which continued until 1962, revealed several potential interfacing problem areas.

The first complete HU2K aircraft became available during the first part of 1959. These included the static test ship, BU. No. 147202, and the first flight test vehicle, BU. No. 147203. Initial ground vibration testing was performed on the static test ship during April of 1959. Because of the results of this testing, which revealed the presence of a 4-per-rev resonance in the transmission and engine support areas, additional shake testing was performed in May 1959.

Tiedown testing of the static test ship was begun 3 June 1959 and continued until Feb. 1961. This testing revealed several drive system design deficiencies related to incompatibility with the dynamic environment imposed by the rotor system.

First flight of the HU-2K vehicle occurred 1 July 1959. Flight testing revealed interfacing problems similar to those experienced in the tiedown testing. These problems were successfully corrected prior to introduction of the UH-2 into the fleet.

UH-2 (TWIN-ENGINE) HELICOPTER

The original proposal for a twin-engine (2 T58-8B G.E. engines) version of the UH-2 was submitted in November of 1963. The configuration proposed at this time features an engine installation which was nearly identical to that used on the single-engine UH-2. The two engines were to be mounted above the cabin, within the existing, but enlarged, fairing structure. The engines were to drive forward directly into the main transmission, which was to be modified with the addition of a second input shaft/bevel gear/spur pinion assembly.

The above engine installation was later revised and a new vehicle configuration proposed in a subsequent submittal. This configuration, which was ultimately incorporated in the UH-2C twin, housed the engines in pod-type nacelles outboard of the existing fuselage structure. The engine driveshafts were revised to drive aft into a new combining gearbox. New aircraft structure had to be installed to accommodate the combining gearbox mounting and the revised engine mountings.

A prototype twin-engine UH-2 (Figure 2) was fabricated and subjected to tiedown testing over the period 1 January to 27 January 1965. Initial flight testing was performed during the following February. During this test series, engine and engine support vibration and vibratory loads were measured and evaluated. A formal power plant vibration survey was performed in mid-1966.

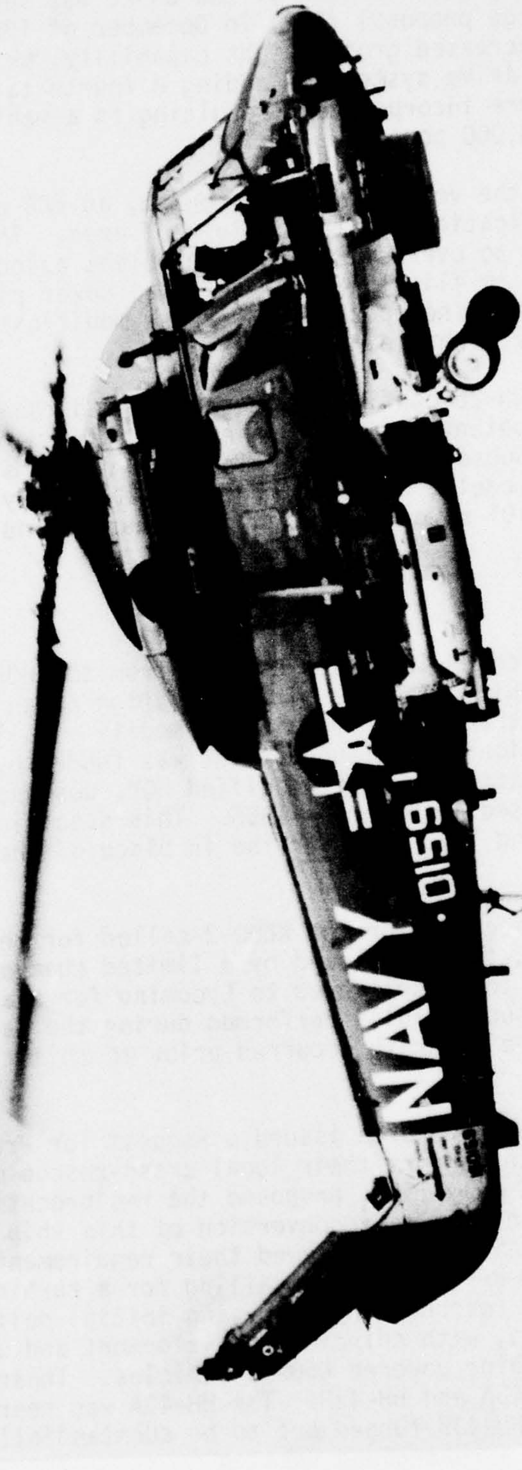

Figure 2. UH-2 Twin Helicopter.

