USAAVLABS TECHNICAL REPORT 66-55

DIAGNOSTIC NOISE STUDY OF POWER TRANSMISSION SYSTEMS

Final Report

By

R. G. Locklin

September 1966

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-249(T)

CURTISS-WRIGHT CORPORATION
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The effort reported herein represents a part of a continuing effort to investigate and evaluate various techniques for determining the condition of aircraft components while installed on the aircraft.

This report presents the results of an investigation and evaluation of the technique which utilizes the measurement or analysis of radiated acoustical energy to determine the condition of enclosed mechanical systems.

The results of the study indicate that the use of this technique is feasible. Good correlation exists between radiated sound pattern deviations and the malfunctions noted through disassembly and inspection.

Task 1M121401D14414
Contract DA 44-177-AMC-249(T)
USAAVLABS Technical Report 66-55
September 1966

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ABSTRACT

The purpose of this investigation was to make a diagnostic noise study of the X-19 power transmission system to demonstrate the feasibility of using the diagnostic sonic technique to determine the mechanical condition of the internal gearing and bearings.

The method employed in monitoring the transmission system utilizes the noise generated by gears and bearings to determine the mechanical integrity of the system. The condenser type microphone system was utilized to record these signals on magnetic tape, and the recorded data were then analyzed using the panoramic sonic analyzer. In addition to the diagnostic sonic concept, a spectrometric oil analysis of the system was also made.

The diagnostic sonic analysis of the X-19 power transmission system was successful in detecting the majority of the system anomalies including a gear fatigue failure, several bearing failures, and gear tooth scuffing conditions. Correlation between acoustic and spectrometric oil analysis was also achieved.

The results of this investigation indicate the ability of the diagnostic sonic analysis technique in determining the mechanical integrity of the X-19 power transmission system. Although spectrometric oil analysis cannot indicate fatigue failures which may occur between sampling periods and obviously cannot detect non-lubricated components, in many cases additional information is obtained by the correlation of the oil sampling and sonic methods. Therefore, it is recommended that in a complete maintenance monitoring system both the spectrometric oil sampling and the diagnostic sonic analysis techniques be utilized.

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LIST OF SYMBOLS

AGB	Accessory gearbox
ch	Channel
C.R.	Cruise
cps	Cycles per second
C_1	First-stage compressor rotor
C_2	Second-stage compressor rotor
C_3	Third-stage compressor rotor
E.T.	Endurance time
ECGB	Engine coupling gearbox
f_1	Frequency caused by irregularity on inner raceway, cps
f_2	Frequency caused by irregularity on outer raceway, cps
f_B	Frequency caused by spin of rolling element, cps
f_B'	Frequency caused by rough spot on rolling element, cps
$3f_B'$	Third harmonic of f_B'
f_R	Fundamental rotational frequency of engine, cps
f_T	Frequency due to rotation of train of rolling elements, cps
G.I.	Ground idle
N_1RPM	T55-L-5 gas producer rotor revolutions per minute
N_2RPM	T55-L-5 power turbine shaft revolutions per minute - Output
ppm/hr	Parts per million per hour
P/S	Power supply

rps	Revolutions per second
S/N	Signal-noise ratio
T.O.	Takeoff
T.R.	Transition
USAAVLABS	United States Army Aviation Materiel Laboratories

I. INTRODUCTION

A diagnostic noise study of the X-19 power transmission system under United States Army Aviation Materiel Laboratories Contract No. DA 44-177-AMC-249(T) has been conducted in conjunction with the X-19 Development, Qualification and Assurance Test Program under Air Force Contract No. AF33(657)-13017.

The mechanical condition of gears and bearings in V/STOL aircraft has a direct relationship to the reliability of the aircraft. One method of monitoring the internal condition of any enclosed mechanical system is by spectrometric analysis of lubricating oil samples to determine the metallic content. This technique, developed by BuWeps, is fully described in BuWeps Instruction 4730.8. A new method of monitoring engine malfunctions, designated the Diagnostic Sonic Analysis Technique, has been developed by the Curtiss Division, Curtiss-Wright Corporation. This new concept is a maintenance monitoring system using acoustical radiated energy to measure the operating condition of machines. The technique and analyzer have been developed, and their application to the monitoring of the mechanical condition of turbine engines and power train components has been demonstrated under several Government contracts.

The use of the diagnostic sonic concept in determining the mechanical integrity of rotating components as well as the spectrometric oil analysis technique in determining the internal condition of the X-19 power transmission provided an excellent opportunity for comparison of these two methods of diagnosing system abnormalities under identical operating conditions.

II. SUMMARY

The X-19 development, qualification and assurance testing of the power transmission system ceased because of contract termination after completion of 91:45 hours of endurance. This endurance testing consisted of simulated flight cycles (hover and takeoff), transition climb and descent, high-speed cruise, hover landing and emergency hover - one-engine-out operation. During this testing, sound recordings were taken at "idle" speed at intervals of approximately 10 hours, and oil samples were taken every 5 hours, depending upon the test schedule.

Diagnostic sonic analysis of the X-19 power transmission system was successful in detecting the majority of the system abnormalities encountered during the test. These malfunctions included ECGB gear fatigue failure, tee box eccentricity and subsequent failure, nacelle bevel gear scuffing, and several bearing failures, including the spalled left nacelle roller bearing failure.

Excellent correlation between acoustic and spectrometric oil analysis was achieved during the last 41:45 hours of endurance as a result of a spalled roller in the left nacelle No. 1 pinion bearing. Other failures showed little or no correlation between the two techniques, possibly due to the nature of the failure, as explained under Sections IV-B and -D of this report.

III. TEST PROCEDURE

A. Recording Equipment

The basic recording equipment utilized during the diagnostic analysis of the X-19 power transmission system included a magnetic tape recorder and a condenser-type microphone system. A list of recording equipment used during these tests is presented in Table I. A photograph of the recording setup in the control room is shown in Figure 1.

A block diagram of the recording system utilizing the Ampex two-channel tape recorder is shown in Figure 2.

A list of the diagnostic sonic analyzer laboratory analysis equipment is presented in Table II, and a block diagram of this data reduction system is shown in Figure 3.

B. Microphone Location

The four condenser-type microphones listed in Table I were located at the ECGB, tee box and both nacelles, as shown in the schematic of the X-19 half-system test rig (Figure 4). These were the positions used during the endurance testing. These positions were also used during most of the preliminary runs after earlier microphone surveys had been conducted during the initial green runs.

The actual location of microphone No. 1 at the ECGB is shown in a photograph (Figure 5) viewing the ECGB from the right side. The No. 2 microphone, which was located directly beneath the tee box housing, is shown in a photograph (Figure 6) viewing the tee box assembly from the left-front side.

Figure 7 is a photograph of the No. 3 microphone aimed at the rear of the left nacelle housing. Microphone No. 4 is located in an identical position at the right nacelle.

These microphones were all located approximately 2 inches away from the basic component in a position which yielded the optimum acoustic signal, as determined from a preliminary microphone survey. A microphone support (see Figure 7), which was attached directly to the nacelle housing, was fabricated for each nacelle. These microphones rotated with the nacelles through the various gimbal angles and thus always maintained the same relative position with the internal components.

C. Fundamental Frequencies

The fundamental frequencies of all rotating components were calculated as shown in Appendix I and are tabulated in Tables III and IV. The mechanical data required for these calculations included bearing dimensions, number of blades on compressor rotors, and number of teeth on all gears. Figure 8 is a schematic of the X-19 half-system drive mechanism which shows the location of the various gears and bearings. Only those frequencies pertinent to the analysis of this transmission system were included in this report. None of the engine frequencies other than the first three compressor stages were shown.

