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EVALUATION OF THE EFFECTIVENESS OF USING SONIC DATA TO DIAGNOSE THE MECHANICAL CONDITION OF ARMY HELICOPTER POWER TRAIN COMPONENTS

By

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May 1972

EUSTIS DIRECTORATE

U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY

FORT EUSTIS, VIRGINIA

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Sound recordings were made on 87 UH-1 helicopters that had either the transmission or a gearbox scheduled for removal for routine overhaul. The mechanical condition of the components was then noted during the overhaul process, and these results were compared with the recorded signals in an attempt to correlate the mechanical condition with the acoustical signals. The sonic analysis procedures were then revised to improve the effectiveness of detecting component malfunctions.

The Curtiss-Wright sonic analyzer shows good good potential as a successful indicator of power train component anomalies for the UH-1 series helicopters based on the satisfactory performance shown during the field application program. Results indicate that before the sonic analyzer is used as an operational maintenance aid for the Army, it should be evaluated using the revised analysis procedures established during this program.

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SUMMARY

This report covers work performed during an in-house program to evaluate the effectiveness of using the sound emitted from helicopter power train components as a data source for diagnosing their mechanical condition. A ground-based UH-1 helicopter sonic analyzer developed by the Curtiss-Wright Corporation under Government contracts was used in the evaluation.

Sound recordings were made on 87 UH-1 helicopters that had either the transmission or a gearbox scheduled for removal for routine overhaul. The mechanical condition of the components was then noted during the overhaul process, and these results were compared with the recorded signals in an attempt to correlate the mechanical condition with the acoustical signals. The sonic analysis procedures were then revised to improve the effectiveness of detecting component malfunctions.

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FOREWORD

This effort was authorized as a portion of DA Task 1F162203A43405, "Diagnostic and Inspection Equipment". This report covers the work performed from July 1969 through December 1970.

The author acknowledges the support of Mr. Charles W. Bowen, Bell Helicopter Company, and of the personnel at the U.S. Army Aeronautical Depot Maintenance Center, Corpus Christi, Texas, in providing teardown data on the UH-1 transmission and gearboxes.

He also acknowledges the support given by the civilian and military personnel at Fort Stewart-Hunter Army Airfield, especially the personnel of the Aircraft Maintenance Brigade, commanded by Colonel Keith J. Bauer, who generously devoted many hours of effort in providing the requested maintenance data and in operating the aircraft. It was only through the outstanding support and cooperation of these people that this research effort was made possible.

The majority of the data correlation and analysis was performed by Mr. W. H. Dawson of the Curtiss-Wright Corporation, who was assisted by Mr. John Nobles of the Eustis Directorate, USAAMRDL. Their perseverance in manually processing and analyzing the voluminous raw data deserves special recognition.

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LIST OF SYMBOLS AND ABBREVIATIONS

ADGB	Accessory drive gearbox
Assy	Assembly
Brg	Bearing
Cal	Calibrate
c	Amplitude of the corrected frequency meter reading, db
cps	Cycles per second
CWEA	Curtiss-Wright Engine Analyzer
C_1	Compressor rotor blade passage frequency
d_1	Bearing inner race diameter, in.
d_2	Bearing outer race diameter, in.
db	Decibels
d_B	Bearing rolling element diameter, in.
f_1	Amplitude of the bearing frequency caused by irregularity on inner raceway, db
f_2	Amplitude of the bearing frequency caused by irregularity on outer raceway, db
f_b	Amplitude of the bearing frequency caused by spin of rolling elements, cps
f_b'	Amplitude of the bearing frequency caused by rough spot on rolling element, db
$3f_b'$	Amplitude of the third harmonic of f_b' (3 times f_b'), db
f_r	Amplitude of the fundamental rotational frequency of engine, gear shaft, or bearing shaft, db
f_t	Amplitude of the bearing frequency due to rotation of train of rolling elements, cps, or tracking frequency, db
fund	Fundamental
ID	Inside diameter, in.

Locking Signal	Frequency used for tracking engine rpm variation (within ±3%) which must be present on all engines 100% of the time and does not have any other discrete signals within ±400 cps. (Any variation in engine rpm above or below the ±3% range will alter this limit accordingly.)
m	Number of bearing rolling elements
Mic	Microphone
n	Noise level, db
N_1	Gas producer rotor speed, rpm
N_2	Power turbine rotor speed, rpm
Norm	Normalize
OD	Outside diameter, in.
Peg, P	Full scale
TBO	Time between overhauls
TT	Total time
Trans, Xmsn	Transmission
TSO	Time since overhaul
X2	Twice the fundamental rotational frequency of engine, gear shaft, or bearing shaft, cps

INTRODUCTION

The Army, in an effort to improve its capability and efficiency in aircraft maintenance, has programs under way to develop diagnostic equipment for use in determining the mechanical condition of Army aircraft components.

One approach that is being investigated uses the sound emitted by the aircraft as a source of information for determining the condition of the aircraft's mechanical components. A device using this principle is the ground-based UH-1 helicopter sonic analyzer, designated CWEA-4, built by the Curtiss-Wright Corporation under USAAMRDL-sponsored programs. This analyzer was designed and fabricated to monitor the mechanical condition of the rotating elements of the engine, transmission, shafting, and tail rotor gearboxes while the components are being operated on the ground at low power. It is designed to detect the majority of the mechanical anomalies, including gear fatigue failures, bearing failures, and gear tooth scuffing conditions.

Field application and evaluation of the sonic analyzer implied that correlation may indeed exist between the analyzer findings and the mechanical condition of the power train components. However, information on the actual mechanical condition of the components being analyzed was lacking, so further effort was needed to confirm the effectiveness of the device.

Therefore, this house task was established to collect field data on a large number of UH-1 helicopters and to correlate the mechanical condition implied by the sonic analyzer with the actual mechanical condition of the components noted during teardown inspections.

It was originally thought that the reject criteria established by previous research effort would prove to be effective in detecting faulty components, even though it was known that the reject criteria had been established on a theoretical basis. However, during the initial data analysis effort, it became apparent that these reject criteria and analysis procedures were only partially effective and that they needed to be revised. Thus, a contract was made with the Curtiss-Wright Corporation for their assistance in the analysis effort and for their recommendations on changes in the reject criteria and analysis procedures.

SYSTEM DESCRIPTION

CWEA-4 SONIC ANALYZER

The CWEA-4 sonic analyzer (Figure 1) consists of a power supply, the basic CWEA sonic analyzer with UH-1 helicopter plug-in module capability, three microphones, a tape programmer, and associated cabling.

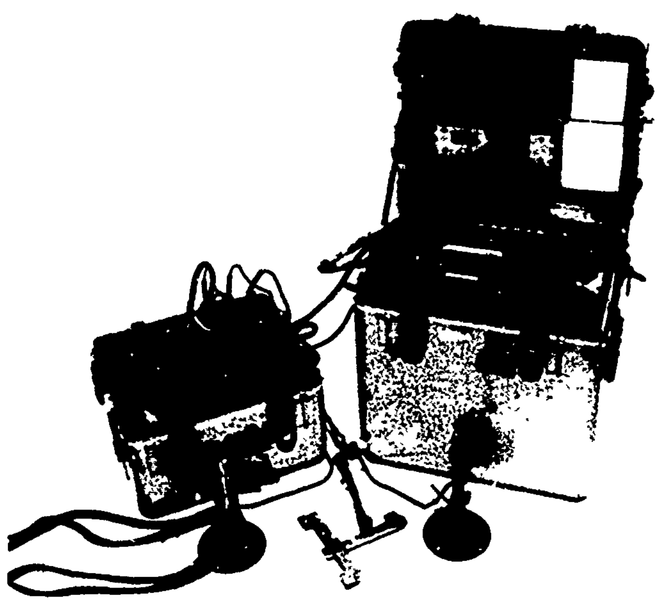
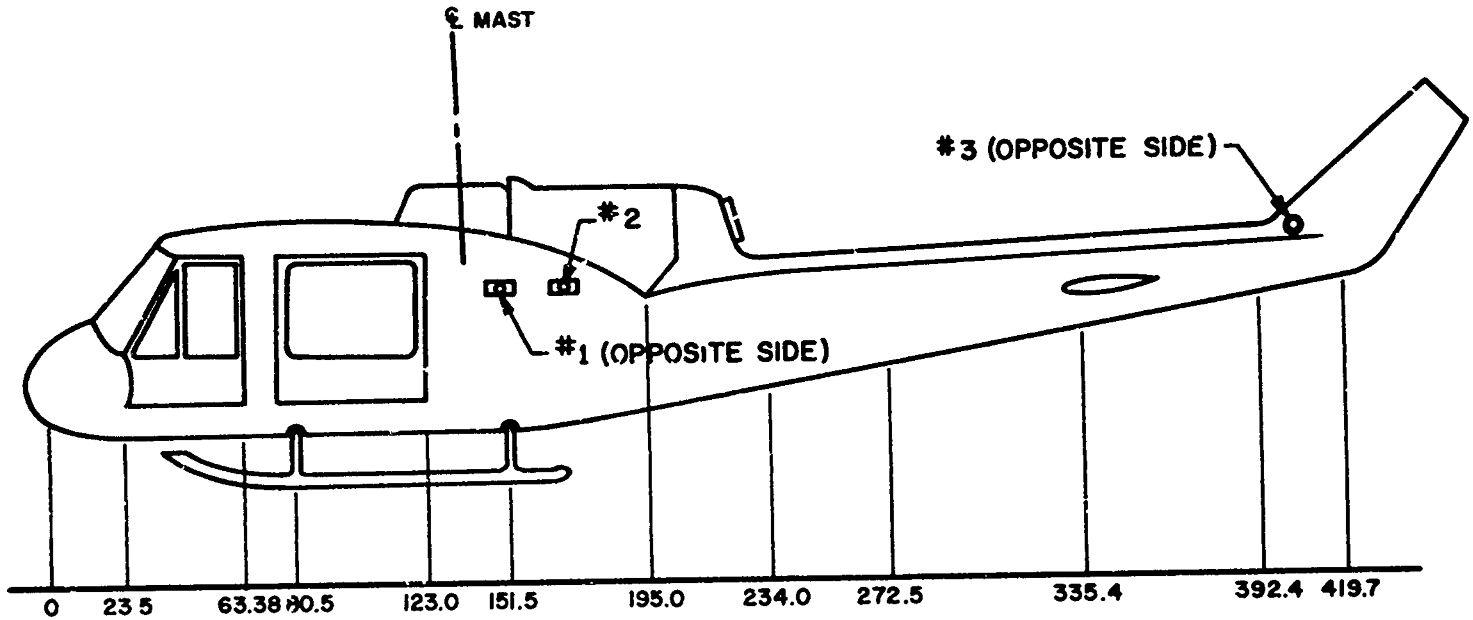


Figure 1. CWEA-4 Sonic Analyzer.

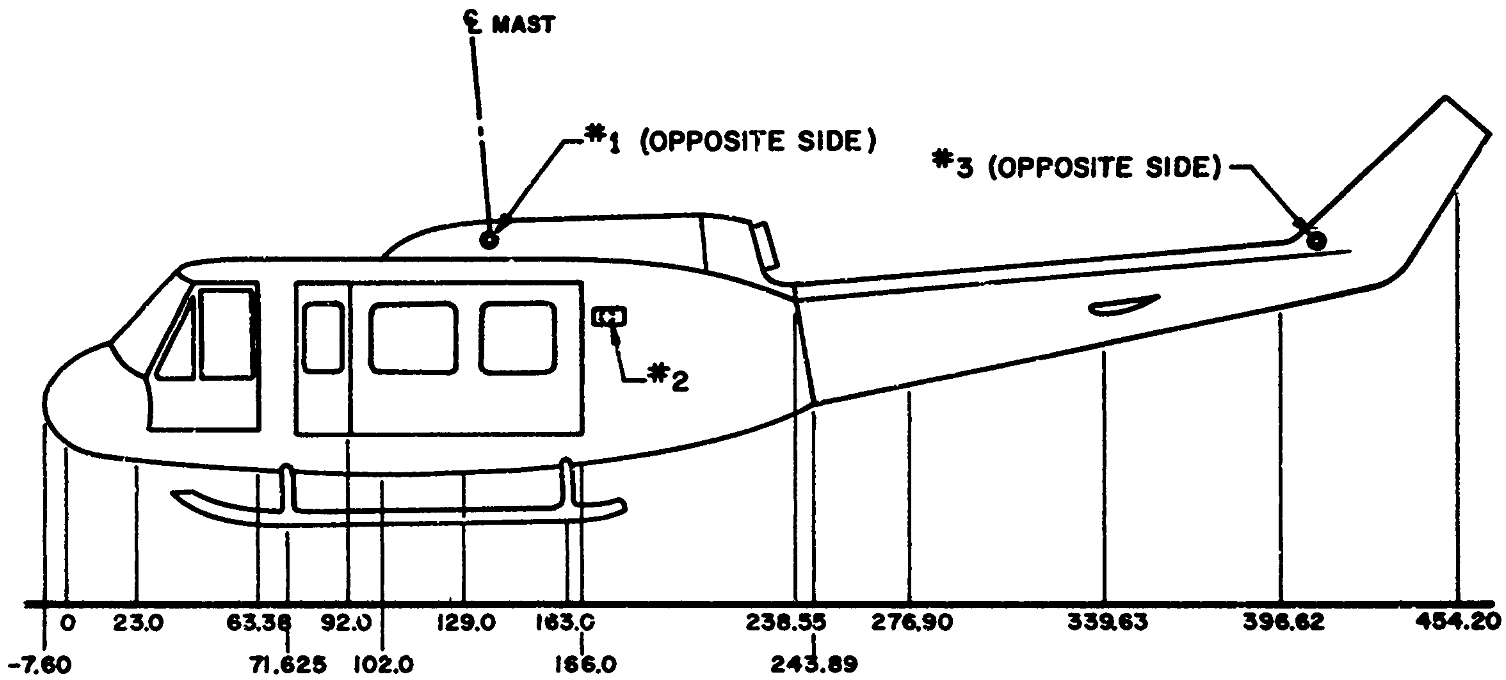
The microphone system consists of three condenser microphones (Figures 2 through 6) located as follows:

Microphone 1	Located approximately 10 inches inside the transmission right inspection door and aimed at the center section of the transmission on the vertical center line for aircraft models UH-1A, UH-1B, and UH-1C. Located approximately 3 inches from the right side of the transmission cover housing



Mic	Location
1	Clamped in forward access panel opening on right side of helicopter - extends 10 inches inside - aimed at vertical center line of transmission center section.
2	Clamped in rear access panel opening on left side of helicopter - extends 10 inches inside - aimed midway between N_1 and N_2 accessory drive gearboxes.
3	Fastened on right side of tail section with suction cup - 3 inches away from skin - aimed at 42-degree gearbox.

Figure 2. Microphone Locations for Main Rotor Transmission and Tail Rotor Gearboxes – Models UH-1A, UH-1B, and UH-1C Helicopters.



Mic	Location
1	Mounted on right side of engine cowl using suction cup - 3 inches away from skin - aimed at mast center line.
2	Clamped in forward access panel opening on left side of helicopter - extends 10 inches inside - aimed midway between N_1 and N_2 accessory drive gearboxes.
3	Fastened on right side of tail section with suction cup - 3 inches away from skin - aimed at 42-degree gearbox.

Figure 3. Microphone Locations for Main Rotor Transmission and Tail Rotor Gearboxes – Model UH-1D Helicopter.

	(6 inches above top of cabin) directly opposite the transmission vertical center line and aimed at the top of the transmission for aircraft model UH-1D.
Microphone 2	Located approximately 10 inches inside the engine left inspection door and aimed at a point halfway between the engine N_1 and N_2 accessory drive gearboxes on a vertical line through the parting line of the two gearbox housings.
Microphone 3	Located approximately 2 inches from the right side of the 42-degree gearbox cover housing and aimed at the center of the gearbox.

A three-prong bracket was used to mount microphones 1 and 2 at the respective transmission and engine inspection doors on the UH-1A, UH-1B, and UH-1C model helicopters (Figure 4). On model UH-1D, a suction cup was used for the microphone 1 installation and a three-prong bracket for microphone 2 (Figure 5). A suction cup was used to mount microphone 3 on all model helicopters (Figure 6).

The analyzer unit itself receives a signal from one of the three microphones, passes the signal through a narrow band-pass filter, and, for some cases, compares the amplitude of the signal with a predetermined amplitude. The normalized signal is then read on the condition-level meter. From this reading, the condition of the component being analyzed can be determined. The initial component limits were established by using the UH-1 helicopter data recorded at Fort Rucker, Alabama, in September 1966.[1] The analysis of these data resulted in a gain setting required to produce a half-scale deflection of the condition-level meter, which reads from 0 to 10. Reject limits for each component have been revised and are discussed later in this report.

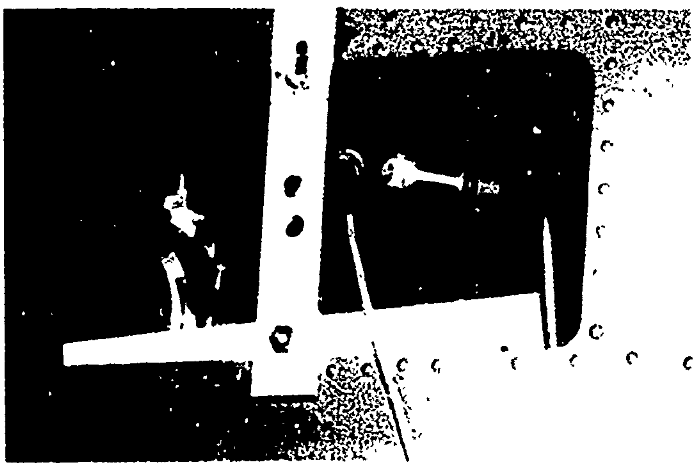


Figure 4. Typical Installation of Microphones 1 and 2 on Models UH-1A, UH-1B, and UH-1C Helicopters.

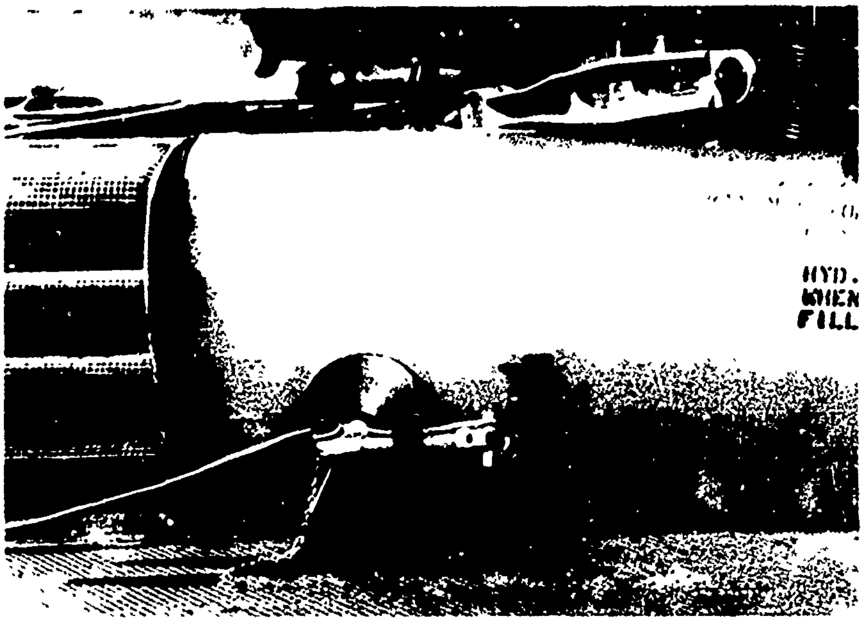


Figure 5. Typical Installation of Microphone 1 on Model UH-1D Helicopter.

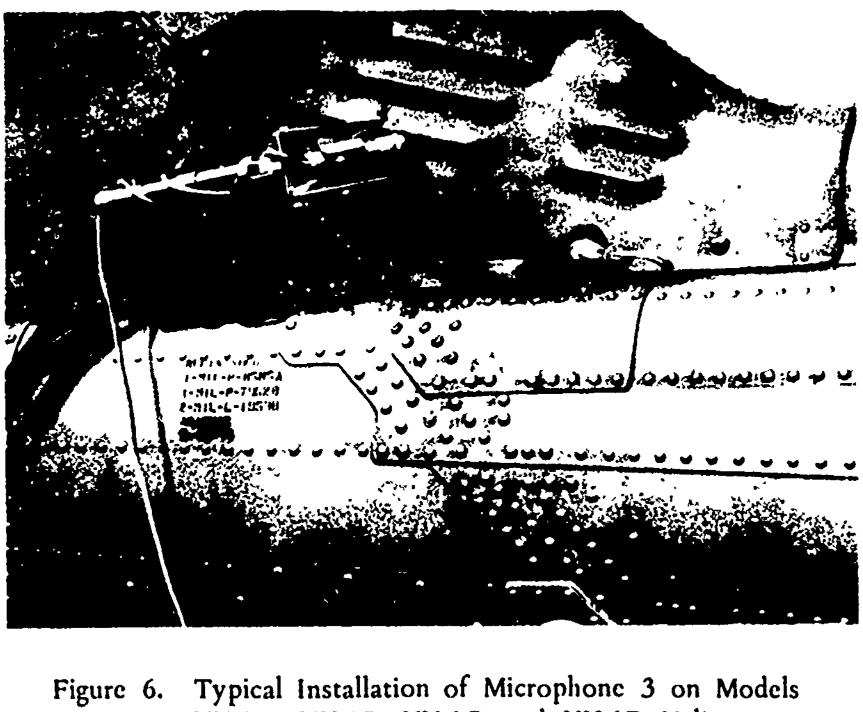


Figure 6. Typical Installation of Microphone 3 on Models UH-1A, UH-1B, UH-1C, and UH-1D Helicopters.