A proposal for a growth version of the UH-2C was submitted through engineering change proposal (ECP) in December of 1968. This was to have a substantially increased gross weight capability, which was to be achieved by uprating the drive system and adding a fourth tail rotor blade. These modifications were incorporated, resulting in a vehicle gross weight capability of 13,000 pounds.

Concurrent with the vehicle growth program, an ECP was submitted covering structural modifications to the cabin roof area. These modifications were deemed necessary to overcome cracking problems associated with extensive service exposure to flight loads. A formal power plant vibration survey was performed after incorporation of these modifications with the now redesignated HH-2D vehicle.

Uprating to the HH-2D configuration represented the last major vehicle change having a potential impact on engine/airframe/drive train dynamic compatibility. Subsequent twin-engine UH-2 versions, including the SH-2D and SH-2F LAMPS models, differed from the HH-2D only with regard to a main rotor redesign (101 rotor), landing gear changes and avionics/weapons specifications.

HH-43 HELICOPTER

The turbine powered HH-43 series evolved from the HOK/HUK/HTK reciprocating engine powered vehicle family. This evolution began in 1955 when Kaman received a subcontract from Lycoming to modify a bailed HOK-1 to a turbine engine configuration. This subcontract was funded by the Air Force. The detailed specification for this modified HOK, designated the K-600-3 or HOK-3, was submitted in December 1955. This specification called for the use of the Lycoming T-53-L-1b turbine in place of the standard reciprocating engine.

The detail specification for the K600-3 called for the performance of a 50-hour tiedown test, to be followed by a limited checkout flight test. The aircraft was then to be delivered to Lycoming for evaluation. The 50-hour tiedown test was successfully performed during the last quarter of 1956. First flight of the aircraft occurred prior to this tiedown testing on 1 October 1956.

In June of 1956 the Air Force issued a Request for Proposal for an off-the-shelf helicopter to perform their local crash-rescue mission. Kaman's response, dated 27 July 1956, proposed the reciprocating engine powered HOK-1, highlighting the ready conversion of this ship to turbine power. Subsequently, the Air Force reviewed their requirements and reissued the local crash-rescue RFP, this time calling for a turbine engine conversion capability. Kaman responded by proposing initial delivery of a number of K600 (HOK) vehicles, with coincident development and subsequent delivery of a number of turbine powered K600-3 vehicles. These two vehicles were designated the HH-43A and HH-43B. The HH-43A was nearly identical to the Navy HOK, and the HH-43B turned out to be substantially different from the HH-43A, not merely a re-engined version.

At the time of the original proposal, it was contemplated that the HH-43B would be a 50% new aircraft. This design was later revised, with the HH-43B becoming a 90% new aircraft.

Rollout of the first HH-43B (Figure 3) occurred on 1 November 1958, at which time a short first flight was performed. This aircraft was then used for an extensive 250-hour tiedown test program. Shortly after, the second vehicle became available and the flight test program was begun.

The 250-hour tiedown program was begun 26 November 1958 and completed 7 August 1959. Only minor problems were encountered during tiedown testing. The flight test program was performed concurrently with tiedown testing.

The first HH-43B acceptance and delivery occurred in July of 1959. Production of this vehicle continued under various contracts through 1963, with a total of 195 vehicles produced. During the course of this production, several variants of the basic HH-43B were produced including C, D and F models. Except for engine and equipment changes, these variants were not substantially different from the basic "B" model.