D. Recording Procedure

Sound recordings were generally taken at intervals of approximately 10 hours at 7000 N_2 RPM. This speed was chosen over the "idle" speed of 6500 N_2 RPM because of the more stable engine operation. A summary log of the acoustic recordings has been included in Appendix II. Since the majority of the recordings were made with a two-channel tape recorder, microphones Nos. 1 and 2 were recorded simultaneously, followed by another simultaneous recording of microphones Nos. 3 and 4.

E. Oil Samples

Oil samples were taken at intervals of approximately 5 hours and sent to the U. S. Naval Air Station, Pensacola, Florida, for spectrometric analysis. These oil samples were taken in accordance with the procedures established by BuWeps Instruction 4730.8.

IV. DISCUSSION

A. Teardown

The X-19 power transmission gearbox system (ECGB, tee box, left and right nacelles) was disassembled for inspection periodically during the endurance testing to determine the mechanical condition of its components.

During the initial green runs, an inspection of the ECGB revealed a web failure of the No. 2 intermediate (idler) gear (P/N 172980) at a total rig time of 328:14 hours. This failure consisted of a pie-shaped section broken out of the gear, originating in a lightening hole in the web. This failure was also detected acoustically during a subsequent analysis of the tape recordings, as explained under Section IV-C.

Inspection of the ECGB at a total rig time of 348:28 hours revealed that the forward No. 4 pinion gear bearing from the No. 2 box had failed. This failure consisted of a grooved outer raceway and slightly grooved and spalled rollers. Photographs of these irregularities are shown in Figures 9 and 10. This bearing failure was detected acoustically during an analysis of a tape recording made at a total rig time of 347:40 hours (see Section IV-C).

During the break-in runs of the nacelle bevel gears, an inspection at a scheduled shutdown revealed gear tooth scuffing of the right nacelle bevel gears. This scuffing condition was corrected by minor regrinding of the tooth profile to improve the tooth contact pattern. A change between the left and right nacelle spectrograms was also noted at this time, as discussed under Section IV-C.

A routine inspection of the complete gearbox system after the completion of 10:00 hours of endurance revealed that a bearing failure occurred on the small water brake which duplicates the load of the accessory drive gearbox. This bearing was found to be completely rusted and practically seized on the shaft. An analysis of the acoustic recordings also revealed this failure.

After 21:15 hours of endurance, an inspection revealed that the No. 3 longitudinal shaft bearing had failed. The inner race which is an integral part of the longitudinal shaft was found spalled, as well as the rolling elements. Indication of this irregularity was detected acoustically during a green run recording at a total rig time of 347:40 hours, as explained in Section IV-C.

The main water brake which duplicates the load of the rear propellers was found to be out of alignment at 21:15 endurance hours.

After alleviation of the discrepancies noted above, endurance continued until at 28:05 hours an overspeed to 16,000 N_2 RPM occurred. Initial inspection of the rig after shutdown disclosed a cracked tee box housing. Further inspection revealed that one tooth had broken off the P/N 171764 bevel gear and had jammed in succeeding tooth meshes. The resulting abnormal loads on the tee box housing caused it to crack. Abnormalities in the acoustic patterns occurring at this time are discussed in Section IV-C.

All of the components were removed and inspected at this time. The transmission was reassembled using a new tee box housing and bevel gear set. The ECGB was also reassembled using new pinion gears and a reworked lube system.

After green runs on the tee box gears showed normal wear patterns, endurance was resumed.

Visual inspection of all components after 50 hours of endurance revealed light pitting of the left nacelle gear set and spalling of the right-hand gear set. Abnormal acoustic patterns obtained at this time were identical to those observed during the previous nacelle gear scuffing conditions. The tee box gears were in excellent condition. However, the tee box turning vane and fan were cracked.

The nacelles were reassembled with new gears with full case depth. A new turning vane and fan were installed on the tee box.

Endurance testing was resumed again and ran trouble free until a routine inspection revealed another cracked tee box fan at 28:00 hours. The fan and stator assembly were replaced, and endurance continued until a stop-test order was received from the Air Force.

Total endurance time at cessation of testing was 91:45 hours.

Due to the cessation of testing by contract termination, visual inspection of all components was made under USAAVLABS Contract DA 44-177-AMC-249(T). This was done to correlate the diagnostic sound recording data with the physical condition of the parts. The results of this inspection revealed that the ECGB, tee box, and right nacelle rotating components were in excellent condition. However, one area of surface was marked on each tooth of the left nacelle ring and pinion gear due to the passage of a particle from the spalled roller of the No. 1 nacelle bearing. Correlation of the acoustic analysis with the mechanical condition as well as with the spectrometric oil analysis is discussed in Sections IV-C and -D.

The transverse and longitudinal shaft assemblies were in excellent condition except for the rear longitudinal shaft which supports the No. 3 bearing. The inner race of this bearing, which is an integral part of the longitudinal shaft, was spalled. Analysis of the acoustic recordings also disclosed this irregularity of the inner raceway.

Inspection of the ECGB at the 28:00-hour endurance period revealed heavy fretting corrosion on the pinion gear internal splines and the mating quill shaft splines. The oil distribution system at the center of each pinion gear was redesigned so that more oil would be delivered to the spline area. Inspection after an additional 22:00 hours of endurance revealed a marked decrease in fretting corrosion and spline wear on the pinion gears. However, at the cessation of testing at 91:45 hours of endurance, there was still some light fretting corrosion on the splines that mesh with the pinion gear.

B. Oil Analysis

In addition to the diagnostic noise study of the X-19 transmission system, a spectrometric analysis of the engine lubricant was also made. Periodic oil samples were taken and analyzed by the U. S. Naval Air Station at Pensacola, Florida, and results deviating from known acceptable particle (iron, aluminum, chromium, silver, copper, tin, magnesium, lead and nickel) levels were reported.

The sample data involving "iron" are of primary importance, with silver particles and levels of aluminum being secondary. With the component oil consumption level low, typical of "stable" systems, the accumulation rate rather than absolute particle level is of most interest. Trends of iron particle accumulation in each gearbox show enough consistency to establish tentative "normal levels" in accumulation rate.

The oil analysis program conducted on the X-19 transmission system has been in accordance with BuWeps Instruction 4730.8 dated June 1963.

During the 91:45 hours of endurance, oil samples were taken at intervals of approximately every 5 hours, depending on the test schedule.

A tabulation of iron content results and cumulative build-up rates is given in Table V. A normal cumulative particle rate for iron content in parts per million per hour (ppm/hr) is estimated for each component as follows:

ECGB	6 ppm/hr
Tee Box	2 ppm/hr
Nacelles	2 ppm/hr

The spectrometric oil sampling technique can show incipient failures due to a rapid rise in element content. However, it cannot indicate fatigue failures which may occur between sampling periods.

The failures determined during visual inspection (see Table VI) discussed under IV-A were not all indicated by spectrometric oil analysis. These failures include fatigue failures, bearings lubricated with grease, and components not requiring lubrication. All of these types of failures, however, are detectable by acoustic analysis, provided these are rotating components.

Although termination of the X-19 aircraft project has prevented the obtaining of all the data required for a full evaluation of the transmission system, enough data have been obtained to predict normal ppm/hr rates and to show the ability of spectrometric oil analysis to predict incipient failure due to wear.

Perhaps the best correlation between mechanical condition and spectrometric oil analysis was achieved due to spalling of the left nacelle No. 1 bearing, as shown in Figure 11. It is evident that this spalling started within the first 5 hours of testing and grew progressively worse. Correlation with acoustic data is also evident, as explained under Sections IV-C and -D.