The analyzer has the capability of operating in three different modes:

1. Manual — The operator manually sets the test level, the gain I and II switches, the ratio select switch, the microphone select switch, and the lock select switch. The read switch is depressed and the condition level is read. This process has to be repeated for each component.

2. Semiautomatic — In this mode of operation, a program tape is used. The program tape automatically sets all of the above logic, and the operator merely depresses the tape driver switch for each successive reading. The condition level is still read as above.

3. Automatic — In this mode, the movement of the automatic tape is controlled by a clock. A predetermined reference signal is contained in the logic circuitry. If the amplitude of the monitored signal is above that of the reference signal, a magnetic latching relay is energized, stopping the tape and lighting the indicator lamp. (Because the reject limits were being changed during this program, the automatic mode of operation was not used.

RECORDING EQUIPMENT

During the effort covered by this report, a four-channel tape recorder was used to shorten the on-line analysis time by recording the data for analysis at a later time. The recordings were also used to obtain spectrograms for use in a comprehensive analysis of the sonic data.

The recording equipment included an AMPEX SP-300 magnetic tape recorder and the three condenser-type microphones of the CWEA-4 analyzer. Direct recordings were made at tape speeds of 7½ inches per second. Three tracks were used to record the signals from the microphones, and a fourth track was used for narrative purposes to record data such as aircraft identity and test conditions.

MECHANICAL DATA

The mechanical data for the various rotating components were obtained by Curtiss-Wright Corporation prior to the fabrication of the module for the UH-1 series helicopters. These data consisted of power transmission speeds, shaft speeds, number of gear teeth for each gear concerned, dimensions of races and rolling elements of bearings, engine installation, and gearbox locations. A detailed description of the mechanical and acoustic analysis, the module design, and the analyzer fabrication is given in Reference 1.

The predicted frequencies of the various rotating components were computed for a flight-idle condition by using these data. These frequencies were, in turn, identified as a ratio between their frequency and the frequency of the N_1 or N_2. Then, by electronically tracking either the N_1 or the N_2 speeds and selecting the predetermined frequency, the frequency associated with any particular component could be studied. The engine and transmission operating speeds for ground operation of the UH-1B and UH-1D helicopter models at flight-idle conditions were established as below:

Helicopter Component Used To Detect N_1 and N_2 Speeds	Helicopter Cockpit Instrument Tachometer Setting
N_1 – Engine Compressor Rotor	
UH-1B	60%
UH-1D	63%
N_2 – Transmission Input Drive Bevel Gear	4500 rpm

It should be noted that these are nominal values, and some helicopter models will have to operate at N_1 and N_2 speed settings that may differ from the nominal speeds. During this in-house program, tracking was successfully accomplished within the range of 59 to 65 percent and 4400 to 4600 rpm. (This tracking capability is often termed as being "locked on".)

Gear train schematics for the power train components of the UH-1 helicopter are shown in Figures 7 and 8. The identification code used in these figures is as follows:

1. The number written in parentheses is used to identify and locate the individual component. This number corresponds to the number in the applicable table and on the program tape.
2. The number printed on the gear indicates the number of gear teeth.
3. The number underlined indicates the component shaft speed in revolutions per second (rps).

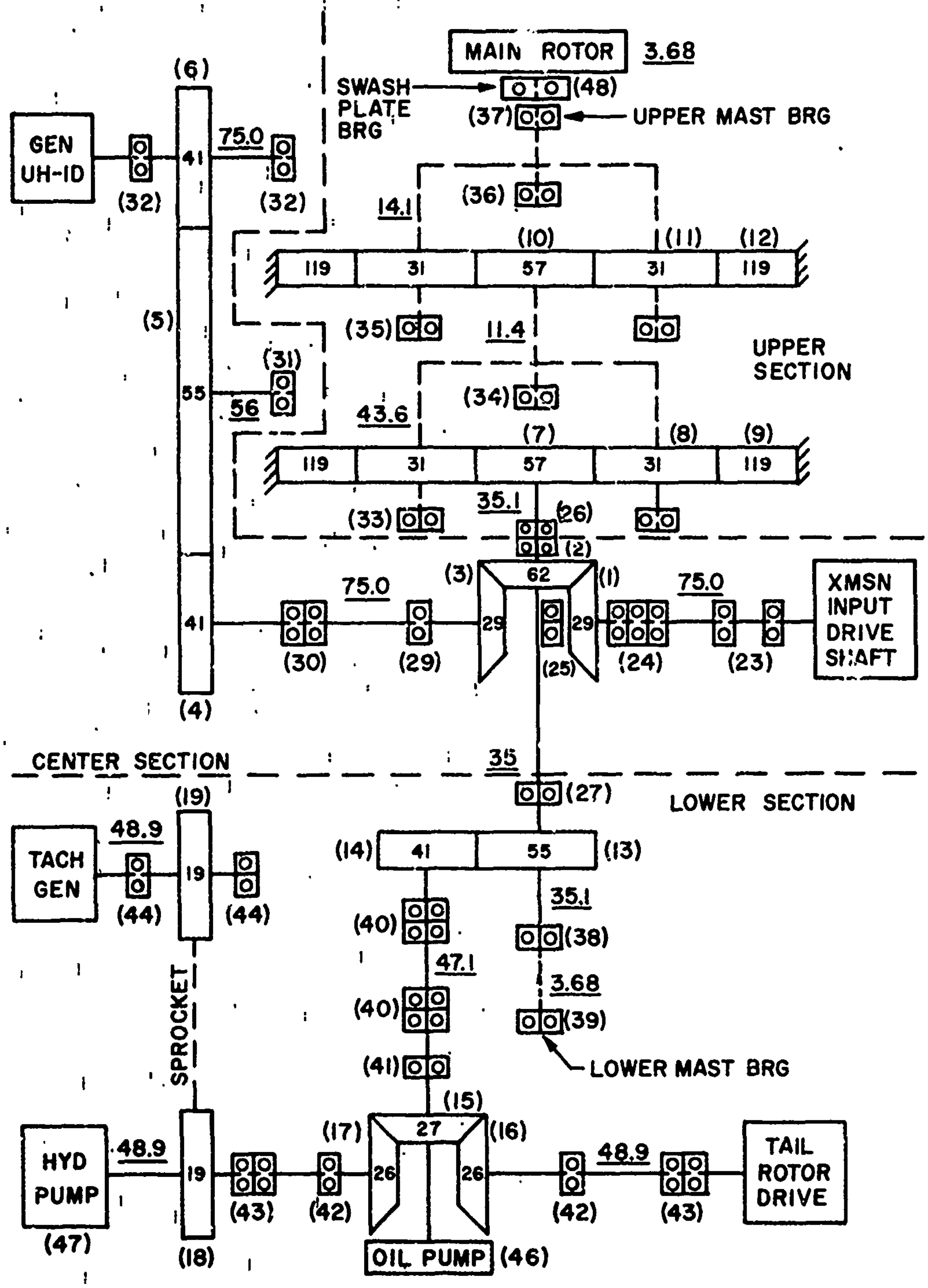
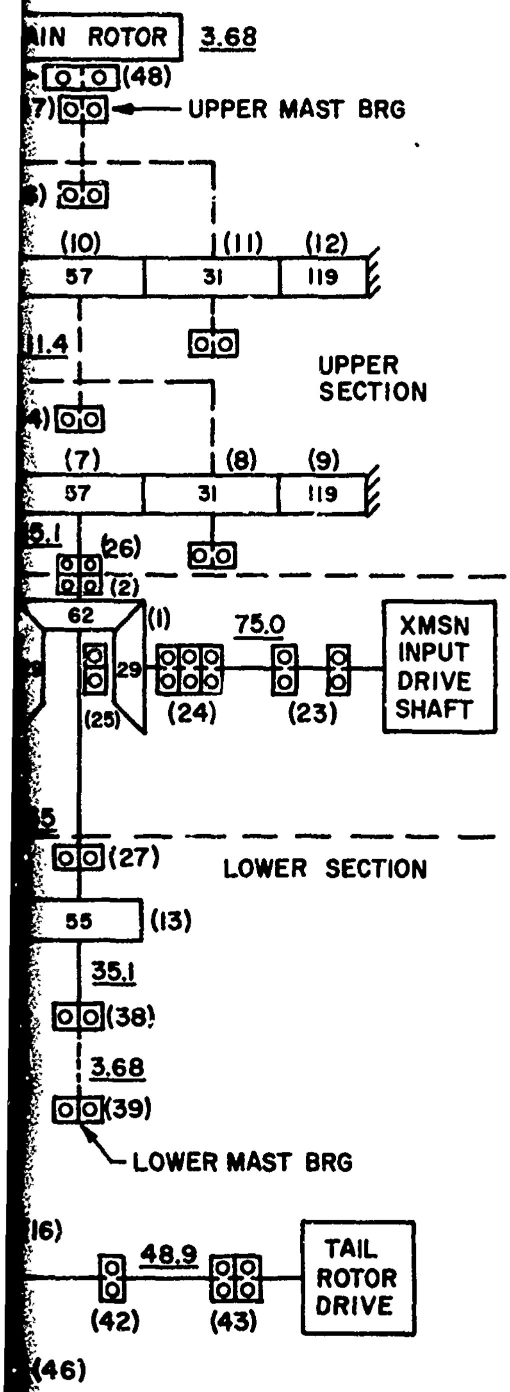


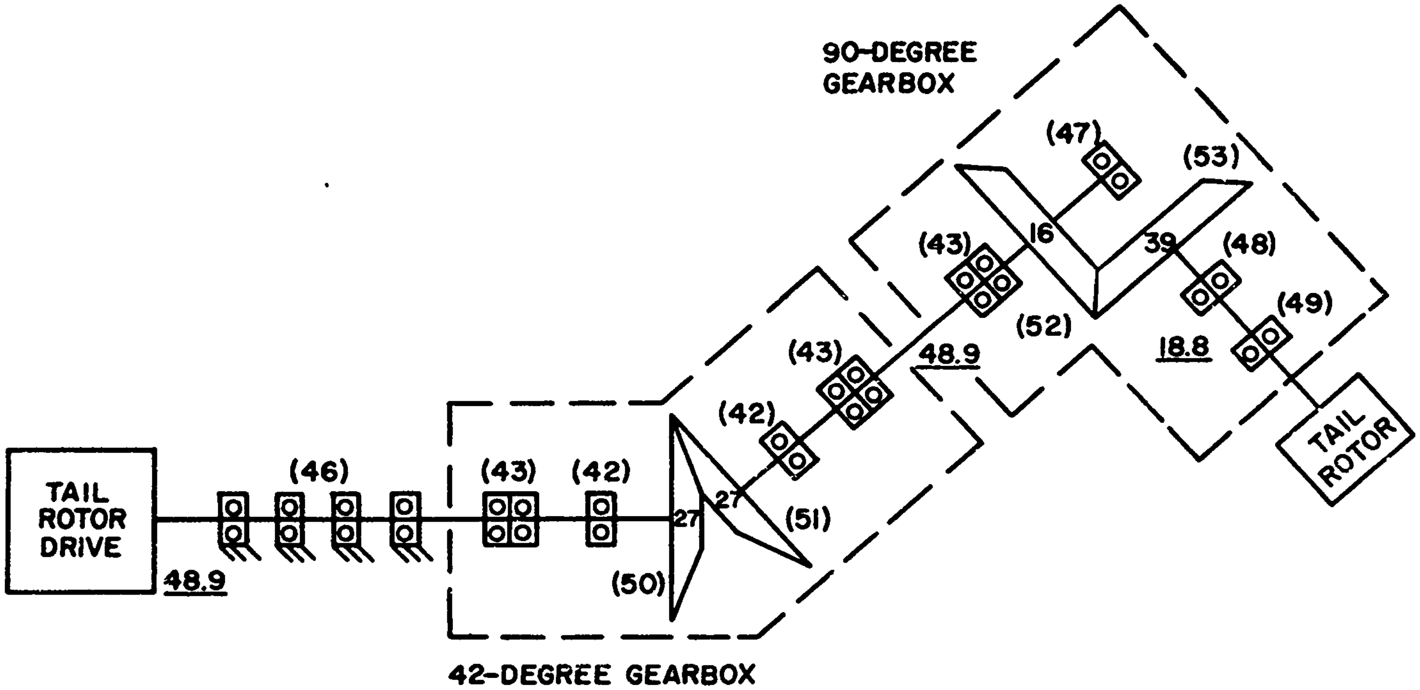
Figure 7. Gear Train Schematic – Model UH-1D Helicopter Main Rotor Transmission.



– Model UH-1D Helicopter Main

Schematic Reference No.	Part Number	Part Name
(1)	204-040-700	Drive Bevel Gear
(2)	204-040-701	Drive Bevel Gear
(3)	204-040-100	Generator Bevel Gear
(4)*	205-040-101	Generator Spur Gear
(5)*	205-040-102	Generator Spur Gear
(6)*	205-040-103	Generator Spur Gear
(7)	204-040-329-1	Lower Sun Gear
(8)	204-040-108-7	Lower Planetary Pinions
(9)	204-040-331-5	Lower Ring Gear
(10)	204-040-330-1,-3	Upper Sun Gear
(11)	204-040-108-7	Upper Planetary Pinions
(12)	204-040-331-5	Upper Ring Gear
(13)	204-040-763	Drive Spur Gear
(14)	204-040-762	Driven Spur Gear
(15)	204-040-103-7	Drive Bevel Gear
(16)	204-040-104-13	Driven Bevel Gear, Tail Rotor
(17)	204-040-105	Driven Bevel Gear, Accessories
(18)*	204-040-112	Sprocket Wheel Assembly
(19)*	204-040-113	Sprocket Wheel, Hydraulic Pump
(23)	204-040-142-1	Input Quill Shaft Bearing
(24)	204-040-346-3	Input Quill Shaft Bearing, Triplex Ball (Input Pinion)
(25)	204-040-269	Roller, Input Quill Shaft Bearing
(26)	204-040-345-3	Input Gear Shaft Bearing, Duplex Ball
(27)	204-040-271	Main Reduction Gear Bearing
(29)*	204-040-105	Generator Drive Shaft Bearing
(30)*	204-040-106	Generator Drive Shaft Bearing
(31)*	204-040-107	Generator Drive Shaft Bearing
(32)*	205-040-108	Generator Drive Shaft Bearing
(33)	204-040-725	Roller Set, Lower
(34)	204-040-135	Main Rotor Reduction Bearing, Lower
(35)	204-040-725	Roller Set, Upper
(36)	204-040-135	Main Rotor Reduction Bearing, Upper
(37)	204-040-136	Upper Mast Bearing
(38)	204-040-135	Lower Transmission Bearing
(39)	204-040-270	Lower Mast Bearing
(40)	204-040-143	Lower Transmission Input Duplex Bearing
(41)	204-040-310	Lower Transmission Input Bearing
(42)	204-040-310-1	Tail Rotor Drive Bearing and Accessory Drive Bearing
(43)	204-040-143-1	Tail Rotor Drive Duplex Bearing
(44)*	204-040-145	Tachometer Drive Shaft Bearing
(48)*	204-101-425	Swash Plate Bearing

*Not analyzing these components



Schematic Reference No.	Part Number	Part Name
(42)	204-040-310-001	42-Degree and 90-Degree Gearbox Bearings
(43)	204-040-143-001	42-Degree and 90-Degree Gearbox Bearings
(46)	204-040-615-003	Tail Rotor Drive Shaft Bearing
(47)	204-040-406	90-Degree Gearbox Roller Bearing
(48)		
(49)		
(50)	204-040-500-009	42-Degree Gearbox Drive Bevel Gear
(51)	204-040-500-010	42-Degree Gearbox Driven Bevel Gear
(52)	204-040-400-009	90-Degree Gearbox Drive Bevel Gear
(53)	204-040-401-007	90-Degree Gearbox Driven Bevel Gear

Figure 8. Gear Train Schematic – UH-1D Helicopter Tail Rotor Gearbox.

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DATA ACQUISITION

An instrument van (Figures 9 and 10) equipped with the sonic analyzer, recording equipment, and supplementary support equipment was taken to Hunter Army Airfield, Savannah, Georgia, where data were collected on UH-1 helicopters. By working closely with the aircraft maintenance personnel, it was possible to collect data on helicopters within a day or two of the time when a major component was to be removed from the aircraft for a scheduled overhaul. The components of interest for the study were the transmission, 42-degree gearbox, and 90-degree gearbox.

The data were collected over a 5-month period from July to November 1969. In all, 87 recordings were made. Of these, 66 were on different aircraft with components scheduled for immediate removal for overhaul.

An identification procedure was established for those components being forwarded to the U.S. Army Aeronautical Depot Maintenance Center (ARADMAC), Corpus Christi, Texas, for overhaul, and the entire shipping process was closely monitored to ensure accountability of the components.

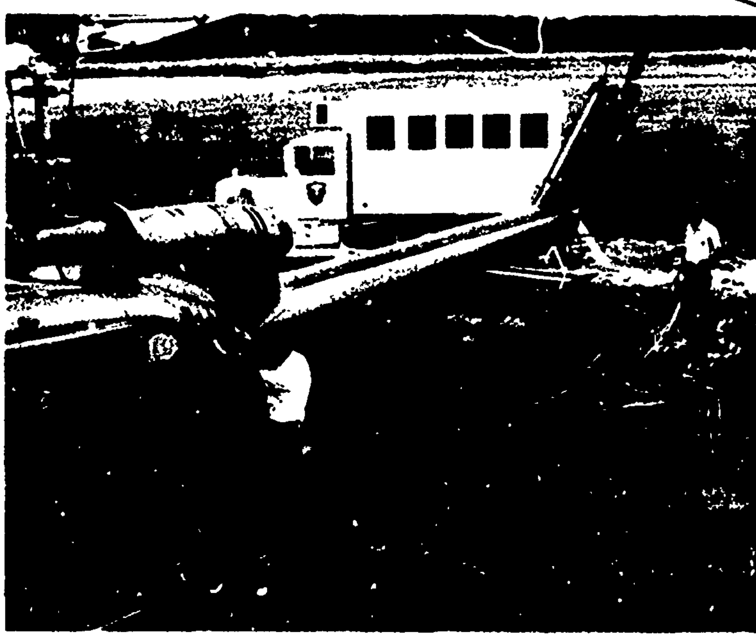


Figure 9. Instrument Van Used for Acquisition of Data of UH-1 Helicopters on the Flight Line.

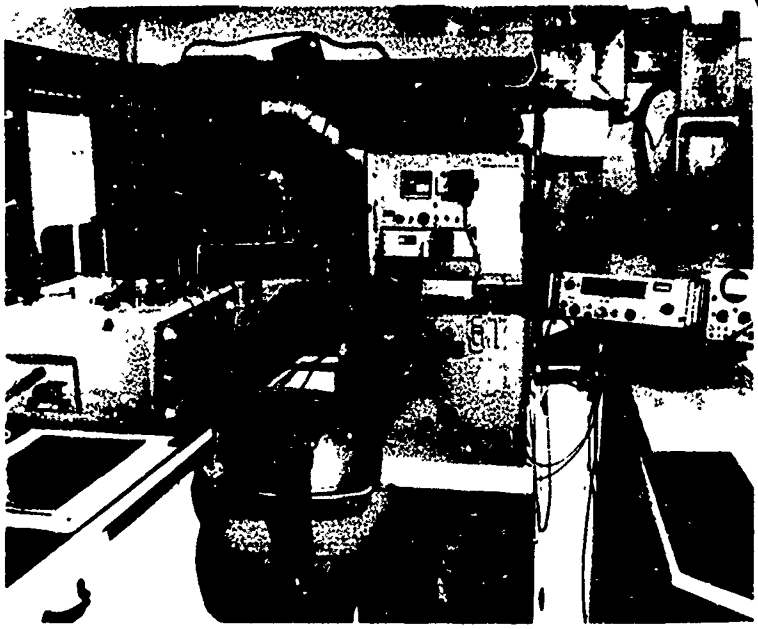


Figure 10. Interior of Instrument Van Containing CWEA-4 Sonic Analyzer.

Hunter Army Airfield proved to be an excellent facility for acquiring data on the UH-1 helicopter. Because of the high number of hours being accumulated on the aircraft and the large number of aircraft available, it was possible to have a UH-1 helicopter with the desired number of flight hours available for data acquisition efforts at essentially any time. A breakdown of the data acquired is shown in Figure 11.