Flight testing continued through the early production phase ending in mid-1960. This test program included contractor airworthiness testing, joint KAC/Edwards airworthiness testing, powerplant performance testing and the structural demo. During the course of this test program, a number of problems were uncovered and corrected.

K-16 TILT-WING RESEARCH VEHICLE

Development of a faired flap propulsive rotor suitable for V/STOL use was initiated in 1954 under internal KAC funding. The initial work included both analytical and test efforts during which the basic feasibility of the concept was demonstrated. This in-house work led directly to the submittal of a proposal to the Navy Air Systems Command (submitted 20 September 1955) calling for whirl testing of a rotoprop prototype. This proposal led to the issuance of Contract NOa(s) 56-439c in February 1956, which funded this work.

During the processing of Contract NOa(s) 56-439c, a proposal covering development of a K-16 research vehicle was submitted. An entirely new V/STOL vehicle was proposed, designed around KAC's rotoprop concept. This vehicle employed two Lycoming T53-L-2 turbines, each driving a rotor through reduction gearing. The rotor drives were to be interconnected, and freewheeling units were provided to permit single-engine operation. No immediate Navy action was taken as a result of this proposal.

The initial Navy contract called for whirl stand testing of a single rotoprop prototype. This testing was performed successfully and, as a result, Contract NOa(s) 56-549c was amended in January of 1957 to cover a more sophisticated concept evaluation ground test.