C. Acoustic Data

The acoustic data presented in this report are divided into three main categories:

1. ECGB Recordings
2. Tee Box Recordings
3. Nacelle Recordings

The discrepancies encountered under each of these categories are compared with normal spectrograms as well as correlated with the spectrometric oil analysis in Section IV-D.

1. ECGB Recordings

(a) ECGB Fatigue Failure

A fatigue failure in the web of the No. 2 ECGB intermediate (idler) gear (see Section IV-A) occurred during the green runs at a total rig time of 328:14 hours. Fortunately, a recording was being made of the ECGB with the engine operating at 14809 N_2RPM at the time of failure. Normally, acoustic recordings are made near "idle" (7000 RPM) because of the increased signal-to-noise ratio. However, the spectrograms produced at this high N_2RPM adequately indicate this fatigue failure.

Figure 12 shows a normal spectrogram of the ECGB gear mesh frequency (cross-hatched signal at 9934 cps) at 14902 N_2RPM. A similar spectrogram of this gear mesh frequency (cross-hatched signal at 9872 cps) at 14809 N_2RPM is shown in Figure 13. However, in Figure 13, this signal is accompanied by a side band (9635 cps) which is displaced from the idler gear signal by 237 cps, which is double the rotational frequency of the shaft supporting the idler gear. Figure 14, an amplitude vs. time trace of this side band frequency (9635 cps), shows that this side band appeared approximately 15 minutes before an unscheduled shutdown as a result of a chip detector warning signal from the ECGB. The drastic increase in amplitude of this signal indicates an irregularity in the gear tooth mesh frequency which was probably a result of an initial crack in the gear web. This crack would allow the adjacent gear teeth to deflect slightly as contact was made with the mating gear, thus producing a modulated acoustic signal. It is believed that the gear was still intact when the above recordings were made. (Note: The sharp decrease in amplitude at 14:19 clock time in Figure 14 is the end of the tape recording.)

(b) ECGB No. 4 Bearing

A recording of the ECGB (total rig time of 347:40 hours) revealed a high bearing signal due to an irregularity on the outer raceway of the ECGB No. 4 pinion gear bearing, as indicated in Figure 15 (cross-hatched signal at 1264 cps). Figure 16 also shows an irregularity in the rolling elements of this same bearing, as indicated by the cross-hatched signal at 3143 cps. This signal is the 3rd harmonic of the roller frequency due to a rough spot on one or more of the rollers.

The shaded areas appearing in both Figures 15 and 16 are resonant frequencies which do not change with engine speed. These resonances have subsequently been attributed to the metal cylinder's enclosing the ECGB microphone, which produced an organ pipe effect; thus, a series of resonant humps in the 1K to 4K frequency range resulted. This cylinder was installed to shield the microphone from ECGB oil leaks.

A description of the above failures, including photographs, is presented in Section IV-A.

(c) No. 3 Longitudinal Shaft Bearing

The cross-hatched signal in Figure 15 at 1765 cps indicates a non-uniformity existing in the No. 3 longitudinal shaft bearing. This signal represents the 3rd harmonic of the frequency due to a rough spot on one or more of the rolling elements. Subsequent removal of this bearing at 21:15 hours of endurance confirmed this detection. A new bearing was installed and relocated to run on a good section of the shaft inner race.

A visual inspection at the end of the endurance testing (91:45 hours) revealed that this No. 3 longitudinal shaft bearing inner race was spalled again. This irregularity was detected in a spectrogram made at 86:00 hours of endurance, as shown in Figure 17. The hump (284 cps) appearing in this figure is the frequency caused by an irregularity on the inner raceway. Figure 18 is a similar spectrogram made at 78:00 hours of endurance, which shows no evidence of this malfunction.

(d) Small Water Brake Bearing

A bearing failure occurring on the small water brake after 10:00 hours of endurance was reflected in the ECGB accessory drive gear mesh frequency. Figure 19 shows the 2nd harmonic of this ECGB accessory drive frequency (cross-hatched signal at 5508 cps). Figure 20, which is a similar spectrogram taken after a new bearing was installed, shows that this signal is no longer present. The actual bearing frequencies were not detected. When this bearing was inspected, the lubricating grease was gone and the bearing was completely rusted, being practically seized on the shaft. This condition imposed an extra load on the shaft and drive gear, which is probably the cause of the high accessory drive gear mesh frequency shown in Figure 19.

2. Tee Box Recordings

Figure 21 is a spectrogram of the tee box showing multiple side bands around the bevel gear mesh frequency made during green runs (total rig time = 324:58 hours). The existence of these side bands is an abnormal acoustic phenomenon and is usually indicative of an eccentricity or misalignment condition. However, other sources of gear noise which may contribute to these acoustic anomalies are as follows:

(a) Stress Waves - due to the release of the local compressive stresses after the tooth is disengaged - usually only the fundamental frequency is excited.

(b) Impact - due to inaccuracies in gear manufacturing and deflection of the tooth under load.

(c) Air Pumping - due to the expulsion of air from the space between two teeth of one gear by the meshing tooth of the corresponding gear and the suction caused by the vacuum between two teeth when the meshing tooth goes out of mesh.

(d) Oil Pocketing - since oil is practically incompressible, if a meshing tooth hits a space between the meshing teeth filled with oil, a heavy shock is unavoidable.

(e) Oil Splashing - if gears operated at high speeds are lubricated by filling the gear casing with oil to such an extent that the lower parts are running through the oil, oil splash noise may be quite noticeable.

(f) Friction - this is one of the major sources of gear noise, if not the major source of noise. The change between "root friction" or "pushing action" and "head friction" or "pulling action" occurs suddenly at the pitch line. This change reverses the direction of forces acting radially on the gears, which leads to a pronounced tooth-contact frequency.

(g) Variation in Radial Forces - caused by inaccuracies of gears, insufficient lubrication of the gear-shaft bearings, or variations in the lubricating oil pressure.

(h) Improper Design and Manufacturing Imperfections - such as shape of gear bodies; accuracy of teeth and tooth ring and shaft concentricity also contribute to the overall gear noise as well as affect discrete frequency components.

Inspection of the tee box at this time revealed no abnormal conditions. The first recording (total rig time = 347:40 hours) made upon re-assembly showed no side bands (see Figure 22). The only known difference between these recordings is that the gear teeth were probably not meshed with the same teeth as before disassembly. The fact that these side bands disappeared after reassembly of the tee box without any parts being changed could substantiate the mis-alignment concept, but in any case it indicates a variation in the assembly of the gearbox components.

A comparison of Figure 22, which shows a normal tee box bevel gear signal (cross-hatched signal), with Figure 23 shows that multiple side bands appeared in Figure 23 (total rig time = 355:49 hours) after the right nacelle had been removed from the system during the left nacelle gear development process. These side bands also appeared on the 2nd, 3rd and 4th harmonics of the tee box bevel gear. It may be reiterated at this time that the existence of side bands is indicative of an eccentricity or misalignment condition. It is evident from these spectrograms that the removal of the right nacelle resulted in some kind of change in the system. Figure 24 (endurance time = 21:15 hours) also shows the existence of multiple side bands after the right nacelle has been reinstalled in the system. The basic frequency and its harmonics are indicated by the cross-hatched signal, while the side bands are shown as the shaded area.

Figure 24, which was made from a recording taken at 6:50 hours before the tee box gear failure, is in itself not an indication of an impending failure but rather an indication of a nonuniformity which possibly imposed a stress on the bevel gear train.