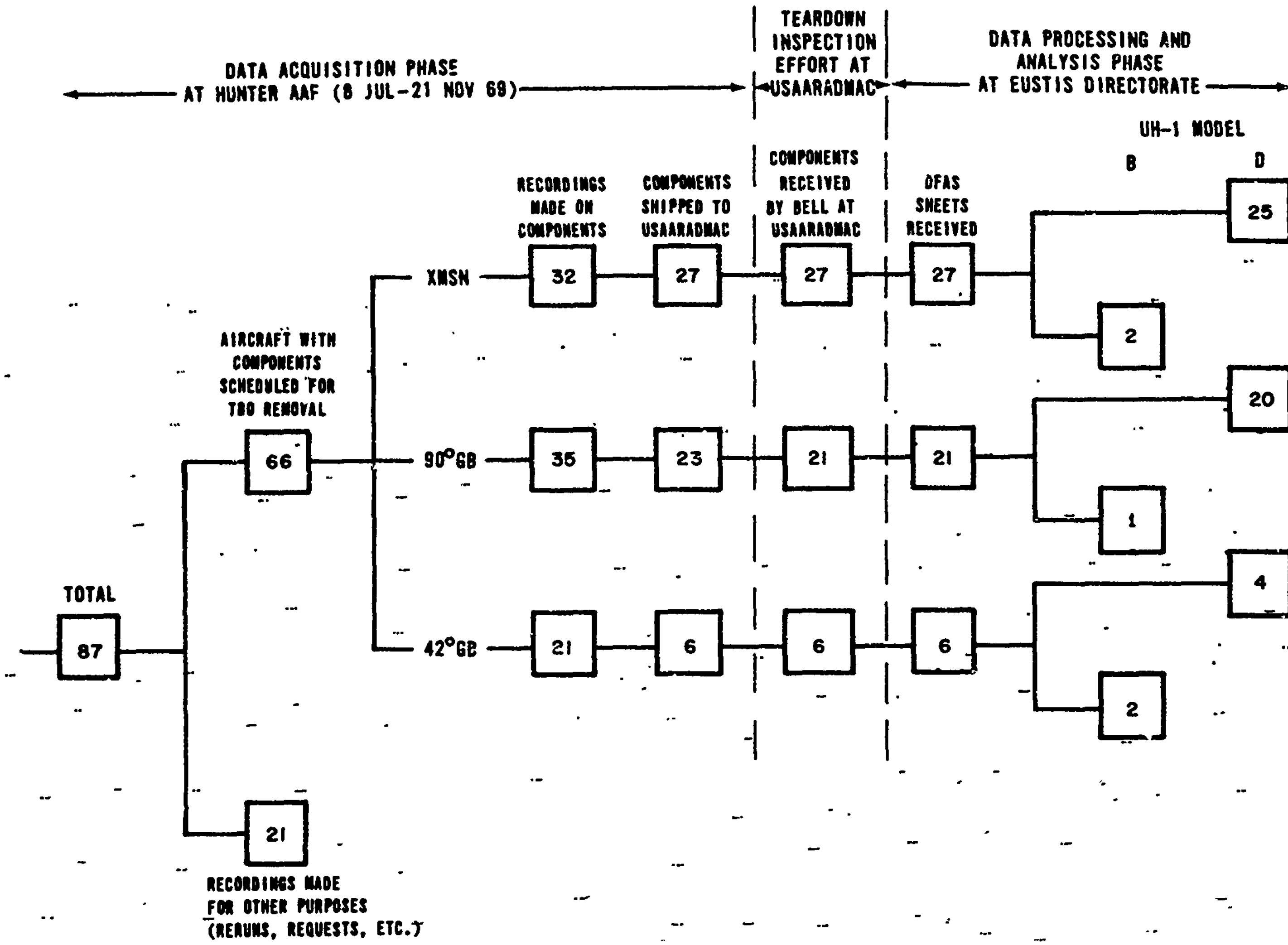


Figure 11. Breakdown of Data Acquired for Analysis.

MECHANICAL DATA INSPECTION AND REDUCTION

When the components arrived at ARADMAC for routine overhaul, they were intercepted by engineers from the Bell Helicopter Company, who in turn noted and recorded their condition during the teardown process.

The information on the condition of the components was forwarded to the Eustis Directorate for use in the analysis phase.

A glossary of common failure terms, compatible with American Gear Manufacturers Association and Anti-Friction Bearing Manufacturers Association standard terminology, was compiled and associated with examples taken from overhaul components to aid in achieving uniformity in reporting. This glossary appears as Appendix I.

The component inspection data were reviewed at the Eustis Directorate both by Directorate personnel and a Curtiss-Wright engineer. The review consisted of classifying the condition of the components as normal, faulty, or questionable. In all, 363 components from 47 different helicopters were inspected. Of these components, 35 (about 9.6 percent) were found to be sufficiently deteriorated to be considered defective. Thirty-one of the defective parts were in the transmission, with 10 of these predicted to fail either "immediately" or "in less than 100 hours". Four of the defective parts were in the 90-degree gearboxes. A summary of the review is shown in Table I.

Table I comprises all test recordings which were considered to be acceptable; that is, they had been properly recorded. These acceptable recordings are identified in the table by a run number. The transmission, 42-degree gearbox, and 90-degree gearbox components are identified with bearings and gears grouped separately. All test runs for which component inspection information (DFAS official formats, handwritten comments, etc.) was available are categorized and identified by a letter in the corresponding run number and component, which indicates the condition of the component. If no comments were received on a component, it has been assumed that its condition was considered to be normal by the inspector, but no letter is shown in the corresponding space.

The inspection information was reviewed in detail by a Curtiss-Wright engineer, and each component's condition was then classified as a failure (F), normal (N), or questionable (Q), and a notation was made in the appropriate space. These, plus supplemental notations, are as shown on the legend of Table I.

TABLE I. SUMMARY OF TEARDOWN INSPECTION FINDINGS ON UH-1D TRANSMISSIONS AND GEARBOXES

		Transmission																					42-Deg Gearbox			90-Deg Gearbox			
		Bearings																Gears					Bearings		Gear	Bearings			Gear
Item	Run No.	23	24	25	26	27	34	36	38	37	39	41	42	40	43	46	48	1-2-3	7-8-9	10-11-12	13-14	15-16-17	42	43	Bevel	43	47	49	Bevel
1	7																									N		N	N
2	9							N											Q	Q			Q	Q	Q				
3	10																						N						
4	12	Q	N																N	N						N			N
5	14	F	F		N														N	Q						N			N
6	15																		F	F			N	N	N				
7	16																						N	N	N				
8	17																												
9	18																									N	N		Q
10	19	N						N											H	H						N			N
11	20																									N			F
12	21																												
13	23																									N	N		N
14	24	N									Q								N	F		N				N			F
15	25					N		H			I	N	I		H				H	H		N							
16	26	N						Q			F								Q	N	N					N			N
17	27	N	N					Q			Q								Q	F						N			N
18	28				N														H	N	H					N			F
19	29	F						Q					F						F	F		N				N			N
20	31																												
21	32	Q				N							N						N	F									
22	33	Q	F								Q								Q	Q									
23	36																									N			N
24	37																									N	N		F
25	38	N	N		Q			N			N								N	F		N							
26	39																												
27	41	F	H		N														F	N									
28	42							Q					Q						N	N	N								
29	43																												
30	44													N					F	F	N								
31	45																												
32	46																												
33	47	N						N											N	F									
34	48																												
35	49																												
36	50																												
37	51																												
38	52	F	Q										N						F	N	N								
39	53																												
40	54																												
41	56																												
42	57																												
43	58																												
44	59																												
45	31																												
46	63																												
47	65																												

Legend:

N Component considered normal
F Component considered faulty; expected life more than 100 hours
Q Component condition questionable
H Component considered faulty; expected life less than 100 hours
I Component considered faulty; failure predicted to be imminent

ACOUSTIC DATA REDUCTION

All of the acoustic recordings were reviewed to eliminate those which were considered to be unsatisfactory for analysis. The causes for elimination varied and could be attributed to one or more of the following:

- Recordings were of poor quality. This could at times be attributed to operator errors or to equipment malfunctions.
- Recordings were made during times when the aircraft's operating speeds exceeded the acceptable limits of the analyzer.
- The signal strength was so low as to cause suspicion in the reliability of the signal.

Narrow-band spectrograms were produced on all of the recordings, using a General Radio Type 1900A narrow-band analyzer having a constant bandwidth of 10 Hertz. The spectrograms proved to be extremely helpful in determining the quality of the recordings and for conducting studies of the various frequencies of interest.

The transmission and gearbox components which were programmed to be checked with the CWEA-4 analyzer were checked for their "go/no-go" condition, and their respective analyzer meter readings were recorded on UH-1 sonic analyzer acoustic log sheets (information from these sheets is presented in Tables II and III). The sheets include the following:

1. Itemized identification of components under investigation and described by schematic component number.
2. The microphone which is used to record the data. This subsequently identified the channel upon which the data of interest are recorded.
3. The lock which is used to ratio the frequency of interest.
4. The octal ratio of this frequency of the component being investigated. (See Appendix II for a description of the establishment of octal ratios.)
5. The condition level that is to be used to determine a go/no-go condition. Since this effort has been one of establishing the go/no-go condition level, the actual level was read and recorded on the sheet for subsequent analysis studies.

6. A schematic reference number of the component under investigation.

7. The Bell Helicopter part number of the component under consideration.

TABLE II. UH-1 SONIC ANALYZER ACOUSTIC LOG SHEET – UH-1D TRANSMISSION

Item	Component	Mic Sel	Lock Sel	Ratio Set	Gain Set	Condition Level	Schematic Ref. No.	Part Number
1	Start	0	0	0.0000	0-0	Start	Start	
2	Clear	0	1	0.0000	0-0	Clear	Clear	
3	N_1 Cal	0	1	0.3223	5-5	Set Max	N_1 Cal	
4	N_2 Cal	0	2	0.3533	5-5	Set Max	N_2 Cal	
5	Mic No. 1 Norm	1	1	1.1223	5-25	Set 5	Mic 1 Norm	
6	Lock Check C-1	1	1	0-7333	5-10	Read Peg	Lock Check	
7	23 f_1 Brg Xmsn Input	1	2	0.1056	1-20	Read	23, Fig 7	204-040-142-001
8	f_2	1	2	0.0736	4-20	Read		
9	$2f_2$	1	2	0.1673	4-15	Read		
10	f_b'	1	2	0.1133	2-25	Read		
11	$3f_b'$	1	2	0.3421	1-25	Read		
12	24 f_1	1	2	0.0641	3-20	Read	24, Fig 7	204-040-346-003
13	f_2	1	2	0.0441	5-15	Read		
14	$3f_b'$	1	2	0-1366	2-25	Read		
15	1-2-3 Noise Input Bevel	1	2	0.2642	4-10	Read	1, Fig 7	204-040-700-001
16	f_t	1	2	0.2525	0-0	Read	2, Fig 7	204-040-701-003
17	$2f_t$	1	2	0.5253	2-15	Read	3, Fig 7	204-040-100-003
18	1-3 $-f_r$	1	2	0-2446	4-10	Read		
19	1-3 $+f_r$	1	2	0.2604	4-10	Read		
20	2 $-f_r$	1	2	0-2477	4-10	Read		
21	2 $+f_r$	1	2	0.2553	4-10	Read		
22	25 f_1 Brg Input Quill	1	2	0.0527	2-20	Read	25, Fig 7	204-040-269-003
23	f_2	1	2	0.0336	2-15	Read		
24	$3f_b'$	1	2	0.1161	2-25	Read		
25	25 f_1 Brg Opt	1	2	0-0474	2-20	Read	25, Fig 7	204-040-269-003
26	f_2	1	2	0.0312	2-15	Read		
27	$3f_b'$	1	2	0.1147	2-25	Read		

TABLE II — Continued

Item	Component	Mic Sel	Lock Sel	Ratio Set	Gain Set	Condition Level	Schematic Ref. No.	Part Number
28	Mic No. 1 Norm	1	2	1.1223	5-25	Set 5	Mic I Norm	
29	7-8-9 Noise Low Pln Gr	1	2	0.1545	4-15	Read	7, Fig 7	204-040-329-001
30	7-8-9 f_t	1	2	0.1520	3-15	Read	8, Fig 7	204-040-108-005
31	$2f_t$	1	2	0.3241	3-15	Read	9, Fig 7	204-040-331-005
32	7 $-f_r$	1	2	0.1501	2-20	Read		
33	7 $+f_r$	1	2	0.1537	3-15	Read		
34	8 $-f_r$	1	2	0.1464	2-20	Read		
35	8 $+f_r$	1	2	0.1554	3-15	Read		
36	9 $-f_r$	1	2	0.1510	2-20	Read		
37	9 $+f_r$	1	2	0.1527	3-15	Read		
38	34 f_1 Brg	1	2	0.0264	4-10	Read	34, Fig 7	204-040-135-001
39	10-11-12 Noise Up Pln Grs	1	2	0.0450	4-10	Read	10, Fig 7	204-040-330-003
40	10-11-12 f_t	1	2	0.0423	4-15	Read	11, Fig 7	204-040-108-007
41	$2f_t$	1	2	0.1046	1-15	Read	12, Fig 7	204-040-331-005
42	10 $-f_r$	1	2	0.0415	3-10	Read		
43	10 $+f_r$	1	2	0.0427	4-10	Read		
44	11 $-f_r$	1	2	0.0411	3-10	Read		
45	11 $+f_r$	1	2	0.0433	3-10	Read		
46	12 $-f_r$ Gr	1	2	0.0420	3-10	Read		
47	12 $+f_r$ Gr	1	2	0.0426	4-10	Read		
48	36 f_1 Brg Rotor Lo Sp	1	2	0.0072	2-15	Read	36, Fig 7	204-040-135-1
49	f_2	1	2	0.0065	2-15	Read		
50	f_b'	1	2	0.0056	2-15	Read		
51	$3f_b'$	1	2	0.0210	2-15	Read		
52	37 f_1 Brg Upper Rotor	1	2	0.0032	1-20	Read	37, Fig 7	204-040-136-7
53	f_2	1	2	0.0024	1-20	Read		
54	f_b'	1	2	0.0021	1-20	Read		

TABLE II – Continued

Item	Component	Mic Sel	Lock Sel	Ratio Set	Gain Set	Condition Level	Schematic Ref. No.	Part Number
55	$3f_b'$	1	2	0.0062	2-15	Read		
56	48 f_1 Brg Swash Plate	1	2	0.0145	2-10	Read	48, Fig 7	204-101-425-1
57	f_2	1	2	0.0137	2-10	Read		
58	f_b'	1	2	0.0107	3-5	Read		
59	$3f_b'$	1	2	0.0325	3-15	Read		
60	Mic No. 1 Norm	1	1	1.1223	5-25	Set 5	Mic 1 Norm	
61	26 f_2 Brg Main Bev Gr	1	2	0.0403	4-15	Read	26, Fig 7	204-040-345-7
62	f_b'	1	2	0.0346	2-15	Read		
63	$3f_b'$	1	2	0.1263	0-25	Read		
64	26 f_b Brg Opt	1	2	0.0323	2-15	Read	26, Fig 7	
65	$3f_b'$	1	2	0.1171	2-25	Read		
66	27 f_2 Brg Main Bev Gr	1	2	0.0503	2-20	Read	27, Fig 7	204-040-271-3
67	$3f_b'$	1	2	0.1415	2-25	Read		
68	13-14 Noise Gr Xmsn Spur	1	2	0.2257	2-15	Read	13, Fig 7 14, Fig 7	204-040-763-1 204-040-762-1
69	13-14 f_t	1	2	0.2273	2-15	Read		
70	13-14 $2f_t$	1	2	0.4566	3-20	Read		
71	13 $-f_r$	1	2	0.2245	5-15	Read		
72	13 $+f_r$	1	2	0.2321	4-15	Read		
73	14 $-f_r$	1	2	0.2235	5-15	Read		
74	14 $+f_r$	1	2	0.2230	4-15	Read		
75	38 f_1 Brg Lower Xmsn	1	2	0.1053	5-15	Read	38, Fig 7	204-040-135-001
76	f_2	1	2	0.0766	5-25	Read		
77	f_b'	1	2	0.0670	3-20	Read		
78	$3f_b'$	1	2	0.2421	1-25	Read		
79	39 f_1 Brg Lower Rotor	1	2	0.0043	3-20	Read	39, Fig 7	204-040-270-003
80	f_2	1	2	0.0035	4-20	Read		

TABLE II — Concluded

Item	Component	Mic Sel	Lock Sel	Ratio Set	Gain Set	Condition Level	Schematic Ref. No.	Part Number
81	f_b'	1	2	0.0031	4-20	Read		
82	$3f_b'$	1	2	0.0112	2-10	Read		
83	Mic No. 1 Norm	1	1	1.1223	5-25	Set 5	Mic 1 Norm	
84	40 f_1 Brg Lower Xmsn	1	2	0.0331	5-15	Read	40, Fig 7	204-040-143-001
85	f_2	1	2	0.0212	4-10	Read		
86	f_b'	1	2	0.0176	4-10	Read		
87	$3f_b'$	1	2	0.0573	3-20	Read		
88	41 f_1 Brg Lower Xmsn Input	1	2	0.0365	0-15	Read		
89	f_2	1	2	0.0251	0-15	Read		
90	f_b'	1	2	0.0234	1-15	Read		
91	$3f_b'$	1	2	0.0722	2-20	Read		
92	15-16-17 Noise Acc Bevel Gr	1	2	0.1421	0-15	Read	15, Fig 7	204-040-103-007
93	15-16-17 f_t	1	2	0.1435	0-15	Read	16, Fig 7	204-040-104-013
94	$2f_t$	1	2	0.3072	0-15	Read	17, Fig 7	204-040-105-021
95	$-f_r$	1	2	0.1377	2-15	Read		
96	$+f_r$	1	2	0.1474	2-15	Read		
97	f_t Oil Pump	1	2	0.0166	1-10	Read		
98	42 f_1 Brg Lower Xmsn	1	2	0.0376	4-15	Read	42, Fig 7	204-040-310-1
99	f_2	1	2	0.0257	4-10	Read		
100	$2f_2$	1	2	0.0536	5-15	Read		
101	$3f_2$	1	2	0.1015	2-20	Read		
102	$3f_b'$	1	2	0.0744	2-25	Read		
103	43 f_1 Brg	1	2	0.0341	3-15	Read	43, Fig 7	204-040-143-1
104	f_2	1	2	0.0217	2-15	Read		
105	f_b'	1	2	0.0203	2-15	Read		
106	$3f_b'$	1	2	0.0611	1-25	Read		
107	Mic No. 1 Norm	1	1	1.1223	5-25	Set 5	Mic I Norm	

TABLE III. UH-1 SONIC ANALYZER ACOUSTIC LOG SHEET – UH-1D TAIL ROTOR

Item	Component	Mic Sel	Lock Sel	Ratio Set	Gain Set	Condition Level	Schematic Ref. No.	Part Number
1	Start	0	1	0.0000	0-0	Start	Start	
2	Clear	0	1	0.0000	0-0	Clear	Clear	
3	N_1 Cal	1	1	0.3223	5-5	Set Max	N_1 Cal	
4	N_2 Cal	1	2	0.3533	5-5	Set Max	N_2 Cal	
5	Mic No. 1 Norm	1	1	1.1223	5-25	Set 5	Mic 1 Norm	
6	Lock Check C-1	1	1	0.7333	5-10	Read Peg	Lock Check	
7	Mic No. 3 Norm	3	1	1.1223	5-25	Set 5	Mic 3 Norm	
8	46 f_1 Brg T/R Shaft	3	2	0.0304	1-0	Read	46, Fig 8	204-040-615-003
9	f_2	3	2	0-0215	0-0	Read		
10	f_b'	3	2	0.0266	1-0	Read		
11	$3f_b'$	3	2	0-1043	2-10	Read		
12	43 f_1 Brg 42-deg & 90-deg Gearbox	3	2	0-0341	2-5	Read	43, Fig 8	204-040-143-001
13	f_2	3	2	0-0217	0-0	Read		
14	f_b'	3	2	0.0203	0-0	Read		
15	$3f_b'$	3	2	0-0611	4-5	Read		

TABLE III – Concluded

Item		Component	Mic Sel	Lock Sel	Ratio Set	Gain Set	Condition Level	Schematic Ref. No.	Part Number
16	42	f_1 Brg 42-deg Gearbox	3	2	0-0376	1-10	Read	42, Fig 8	204-040-310-001
17		f_2	3	2	0-0257	3-10	Read		
18		f_b'	3	2	0-0241	5-0	Read		
19		$3f_b'$	3	2	0-0743	2-5	Read		
20	50 51	Noise Gr 42-deg Bevel	3	2	0.1553	4-0	Read	50, Fig 8 51,	204-040-500-009 204-040-500-010
21	50 51	f_t Gr 42-deg Bevel	3	2	01474	0-0	Read		
22		$2f_t$	3	2	0.3171	1-0	Read		
23		$-f_r$	3	2	0.1436	1-0	Read		
24		$+f_r$	3	2	0.1533	1-0	Read		
25	52 53	Noise Gr 90-deg Bevel	3	2	0.0773	1-0	Read	52, Fig 8 53,	204-040-400-009 204-040-401-007
26	52 53	f_t Gr 90-deg Bevel	3	2	0.0714	0-0	Read		
27		$2f_t$	3	2	0-1630	0-0	Read		
28		$-f_r$	3	2	0-0655	0-0	Read		
29		$+f_r$	3	2	0.0753	0-0	Read		
30	Mic No. 3 Norm		3	1	1.1223	5-25	Set-5	Mic 3 Norm	

DATA ANALYSIS

FREQUENCY/AMPLITUDE PROCEDURE

Prior to this house task, the procedure followed in analyzing a component using the UH-1 CWEA-4 sonic analyzer was to identify a frequency representative of the component under analysis and to establish an amplitude above which the component's condition was considered to be faulty. This method of analysis is quick and simple, inasmuch as the frequency of interest can be selected on the sonic analyzer and the amplitude can be read directly.

This method proved to be satisfactory for the bearing analysis, but it was unsatisfactory for the gear analysis.

The reason that it was unsatisfactory for gears and the subsequent revised technique used are discussed in the following section.