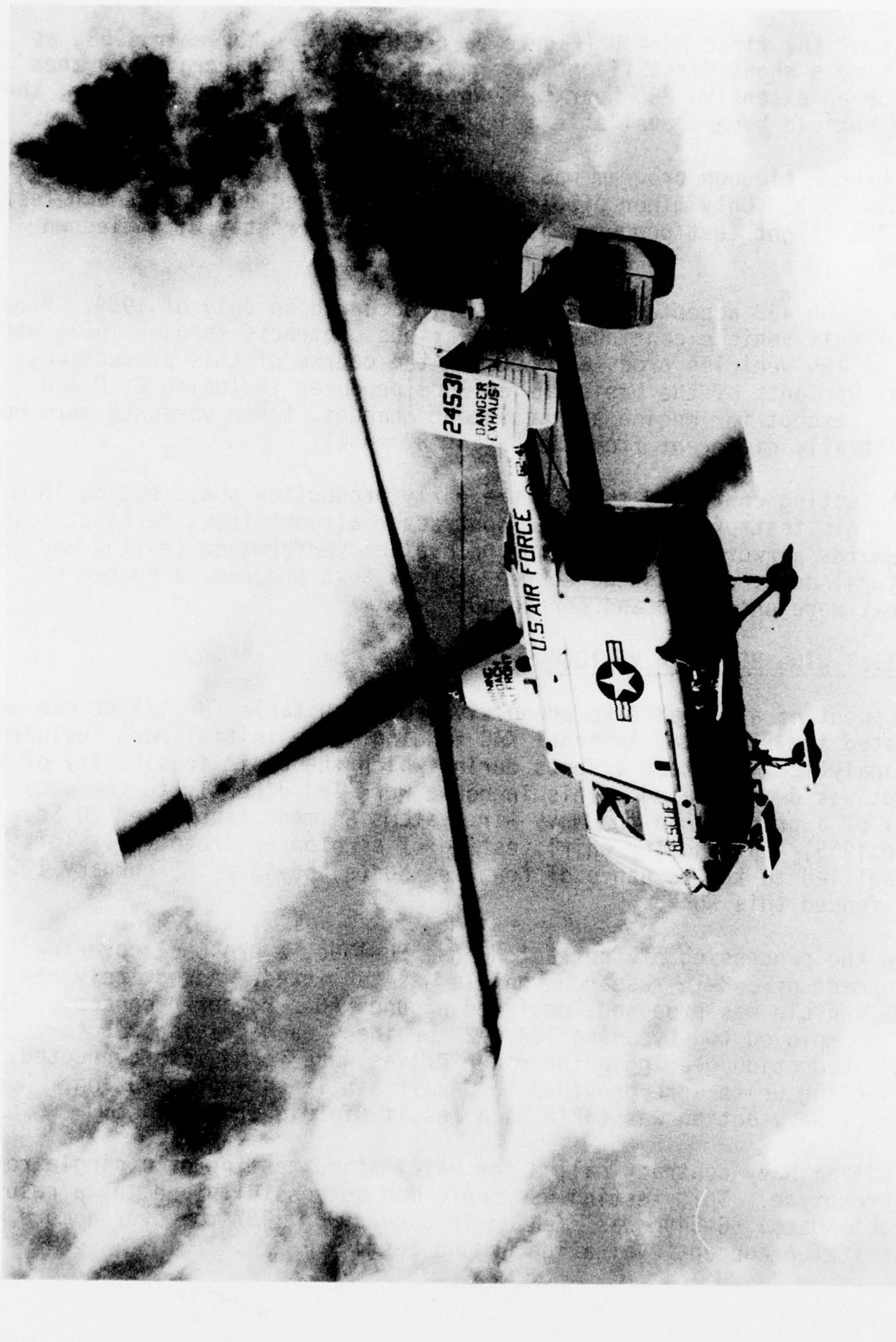

Figure 3. HH-43B Helicopter.

The second series of rotoprop ground testing included consideration of the rotoprop/nacelle/wing/flap combination. This test program was also successful, which encouraged the Navy to proceed with development of a full scale research vehicle program loosely patterned after that proposed previously. This program was authorized in June 1958 through amendment of the original contract.

The authorization to proceed with the full-scale research vehicle program also called for dynamic substantiation of the rotor and of the power and drive system. A flight vehicle configuration, consisting of a surplus JFR-5 fuselage, two YT58-G8E6 turbines and Kaman's propulsive rotors was specified, and an analytical and test substantiation program was developed. Significant analytical efforts included load and stress analyses of the transmission mount structure and the drive system. A torsional dynamic analysis of the drive system was also performed.

Verification of rotor/drive system compatibility and adequacy was demonstrated through endurance testing of a complete dynamic system. This approach was taken, in contrast to the more common separate component test approach, in the interest of economy. The risks of this approach were recognized at the time the decision was made to pursue total dynamic system endurance testing. Development of the flight test article (Figure 4) was conducted in parallel with the dynamic system endurance testing. Shake testing was performed as part of the flight vehicle qualification program.

A tiedown test of the complete vehicle was performed in two parts. First, a functional tiedown test was conducted at Kaman. This was followed by shipment to NASA Ames, where static thrust stand testing was performed. The vehicle was installed in the 40-x-80-foot wind tunnel at NASA Ames, following the thrust stand test.

Development of the K-16 concept was terminated after completion of the wind tunnel program in September 1962. While numerous reasons have been given for the apparent failure of this concept, it is safe to say that the numerous engine/airframe/drive train compatibility problems which plagued the program almost throughout contributed substantially to discouragement on the part of the funding agency.