3. Nacelle Recordings

(a) Nacelle Bevel Gear Scuffing

Figure 25 (total rig time = 347:43 hours) represents a normal nacelle bevel gear spectrum determined empirically in which the 3rd harmonic is larger than the even harmonics (2nd and 4th). These characteristics are peculiar to this gear configuration, as determined from previous analysis, and may not be true for other gear trains. Comparing Figure 25, which is a spectrogram of the left nacelle, with the right nacelle spectrogram, Figure 26, shows that the right nacelle spectrum does not contain the 3rd harmonic of the nacelle bevel gear, whereas the 2nd and 4th harmonics are approximately the same as the left nacelle. Inspection of these nacelles at the scheduled shutdown revealed gear tooth scuffing of the right nacelle bevel gears. This phenomenon was corrected by minor regrinding of the tooth profile to improve the tooth contact pattern. After the nacelle bevel gear development process was successfully completed through successive regrinds, the 3rd harmonic again appeared.

An analysis of Figures 25 and 26, together with the results of the mechanical condition of the nacelles, led to the conclusion that the absence of the 3rd harmonic in the right nacelle spectrogram (Figure 26) was indicative of a difference in the tooth contact pulse shape.

After 50 hours of endurance testing, spalling of the right nacelle bevel gear set showed an acoustic pattern similar to that in Figure 26, in which the 3rd harmonic of the bevel gear mesh frequency disappeared. The light pitting of the left nacelle gear set was not indicated in the spectrograms.

(b) Left Nacelle No. 1 Bearing Failure

Figure 27 shows a comparison of the left and right nacelles over a 35-hour period of endurance ranging from 51 to 86 hours. The discrete signals under observation were the nacelle bevel gear mesh frequency (382 cps @ 7000 N_2RPM) and the nacelle No. 1 bearing frequency ($f_B' = 374$ cps @ 7000 N_2RPM). All of these spectrograms were not recorded at exactly 7000 N_2RPM, which accounts for the slight deviation in frequency. A comparison of the left and right sets of spectrograms shows a distinct increase in amplitude after 63 hours of endurance for the left nacelle, whereas the right nacelle frequencies remain relatively constant. The proximity of the bevel gear mesh frequency and the No. 1 bearing (f_B') frequency unfortunately produces a single hump. However, Figure 28, which is a spectrogram made with higher resolution than Figure 27, shows two separate signals appearing in place of the single hump. As noted in Figure 28, these signals are attributed to the nacelle bevel gear mesh frequency (386 cps @ 7074 N_2RPM) and the No. 1 bearing frequency ($f_B' = 378$ cps @ 7074 N_2RPM).

D. Spectrometric Oil Data vs. Acoustic Data

Table VI presents a list of malfunctions identified by either acoustic or spectrometric oil analysis. While the majority of the malfunctions listed in Table VI were indicated by acoustic analysis, only four were picked up through oil analysis. Some of the bearings are lubricated with grease rather than oil, and the tee box fan and stator assembly are not lubricated. Consequently, these items cannot be detected through oil sample methods. The spectrometric oil sampling technique cannot indicate fatigue failures which may occur between sampling periods. Therefore, only items 7, 8, 9 and 12 in Table VI should have been detected by spectrometric oil analysis, whereas all the items should have been detected by acoustic analysis.

Although items 7, 8 and 9 were detected by both techniques, only item 9 in Table VI, the nacelle No. 1 bearing failure, shows a direct correlation.

Figure 11 is a plot of iron content vs. running hours for both nacelles. It is obvious from this plot that spalling of the left nacelle started within the first 5 hours. The points superimposed on this left nacelle curve represent the endurance hours noted on the acoustic spectrograms shown in Figure 27. Comparison of Figures 11 and 27 shows a definite correlation of acoustic data and spectrometric oil analysis beginning with

63 hours of endurance. At both 63 and 86 hours of endurance (Figure 27), the amplitude of the nacelle gear and bearing frequency has increased progressively along with an increased iron content, as shown in Figure 11. A visual inspection revealed a spalled roller on the left nacelle No. 1 bearing and marked bevel gears. A photograph of this spalled bearing is shown in Figure 29. No scuffing or pitting was evident. Unfortunately, no recordings were taken at "idle" RPM after 86 hours of endurance due to the cessation of testing because of contract termination. Consequently, at the maximum iron content shown in Figure 11 at 91:45 hours of endurance, there is no corresponding acoustic spectrogram.

V. CONCLUSION

The results of the diagnostic sonic analysis of the X-19 power transmission system indicate the ability of this technique in determining the integrity of a mechanical system.

The major accomplishments developed during this study may be summarized as follows:

A. Any bearing signals which may appear are indicative of one or more of the following malfunctions, which may be incipient conditions:

1. Any rough spot or indentation of a rolling element.
2. Any high spot or indentation on the inner raceway.
3. Any high spot or indentation on the outer raceway.

These irregularities may appear in the form of pitting, spalling, flaking, cracking, smearing, fretting corrosion, scoring, fluting and wearing.

B. Any gear frequencies including harmonics accompanied by side bands are indicative of an eccentricity, misalignment or other nonuniformity in the environment of the gear mesh.

C. In the case of the nacelle bevel gears, the harmonic content is also a guide for impending malfunctions, depending upon the amplitude comparison of the odd and even harmonics. The absence of the odd harmonics, particularly the 3rd, is an indication of a difference in the tooth contact pulse shape, which could be caused by tooth scuffing or other abnormal wear characteristics.

The spectrometric oil sampling technique can show incipient failure because of a rapid rise in element content such as the spalled roller on the left nacelle pinion bearing. Excellent correlation between acoustic and spectrometric oil analysis is evident for this type of failure.

Spectrometric oil analysis cannot indicate fatigue failures which may occur between sampling periods and obviously cannot detect nonlubricated components. It is in this area that diagnostic sonic analysis has an advantage over the spectrometric oil sampling technique. The diagnostic sonic analysis method can more accurately identify the discrepant component in the lubricated system. Additionally, it is possible to set absolute go/no-go limits for each component which do not rely on a trend or ratio analysis and are equally valid for the initial operation of the system after assembly as well as for all subsequent operation.

In some cases, added information about the mechanical condition of components may be obtained by the correlation of the oil sampling and sonic methods. It is recommended that in a complete maintenance monitoring system, both the spectrometric oil sampling and the diagnostic sonic analysis techniques be utilized.

TABLE I

DIAGNOSTIC SONIC ANALYZER - RECORDING EQUIPMENT

Quantity	Description	Model
1	Ampex Magnetic Tape Recorder	354P
1	Microphone Switch Box	-
4	Altec Microphone Power Supplies	526B
4	Altec Microphone Bases	165A
4	Altec Microphones	21BR150
400 Feet	Belden Microphone Cable	8426
147 Rolls	Scotch Recording Tape	1/4-120-12
1	Talk Microphone and Head Set	-
4	Special Microphone Holders	-

TABLE II

DIAGNOSTIC SONIC ANALYZER

LABORATORY ANALYSIS EQUIPMENT

Quantity	Description	Model
1	Ampex Tape Recorder - Dual Channel	354P
1	Panoramic Sonic Analyzer System	
(1)	Panoramic Sonic Analyzer (Modified)	LP-1a
(1)	Auxiliary Function Unit	C-2
(1)	Panoramic Recorder and Sawtooth Wave Generator	RC-3b/1
(1)	Panoramic Power Supply	LP-1a
(1)	Sola Constant Voltage Transformer	
1	Normalizing Amplifier	-
1	Hewlett-Packard VTVM	400AB
1	Hewlett-Packard Wide Range Oscillator	200CD
1	Berkeley E-put Meter	7150B

TABLE III

FUNDAMENTAL FREQUENCY AT GROUND IDLE

COMPRESSOR AND GEARS

T55-L-5 Compressor (N_1 = 7500 RPM)