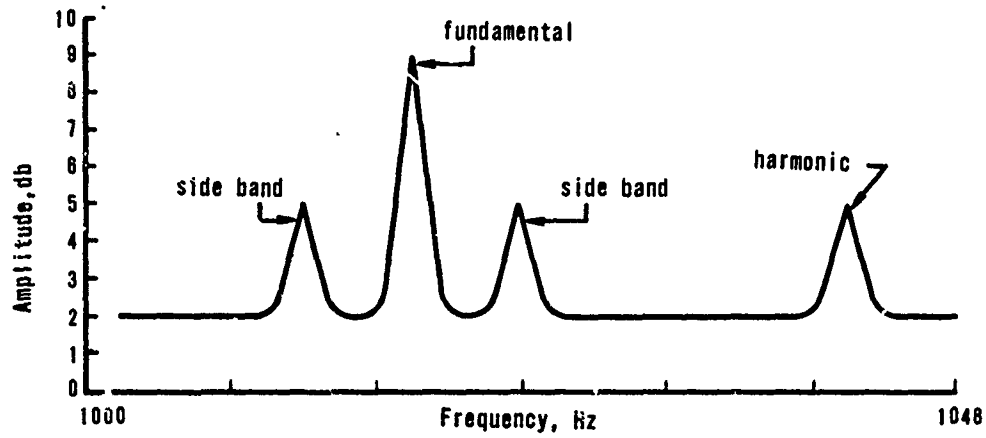
GEAR ANALYSIS PROCEDURE

A simple spectrum representing a faulty gear is shown in Figure 12(a). The fundamental frequency, two side-band frequencies, and one harmonic frequency are shown. Figures 12(b), (c), and (d) present spectrums representing three good gears of the same type.

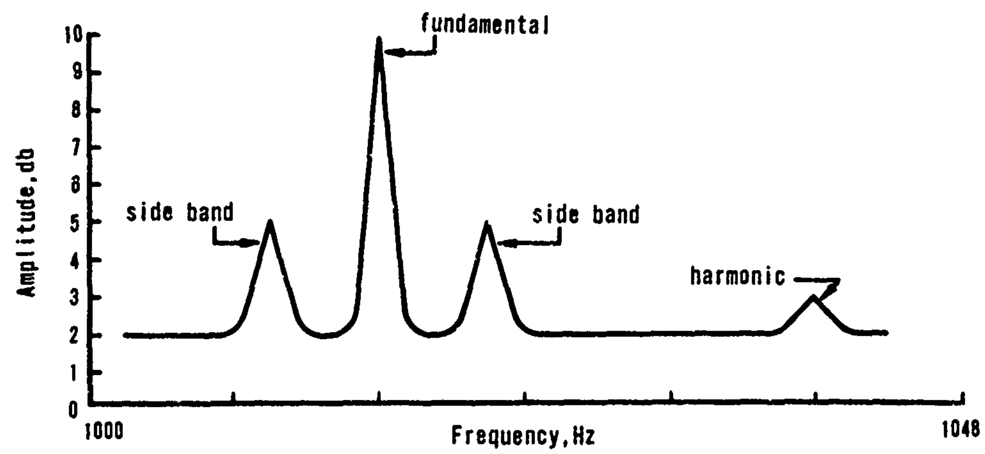
The amplitudes of the frequencies of interest for the examples are as follows:

	Faulty Gear	Good Gears		
	Figure 12(a)	Figure 12(b)	Figure 12(c)	Figure 12(d)
f_t	9	10	8	9
$+f_r$	5	5	4	4
$-f_r$	5	5	4	4
$2f_r$	5	3	4	6
Total	24	23	20	23

Earlier criteria for the rejection of gears include the use solely of the exceedance of a preselected amplitude of the fundamental frequency or the exceedance of the ratio of the amplitudes of the fundamental frequency and one of the side-band frequencies. These criteria thus far have not produced satisfactory results. The reason for this is readily apparent. By comparing the amplitudes of frequencies of interest in the various spectrums, it can be seen that the faulty gear could not be identified by noting the exceedance of any particular frequency amplitude. For example, it is seen that the amplitude of the fundamental frequency of one of the good gears exceeds that of the faulty gear. On the other hand, it can be observed that the summation of all of the frequency amplitudes of each gear results in values where the faulty gear value is higher than those of the good gears. The summation approach is used as the procedure for identifying faulty gears.

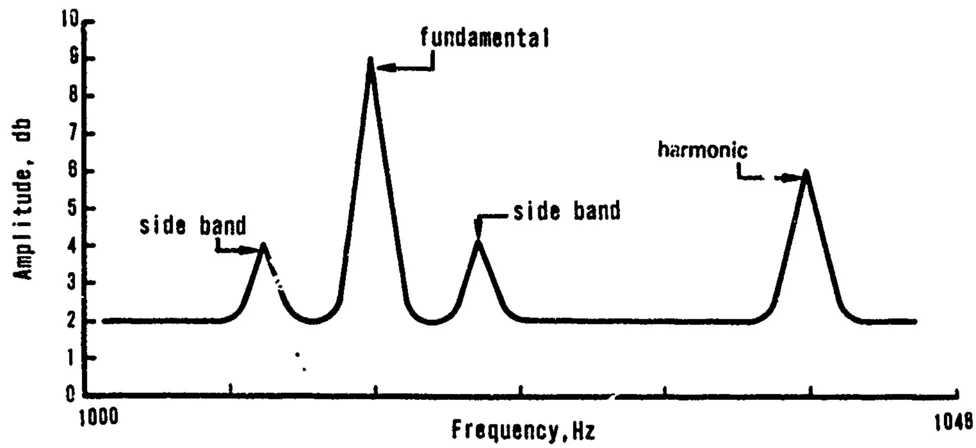


a. Typical Faulty Gear.

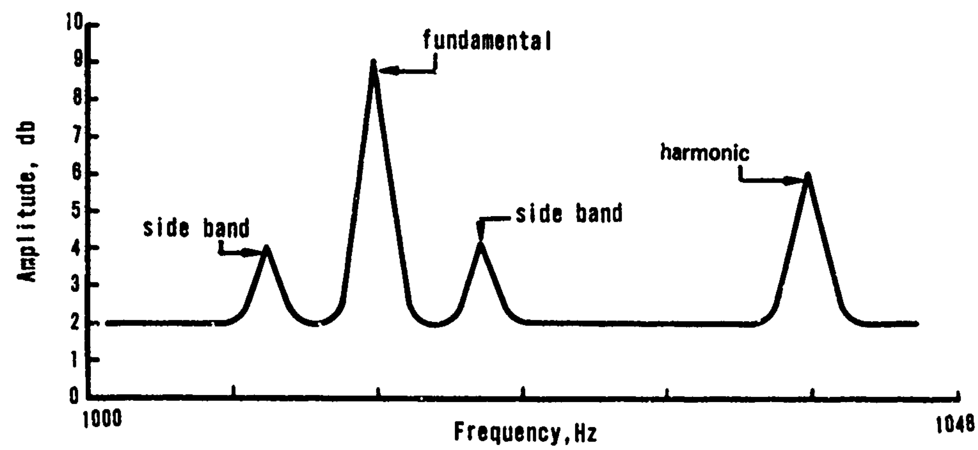


b. Good Gear, Where the Amplitude of the Second Harmonic Is Low.

Figure 12. Simple Frequency/Amplitude Spectrums.



c. Typical Good Gear, Where the Amplitude of the Second Harmonic Side Bands of the Fundamental Frequency Are Essentially the Same.



d. Typical Good Gear, Where the Amplitude of the Second Harmonic Is High.

Figure 12. Continued.

NORMALIZATION

On the example spectrums of Figure 12, it was assumed that the noise levels of all the gears were the same. In real life, this is not the case, inasmuch as the noise level in the neighboring frequency range associated with any component is different from run to run. Therefore, in order to compare spectrums of various runs, the spectrums had to be normalized. There appeared to be a relationship between the noise level of a good gear and the amplitude of the characteristic frequency, inasmuch as those spectrums that displayed a high noise level also displayed a high frequency amplitude. In other words, the signal-to-noise ratio appeared to remain mathematically relatable, even constant, for good gears of the same type. This is depicted graphically in Figure 13.

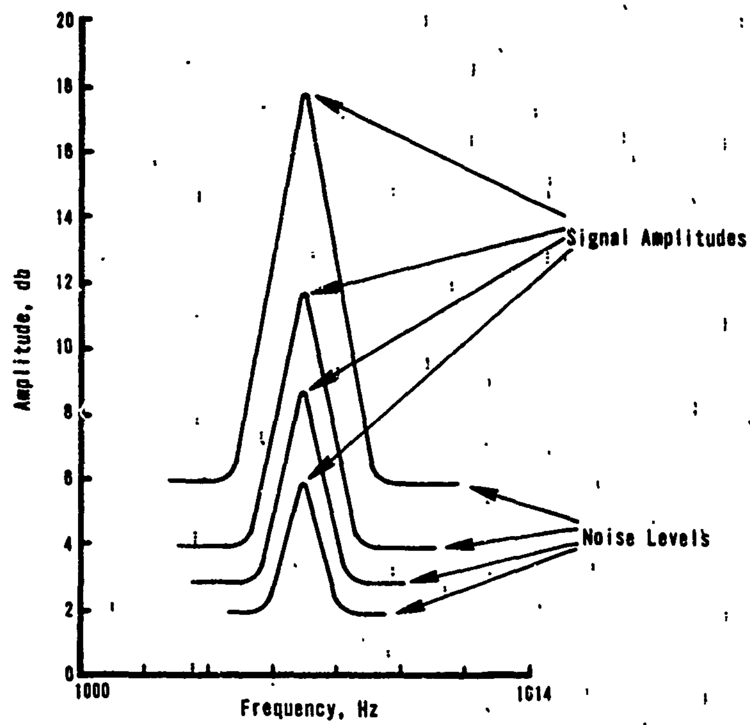


Figure 13. Typical Relationship Between Signal Amplitudes and Noise Levels for a Good Gear.

Now, in order to determine what the amplitude of a good gear signal would be for any observed noise level, it is first necessary to empirically derive an equation which gives an approximate relationship between the good gear signal amplitude and the noise level. This must be done for each frequency of interest, inasmuch as the signal-to-noise ratio (equation to be derived) would not be expected to be the same for all of the signals generated by the various components. An example of how such an equation is derived follows, using the data related to the 90-degree gearbox bevel gears.

90-DEGREE GEARBOX GEAR ANALYSIS

The meter readings for the 90-degree gearbox are presented in Table IV. Using the signal amplitude (f_t) and noise values of the 90-degree gearbox, as recorded in this table, a plot of signal versus noise has been made (see Figure 14). Although the scatter of data is such that a straight line cannot be drawn through the majority of the points, a first-degree equation has been written to define the average value of the fundamental frequency meter reading for various noise values: $f_t = 2(n) + 2$. It can be seen that the use of a higher order equation to define the average value would have resulted in a more accurate definition of the relationship. However, in order to maintain a relatively simple analysis procedure, the first-degree equation was used.

The gains used on the Curtiss-Wright signal conditioner are set so that the meter readings for good components should, on the average, read a value of 5. It can then be seen in Figure 14 that for a meter reading of 5, a noise level of 1.5 should be observed for a good component. Therefore, the procedure of normalizing the signal for a particular noise level is based on the noise level of 1.5.

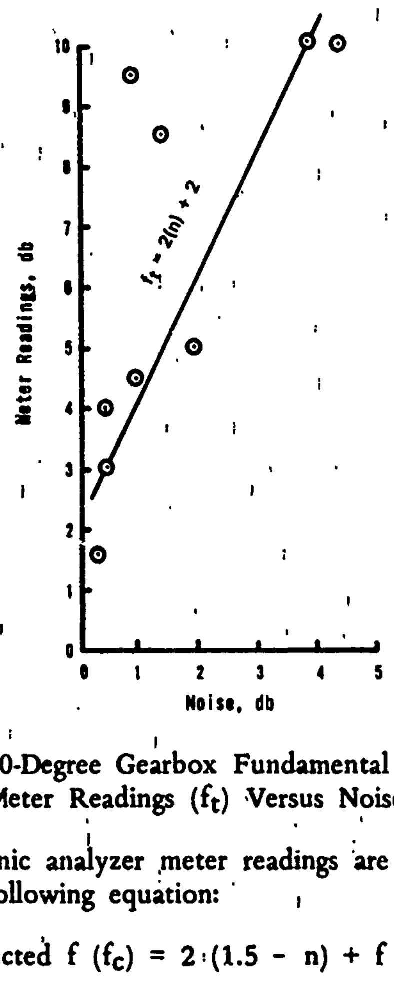


Figure 14. 90-Degree Gearbox Fundamental Frequency Meter Readings (f_t) Versus Noise Readings.

Corrected values of the sonic analyzer meter readings are then established for the frequencies by using the following equation:

$$\text{corrected } f\ (f_c) = 2(1.5 - n) + f$$

This equation then shows that at a noise level of 1.5, $f_{tc} = f_t$, and for any other noise level, the corrected value would be different from the value read from the meter. The corrected values of the analyzer meter readings, using this equation, are shown in Table V. Table VI summarizes the analysis of the 90-degree gearbox and bevel gears.

TABLE IV. SONIC ANALYZER METER READINGS FOR 90-DEGREE GEARBOX BEVEL GEARS (52) AND (53)

Gear Condition	Satisfactory									Faulty				
Run No.	7	12	14	19	23	26	27	29	36	18	20	24	28	37
Tape Item No.														
26A f_t	1.6	4.5	3.0	4.5	8.5	5.0	P	P	9.5	6.5	P	6.5	P	P
26B n	0.3	1.0	0.5	0.5	1.5	2.0	4	4.5	1.0	1.5	1.5	1.0	1.5	2.5
27 $-f_r$	0.5	0.5	1.0	2.5	1.5	2.5	3.5	4.5	1.0	3.0	1.5	3.0	3.0	2.0
28 $+f_r$	0.5	0.5	0.5	1.5	1.0	2.5	3.5	5.0	1.0	3.0	5.5	2.5	5.5	3.0
29 $2f_t$	0.5	1.0	1.0	0.5	1.5	2.5	1.5	3.5	1.5	2.5	1.5	1.5	1.5	5.5
Total (less 26B n)	3.1	6.5	5.5	9.0	12.5	12.5	18.5	23.0	13.0	15.0	18.5	13.5	20.0	20.5

TABLE V. CORRECTED SONIC ANALYZER METER READINGS FOR 90-DEGREE GEARBOX BEVEL GEARS (52) AND (53)

Gear Condition	Satisfactory									Faulty				
Run No.	7	12	14	19	23	26	27	29	36	18	20	24	28	37
Tape Item No.														
26A f_{tc}	4.0	5.5	5.0	6.5	4.5	4.0	5.0	4.0	10.5	6.5	10.0	7.5	10.0	8.0
27 $-f_{rc}$	1.4	0.9	1.7	3.2	0.1	2.1	1.7	2.3	1.4	3.0	1.5	3.4	3.0	1.3
28 $+f_{rc}$	1.4	0.9	1.2	2.2	-0.4	2.1	1.7	2.8	1.4	3.0	5.5	2.9	5.5	2.3
29 $2f_{tc}$	1.4	1.4	1.7	1.2	0.1	2.1	-0.3	1.3	1.9	2.5	1.5	1.9	1.5	4.8
Total	8.2	8.7	9.6	13.1	4.3	10.3	8.1	10.4	15.2	15.0	18.5	15.7	20.0	16.4

TABLE VI. GEAR ANALYSIS SUMMARY – 90-DEGREE GEARBOX BEVEL GEARS (52) AND (53)

Run No.	Corrected Analyzer Reading Summation Value (db)	Sonic Analysis Rejection (15.5)	Teardown Inspection Rejection	Inspection Comments
7	8.2	No	No	Both gears OK
12	8.7	No	No	Both gears OK
14	9.6	No	No	Both gears OK
19	13.1	No	No	Patterns look good
23	4.3	No	No	Both gears OK
26	10.3	No	No	Both gears OK
27	8.1	No	No	Both gears OK
29	10.4	No	No	Both gears OK
36	15.2	No	No	Both gears OK
18	15.0	No	Questionable	Some coast side pattern on both gears
20	18.5	Yes	Yes	Gears not failed, but heavy wear.
24	15.7	Yes	Yes	Gear 52 assumed OK, Gear 53 barber-poling.
28	20.0	Yes	Yes	Good gear pattern with hard line on gear 52. Input pinion has heavy pattern on toe with bright hard line on gear 53.
37	16.4	Yes	Yes	Heavy pattern with hard line.

Side-Band and Second-Harmonic Meter Reading Corrections

Plots of the second-harmonic frequency and the upper and lower side-band frequency meter readings versus noise readings are presented in Figures 15, 16, and 17. The values used are from Table IV. Since the slope of the average value for the meter readings versus noise readings for all three figures was found to be essentially the same (.72), one general equation can be written to correct all three frequency readings for a normalized noise level of 1.5. The resulting equation, expressed in terms of an approximating first-degree equation, is thus:

$$f_{-rc} = .72\ (1.5 - n) + f_{-r}$$

$$f_{+rc} = .72\ (1.5 - n) + f_{+r}$$

$$2f_{tc} = .72\ (1.5 - n) + 2f_t$$

These corrected values are tabulated in Table VI.

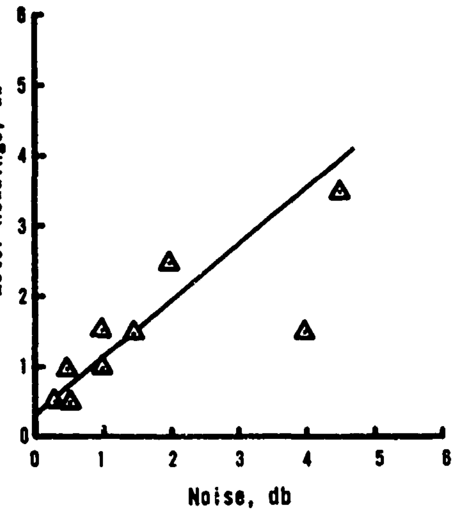


Figure 15. 90-Degree Gearbox Bevel Gears – Second Harmonic Meter Readings ($2f_t$) Versus Noise Readings

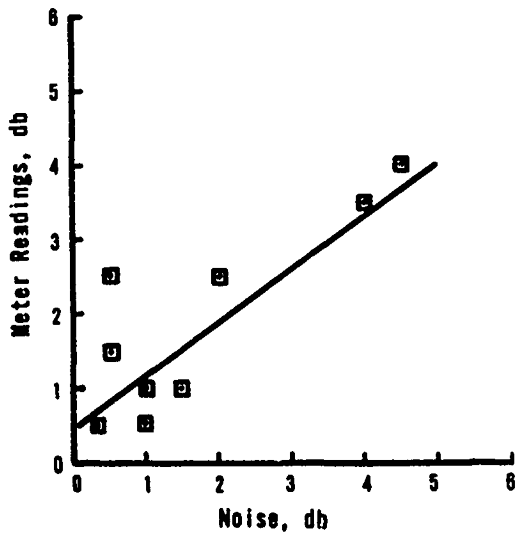


Figure 16. 90-Degree Gearbox Bevel Gears – Lower Side-Band Meter Readings ($-f_r$) Versus Noise Readings.

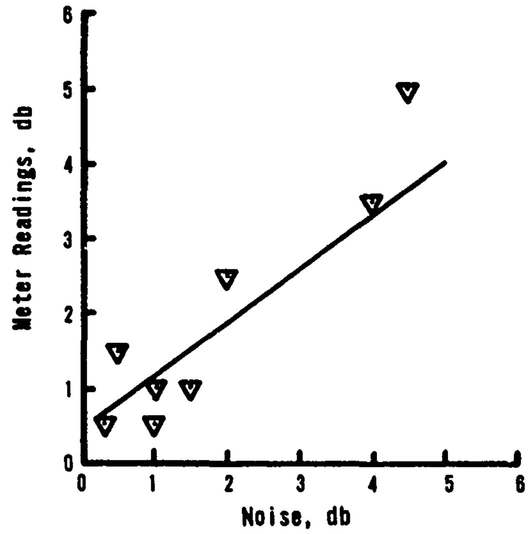


Figure 17. 90-Degree Gearbox Bevel Gears – Upper Side-Band Meter Readings ($+f_t$) Versus Noise Readings.

Establishment of Rejection Value

By plotting (Figure 18) the values of the sum of the four corrected frequency readings versus the test runs identified as being on good or faulty gears, it can be observed that a reject limit of 15.5 can be established.

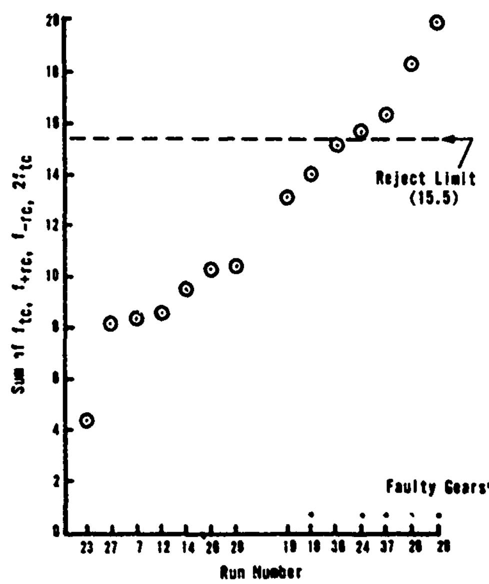


Figure 18. Summation of Corrected Meter Readings for the 90-Degree Gearbox Bevel Gears.

42-DEGREE GEARBOX GEAR ANALYSIS

Because the information received from the mechanical condition analysis was limited to only four gearboxes, none of which were reported as faulty, the reject limit for the 42-degree gearbox could not be statistically established. Table VII summarizes the information compiled on the four gearbox bevel gears, but no conclusions were drawn since the analysis was not complete; the information was recorded only as data for future investigations.