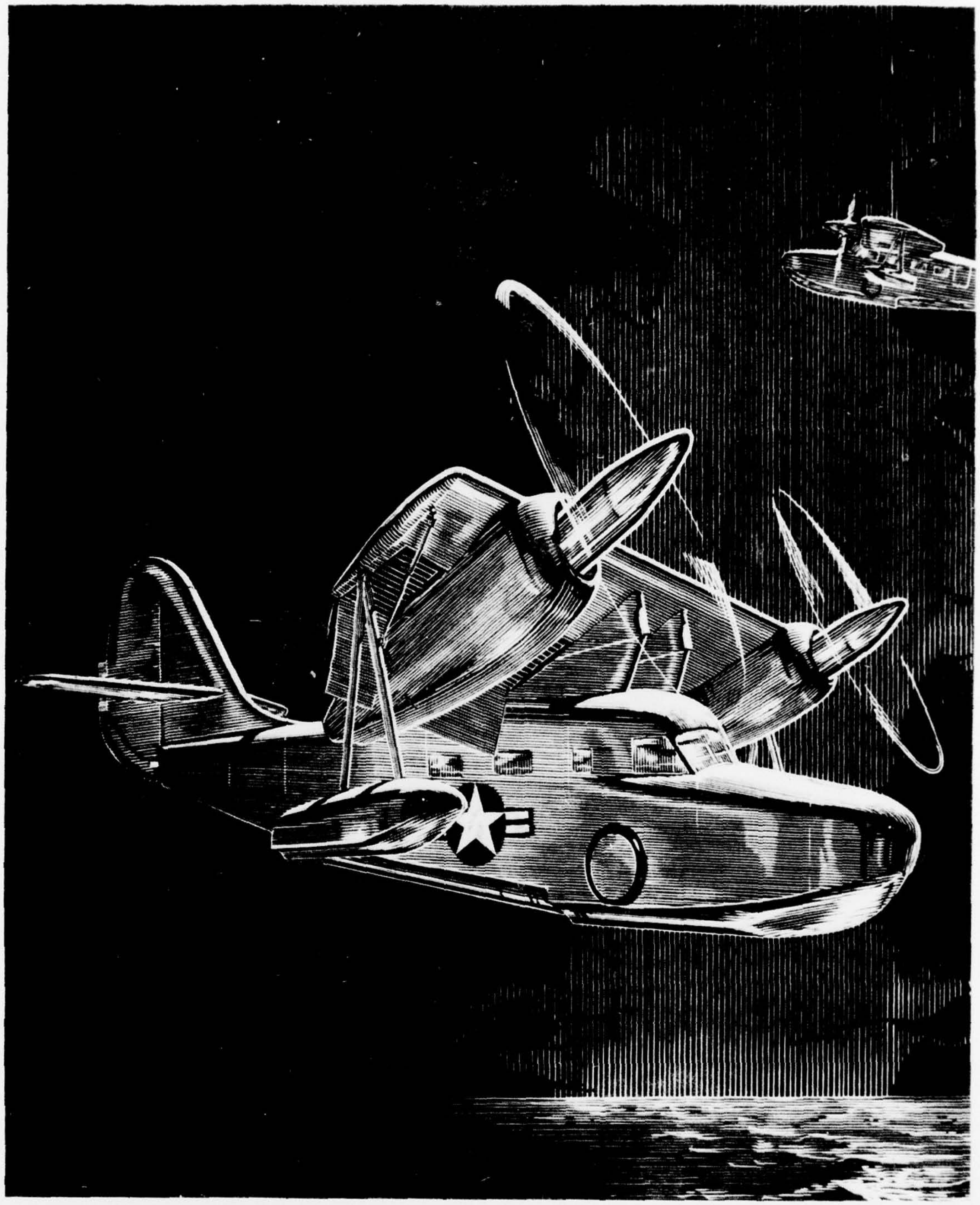

Figure 4. K-16B Tilt-Wing Research Vehicle.

3.0 DYNAMIC INTERFACING EFFORTS

Engine/airframe/drive train dynamic compatiblity problems were encountered during the development of each of the helicopter models described in the previous section. Although varied in nature, these problems were found to fall into four general categories:

1) Inability of subsystem components to tolerate normally occurring rotor system induced vibrations.

2) Inability of subsystem components to tolerate normally occurring drive system induced vibrations.

3) Inability of subsystem components to tolerate amplified rotor induced vibrations resulting from structural resonances.

4) Inability of subsystem components to tolerate amplified drive system induced vibrations resulting from structural resonances.

Dynamic interfacing efforts performed to resolve these problems are discussed in the following paragraphs.

INCOMPATIBILITY WITH NORMAL ROTOR INDUCED VIBRATION

Helicopter rotors typically produce large vibratory forces and moments which excite all elements of the vehicle structure and all components attached to this structure. Frequently, the vibration induced by these excitations results in failure or improper operation of the engine, drive system or their supporting structures. When this occurs, it can be said that the failed or improperly operating system or component is incompatible with the rotor induced vibration environment to which it is subjected. In most cases, this incompatibility results from underestimation of the magnitude of the vibration environment, rather than overestimation of the strength or environmental capabilities of the affected system or component. Failure to accurately assess vibration magnitude may result from two basic causes:

- Improper modeling of rotor dynamic force generating mechanisms.
- Improper modeling of vehicle structural dynamic response characteristics.