C_1 = 3500 cps

C_2 = 4500 cps

C_3 = 5000 cps

Gears (N_2 = 6500 RPM)

Engine Coupling Gearbox		
No. 1 Box	=	4333 cps
No. 2 Box	=	4333 cps
Accessory Drive	=	2557 cps
Tee Box		
Bevel Gear Angle Drive	=	888 cps
Pump. Tach. Drive	=	1979 cps
Nacelles		
Bevel Gear Set	=	355 cps
Pump Tach. Drive	=	936 cps
Prop. High Pressure Pump Drive	=	1247 cps
Propeller (Blade)	=	26 cps

TABLE IV

FUNDAMENTAL FREQUENCY AT GROUND IDLE (N_2 = 6500 RPM) - BEARINGS

Component & Bearing No.	f_R	f_T	f_B	f_B'	$3f_B'$	f_1	f_2
Shaft							
No. 1	36	19	294	588	1765	264	304
No. 2	25	12	149	299	897	412	348
Engine Coupling Gearbox							
No. 1 (Gear A)	43	18	146	292	877	365	274
No. 1 (Gear F)	26	11	89	177	532	221	166
No. 2	36	16	181	363	1088	546	449
No. 3	36	16	166	332	995	334	270
No. 4	108	49	524	1048	3143	1552	1264
No. 5	52	21	145	289	868	424	299
No. 6	26	11	103	205	616	261	204
Tee Box							
No. 1	25	11	110	221	662	323	260
No. 2	25	11	104	209	627	310	248
No. 3	36	15	100	199	598	332	237
No. 4	36	15	127	254	762	382	293
Sleeve Brg.	30	-	-	-	-	-	-
Nacelles							
No. 1	25	11	106	213	638	309	249
No. 2	25	10	73	146	439	222	158
No. 3	9	4	50	100	300	151	127
No. 4	9	4	40	80	240	125	100
No. 5	33	14	87	175	524	198	136
No. 6	83	30	141	282	847	370	212
Water Brake - AGB							
No. 1	26	10	62	125	375	139	93
No. 2	26	10	51	103	308	128	79
Water Brake - Main							
No. 1	36	14	96	192	576	209	146
No. 2	36	13	67	134	401	178	107
No. 3	36	15	101	202	606	229	162

TABLE V

SAMPLE DATA, FERROUS CONTENT X-19 TRANSMISSION DEVELOPMENT AND QUALIFICATION TESTS

Previous Endurance Tests

Component	1st 50 Hours Endurance		3rd 50 Hours Endurance	
	Max ppm	ppm/ hr	Max ppm	ppm/ hr
Gearbox				
No. 1 ECGB	182	3.03	115	1.9
No. 2 ECGB	204	3.4	87	1.4
Tee Box	182	3.03	300	5.0
No. 1 Nacelle	104	1.7	218	3.6
No. 4 Nacelle	80	1.3	245	4.1

150-Hour Development, Qualification and Assurance Test

Component	28 Hours Endurance		22 Hours Endurance		41:45 Hours Endurance	
	Cumulative ppm	ppm/ hr	Cumulative ppm	ppm/ hr	Cumulative ppm	ppm/ hr
Gearbox						
No. 1 ECGB	562	16.5	325	12.9	250	5.5
No. 2 ECGB	567	16.7	318	12.6	267	5.9
Tee Box	152	4.5	109	4.3	147	1.8
No. 1 Nacelle	121	3.6	27	1.1	338	7.5
No. 4 Nacelle	64	1.9	52	2.1	88	1.9

TABLE VI

MALFUNCTIONS IDENTIFIED BY DIAGNOSTIC SONIC ANALYSIS

AND/OR BY SPECTROMETRIC OIL ANALYSIS

Item	Malfunction	Rig Time (Hours)	Endurance Time (Hours)	Acoustic Analysis	Spectrometric Oil Analysis
1	ECGB - Fatigue Failure	328:14	0	Yes	No
2	Tee Box Eccentricity and Subsequent Failure	384:55	21:15	Yes	No
3	ECGB No. 4 Bearing (Pinion Gear)	347:40	0	Yes	No
4 *	No. 3 Longitudinal Shaft Bearing	347:40	0	Yes	No
5 *	No. 3 Longitudinal Shaft Bearing	467:22	36:00	Yes	No
6 *	Small Water Brake Brg.	372:34	10:00	Yes	No
7	Nacelle Bevel Gear Set Scuffing	347:43	0	Yes	Yes
8	Nacelle Bevel Gear Set Scuffing	419:00	48:24	Yes	Yes
9	No. 1 Nacelle (Left) Brg.	458:44	78:00	Yes	Yes
10 *	Tee Box Fan & Stator Assembly	420:55 392:01	50:00 78:00	No -	No -
11 *	Main Water Brake Mis-alignment	385:01	21:15	No	No
12	ECGB - fretting corrosion on pinion gear internal splines and mating quill shaft	393:02 420:55 473:27	28:00 50:00 91:45	No - -	Yes - -

* Grease bearings or not lubricated.

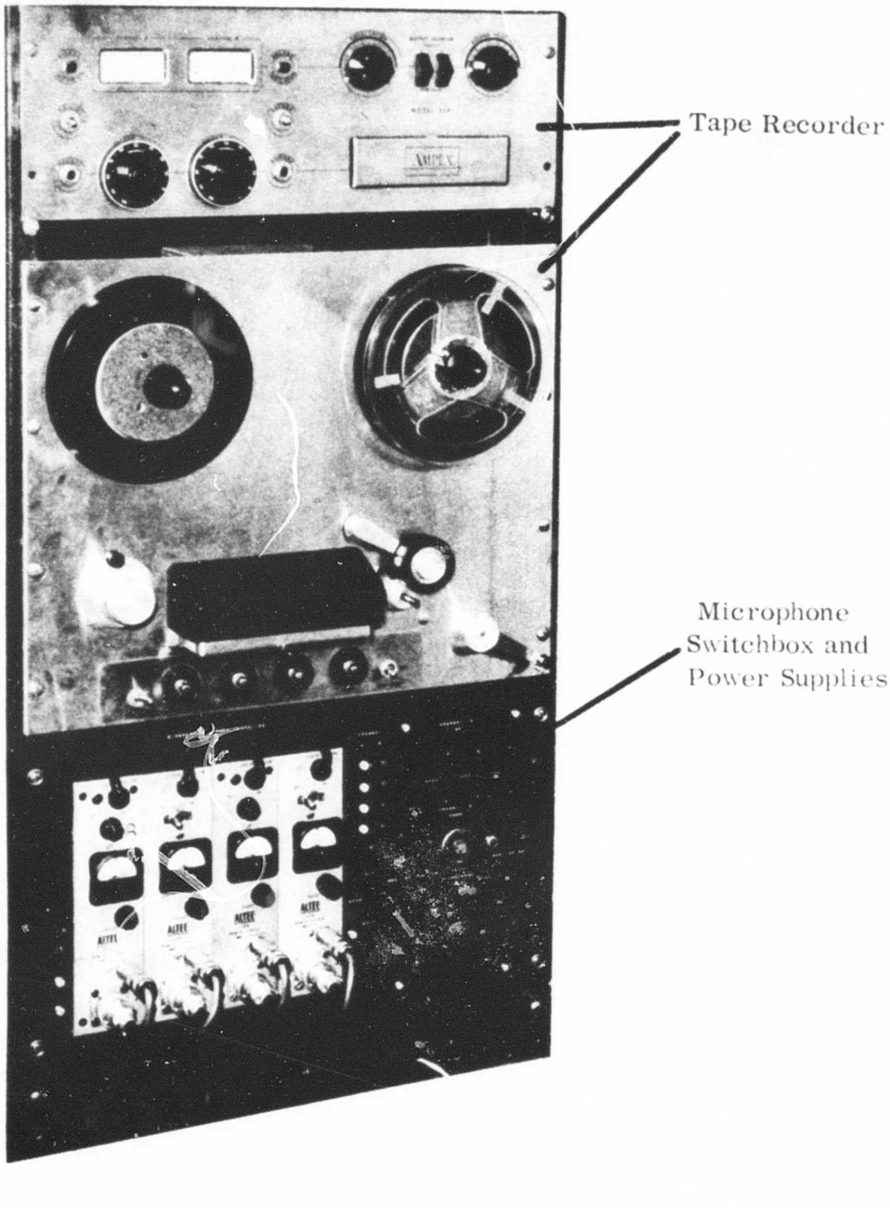


Figure 1. Diagnostic Sonic Recording Equipment.