TABLE VII. SONIC ANALYZER METER READINGS FOR 42-DEGREE GEARBOX BEVEL GEARS (50) AND (51)

Tape Item Number		Run Number 9	10	15	16
21A	f_t	5.0	5.0	3.5	4.0
21B	Noise	1.0	0.5	0.5	1.0
21C	f_t	7.0	7.5	5.5	6.0
22	$-f_r$	1.0	0.5	0.5	1.0
23	$+f_r$	1.5	1.0	1.0	0.5
24	$2f_t$	1.0	1.0	0.5	1.5

TRANSMISSION GEAR ANALYSIS

Input Drive Bevel Gears (1), (2), and (3)

There were no faulty input drive bevel gears reported on any of the transmission inspection reports, so they were all considered to be normal. As additional data are collected in future efforts, reject limits for faulty gears (1), (2), and (3) will be established.

Lower Planetary Gears (7), (8), and (9)

Using the same procedure as that discussed for the 90-degree gearbox analysis, a meter reading correction equation was established:

$$f_c = 1.25\ (1.5 - n) + f$$

Applying this equation to the meter readings in Table VIII resulted in the corrected readings shown in Table IX. It was determined that the correction equation should be applied to all of the frequencies of interest except for the first-harmonic meter readings, where no correcting was found to be necessary.

As shown in Figure 19, a reject limit of 23 has been established for gears (7), (8), and (9). It can be easily seen that this limit will accept three of the four satisfactory gears and will reject all of the faulty gears.

A gear analysis summary for the lower planetary gears is presented in Table X.

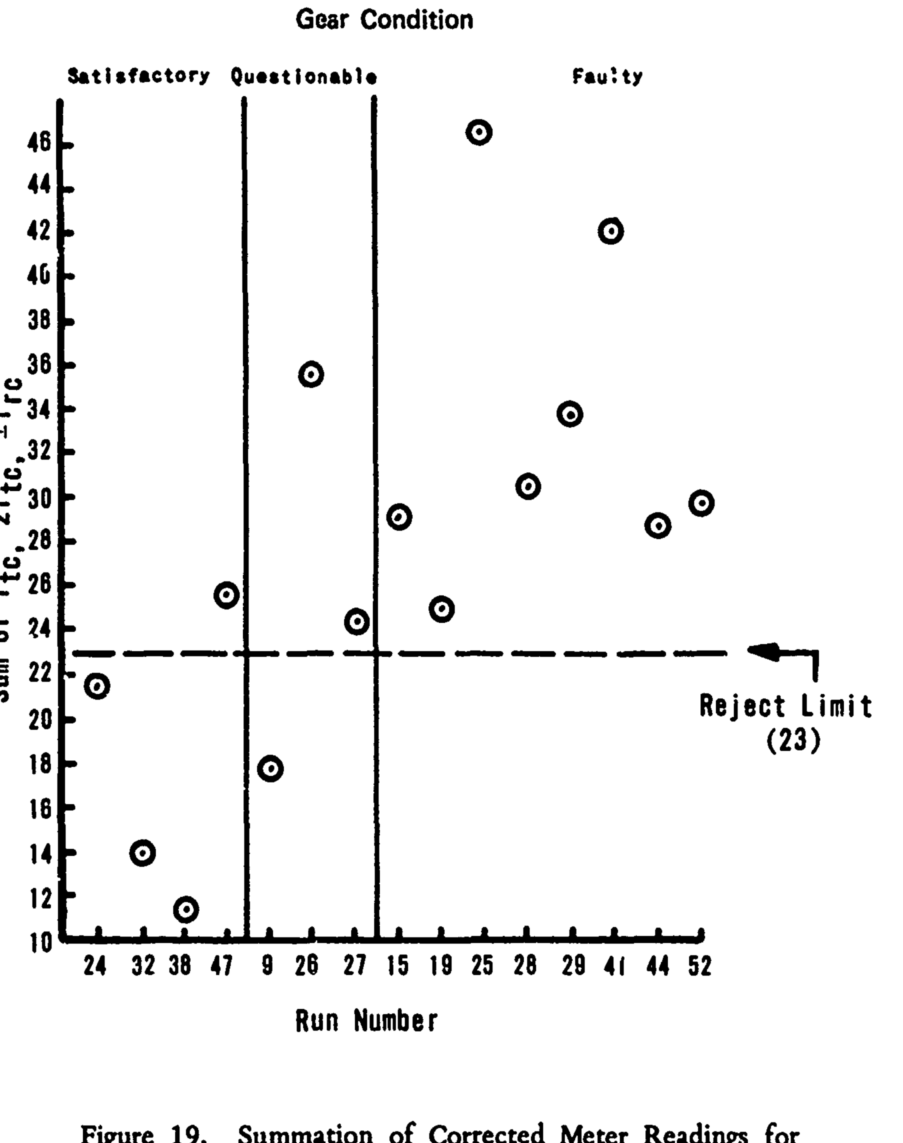


Figure 19. Summation of Corrected Meter Readings for Lower Planetary Gears (7), (8), and (9).

TABLE VIII. SONIC ANALYZER METER READINGS FOR LOWER PLANETARY GEARS (7), (8), AND (9)

Gear Condition	Satisfactory				Questionable			Faulty							
Run No.	24	32	38	47	9	26	27	15	19	25	28	29	41	44	52
Noise	1.7	3.2	3.2	2.7	1.5	2.7	2.0	1.0	.75	1.2	1.5	2.0	3.0	2.2	3.0
f_t	2.0	4.0	3.0	3.2	2.2	5.0	4.0	3.5	1.5	4.5	2.5	2.5	4.0	3.5	3.5
$2f_t$	3.5	3.5	2.0	3.5	5.0	10.0	4.0	1.5	2.5	2.0	3.0	6.0	7.0	2.5	6.0
7 $-f_r$	3.0	3.5	5.0	4.5	2.0	4.5	2.0	1.5	1.5	2.0	3.5	6.5	6.5	4.5	6.0
7 $+f_r$	3.0	3.5	3.5	4.5	1.5	4.5	4.5	5.5	3.0	9.0	5.5	4.0	7.0	5.5	4.5
8 $-f_r$	2.5	3.5	3.0	3.5	2.5	5.0	2.5	1.5	2.0	3.0	3.0	5.0	6.0	4.5	6.0
8 $+f_r$	3.0	3.5	2.5	3.0	1.0	4.5	5.0	2.5	2.0	6.5	3.5	5.0	7.0	3.0	4.0
9 $-f_r$	1.5	3.5	2.0	2.0	1.0	2.5	1.5	1.0	0.5	1.5	1.5	2.0	3.0	1.5	2.0
9 $+f_r$	4.0	3.5	5.0	12.0	2.5	10.1	5.0	8.0	6.0	15.0	8.0	7.0	12.0	10.0	8.0
Total (less noise)	22.5	28.5	26.0	36.2	17.7	46.1	28.5	25.0	19.0	43.5	30.5	38.0	52.5	35.0	40.0

TABLE IX. CORRECTED SONIC ANALYZER METER READINGS FOR LOWER PLANETARY GEARS (7), (8), AND (9)

Gear Condition	Satisfactory				Questionable			Faulty							
Run No.	24	32	38	47	9	26	27	15	19	25	28	29	41	44	52
f_{tc}	1.8	1.9	0.9	1.7	2.2	3.5	3.4	4.1	2.4	4.9	2.5	1.9	2.5	2.4	2.0
$2f_{tc}$	3.5	3.5	2.0	3.5	5.0	10.0	4.0	1.5	2.5	2.0	3.0	6.0	7.0	2.5	6.0
7 $-f_{rc}$	2.8	1.4	2.9	3.0	2.0	3.0	1.4	2.1	2.4	2.4	3.5	5.9	5.0	3.6	4.5
7 $+f_{rc}$	2.8	1.4	1.4	3.0	1.5	3.0	3.9	6.1	3.4	9.4	5.5	3.4	5.5	4.6	3.0
8 $-f_{rc}$	2.3	1.4	0.9	2.0	2.5	3.5	1.9	2.1	2.9	3.4	3.0	4.4	4.5	3.6	4.5
8 $+f_{rc}$	2.8	1.4	0.4	2.0	1.0	3.0	4.4	3.1	2.9	6.9	3.5	4.4	5.5	2.1	2.5
9 $-f_{rc}$	1.3	1.4	-	0.5	1.0	1.0	0.9	1.6	1.3	1.9	1.5	1.4	1.5	0.6	0.5
9 $+f_{rc}$	3.8	1.4	2.9	10.0	2.5	8.6	4.4	8.6	6.9	15.4	8.0	6.4	10.5	9.1	6.5
Total	21.1	13.8	11.4	25.7	17.7	35.6	24.3	29.2	24.7	46.3	30.5	33.8	42.0	28.5	29.5

TABLE X. GEAR ANALYSIS SUMMARY – LOWER PLANETARY GEARS (7), (8), AND (9)

Run No.	Corrected Meter Reading Total (db)	Reject Limit Exceeded (23.0)	Teardown Inspection Reject	Inspection Comments
24	21.1	No	No	Sun gear (7) looks very good; no comments on gear (8); gear (9) is assumed OK.
32	13.8	No	No	Sun (7), planetary (8), and ring (9) gears look very good.
38	11.4	No	No	Sun gear has light tip loading, but looks OK; planetary gear looks good; ring gear looks good.
47	25.7	Yes	No	All gears look good.
9	17.7	No	Questionable	One planetary pi[illegible]n ge[illegible] very light pick-[illegible] in roo[illegible] gear OK; sun gear has heavy tip erosion, but looks OK.
26	35.6	Yes	Questionable	Sun gear assumed OK; ring gear assumed OK; four planetary pinions have some pitch line pitting.
27	24.3	Yes	Questionable	Sun gear has some tip wear.
15	29.2	Yes	Yes	Two planetary pinions scrapped; another pinion has pitting and slight flank wear; sun gear has heavy tip wear and pitting; ring gear assumed OK.
19	24.7	Yes	Yes	Sun gear has heavy tip wear with no pitting or spalling; ring tooth chipped on upper end; light wear on two lower planetary cages.
25	46.3	Yes	Yes	Sun gear has heavy wear pattern almost to pitch line; cannot rotate transmission by hand; pinions have heavy flank wear. This transmission has two components in the "failure imminent" category and three components "with less than 100 hr to failure".

TABLE X – Continued				
Run No.	Corrected Meter Reading Total (db)	Reject Limit Exceeded (23.0)	Teardown Inspection Reject	Inspection Comments
28	30.5	Yes	Yes	Sun gear has heavy tip wear; lower top corner has check failure indication.
29	33.8	Yes	Yes	Sun gear has moderate tip wear and some pitting throughout wear area; arrested pitting, destructive wear, interference wear, etc.
41	42.0	Yes	Yes	Sun gear has tip wear; one pinion has moderate flank wear; misalignment, destructive wear.
44	28.5	Yes	Yes	Ring gear teeth chipped; sun gear and planetary pinions are OK.
52	29.5	Yes	Yes	Sun gear has excessive wear on teeth, with visible change in involute profile; destructive wear, etc.

Upper Planetary Gears (10), (11), and (12)

Using the procedure previously described, meter reading correction equations were established:

$$\text{for } f_t: \quad f_{tc} = 4.2\,(1.5 - n) + f$$

$$\text{for } +f_r: \quad +f_{rc} = 4.2\,(1.5 - n) + (+f_r)$$

$$\text{for } -f_r: \quad -f_{rc} = 1.0\,(1.5 - n) + (-f_r)$$

for $2f_t$: no correction necessary

Applying these equations to the meter readings for the upper planetary gears in Table XI resulted in the corrected readings shown in Table XII and Figure 20. The upper planetary gear analysis is summarized in Table XIII.

TABLE XI. SONIC ANALYZER METER READINGS FOR UPPER PLANETARY GEARS (10), (11), AND (12)															
Gear Condition	Satisfactory				Questionable	Faulty									
Run No.	26	28	41	52	9	15	19	24	25	27	29	32	38	44	47
Noise	2.2	2.5	1.9	2.2	1.1	1.3	0.8	1.5	1.7	2.2	1.5	1.7	1.9	1.5	1.5
f_t	6.0	8.5	15.0	12.0	3.0	3.0	5.0	7.0	5.0	6.0	6.0	6.5	6.0	4.0	5.0
$2f_t$	2.0	1.5	3.0	4.0	0.05	1.0	1.0	1.5	1.5	2.5	1.0	3.5	2.0	1.5	1.5
10 $-f_r$	2.5	2.5	3.0	2.0	1.0	1.5	1.0	1.5	2.0	3.5	1.5	2.0	2.5	1.5	1.5
10 $+f_r$	4.0	5.5	8.5	6.5	1.5	2.0	3.0	4.0	3.5	3.5	4.5	4.0	4.0	3.0	3.0
11 $-f_r$	2.5	2.5	3.0	2.0	1.0	1.5	1.0	1.5	2.0	3.5	2.0	2.5	2.5	1.5	1.5
11 $+f_r$	3.0	4.0	6.0	4.0	1.0	1.5	2.0	3.0	2.5	3.5	3.5	3.0	3.0	1.5	1.5
12 $-f_r$	2.5	3.5	3.5	3.5	1.0	1.5	1.5	2.0	2.0	3.5	2.5	2.0	2.5	1.5	2.5
12 $+f_r$	4.0	4.5	9.0	7.0	2.0	1.5	3.5	4.5	3.5	3.5	4.5	4.0	4.0	3.0	3.0
Total (less noise)	26.5	32.5	51.0	41.0	10.0	13.5	18.0	26.0	22.0	29.5	25.5	27.5	26.5	17.5	19.5

TABLE XII. CORRECTED SONIC ANALYZER METER READINGS FOR UPPER PLANETARY GEARS (10), (11), AND (12)															
Gear Condition	Satisfactory				Questionable	Faulty									
Run No.	26	28	41	52	9	15	19	24	25	27	29	32	38	44	47
f_{tc}	3.1	2.2	13.3	9.1	1.3	3.8	7.9	7.0	4.2	3.1	6.0	5.7	4.3	4.0	5.0
$2f_{tc}$	1.5	1.5	3.0	4.0	.05	1.0	1.0	1.5	1.5	2.5	1.0	3.5	2.0	1.5	1.5
10 $-f_{rc}$	1.8	-1.0	2.6	1.3	1.4	1.7	[illegible]	1.5	1.8	2.8	1.5	1.8	2.1	1.5	1.5
10 $+f_{rc}$	1.1	1.0	6.8	3.6	-0.2	2.8	[illegible]	4.0	2.7	0.6	4.5	3.2	2.3	3.0	3.0
11 $-f_{rc}$	1.8	1.0	2.6	1.3	1.4	1.7	1.7	1.5	1.8	2.8	2.0	2.3	2.1	1.5	1.5
11 $+f_{rc}$	0.6	-2.3	4.3	1.1	-0.7	2.3	4.9	3.0	1.7	0.6	3.5	2.2	1.3	1.5	1.5
12 $-f_{rc}$	2.8	2.0	3.1	2.8	1.4	1.7	2.2	2.0	1.8	2.8	2.5	1.8	2.1	1.5	2.5
12 $+f_{rc}$	1.1	-1.8	7.3	4.1	0.3	2.3	5.9	4.5	2.7	0.6	4.5	3.2	2.3	3.0	3.0
Total	13.8	2.6	43.0	27.3	4.0	17.3	31.2	25.0	18.2	15.6	25.5	23.7	18.5	17.5	19.5

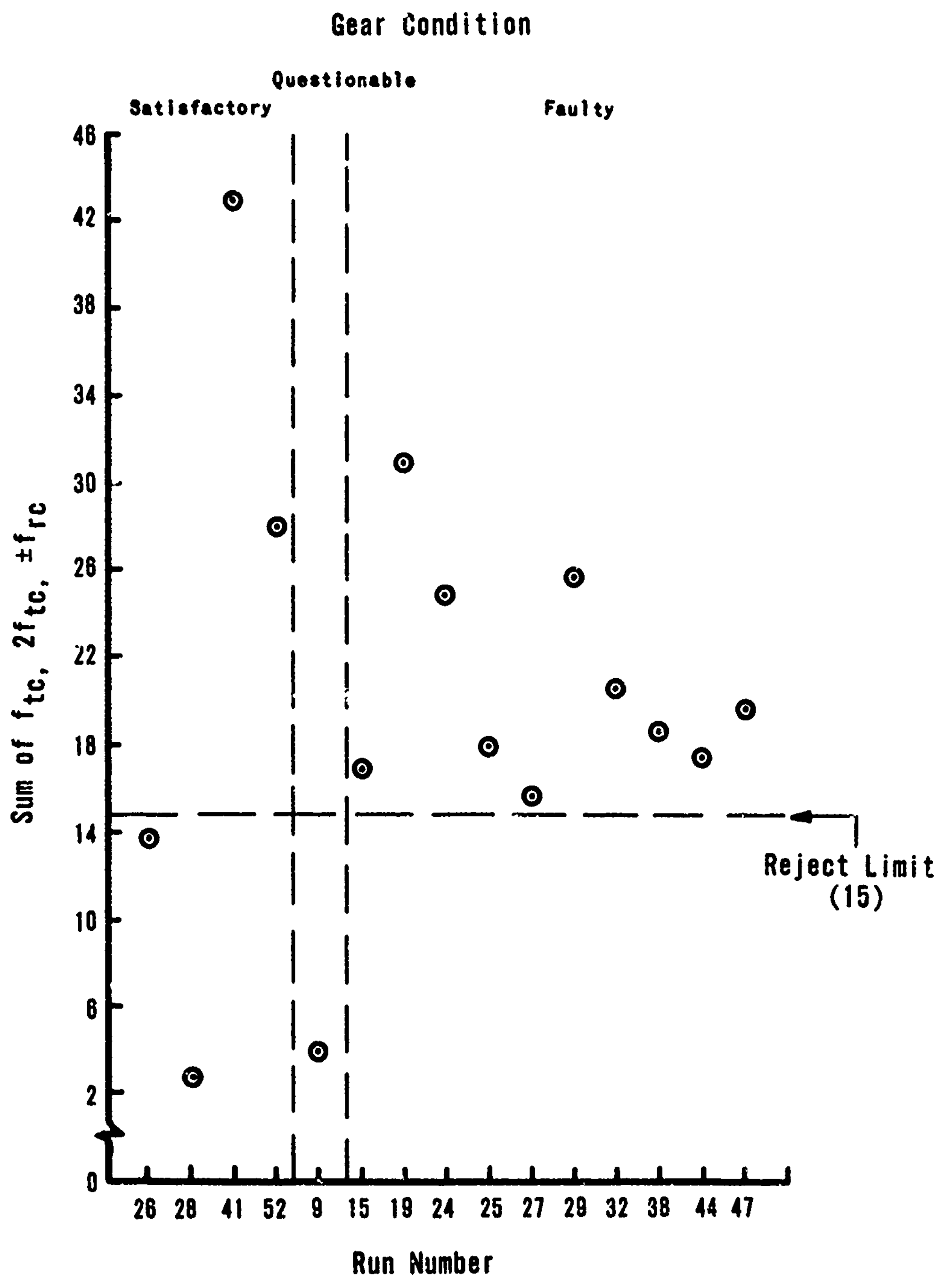


Figure 20. Summation of Corrected Meter Readings for Upper Planetary Gears (10), (11), and (12).

TABLE XIII. GEAR ANALYSIS SUMMARY – UPPER PLANETARY GEARS (10), (11), AND (12)

Run No.	Corrected Meter Readings (db)	Reject Limit Exceeded (15.0)	Teardown Inspection Reject	Inspection Comments
26	13.8	No	No	Sun gear has tip loading at lower end, otherwise OK; ring gear and pinions assumed OK.
28	2.6	No	No	Wear is moderate on the sun gear, but pits are occurring in the wear area; no spalling. Ring gear and pinions assumed OK.
41	43.0	Yes	No	Heavy tip wear on the sun gear; ring gear is OK; pinions have slight flank hard line.
52	27.3	Yes	No	Good, even pattern on sun gear; good wear pattern on ring gear; very light wear in flank of tooth on pinions.
9	4.0	No	Questionable	Two teeth spalled on sun gear. Ring gear assumed OK. Pinion looks OK; arrested pitting.
15	17.3	Yes	Yes	Misalignment on sun gear; no spalling, but some light pitting in wear area, with corrosive wear; interference wear on pinions.
19	31.2	Yes	Yes	Misalignment on sun gear, with some pitting the full length of wear area; end of tooth chipped and misalignment and interference wear on ring gear.
24	25.0	Yes	Yes	Spalling, interference wear, and misalignment on sun gear; one tooth has 1/8-in.-dia. spalled spot at lower end; ring is assumed OK; rust pitting on pinion.
25	18.2	Yes	Yes	Gear teeth beginning to break out at tips of sun gear – heavy wear at tips, with some pitting. Ring gear assumed OK; one planet frozen in pinion, with moderate flank wear and light but extensive corrosion pitting on gear teeth.

TABLE XIII — Continued				
Run No.	Corrected Meter Readings (db)	Reject Limit Exceeded (15.0)	Teardown Inspection Reject	Inspection Comments
27	15.8	Yes	Yes	Interference wear on sun gear, with metal breakout where tip loading is occurring; ring gear looks OK; pinions assumed OK.
29	25.5	Yes	Yes	Fairly light tip loading toward lower end of sun gear; upper teeth chipping at top side of ring gear; heavy flank wear on pinion.
32	23.7	Yes	Yes	Tip loading toward upper end of sun gear with several teeth spalled; ring gear assumed OK; heavy flank wear on pinions; upper rollers show heavy wear; streak of corrosion across both bearing raceways in one pinion — scrapped; very light pitting in roots of two pinions.
38	18.5	Yes	Yes	Sun gear looks OK; tip loading moderate with some pitting in loaded area; ring gear assumed OK; interference wear on pinion — end loading with moderate arrested pitting.
44	17.5	Yes	Yes	Sun gear looks very good, only one small area of tip wear; ring gear has four bad chips on teeth; pinions all OK.
47	19.5	Yes	Yes	Moderate tip wear on sun gear, with pitting in wear area mostly at very tip; ring gear assumed OK; pinions have arrested pitting — scrapped; bearing has interference wear with moderate wear in flank with some pick-out of material — scrapped.