The effects of the above modeling errors are identical in that they both can result in system or component dynamic stresses in excess of their design capabilities. It is, however, important to distinguish between these two causes of dynamic incompatibility because the methods which are effective in solving the problems due to these two causes may be quite different. For example, if an engine mount is failing because of excessive rotor vibratory loading which is being applied at a frequency just above the natural frequency of the engine/support structure, strengthening the engine mount may aggravate the condition by moving the natural frequency closer to the excitation frequency. If, on the other hand, the frequency of excitation is well removed from this natural frequency, strengthening the mount may well be effective.

In keeping with the distinction expressed in the preceding paragraphs, incidents of interfacing problems discovered in the historical review and found to be traceable to excessive rotor induced vibration have been divided into two categories. The first of these categories consists of problems associated with normally occurring rotor vibrations. This category is limited to situations where excessive vibration cannot be related to structural resonance. Instances of dynamic compatibility problems and/or interfacing efforts falling into this category are discussed in this report section. Instances falling into the second category, where structural resonance is clearly a contributing factor, are discussed in the next report section.

Instances of inability to tolerate normally occurring rotor induced vibration were encountered during the development of only one vehicle. In this case, the problem arose because rotor vibratory excitations were substantially underestimated and, consequently, structures designed to these loads were found to be inadequate in practice. This problem was discovered early in the test rig program when premature fatigue failures of the engine support struts began to occur. In order to keep the test program going ahead, temporary fixes consisting of strengthened support hardware were installed. These fixes were not reflected as changes in the aircraft design because it was felt that the vibration problem was specific to the rig and would not occur on the actual aircraft. Although fatigue failures did continue throughout the ground test program, this situation was eventually corrected through evolution of the rotor design, which resulted in greatly reduced rotor vibration.

INABILITY TO TOLERATE AMPLIFIED ROTOR INDUCED VIBRATION

In contrast to the problem discussed in the preceding paragraphs, excessive helicopter vibration can usually be traced to improper tuning of the vehicle structure. This improper tuning results in coincidence or near coincidence of rotor excitation frequencies with the natural frequencies of the structure, and this leads to amplified vibratory responses. In this situation, the logical approach for reducing vibration consists of changing the structure to shift the natural frequencies away from the rotor exciting frequencies. The following paragraphs describe several instances where this approach has been successfully used to overcome engine/drive train/airframe dynamic incompatibility problems.

Shake testing of a static test vehicle revealed the presence of an airframe/engine/drive train resonance within the range of 4-per-rev of the rotor. This resonance was characterized by high rigid body lateral responses of the engine on its supports. Because of the potential for problems in flight and tiedown testing, a concerted effort was made to correct this situation through modification of the engine support system.

A series of localized shake tests was performed to evaluate various alternative engine mounting arrangements. The most effective fix turned out to be the addition of a redundant mounting strut to the forward engine support. This strut connected the engine to the firewall structure. Although successful from the dynamics standpoint, this fix was considered temporary only, because of the secondary nature of the firewall structure and also because of the possibly deleterious effect of redundant mounting on induced engine bending loads. It is interesting to note, however, that this temporary fix was maintained and incorporated in all production aircraft until it was determined that its removal did not significantly affect engine vibration levels in flight.

A second drive system resonant condition was discovered with this same vehicle only during the flight test phase. This more serious resonance occurred in the torsional system and was characterized by excessive 4-per-rev vibratory torque through the drive train, as well as high in-plane rotor blade bending moments. This resonance was serious enough to limit aircraft speed capability, and the development program through which a cure was affected seriously delayed the flight test effort.