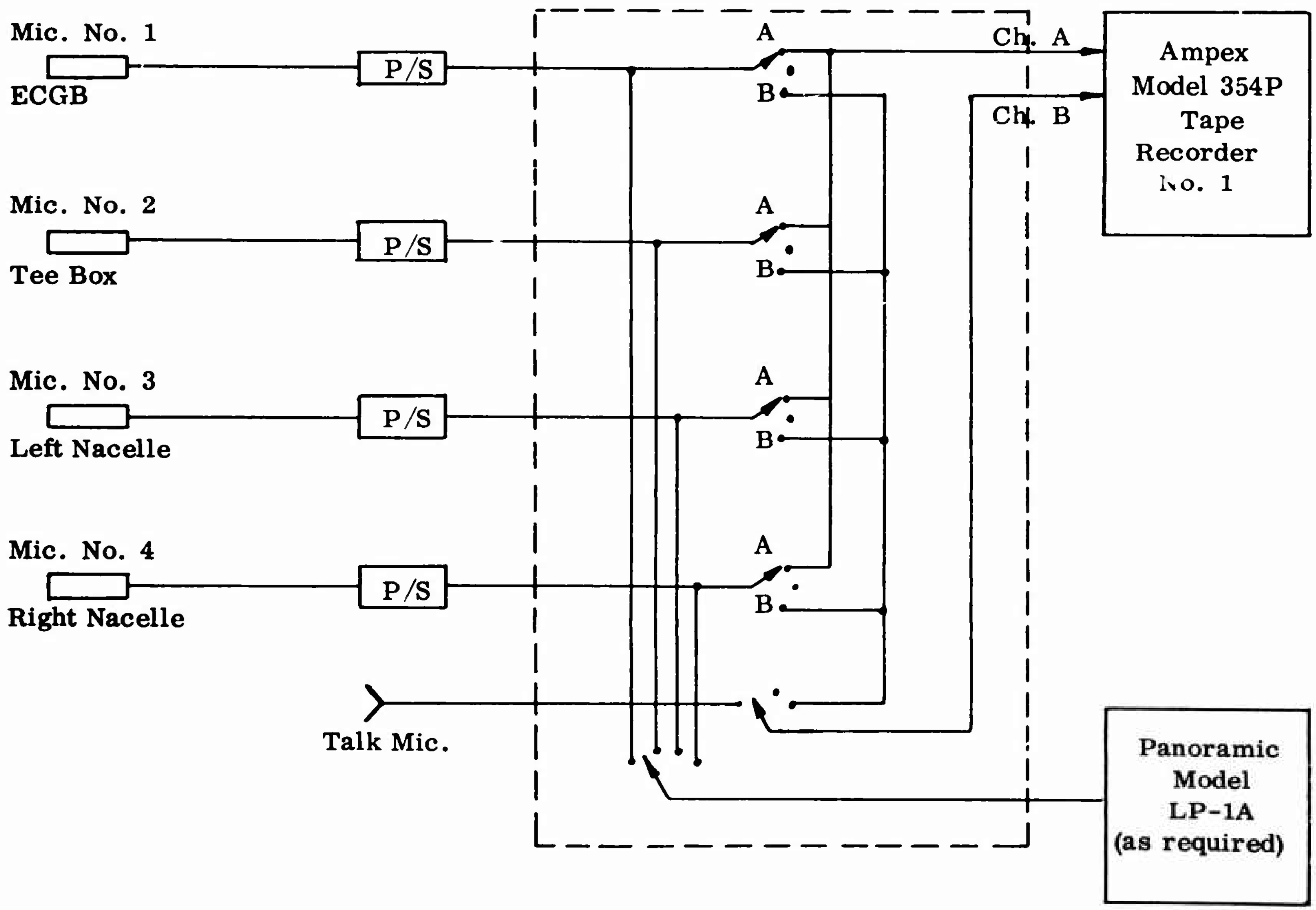


Figure 2. Block Diagram - Data Acquisition System.

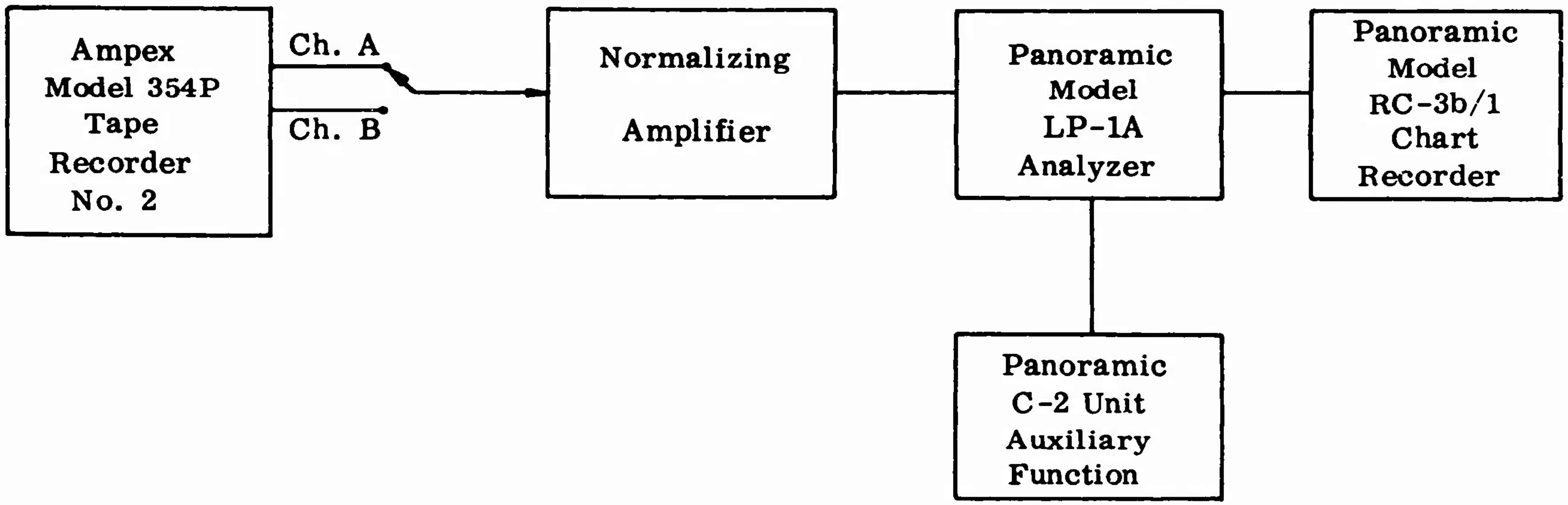


Figure 3. Block Diagram - Data Reduction System.