Transmission Spur Gears (13) and (14)

Because there were no faulty conditions reported for these spur gears, no statistical reject limit was established. It was noted that the gain setting assigned to the analysis program tended to give consistent readings, and it is thus believed that similar readings found in future analyses could be indicative of good gears of this type. As additional data are collected in future efforts, the establishment of reject limits will be possible.

Transmission Output Drive Bevel Gears (15), (16), and (17)

The comments on gears (13) and (14) are also applicable to the output drive bevel gears (15), (16), and (17), inasmuch as there were no faulty conditions reported for these gears.

BEARING ANALYSES

Bearing analyses for the transmission, 42-degree gearbox, and 90-degree gearbox are summarized in Tables XIV through XXIII.

TABLE XIV. BEARING ANALYSIS SUMMARY — LOWER MAIN ROTOR REDUCTION BEARING (34), UPPER MAIN ROTOR REDUCTION BEARING (36), AND LOWER TRANSMISSION BEARING (38)

Run No.	Bearing No.	Meter Readings (db) f_1	f_2	f_b'	$3f_b'$	Reject Limit Exceeded (6.0)	Teardown Inspection Reject	Inspection Comments
9	(34)	—	—	—	—	No	No	Both upper and lower bearings OK.
	(36)	2.0	2.5	3.5	2.5			
	(38)	1.0	2.0	1.0	3.0			
19	(34)	—	—	—	—	No	No	Can find nothing wrong; a little dirt and sludge possibly accounting for roughness.
	(36)	2.5	2.5	3.0	2.5			
	(38)	3.0	2.0	1.5	3.5			
25	(34)	—	—	—	—	Yes	Yes	Bearings (36) and (38 have less than 100 hours to failure.
	(36)	6.5	5.5	7.0	4.5			
	(38)	8.0	6.5	4.5	5.0			
26	(34)	—	—	—	—	Questionable	Questionable	Spalls and corrosion on ball path.
	(36)	6.0	6.0	6.5	5.5			
	(38)	5.0	6.0	3.5	6.0			
27	(34)	—	—	—	—	Yes	Questionable	Slight corrosion — rough.
	(36)	Peg	Peg	Peg	6.0			
	(38)	Peg	6.5	3.0	Peg			
29	(34)	—	—	—	—	Questionable	Questionable	One bearing has disussembly damage, the other has rusty balls, with possible chips from gears.
	(36)	4.0	3.5	3.5	4.0			
	(38)	3.5	4.0	2.0	Peg			
38	(34)	—	—	—	—	No	No	
	(36)	5.0	5.0	5.0	5.0			
	(38)	5.5	5.0	4.0	10.0			
42	(34)	—	—	—	—	Yes	Questionable	Scrapped; brinelling and disassembly damage.
	(35)	5.0	4.5	5.0	6.5			
	(38)	6.0	7.0	3.0	10.0			
47	(34)	—	—	—	—	No	No	Nothing found wrong.
	(36)	2.0	3.5	4.0	4.5			
	(38)	4.5	5.0	2.5	6.0			
Ten additional runs						No	No	

TABLE XV. BEARING ANALYSIS SUMMARY – INPUT QUILL SHAFT BEARING (23)

Run No.	Meter Readings (db) f_1	f_2	f_b'	$3f_b'$	Reject Limit Exceeded (6.0)	Teardown Inspection Reject	Inspection Comments
9	1.0	3.5	1.5	5.5	No	No	No data sheets received.
12	1.0	3.5	1.5	4.5	No	Questionable	Bearing not scrapped, but shows signs of brinelling, fretting, and light rust.
19	2.5	5.0	3.5	3.5	No	No	Bearing not scrapped, but has typical brinelling and fretting.
24	2.5	4.0	2.5	4.5	No	No	Reported disassembly damage, otherwise OK.
26	8.5	5.0	3.5	4.5	No	No	Bearing not scrapped, but has typical brinelling and fretting.
27	6.0*	4.5	4.5	4.5	No	No	Bearing not scrapped, but has typical brinelling and fretting.
29	1.5	4.5	1.5	8.0	Yes	Yes	Bearing was full of chips from external source.
33	3.0	5.5	4.5	9.0	Yes	Questionable	Bearing not scrapped, but has typical brinelling and fretting. Neighboring bearing has heavy spall.
38	2.0	5.5	4.5	4.0	No	No	Bearing not scrapped, but has typical brinelling and fretting.
41	5.0	8.0	5.0	3.0	Yes	Yes	Bearing scrapped; brinelling and fretting.
42	3.5	4.0	4.5	5.0	No	No	No data sheets received.
47	2.0	3.5	3.5	5.0	No	No	Typical brinelling on inner race.
52	7.5	6.0	5.0	5.0	Yes	Yes	Bearing scrapped; brinelling and fretting.

*This reading is not considered usable because the frequency was masked by f_1 of Run No. 38.

TABLE XVI. BEARING ANALYSIS SUMMARY – INPUT QUILL SHAFT BEARING, TRIPLEX BALL (24)

Run No.	Meter Readings (db) f_1	f_2	f_b'	$3f_b'$	Reject Limit Exceeded (6.0)	Teardown Inspection Reject	Inspection Comments
9	1.0	1.5	–	1.5	No	No	No defects.
12	1.5	2.5	–	2.0	No	No	Very light defect, but not scrapped.
14	1.5	2.0	–	1.0	No	Yes	Outer race failing; one spall spot on inner race.
24	2.0	4.0	–	5.0	No	No	No defects.
27	3.0	5.5	–	5.0	No	No	Superficial corrosion on outer race, but not scrapped.
33	4.5	6.5	–	6.0	Yes	Yes	Large spall on outer race.
38	3.0	4.5	–	4.5	No	No	Slight spall on outer race, but not scrapped.
41	4.0	4.5	–	8.0	Yes	Yes	.08-in. spall on outer race; less than 100 hours to failure – scrapped.
42	3.0	3.0	–	5.0	No	No	No defects.
44	2.0	3.5	–	Peg	Yes	No	No defects.
47	–	2.5	2.0	3.5	No	No	Bearing feels and looks OK.
50	2.5	4.0	–	8.0	Yes	Questionable	Bearing OK, but neighboring bearing (23) scrapped for being rough, brinelled, and fretted.
15, 19, 25, 26, 28, 29, 32					No	No	No data sheets available, so assumed OK.

TABLE XVII. BEARING ANALYSIS SUMMARY — INPUT GEAR SHAFT BEARING, DUPLEX BALL (26)

Run No.	Meter Readings (db) f_1*	f_2	f_b'	$3f_b'$	Reject Limit Exceeded (6.0)	Teardown Inspection Reject	Inspection Comments
9		2.0	1.0	1.5	No	No	No data sheets.
14		3.0	2.5	1.5	No	No	Isolated spots of corrosion, but not scrapped.
24		3.5	2.5	2.5	No	No	No data sheets.
28		3.5	2.5	2.5	No	No	Very light corrosion, but not scrapped.
38		4.0	3.5	7.0	Yes	Questionable	No defects.
41		4.0	7.5	6.0	No	No	No data sheets.
42		3.5	2.0	6.0	No	No	Bearing looks and feels OK.
47		2.5	2.0	3.5	No	No	Bearing looks and feels OK.
51		4.0	3.0	3.5	No	No	Bearing looks and feels OK.
12, 15 19, 25 26, 27 29, 32 33, 44					No	No	No data sheets.

*Not recorded.

TABLE XVIII. BEARING ANALYSIS SUMMARY – INPUT MAIN REDUCTION GEAR BEARING (27)

Run No.	Meter Readings (db) f_1	f_2	f_b'	$3f_b'$	Reject Limit Exceeded (6.0)	Teardown Inspection Reject	Inspection Comments
25	–	3.5	–	3.5	No	No	Slight rusting on outer rings and rollers.
32	–	3.5	–	4.0	No	No	Disassembly damage.

NOTE: Seventeen additional runs were made, all resulting in low meter readings and no data reports.

TABLE XIX. BEARING ANALYSIS SUMMARY – LOWER MAST BEARING (39)

Run No.	Meter Readings (db) f_1	f_2	f_b'	$3f_b'$	Reject Limit Exceeded (6.0)*	Teardown Inspection Reject	Inspection Comments
24	7.0	5.0	3.0	1.5	Yes (7.0+2)	Questionable	A shaft was scrapped.
25	6.0	4.0	3.0	1.5	Yes (6.0+2)	Yes	Imminent failure; heavy corrosion damage on rollers and outer race.
26	6.0	5.0	5.0	2.0	Yes (6.0+2)	Yes	Corrosion on a few rollers and outer ring; lines of corrosion where rollers were in contact with race during some period of inactivity.
27	9.0	6.5	6.0	3.0	Yes (9.0+2)	Questionable	Slight corrosion; rough.
33	7.0	5.0	4.0	2.0	Yes (7.0+2)	Questionable	Chips were found on magnetic plug.
41	3.5	3.5	2.0	2.0	No (3.5+2)	No	Bearing looks OK.
42	3.0	2.5	2.5	1.5	No (3.0+2)	No	No data sheets.
47	2.5	2.5	1.5	1.0	No (2.5+2)	No	Bearing looks OK.
Eleven additional runs					No	No	

*Necessary gain revisions would result in high meter readings by a value of +2.

TABLE XX. BEARING ANALYSIS SUMMARY — LOWER TRANSMISSION INPUT BEARING (41) AND ACCESSORY DRIVE AND TAIL ROTOR DRIVE BEARINGS (42)*

Run No.	Bearing No.	Meter Readings (db) f_1	f_2	f_b'	$3f_b'$	Reject Limit Exceeded (6.0)	Teardown Inspection Reject	Inspection Comments
25	(41)	2.5	3.5	3.0	3.0	No	No	Two data sheets — one reports that failure is imminent, the other reports failure in less than 100 hours, with pitting and corrosion.
	(42)	4.5	9.0	—	4.0	Yes	Yes	
29	(41)	2.0	2.5	3.0	2.0	No	No	Not scrapped.
	(42)	2.5	3.0	—	2.5	No		
32	(41)	2.5	3.0	3.5	3.0	No	No	Bearings OK.
	(42)	4.5	4.0	—	5.0			
38	(41)	4.5	7.5**	3.5	4.0	No	No	No data comments.
	(42)	—	—	—	—			
42	(41)	3.5	Peg**	3.0	5.5	No	No	No data comments.
	(42)	—	—	—	—			
52	(41)	3.5	10.0**	5.0	8.0	No	No	No data comments.
	(42)	—	—	—	—			
Thirteen additional runs						No	No	

*These bearings are investigated simultaneously here because they have the same part numbers on the data sheets and are not identified specifically.

**Reading considered not valid because of frequency masking by N_1 f_r.

TABLE XXI. BEARING ANALYSIS SUMMARY – LOWER TRANSMISSION INPUT DUPLEX BEARING (40) AND TAIL ROTOR DRIVE DUPLEX BEARING (43)

Run No.	Bearing No.	Meter Readings (db) f_1	f_2	f_b'	$3f_b'$	Reject Limit Exceeded (6.0)	Teardown Inspection Reject	Inspection Comments
25	(40) (43)	2.5 3.0	3.0 4.0	4.0 4.0	4.0 4.0	No	Yes	Two data comments were available – one reported moderate wear, the other reported heavy wear, with less than 100 hours to failure.
27	(40) (43)	4.5 4.5	4.0 7.0	5.0 8.0	5.0 5.0	Yes	No	No data comments.
44	(40) (43)	2.0 2.5	4.5 5.0	4.0 4.0	6.0 3.5	No	No	Only minute wear.

NOTE: It is suspected that these bearing signals are buried in the noise and that the meter readings are actually noise rather than discrete signals.

TABLE XXII. BEARING ANALYSIS SUMMARY – 42-DEGREE GEARBOX BEARINGS (42) AND (43)

Run No.	Bearing No.	Meter Readings (db)				Reject Limit Exceeded (6.0)	Teardown Inspection Reject	Inspection Comments
			f_2	f_b'	$3f_b'$			
9	(42)	–	2.0	–	–	No	Questionable	Small dents on roller; question sonic run.
10	(42)		2.0	–	–	No	No	Pitting on rollers – replaced.*
15	(42)	–	2.0	–	–	No	No	Bearings OK.
16	(42)	–	2.5	–	–	No	No	Bearings OK.*
9	(43)	–	2.5	–	–	No	Questionable	No data comments, but question the sonic run.
10	(43)	–	2.0	–	–	No	No	No data comments.
15	(43)	–	2.0	–	–	No	No	Bearings OK.
16	(43)	–	2.0	–	–	No	No	No data comments.

*Data reports all bearings OK for Run 16; however, bearing was still replaced. This leads to doubt of actual faulty condition.

TABLE XXIII. BEARING ANALYSIS SUMMARY – 90-DEGREE GEARBOX BEARING (43)

Run No.	Meter Readings (db) f_1	f_2	f_b'	$3f_b'$	Analyzer Limit Reject	Teardown Inspection Reject	Inspection Comments
7	–	–	1.0	–	No	No	Bearings OK
12	–	–	2.0	–	No	No	Bearings OK
14	–	–	2.0	–	No	No	Bearings OK
18	–	–	3.5	–	No	No	Bearings OK
19	–	–	3.0	–	No	No	Bearings OK
20	–	–	3.5	–	No	No	Bearings rough
23	–	–	5.5	–	No	No	Bearings OK
24	–	–	6.0	–	No	No	Bearings OK
26	–	–	5.0	–	No	No	Bearings OK
27	–	–	6.0	–	No	No	Bearings OK
28	–	–	4.0	–	No	No	Bearings OK
29	–	–	5.5	–	No	No	Bearings rough
36	–	–	4.0	–	No	No	Bearings OK
37	–	–	4.0	–	No	No	No data comments

RESULTS

SUMMARY OF ANALYSES

Because the data acquisition effort was based on acquiring data on transmissions and gearboxes which were scheduled for overhaul, only a very low percentage of the components were found to be faulty. This is to be expected because the number of hours established for removal for overhaul are set at a level where it is anticipated that failures will seldom occur. The lack of a large number of faulty components and even the complete absence of any report of faulty conditions for some components restricted the scope of what could be accomplished by this effort.

The significance of the data processing and analyses can best be interpreted by reviewing Tables XXIV and XXV, which summarize the correlation of the analysis findings with the mechanical condition findings.

The column of data labeled "yes–yes" records the case where a defect was noted in the teardown inspection and where a defect was indicated by the analyzer. It can be seen that this category resulted in a high percentage of effectiveness: an 83-percent overall effectiveness for bearings and a 100-percent overall effectiveness for gears. Recalling that the reject criteria used in this analysis effort were established using the same data that were used to determine effectiveness, it is only natural to expect that there would be good effectiveness results; that is to say, when a reject limit was established, it was set at a value where it was observed to cause rejection of most of the reported faulty components and acceptance of most of the reported good components.

Likewise, this contributes to the low percentages in the "yes–no" column, which is depicting the situation where the component was found to be mechanically faulty during inspection but the analyzer failed to detect the faulty condition.

For the third column, the "no–yes" situation, the component was found to be in good mechanical condition but the analyzer classified the component as faulty. This is a "false alarm" situation and is one which did not occur excessively.

The fourth column, the "no–no" situation, is obviously the most common occurrence, because most components which are removed for overhaul are still in good condition.

A high percentage of statistical effectiveness was attained. However, of more significance is the fact that the effort has demonstrated that the acoustical data can be differentiated in such a manner as to categorize mechanical conditions.

TABLE XXIV. COMPARISON OF BEARING CONDITIONS INDICATED BY THE ANALYZER VERSUS BEARING CONDITIONS OBSERVED DURING TEARDOWN INSPECTION

Component Schematic No. and Name	Defects Indicated by Inspection–Analyzer: Yes – Yes		Yes – No		No – Yes		No – No		Number of Questionable Runs	Number of Runs Investigated
	Qty	Pct	Qty	Pct	Qty	Pct	Qty	Pct		
(23) Input Quill Shaft Bearing	4	100	0	0	0	0	12	100	3	19
(24) Input Quill Shaft Triplex Ball Bearing	2	67	1	33	1	7	14	93	1	1[illegible]
(26) Input Gear Shaft Bearing Duplex Ball	0	–	0	–	0	0	18	100	1	1[illegible]
(27) Input Main Reduction Gear Bearing	0	–	0	–	0	0	19	100	–	19
(34) Lower Main Rotor Reduction Bearing	–	–	–	–	–	–	–	–	–	–
(36) Upper Main Rotor Reduction Bearing	–	–	–	–	–	–	–	–	–	–
(38) Lower Transmission Bearing	1	100	0	0	0	0	14	100	4	1[illegible]
(39) Lower Mast Bearing	2	100	0	0	0	0	14	100	3	1[illegible]
(41) Lower Transmission Input Bearing	–	–	–	–	–	–	–	–	–	–
(42) Accessory Drive and Tail Rotor Drive Bearings	1	100	0	0	0	0	17	100	1	1[illegible]
(40) Lower Transmission Input Duplex Bearing	–	–	–	–	–	–	–	–	–	–
(43) Tail Rotor Drive Duplex Bearings	0	0	1	100	1	6	17	94	0	1[illegible]
42-Degree Gearbox Bearing (42)	0	–	0	–	0	0	3	100	1	[illegible]
Bearing (43)	–	–	–	–	0	0	3	100	1	[illegible]
90-Degree Gearbox Bearing (43)	0	–	0	–	0	0	14	100	0	1[illegible]
TOTALS	10	83	2	17	2	1	145	99	15	17[illegible]

TABLE XXV. COMPARISON OF GEAR CONDITIONS INDICATED BY THE ANALYZER VERSUS GEAR CONDITIONS OBSERVED DURING TEARDOWN INSPECTION

Component Schematic No. and Name	Defects Indicated by Inspection–Analyzer: Yes – Yes Qty	Yes – Yes Pct	Yes – No Qty	Yes – No Pct	No – Yes Qty	No – Yes Pct	No – No Qty	No – No Pct	Number of Questionable Runs	Number of Runs Investigated
(7), (8), (9) Lower Planetary Gears	8	100	0	0	1	25	3	75	3	15
(10), (11), (12) Upper Planetary Gears	10	100	0	0	2	50	2	50	1	15
(13), (14) Transmission Spur Gears *	–	–	–	–	–	–	–	–	–	–
(1), (2), (3) Input Drive Bevel Gears *	–	–	–	–	–	–	–	–	–	–
(15), (16), (17) Output Drive Bevel Gears *	–	–	–	–	–	–	–	–	–	–
(50), (51) 42-Degree Gearbox Bevel Gears	0	–	0	–	0	0	3	100	1	4
(52), (53) 90-Degree Gearbox Bevel Gears	4	100	0	0	0	0	9	100	1	14
TOTAL	22	100	0	0	3	15	17	85	6	48

*No faulty components reported from inspections; correlation not attempted because of lack of faulty data to establish reject units.

HOW BAD IS BAD?

During any diagnostic equipment research or development effort, the inevitable question is asked: "Just how bad is a component that is considered bad?" The answer to that question is difficult to define and seems to vary with the conditions.

A "bad" component, as defined in this report, is one where a defect was noted during the overhaul process which caused replacement of the component. It is readily apparent that by this definition, the condition could actually be one of severity, ranging from a barely detectable defect to a situation where the component disintegrated into a multitude of pieces.

Those "bad" components that had relatively minor defects could easily have been classified as "good", if the reject criteria used during the inspection-overhaul process had not been quite so stringent. A review of the effects of various reject limits produces interesting observations.

Figure 21 represents the hypothetical, but plausible, deterioration rates of three components of the same type. The point to be made here is that even though they are all three the same type, their rates of deterioration are different.

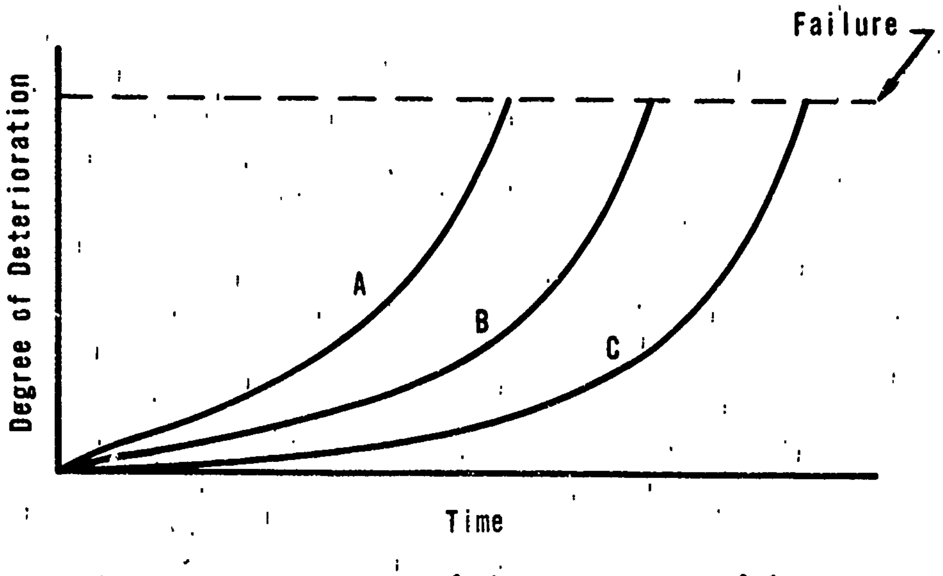


Figure 21. Wearout Rates of Three Components of the Same Type.

Figure 22 shows a desirable schedule of the inspection and overhaul procedure. Here, it is shown that the combination of the interval between inspections and the reject limit used during the inspections is providing assurance that a component of this type will not fail during the interval between inspections.