The torsional resonance involved a coupled response of the rotor and drive train. Several solutions were postulated for this problem, including stiffening the main rotor drive shaft. Ultimately, however, it was decided to cure the problem by increasing the in-plane rotor stiffness, which caused a major redesign of the rotor blade. This design change entirely eliminated the torsional resonance problem.

This same vehicle developed a third major dynamic compatibility problem when it was subsequently uprated to a twin-engine configuration. This modification involved extensive changes in the power plant installation design, including the addition of a gearbox for combining the two engine inputs. This combining gearbox was initially rigidly mounted to existing structure. During power plant installation demonstration testing, however, it was discovered that engine drive shaft vibratory bending was exceeding the established specification because of a lateral rigid body resonant response of the combining gearbox. A program was undertaken to correct this situation by redesigning the combining gearbox mount system.

A set of elastomeric bushings was designed and fabricated for use in the combining gearbox mounts. These bushings were designed to be soft in the lateral direction and stiff in the vertical direction. They were installed, tested, and found to result in greatly reduced power plant vibration.

INABILITY TO TOLERATE DRIVE SYSTEM OR ENGINE INDUCED VIBRATION

Although the rotor system is generally the dominant source of helicopter vibration, elements of the engine and drive system also produce vibratory excitations. All rotating shafts, for example, produce excitations at their respective rotation rates in proportion to their inherent imbalance. Shaft misalignment couplings, particularly universal joint type couplings, can produce large excitations, depending upon installation geometry and induced misalignment. Operation of the drive system at or near one of its critical speeds, where half the shaft rotation rate is coincident with a shaft natural frequency, can be the cause of severe, often destructive vibration. Finally, aerodynamic excitations are produced by the engine compressor, turbine and exhaust flow.

In performing the historical review, an attempt was made to document all engine/airframe/drive train dynamic compatibility problems encountered at Kaman, including problems falling into each of the categories of this section. No instances were found, however, of problems due to normally occurring drive system/engine induced dynamic excitations. This leads to the perhaps obvious conclusion that these excitations are generally negligible, unless amplified by structural resonance. On the other hand, instances where resonant amplification of these excitations did lead to significant problems were encountered in each of Kaman's helicopter development programs.

Initial running of a dynamic endurance test rig indicated the presence of high vibration levels in both the fixed and rotating systems occurring at 2-per-rev of the engine drive shaft, or 190 Hz. These high vibration levels were assumed to be caused by the Hooke's joint misalignment coupling used on this shaft. It was further determined that the magnitude of torsional vibration could not be accounted for simply on the basis of normally occurring excitation forces and that, consequently, a torsional resonance (critical speed) was suspected, although previous analyses did not disclose such a condition.

Initial suspicions about the 2-per-rev resonance were aroused only after two of the sprag clutch units used in the system experienced premature failures. The first attempted solution to this clutch failure problem consisted of replacing the clutch with one of higher capacity. This clutch, however, failed more quickly and at this point it was decided to rework the original torsional analysis using a more involved model. This was done concurrently with an experimental study of sprag clutch load/deflection characteristics.

The results of clutch testing indicated that the clutch outer race deformed elliptically under load, causing unloading of the majority of the sprags and excessive loading of a few. This loading pattern, which departs strongly from the uniform loading which was originally assumed, resulted in a dramatically reduced clutch torsional spring rate relative to that assumed in the original analysis. When the proper clutch stiffness was used in the reworked torsional model, the presence of a system critical speed at 2-per-rev was predicted. Subsequent evaluation indicated that the original, much simpler model would have predicted this as well if the proper clutch spring rate had been used.

Having established an appropriate analytical model, a study was performed to arrive at a solution to the resonance problem. This study revealed that replacement of the aluminum engine drive shaft with a steel shaft would raise the critical speed well above the 2-per-rev excitation frequency. This change was made on the dynamic system test rig, and it resulted in a substantial reduction in 2-per-rev vibration levels, which still remained excessive. At this point it was concluded that the remaining 2-per-rev was due to normal Hooke's joint excitation, the effects of which were amplified somewhat by engine fixed system response.