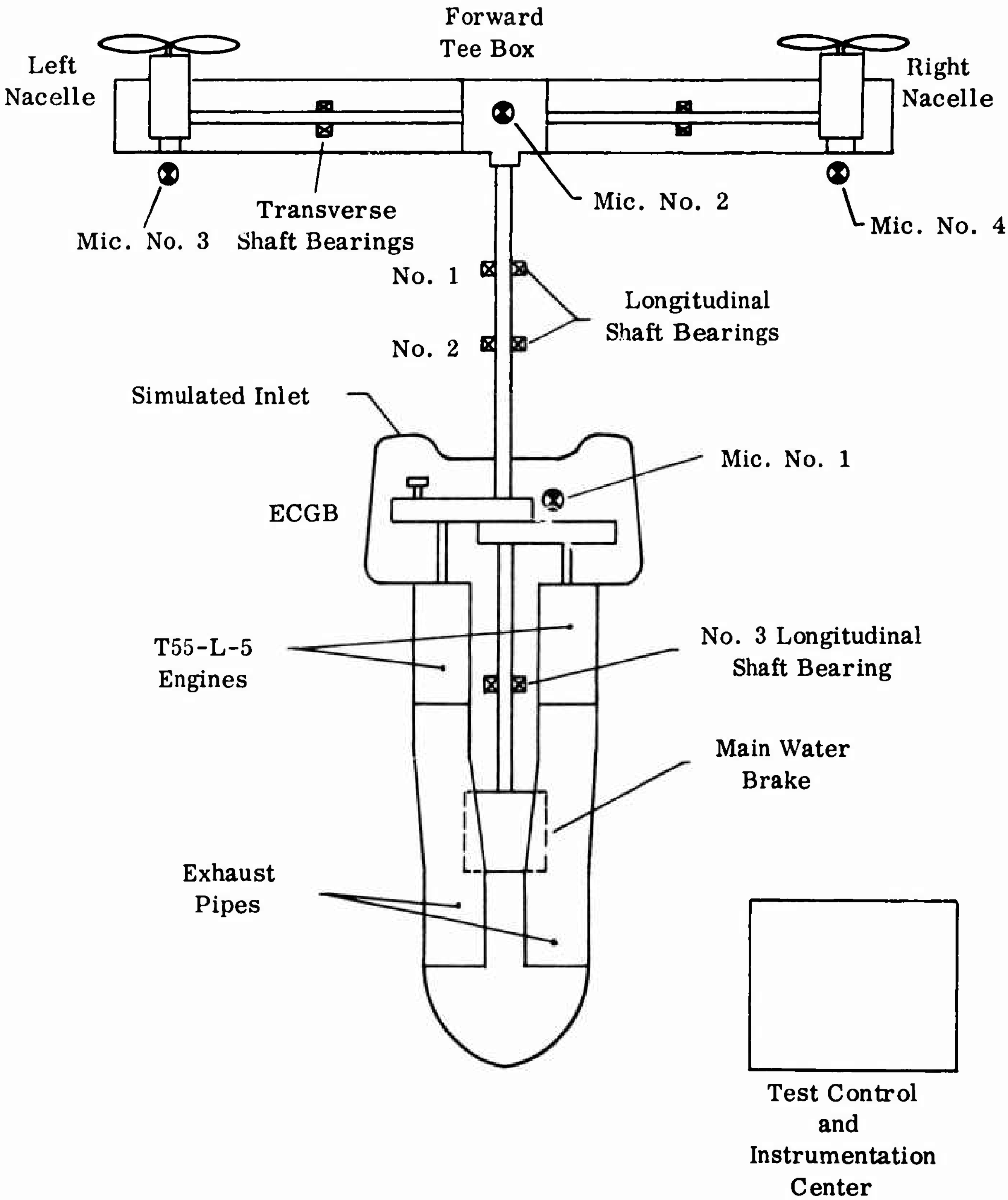
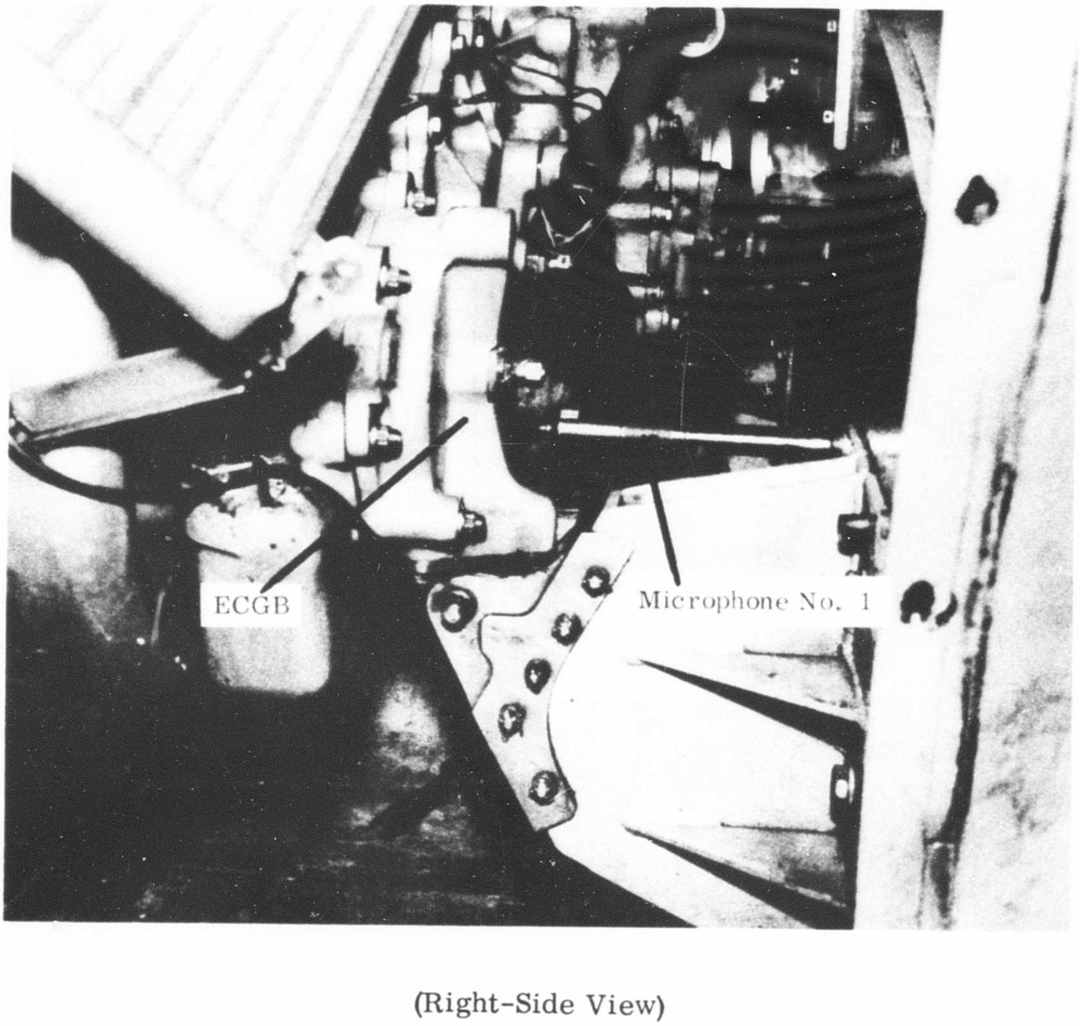


Figure 4. Schematic X-19 Half-System Test Rig.



(Right-Side View)

Figure 5. Microphone No. 1 Location at ECGB.