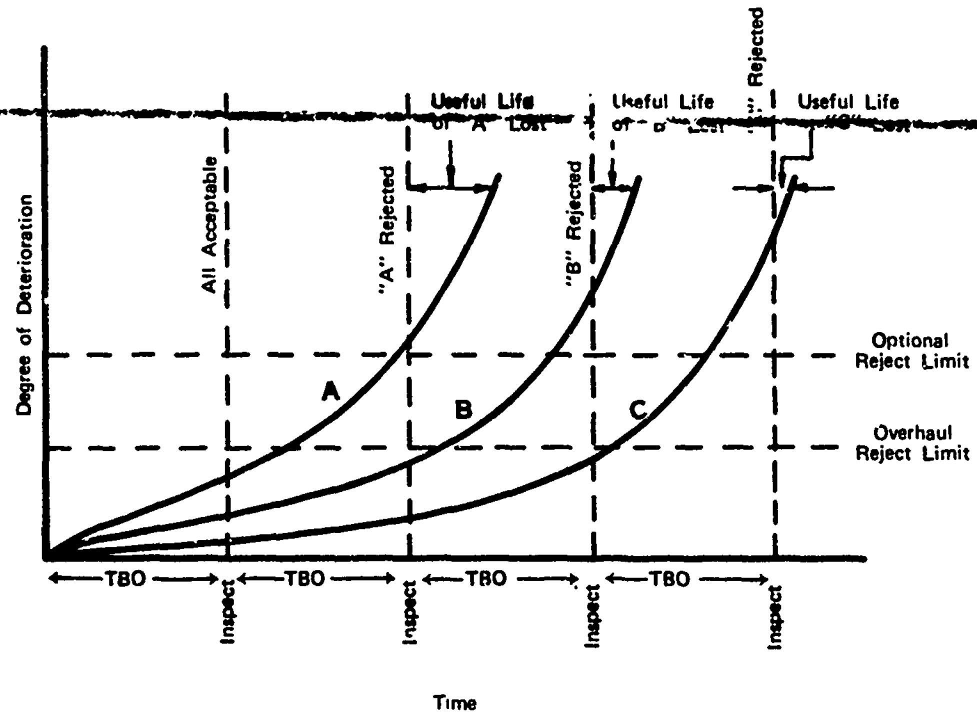


Figure 22. Reject Limit Established by the Inspection and Overhaul Procedure (First Example).

The number of hours that a component could have been operated if it had not been rejected during inspection comprises the useful life lost. It can be seen that if the reject limit were raised to some higher value representing a higher degree of deterioration, it would have the propitious effect of reducing the useful life lost, up to the point where the reject level becomes so high that a part is not rejected during the inspection process and then fails before the next inspection cycle. This can be seen to occur in case "A", if the reject limit were higher than the optional reject limit shown in Figure 22.

Figure 23 shows the same curves, reject limit, and time-between-overhauls as Figure 22. However, in Figure 23, the phasing of the overhauls differs. It can be seen that this difference in phasing causes the components to be rejected earlier, thus creating the adverse effect of increasing the useful life lost.

Now, one might ask what would be the effect of eliminating the inspection/TBO procedure altogether and, instead, using an analyzer which continuously monitors the mechanical condition of the component. Figure 24 shows the effect of such a procedure. It can be seen that this procedure would be less desirable than the inspection/TBO procedure, if the same reject criteria are used, because it increases the useful life lost. This curious result is one for contemplation of the fallacy of using such an analyzer approach.

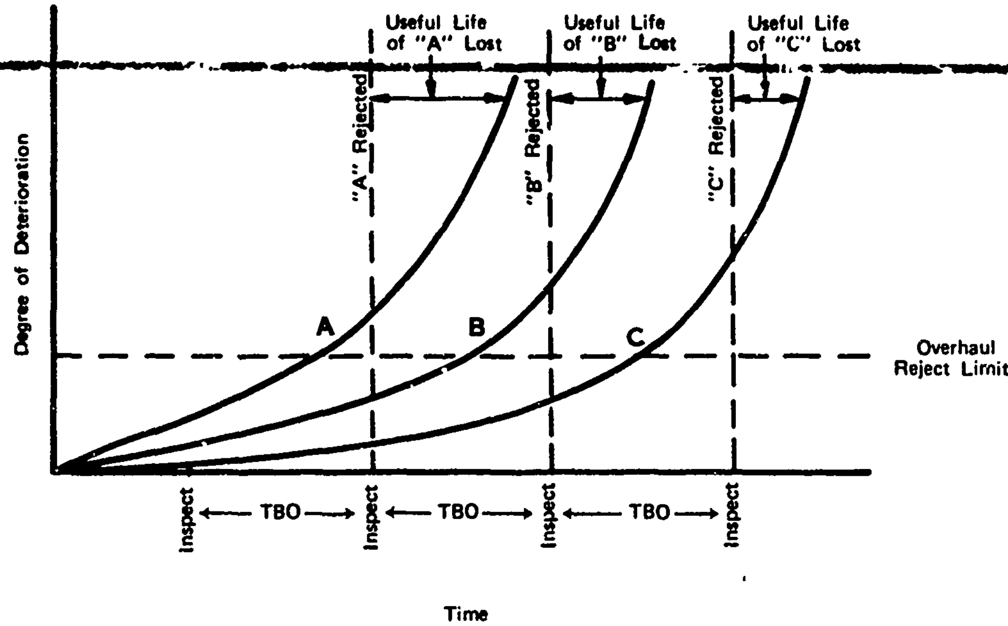


Figure 23. Reject Limit Established by the Inspection and Overhaul Procedure (Second Example).

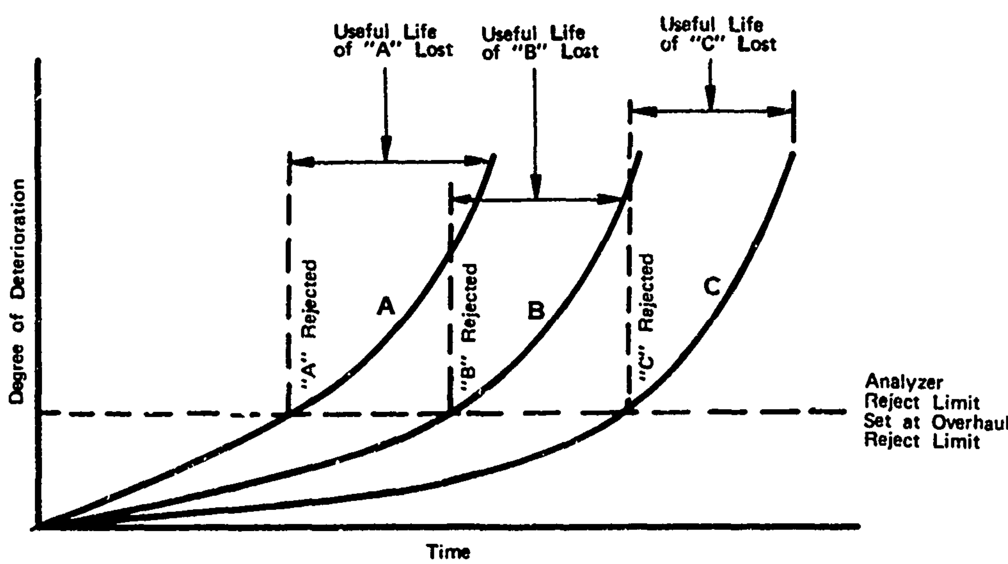


Figure 24. Reject Limit Established by an Analyzer Using Limit Criteria Set by Overhaul Procedure.

The fallacy of the approach and the obvious correction that should be made can be seen in Figure 25. Because the analysis process can be continuous, the need to allow for any deterioration that may occur after the inspection can be eliminated. This means that the analyzer reject limit could be evaluated to a level that is just short of the failure point by an amount which would permit sufficient time to order a replacement component and to replace the component prior to complete failure.

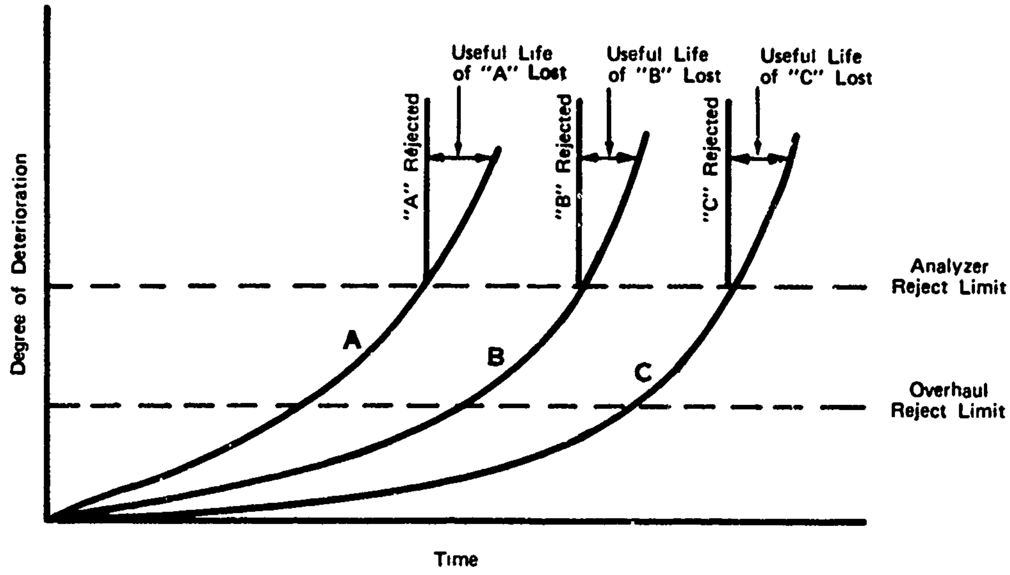


Figure 25. Reject Limit Established by an Analyzer Using Limit Criteria Set by the Analyzer's Capabilities.

The effectiveness study that has been reported herein compared the ability of the analyzer to detect components that had been rejected by the inspection/overhaul process. By what has just been discussed, it is obvious that this may be an unfair test of effectiveness, because it has placed the burden on the analyzer to be able to detect deterioration levels that are lower than that necessary for an optimum inspection process using an analyzer.

CONCLUSIONS

It is concluded that:

1. The concept of using acoustic data generated by a helicopter under low power conditions to diagnose the mechanical condition of helicopter transmissions and gearboxes is feasible.

2. The ground-based CWEA-4 sonic analyzer developed by the Curtiss-Wright Corporation is a reliable and effective instrument for use in determining the mechanical condition of helicopter power train components by analyzing helicopter acoustic data.

3. The effectiveness of the sonic data analysis approach to diagnostics could be improved by additional data acquisition efforts and subsequent refinement of data acquisition techniques and reject criteria identification.

RECOMMENDATIONS

It is recommended that:

1. Additional efforts be conducted using the sonic analysis techniques to check the condition of helicopter components where the condition is known. Both good and faulty conditions of components should be investigated.

2. Investigations be conducted to identify any relationships that exist between the loading and/or operating speeds of gears and bearings and the acoustic spectrums generated.

3. Additional analysis techniques be investigated to ensure that the optimum techniques are being applied.

4. Sensor studies be conducted to optimize the location and type of microphones that should be used. The studies should also determine whether or not a microphone is the best type of sensor to use to acquire the data necessary for the analysis techniques used.

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APPENDIX I
GLOSSARY OF FAILURE ANALYSIS TERMS

GEAR TOOTH OR SPLINE

Wear

1. Destructive Wear

   Destructive wear is wear that has resulted in a corrosive change in the involute shape of the gear tooth. Destructive wear would be accompanied by extremely rough operations, nonuniform motion, and shock overloads which would probably result in tooth breakage.

2. Abrasive Wear

   Under normal circumstances of lubrication, the occurrence of abrasive wear would be extremely infrequent. If sand and water are present in appreciable quantities, abrasive wear may be observed. Fully case-hardened gears are not likely to exhibit any significant abrasive wear. Medium hard and soft gears will frequently exhibit this type of wear.

3. Galling

   Galling is a form of contact welding that results in the transfer of material from one gear member to another. It is also quite infrequent in moderate- to high-speed gearing, but is often seen in low-speed and stop/start type operations. An excellent example of spline galling occurs on the Model 206 sun gear spline.

4. Scoring

   This type of wear is often referred to as "scuffing" and is evidenced by radial wear lines superimposed on a roughened thin layer of melted material. Bright, shiny wear on black oxided gear teeth must not be confused with true scoring. This condition, although considered normal for many applications, represents a lubrication state intermediate between thick film asperity separation and film failure conditions associated with scoring.

5. Frosting

   The term frosting will be limited in use to fully hardened gear tooth profiles. It will be used to define the existence of a large number of small round or elliptical patches which under high magnification exhibit the general appearance of minute scorings.

6. Corrosive Wear

This term should not be used to define the existence of ordinary oxidation corrosion which is cause for replacement of the component. True corrosive wear occurs most generally in overtemperature operations in the presence of extremely strong EP additive lubricant of the chlorine or sodium families and therefore will be an infrequent occurrence.

7. Interference Wear

Interference wear defines the effects of the tip of one gear tooth member's contacting the fillet or root area of its mating gear tooth. If this occurs in the helicopter transmission, it will probably be accompanied by an extreme overtemperature condition or an unusual type of support bearing failure which reduces the operating clearance or backlash of the gear set. Interference wear does not occur in correctly designed, properly operating gear sets.

8. Burning

Burning indicates surface tempering or softening of the tooth member. It will most probably be accompanied by a total loss of lubricant. Scoring, destructive wear, and tooth breakage may also be present. In general, burning is an advanced condition of the following term.

9. Discoloration

This term is used to locate the existence of surface temper coloring of the active profile, the top land, or the coast side of the gear tooth. There is generally no appreciable softening of the metal to any significant depth. The condition may be indicative of marginal lubrication or excessive power operations.

10. Misalignment

Misalignment indicates operation of the gear or spline set at axes skewed from those intended by the designer. When this term is checked, at least one other term must also be checked to explain the physical result of the indicated misalignment.

11. Surface Treatment Worn Through

This term implies that the gear or spline in question was treated with an antiwear surface coating such as Electro-Film, Dicronite, or in some instances, soft metal plating.

12. Oil Absent

This term indicates the partial or complete failure of the lubrication system in either the immediate area of concern or the entire transmission.

13. Corrosion – Other

This term is used to define the existence of ordinary oxidation corrosion which is cause for replacement of the component. This may occur during helicopter nonoperation intervals under severe moisture conditions or may occur in transit, storage, or handling due to improper preservation.

Surface Contact Fatigue

1. Destructive Pitting

Destructive pitting will be used to define the existence of advanced state of tooth profile deterioration. This term is used without concern as to the origin or generic identification. It further indicates that complete loss of function of the gear tooth is imminent.

2. Spalling – Fan Shape

This term will be used to define a pitting condition whose origin can be physically detected at the apex of the fan-shaped portion of the damaged area. This is a surface-initiated type of fatigue, which has its origin in the surface tensile cracking which leads to the gradual erosion and exfoliation of increasingly larger pieces of gear material as the fan widens out in the direction of sliding action. The cracks will ultimately undermine the entire case of case-hardened gear teeth as the spalling approaches the extremities of the addendum.

3. Arrested Pitting

This term will be used to indicate the existence of very small shallow pits that are not propagating into larger failure areas. A good example of this frequently occurs in the flank of the -108 planet pinions in contact with the nitrided -331 ring gears. This type of pitting has also been observed on spiral bevel gears and is frequently associated with the waviness condition referred to as "barber pole". This pitting is often considered corrective in that it progresses immediately to the point of relieving local compressive stress of overload.

4. Pitch Line

Pitch-line pitting belongs to the family of rolling contact fatigue and is totally surface in origin. It is not generally associated with a condition of lubrication distress but generally occurs at relatively high cycles of loading. In fully hardened, properly designed gears, it is seldom seen in less than 100,000 cycles of operation.

5. Addendum Origin

Checking this term merely signifies the site of origin of one of the above types of pitting or spalling.

6. Dedendum Origin

Checking this term merely signifies the site of origin of one of the above types of pitting or spalling.

7. Case Crushing

Case crushing means sheer failure of the core-case interface in case-hardened gear teeth. Generally, insufficient case depth for the load magnitude is indicated. Multiple cracking, often both transverse and longitudinal, is generally observed in the tooth face.

Breakage

1. Fatigue

Fatigue will be used to define high cycle repeating stress failure with a fracture surface being well defined with the customary clamshell or bench marks. Unless otherwise defined, it will be assumed that the failure origin is in the root fillet area of the gear tooth.

2. Wear

This term should not be used alone in the breakage category but merely serve as a modifier to indicate that some other form of breakage was accelerated by the presence of wear.

3. Overload

In the instance of properly manufactured gears, the occurrence of overload breakage is evidenced by low cycle fatigue with few, if any, bench marks. The failure interface may in fact resemble the crystalline appearance of a static failure.

4. Misalignment

Misalignment is operations at skewed axes which result in a particular form of breakage defined elsewhere in this category.

5. Quench Cracks

Quench cracks are generally cracks that occur at or near the interface of the core-case structure and result from either excessive case depth or improper location of the part relative to the quenching dies during the hardening process.

6. Grinding Cracks

Grinding cracks result from excessive temperature between the wheel and tooth interfaces during manufacture, which induces a tensile stress field in excess of the elastic properties of the material. This type of crack is generally found to occur orthogonally to the direction of the grinding wheel passage.

7. Impact

Impact breakage is that which results from sudden stoppage or debris in mesh. It will be a completely static fracture and will be accompanied by extreme deformation of the failed tooth in all cases except static fractures in nitrided gears.

Debris in Mesh

1. Moderate Damage

Moderate damage is defined as that level of damage which does not impair the basic functional operation of the gear tooth.

2. Heavy Damage

Heavy damage is defined as that level of damage which impairs the basic functional operation of the gear tooth and leads to catastrophic failure of the gear.

Bearings

1. Spalling

This term is used to define a flaking condition whose origin may be of the classical subsurface fatigue mode or a surface-initiated type of fatigue.

2. Pitting

This term is used to indicate the existence of very small, shallow pits that are not propagating into larger failure areas.

3. Corrosion

This term is used to define the existence of ordinary oxidation corrosion that is cause for replacement of the component. This may occur during helicopter nonoperation intervals under severe moisture conditions with or without the presence of highly contaminated oil.

4. Denting

Dents (indentations) in the raceway occur when foreign particles are introduced into the bearing and are pressed between the rolling elements and the rings. Item 5 or Item 6 should be marked in conjunction with this failure mode. Denting is not to be confused with brinelling, which is explained in Item 13 below.

5. External Debris

This indicates that the debris which caused bearing damage did not originate from the bearing itself, but from another (external) failed or damaged part.

6. Internal Debris

This indicates that the debris which caused the bearing damage originated within the subject bearing; for example, debris from inner race failure causing damage to the outer race.

7. Break

This term is used to define the condition where the bearing element is fractured completely through the element cross section.

8. Crack

a. Grinding Cracks

Grinding cracks result from excessive temperature between the wheel and bearing element interfaces during manufacture which induces a tensile stress field in excess of the elastic properties of the material. This type of crack generally occurs orthogonally to the direction of the grinding wheel passage.

b. Rubbing Cracks

If a hardened bearing ring under rotation rubs against a stationary part, rubbing cracks may develop. These cracks always run perpendicular to the direction of rubbing.

c. Defective Material Cracks

Cracks caused by defective material ordinarily have an easily recognizable character, but their actual cause can often be determined only by metallurgical investigation.

9. Smearing

Smearing occurs because of rolling element skidding in the absence of sufficiently viscous lubrication. Smearing, as the name implies, is evidenced by a smeared-appearing deterioration of the raceway surface.

10. Glazing

This is a form of smearing whereby the affected area on the raceway becomes shiny appearing, similar to the finish on a new ball. Metal flow has taken place during this mode of failure.

11. Wear

This is the deterioration of the bearing rolling surfaces through normal use. Abrasives in the lubricant and poor lubrication accelerate the wear process.

12. Grooving

Grooving is continuous circumferential indentation on balls produced by balls' running on retaining diameter of counterbored raceway.

13. Brinelling

Brinelling is a term applied to a bearing which has been statically loaded to an extent such that the raceways and rolling elements are permanently deformed. A brinelled bearing has indentations in the raceways and often has corresponding flats on the rolling elements.

14. Fretting

Fretting is generally considered to be a corrosive form of wear caused by very slight movement between two metal surfaces under very high contact pressure. The formation of an iron-oxide paste between two fretting steel members is not uncommon. It is often seen between the inner ring and the shaft.

15. Creeping

Creeping is a relative movement between the bearing inner ring and the shaft, caused by inadequate interference fit for the applied load. Creeping causes not only undesirable ring wear but also excessive shaft wear. Creeping is evidenced by circumferential scoring on the bearing bore and shaft. It may be an advanced stage of fretting.

16. Spinning

Spinning is an advanced stage of creeping. The relative movement between inner ring and shaft is much greater than in creeping and the sliding surfaces may become polished. The iron-oxide from the fretting phase may still be present and assist in further wear.

17. Incorrect Installation

This term will be used when the bearing has obviously been damaged during installation or has been installed incorrectly. A common example is forcing an assembled roller bearing over the inner race with the rollers misaligned, causing marks (smeared streaks) on the inner race.

18. Diassembly Damage

This term will be used when the bearing was damaged at disassembly.

19. Discoloration Due to Temperature

Discoloration of bearing elements indicates operation with marginal lubrication or at excessive power conditions.