Attempts were subsequently made to stiffen the engine mounting structure and thereby reduce engine vibration at 2-per-rev of the engine drive shaft. A redundant mounting strut was installed which partially alleviated the problem. This change resulted in extended engine life which, however, still remained excessively short.

When the complete vehicle entered the tiedown test phase, 2-per-rev vibration problems were encountered similar to those experienced in the rig testing. These problems remained even though modifications were made to the drive system shafting and engine support structure as discussed in the previous paragraphs. The fact that these problems were never completely solved is evidenced by the fact that a number of clutches and engines were failed due to high 2-per-rev vibratory induced failures even after the dynamic system components were redesigned. These failures continued through the wind tunnel test phase.

A second similar instance of engine/airframe/drive train incompatibility was encountered during rig testing of the dynamic components of another Kaman vehicle. This problem involved operation of the engine/transmission drive shaft at its first critical speed. This situation occurred because the drive shaft, which was the responsibility of Kaman, was analyzed and designed without regard for the inertia and stiffness characteristics of the engine speed reducer. Once these characteristics were taken into account, good correlation between measured and predicted critical speed was obtained, and a fix, involving increased shaft stiffening, was successfully developed.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Each of the dynamic interfacing problems discussed in Section 3.0 can be attributed to imperfect modeling of either dynamic responses or vibratory excitations. The vehicles which experienced these problems were developed 15 to 20 years ago, and significant improvements in dynamic modeling methods have been made since then. Nonetheless, it is felt that problems of a similar nature are being encountered today and will be encountered in the future, despite improvements in modeling technology. This conclusion is based on the fact that the helicopter is an extremely complex dynamic system which is not amenable to precise modeling. Furthermore, the dynamics of this system are such that even small modeling errors can lead to serious underestimation of the dynamic environment, particularly when structural response characteristics are modeled erroneously.

An increasing amount of effort and funding is being expended in producing more and more complex dynamic models of helicopter structures. Finite element representations including thousands of individual elements are now developed and used in the design of all new helicopter vehicles. These methods have been applied with the intention of obtaining desirable structural response characteristics at the design stage, thus minimizing the amount of effort which must be made to correct undesirable characteristics during development testing. Despite the use of these advanced methods, however, the experiences of recent programs have shown that a significant dynamic development test effort is still necessary. It is clear that dynamic modeling technology has not reached the stage where engine/airframe/drive train dynamic compatibility can be assured by design.

Based on the above conclusions, it is recommended that dynamic compatibility research be directed toward application of advanced technology dynamic testing techniques. These techniques, which are based on mechanical impedance methods, can be readily applied to the problems of engine/airframe/drive train dynamic incompatibility. Mechanical impedance testing should be an integral part of the overall dynamic development program. In this regard, it would be beneficial to develop analytical models in such a way that their validity can be verified through testing at the earliest possible time. Since in all cases component hardware is available long before the first test vehicle, analytical models should be developed on a component basis. These models could then be verified as the components become available. Alternatively, component designs could be changed to improve their dynamic characteristics. In this way, the dynamic development period could be appreciably shortened and its cost reduced.

TABLE 1. SUMMARY OF DYNAMIC INTERFACING PROBLEMS

Problem	Date	Symptoms	Solution
High Vibratory Stresses at 4-P in Engine Supports	1959	Support Fatigue	Reduced Rotor Vibration Through Design Evolution
Lateral Rigid Body Engine Resonance at Rotor 4-P	1959	Found in Shake Test	Revised Mounting
Torsional Resonance at Rotor 4-P	1959	High Shaft Stresses	Increased Rotor Blade Chordwise Stiffness
Drive Shaft Critical Speed	1959	High Vibration	Redesigned Shaft Based on Better Engine Dynamic Model
Torsional Resonance at Drive Shaft 2-P	1960	High Vibration	Redesigned Shaft Based on Better Clutch Dynamic Model
Engine Vibration at Drive Shaft 2-P	1960	Turbine Rub	Changed Mounting Design
Gearbox Rigid Body Resonance	1968	High Vibration	Soft Mounting

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