APPENDIX II
SAMPLE CALCULATIONS

The following sample calculations are based on data from engine models T53-L-9, T53-L-9A, and T53-L-11:

1. Compressor

Example: 1st stage = 26 blades, N_1 = 15,088 rpm

a. Fundamental rotational frequency

$$f_r = \frac{℄ \text{ of compressor rotor, } N_1 \text{ (rpm)}}{60} = \frac{15{,}088}{60} = 251.5 \text{ cps}$$

b. Compressor rotor blade passage frequency

$$C_1 = f_r \times \text{no. of rotor blades} = 251.5 \times 26 = 6539 \text{ cps}$$

2. Accessory Drive Gearbox – Gas Producer Driven

Example: Inner drive spur gear (4b), N_1 = 15,088 rpm,
gear (1) = 34 teeth, gear (2) = 63 teeth, gear (3) = 21 teeth,
gear (4a) = 40 teeth, and gear (4b) = 24 teeth (refer to Figure 7 of Reference 2 for location of these gears)

a. RPM of gear

$$N_{gear(4b)} = N_1 \times \frac{\text{No. of teeth on drive gear (1)}}{\text{No. of teeth on driven gear (2)}} \times \frac{\text{No. of teeth on drive gear (3)}}{\text{No. of teeth on driven gear (4a)}}$$

$$= 15{,}088 \times \frac{34}{63} \times \frac{21}{40} = 4274.9 \text{ rpm}$$

b. Rotational frequency

$$f_{gear(4b)} = \frac{\text{rpm of gear}}{60} \times \text{no. of gear teeth} = \frac{4274.9}{60} \times 24$$

$$= 1710 \text{ cps}$$

3. Bearing Formulas

Example: No. 1 main engine bearing, $N_1 = 15{,}088$ rpm, $d_B = 0.5000$ in., $d_1 = 2.2720$ in., $d_2 = 3.2720$ in., and $m = 13$

a. Fundamental rotational frequency

$$f_r = \frac{\text{rpm of shaft}}{60} = \frac{15{,}088}{60} = 251.5 \text{ cps}$$

b. Frequency caused by irregularity on inner race

$$f_1 = f_r\, m\, \frac{d_2}{d_1 + d_2}$$

$$= 251.5 \times 13 \times \frac{3.2720}{2.2720 + 3.2720} = 1929.6 \text{ cps}$$

c. Frequency caused by irregularity on outer race

$$f_2 = f_r\, m\, \frac{d_1}{d_1 + d_2}$$

$$= 251.5 \times 13 \times \frac{2.2720}{2.2720 + 3.2720} = 1339.9 \text{ cps}$$

d. Frequency caused by spin of rolling element

$$f_b = f_r\, \frac{d_2}{d_B}\, \frac{d_1}{d_1 + d_2}$$

$$= 251.5 \times \frac{3.2720}{0.5000} \times \frac{2.2720}{2.2720 + 3.2720} = 674.5 \text{ cps}$$

e. Frequency caused by rough spot on rolling element

$$f_b' = 2f_b = 2 \times 674.5 = 1349.0 \text{ cps}$$

f. Frequency due to rotation of train of rolling elements

$$f_t = \frac{f_2}{m} = \frac{1339.9}{13} = 103.1 \text{ cps}$$

4. Ratios

Example: Component frequency = 7504 cps
Tracking frequency = 6525 cps

a. Decimal Ratio

$$\text{Decimal ratio} = \frac{\text{component frequency}}{\text{tracking frequency}} = \frac{7504}{6525} = 1.15003$$

b. Octal Ratio

Convert the decimal ratio to an octal ratio as follows:

(1) The number to the left of the decimal ratio is the first number of the octal number.

(2) Multiply all digits to the right of the decimal point in the decimal ratio by 8. The number to the left of the decimal point in this product is the first number to the right of the decimal point in the octal number.

(3) Multiply all digits to the right of the decimal point in the product obtained in (2) by 8. The number to the left of the decimal point in this product is the second number to the right of the decimal point in the octal number.

(4) Continue this process until the desired number of decimal places for the octal ratio are obtained.

(5) Round off the last decimal place using the number 4 as the mid-point since these numbers are to base 8.

Example: Decimal ratio = 1.15003

Multiply
$$0.15003 \times 8 = 1.20024$$
$$0.20024 \times 8 = 1.60192$$
$$0.60192 \times 8 = 4.81536$$
$$0.81536 \times 8 = 6.52288$$
$$0.52288 \times 8 = 4.18304$$

Therefore, the octal ratio = 1.1146 rounded off to 4 decimal places. If the octal number had been 1.11475, the number rounded off to 4 decimal places would be 1.1150.

APPENDIX III
TRANSMISSION BEARINGS AND GEARS
AND
N_2 RELATED ENGINE GEARS

Frequency	Octal Ratio	Parameter and Component Number
32	.0024	f_2 (37)
42	.0032	f_1 (37)
47	.0035	f_2 (39)
56	.0043	f_1 (39)
74	.0056	f_2 (35)
80	.0062	$3f_b'$ (37)
84	.0064	f_2 (36)
93	.0072	f_1 (36)
109	.0105	f_1 (35)
118	.0112	$3f_b'$ (39)
151	.0137	f_2 (48)
161	.0145	f_1 (48)
175	.0156	f_2 (44)
188	.0166	fund. (46) oil pump
199	.0175	f_2 (31)
213	.0206	$3f_b'$ (35)
217	.0210	$3f_b'$ (36)
219	.0212	f_2 (40)
228	.0217	f_2 (43)
229	.0220	f_2 (33)
259	.0242	f_2 (34)
264	.0246	f_1 (44)
269	.0251	f_2 (41)
279	.0257	f_2 (42)
286	.0264	f_1 (34)
304	.0277	f_1 (31)
322	.0312	f_2 (25)
338	.0324	f_1 (33)

Frequency	Octal Ratio	Parameter and Component Number
340	.0325	$3f_b'$ (48)
346	.0331	f_1 (40)
353	.0336	f_2 (25)
359	.0341	f_1 (43)
377	.0355	fund. X 2 – oil pump
390	.0365	f_1 (41)
405	.0376	f_1 (42)
413	.0403	f_2 (26)
437	.0422	f_2 (29)
438	.0423	fund. (10–11–12)
440	.0424	fund. (47) hydraulic pump
459	.0440	f_2 (32)
460	.0441	f_2 (24)
479	.0455	f_2 (30)
499	.0471	f_1 (26)
503	.0474	f_1 (25)
514	.0503	f_2 (27)
547	.0527	f_1 (25)
565	.0543	fund. X 3 – oil pump
591	.0563	f_1 (32)
604	.0573	$3f_b'$ (40)
608	.0576	f_1 (27)
612	.0600	f_1 (29)
627	.0611	$3f_b'$ (43)
646	.0625	f_1 (30)
659	.0636	$3f_b'$ (33)
665	.0641	f_1 (24)
669	.0644	$3f_b'$ (34)
692	.0662	$3f_b'$ (44)
743	.0722	$3f_b'$ (41)
761	.0736	f_2 (23)
772	.0744	$3f_b'$ (42)
773	.0745	$3f_b'$ (31)
799	.0766	f_2 (38)
876	.1046	fund. X 2 (10–11–12)

Frequency	Octal Ratio	Parameter and Component Number
880	.1050	fund. X 2 – hydraulic pump
885	.1053	f_1 (38)
889	.1056	f_1 (23)
926	.1105	fund. (18–19)
955	.1127	fund. (7–8) engine N_2
979	.1146	$3f_b'$ (25)
996	.1161	$3f_b'$ (25)
1005	.1167	fund. (9–10) engine N_2
1008	.1171	$3f_b'$ (26) option
1101	.1263	$3f_b'$ (26)
1174	.1341	$-2f_r$ (15–16–17)
1208	.1366	$3f_b'$ (24)
1222	.1377	$-f_r$ (15–16–17)
1245	.1415	$3f_b'$ (27)
1265	.1431	$-2f_r$ (8)
1270	.1435	fund. (15–16–17)
1281	.1444	f_2 (4) engine main
1306	.1463	$-2f_r$ (7–8)
1312	.1470	$3f_b'$ (29)
1314	.1471	fund. X 3 (10–11–12)
1318	.1473	$+f_r$ (15–16–17)
1320	.1474	fund. X 3 (47) – hydraulic pump
1328	.1501	$-f_r$ (7–9)
1340	.1510	$-f_r$ (9)
1352	.1520	fund. (7–8–9)
1363	.1527	$+f_r$ (9)
1366	.1531	$+2f_r$ (15–16–17)
1375	.1537	$+f_r$ (7–9)
1376	.1540	f_r (4) engine main
1398	.1555	$+2f_r$ (7–8)
1439	.1607	$+2f_r$ (8)
1484	.1644	fund. (11–12–13) engine N_2
1491	.1650	$3f_b'$ (30)
1772	.2130	$-3f_b'$ (32)

Frequency	Octal Ratio	Parameter and Component Number
1835	.2200	$-f_r$ (14)
1844	.2206	$-f_1$ (4) engine main
1852	.2212	fund. X 2 (18–19)
1859	.2217	$-2f_r$ (13)
1882	.2235	$-f_r$ (14)
1894	.2245	$-f_r$ (13)
1910	.2257	fund. X 2 (7–8) engine N_2
1929	.2273	fund. (13–14)
1964	.2321	$+f_r$ (13)
1976	.2330	$+f_r$ (14)
1989	.2341	f_1 (4) engine main
1999	.2347	$+2f_r$ (13)
2010	.2356	fund. X 2 (9–10) engine N_2
2023	.2366	$+2f_r$ (14)
2025	.2367	$-2f_r$ (1–3)
2066	.2421	$3f_b'$ (38)
2100	.2446	$-f_r$ (1–3)
2104	.2451	f_2 (3) engine main
2105	.2451	$-2f_r$ (2)
2140	.2477	$-f_r$ (2)
2175	.2525	fund. (1–2–3)
2210	.2553	$+f_r$ (2)
2245	.2601	$+2f_r$ (2)
2250	.2604	$+f_r$ (1–3)
2300	.2642	noise for (1–2–3)
2325	.2663	$+2f_r$ (3)
2376	.2724	fund. (5–6) engine N_2
2475	.3022	fund. (3–4) engine N_2
2540	.3072	fund. X 2 (15–16–17)
2704	.3241	fund. X 2 (7–8–9)
2704	.3241	f_1 (3) engine main
2778	.3320	fund. X 3 (18–19)
2865	.3406	fund. X 3 (7–8) engine N_2
2881	.3421	$3f_b'$ (23)

Frequency	Octal Ratio	Parameter and Component Number
2968	.3507	fund. X 2 (11–12–13) engine N_2
3015	.3545	fund. X 3 (9–10) engine N_2
3075	.3612	fund. (4–5–6)
3810	.4530	fund. X 3 (15–16–17)
3846	.4556	$3f_b'$ (4) engine main
3858	.4566	fund. X 2 (13–14)
3868	.4574	$3f_b'$ (4) engine main
4056	.4762	fund. X 3 (7–8–9)
4350	.5253	fund. X 2 (1–2–3)
4452	.5353	fund. X 3 (11–12–13) engine N_2
5721	.7007	$3f_b'$ (3) engine main
5787	.7061	fund. X 3 (13–14)
6150	.7424	fund. X 2 (4–5–6)
6525	1.0000	fund. X 3 (1–2)
9225	1.3237	fund. X 3 (4–5–6)

APPENDIX IV
TAIL ROTOR DRIVE
AND 42-DEGREE AND 90-DEGREE GEARBOX SIGNALS S

Frequency	Octal Ratio	Parameter and Component Number
37.5		fund. T/R
75.0		X 2
112.5		X 3
125	.0116	f_b' (49) SKF/Fafnir – 90 deg
136	.0125	f_2 (49) SKF/Fafnir – 90 deg
140	.0130	f_b' (49) SKF – 90 deg
147	.0134	f_2 (49) SKF – 90 deg
148	.0135	f_2 (49) MRC – 90 deg
148		f_b' (49) MRC – 90 deg
150	.0136	f_b' (48) MRC – 90 deg
150		4 X (T/R)
165	.0147	f_2 (48) MRC – 90 deg
167	.0151	f_2 (48) Bower – 90 deg
170	.0152	f_b' (48) Bower – 90 deg
183	.0163	f_1 (49) SKF/Fafnir – 90 deg
187		5 X (T/R)
190	.0167	f_1 (49) MRC – 90 deg
192	.0170	f_1 (49) SKF – 90 deg
208	.0202	f_1 (48) Bower – 90 deg
209	.0203	f_b' (43) SKF/MRC – 42 deg
209		f_b' (43) SKF/MRC – 90 deg
211	.0205	f_1 (48) MRC – 90 deg
225	.0215	f_2 (46) SKF/MRC – drive shaft
225		6 X (T/R)
228	.0217	f_2 (43) SKF/MRC – 42 deg
228		f_2 (43) SKF/MRC – 90 deg
240	.0227	f_2 (47) N – H – 90 deg
258	.0242	f_b' (42) SKF/MRC – 42 deg
259	.0243	f_b' (47) N – H – 90 deg

Frequency	Octal Ratio	Parameter and Component Number
260	.0243	f_b' (47) MRC – 90 deg
262		7 X (T/R)
279	.0257	f_2 (42) SKF/MRC – 42 deg
280	.0260	f_2 (47) MRC – 90 deg
287	.0264	f_2 (47) Bower – 90 deg
288	.0265	f_b' (47) Bower – 90 deg
290	.0266	f_b' (46) SKF/MRC – drive shaft
300		8 X (T/R)
313	.0304	f_1 (46) SKF/MRC – drive shaft
337.5		9 X (T/R)
347	.0332	f_1 (47) N – H – 90 deg
359	.0341	f_1 (43) SKF/MRC – 42 deg
359		f_1 (43) SKF/MRC – 90 deg
375	.0354	$3f_b'$ (49) SKF/F[illegible] – 90 deg
375		10 X (T/R)
404	.0376	f_1 (47) MRC – 90 deg
405	.0376	f_1 (42) SKF/MRC – 42 deg
412		11 X (T/R)
419	.0407	$3f_b'$ (49) SKF – 90 deg
450		12 X (T/R)
451	.0433	$3f_b'$ (48) MRC – 90 deg
487		13 X (T/R)
509	.0477	$3f_b'$ (48) Bower – 90 deg
525		14 X (T/R)
537	.0521	$-4f_r$ (52–53) – 90 deg
562		15 X (T/R)
586	.0560	$-3f_r$ (52–53) – 90 deg
627	.0612	$3f_b'$ (43) SKF/MRC – 42 deg
627		$3f_b'$ (43) SKF/MRC – 90 deg
635	.0616	$-2f_r$ (52–53) – 90 deg
684	.0655	$-f_r$ (52–53) – 90 deg
733	.0714	fund. (52–53) – 90 deg
772	.0744	$3f_b'$ (42) SKF/MRC – 42 deg
777	.0750	$3f_b'$ (47) N/H – 90 deg

Frequency	Octal Ratio	Parameter and Component Number
780	.0751	$3f_b'$ (47) MRC – 90 deg
782	.0753	$+f_r$ (52–53) – 90 deg
831	.1012	$+2f_r$ (52–53) – 90 deg
865	.1037	$3f_b'$ (47) Bower – 90 deg
870	.1042	$3f_b'$ (46) SKF/MRC – drive shaft
880	.1050	$+3f_r$ (52–53) – 90 deg
929	.1107	$+4f_r$ (52–53) – 90 deg
1124	.1302	$-f_r$ (50–51) – 42 deg
1173	.1340	$-2f_r$ (50–51) – 42 deg
1222	.1377	$-3f_r$ (50–51) – 42 deg
1271	.1436	$-4f_r$ (50–51) – 42 deg
1320	.1474	fund. (50–51) – 42 deg
1369	.1533	$+f_r$ (50–51) – 42 deg
1418	.1572	$+2f_r$ (50–51) – 42 deg
1466	.1630	fund. X 2 (52–53) – 90 deg
1467	.1631	$+3f_r$ (50–51) – 42 deg
1516	.1670	$+4f_r$ (50–51) – 42 deg
2199	.2544	fund. X 3 (52–53) – 90 deg
2640	.3171	fund. X 2 (50–51) – 42 deg
3960	.4666	fund. X 3 (50–51) – 42 deg

APPENDIX V
N_1 RELATED ENGINE BEARINGS AND GEARS

Frequency	Octal Ratio	Parameter and Component Number
166	.0140	f_2 (19)
171	.0143	f_2 (18)
186	.0154	f_2 (20)
193	.0160	f_2 (17)
196	.0162	f_2 (21)
213	.0174	f_2 (14)
232	.0207	f_2 (16)
234	.0210	f_2 (17)
238	.0212	f_2 (21)
241	.0214	f_1 (19)
249	.0221	f_1 (18)
262	.0230	f_1 (20)
269	.0234	f_1 (17)
274	.0237	f_1 (21)
312	.0265	f_1 (17)
317	.0270	f_1 (21)
338	.0304	f_1 (16)
357	.0320	f_1 (14)
407	.0355	fund. (27)
427	.0370	fund. (25)
437	.0376	f_2 (15)
490	.0435	f_2 (13)
559	.0505	f_2 (11)
561	.0506	f_1 (15)
639	.0564	$3f_b'$ (19)
641	.0565	fund. (26)
660	.0600	$3f_b'$ (18)
703	.0631	$3f_b'$ (20)
732	.0652	f_1 (13)
739	.0656	$3f_b'$ (17)

Frequency	Octal Ratio	Parameter and Component Number
751	.0665	$3f_b'$ (21)
787	.0712	$3f_b'$ (14)
799	.0721	f_1 (11)
814	.0731	fund. X 2 (27)
832	.0744	f_2 (12)
854	.0761	fund. X 2 (25)
868	.0771	$3f_b'$ (17)
882	.1001	$3f_b'$ (21)
895	.1010	$3f_b'$ (16)
1068	.1155	f_1 (12)
1221	.1306	fund. X 3 (27)
1281	.1351	fund. X 3 (25)
1282	.1352	fund. X 2 (26)
1282	.1353	fund. (22–23–24)
1340	.1413	f_2 (1) main bearing
1440	.1506	f_2 (1) main option
1596	.1640	fund. (6–7)
1699	.1734	$3f_b'$ (15)
1710	.1742	fund. (4b–5–8)
1751	.1772	fund. (9–10)
1754	.1774	f_2 (2) main option
1923	.2137	fund. X 3 (26)
1930	.2142	f_1 (1) main bearing
1972	.2173	$3f_b'$ (13)
2081	.2272	f_1 (1) main option
2201	.2400	f_2 (2) main bearing
2233	.2433	$3f_b'$ (11)
2270	.2450	f_1 (2) main option
2564	.2723	fund. X 2 (22–23–24)
2829	.3155	f_1 (2) main bearing
2850	.3172	fund. (3–42)
3192	.3501	fund. X 2 (6–7)
3229	.3526	$3f_b'$ (12)
3241	.3535	$3f_b'$ (12) option

Frequency	Octal Ratio	Parameter and Component Number
3420	.3705	fund. X 2 (4b–5–8)
3502	.3765	fund. X 2 (9–10)
3846	.4275	fund. X 3 (22–23–24)
4024	.4444	$3f_b'$ (1) main option
4047	.4462	$3f_b'$ (1) main bearing
4788	.5341	fund. X 3 (6–7)
5130	.5650	fund. X 3 (4b–5–8)
5253	.5757	fund. X 3 (9–10)
5700	.6363	fund. X 2 (3–42)
5809	.6463	$3f_b'$ (2) main option
5985	.6631	$3f_b'$ (2) main bearing
6288	.7111	$(C_1) - f_r$
6539	.733	(C_1)
6790	.7555	$(C_1) + f_r$
6791	.7556	$(C_2) - f_r$
7042	1.0000	(C_2)
7293	1.0222	$(C_2) + f_r$
8550	1.1555	fund. X 3 (3–42)
8551	1.1556	(C_3)
9054	1.2222	(C_4) and centrifugal impeller
9557	1.2667	(C_5)
16599	2.2667	Turbine rotor stage (1) N_1

APPENDIX VI
N_2 RELATED ENGINE BEARINGS

Frequency	Octal Ratio	Parameter and Component Number
174	.0155	f_2 (19)
195	.0172	f_2 (22–23)
218	.0211	f_1 (19)
219	.0212	f_2 (21)
230	.0220	f_2 (20)
265	.0246	f_2 (18) option
284	.0262	f_1 (22–23)
291	.0267	f_2 (18)
308	.0301	f_1 (21)
323	.0312	f_1 (18–20) option
345	.0330	f_1 (18)
382	.0360	f_2 (15) option
386	.0362	f_2 (15)
524	.0511	$3f_b'$ (18) option
534	.0517	f_2 (16)
546	.0527	f_2 (16) option
603	.0572	f_1 (15)
608	.0576	f_1 (15) option
656	.0634	$3f_b'$ (19)
728	.0711	f_1 (16) option
741	.0721	f_1 (16)
752	.0730	$3f_b'$ (22–23)
806	.0772	f_2 (17)
826	.1006	$3f_b'$ (21)
865	.1037	$3f_b'$ (18–20)
993	.1157	f_1 (17)
1185	.1350	f_2 (14) option
1204	.1364	f_2 (14)
1239	.1412	$3f_b'$ (15) option
1292	.1453	$3f_b'$ (15)

Frequency	Octal Ratio	Parameter and Component Number
1352	.1521	$3f_b'$ (16)
1548	.1714	$3f_b'$ (16) option
1680	.2036	f_1 (14)
1700	.2053	f_1 (14) option
2146	.2503	$3f_b'$ (17)
2162	.2515	$3f_b'$ (17) option
3650	.4363	$3f_b'$ (14) option
4253	.5156	$3f_b'$ (14)