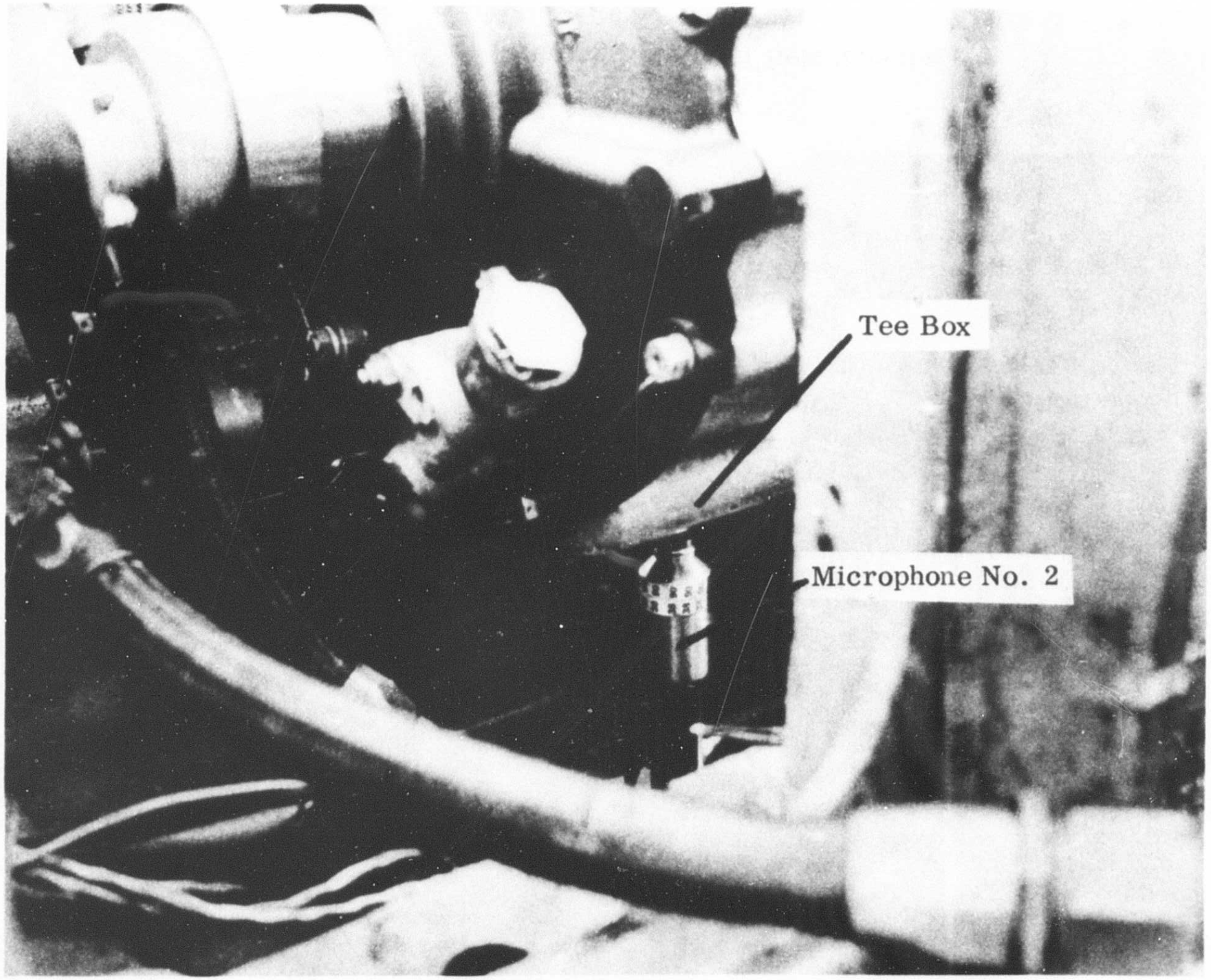
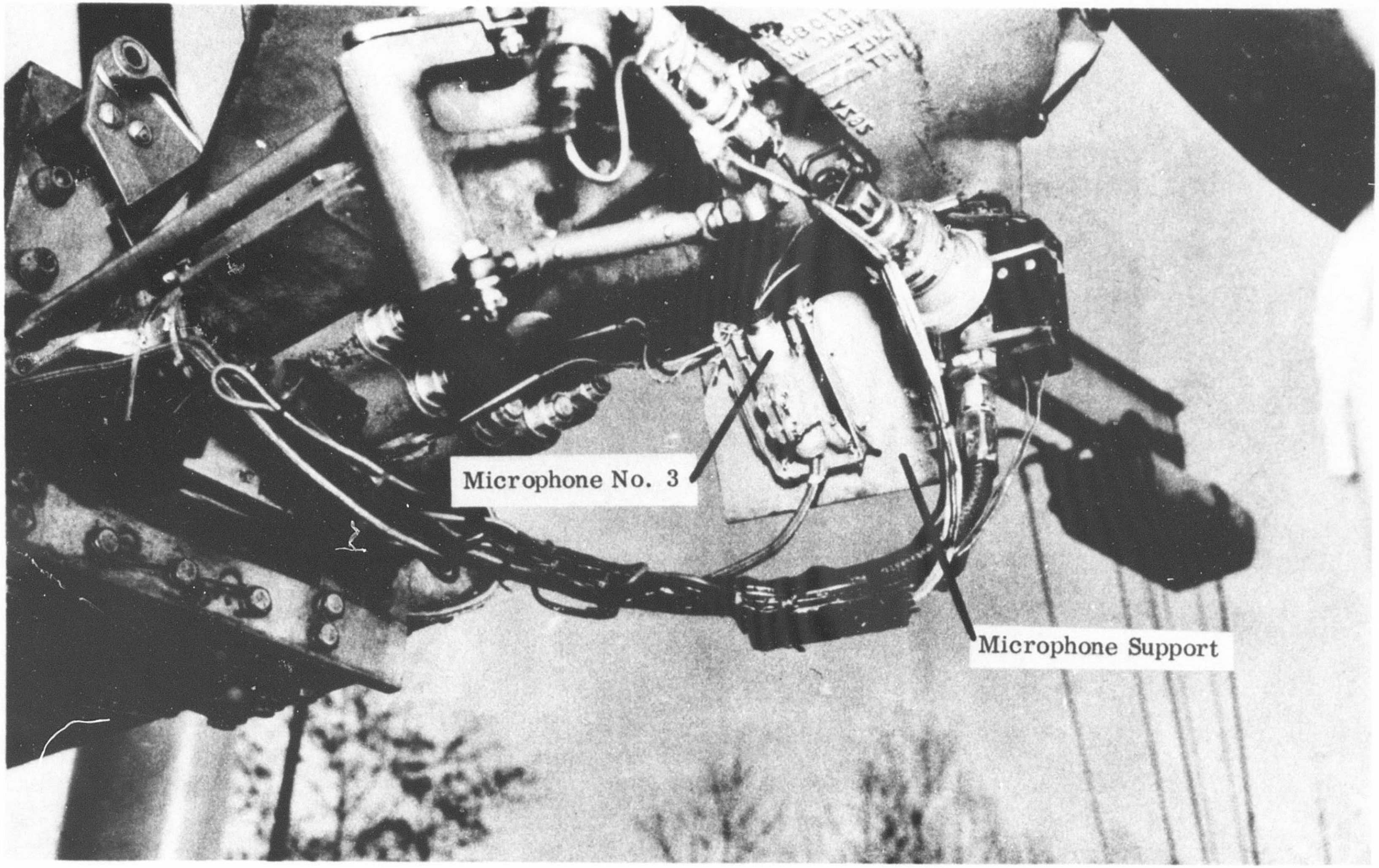


Figure 6. Microphone No. 2 Location at Tee Box



(Viewing Bottom of Left Nacelle)

Figure 7. Microphone No. 3 Location at Left Nacelle

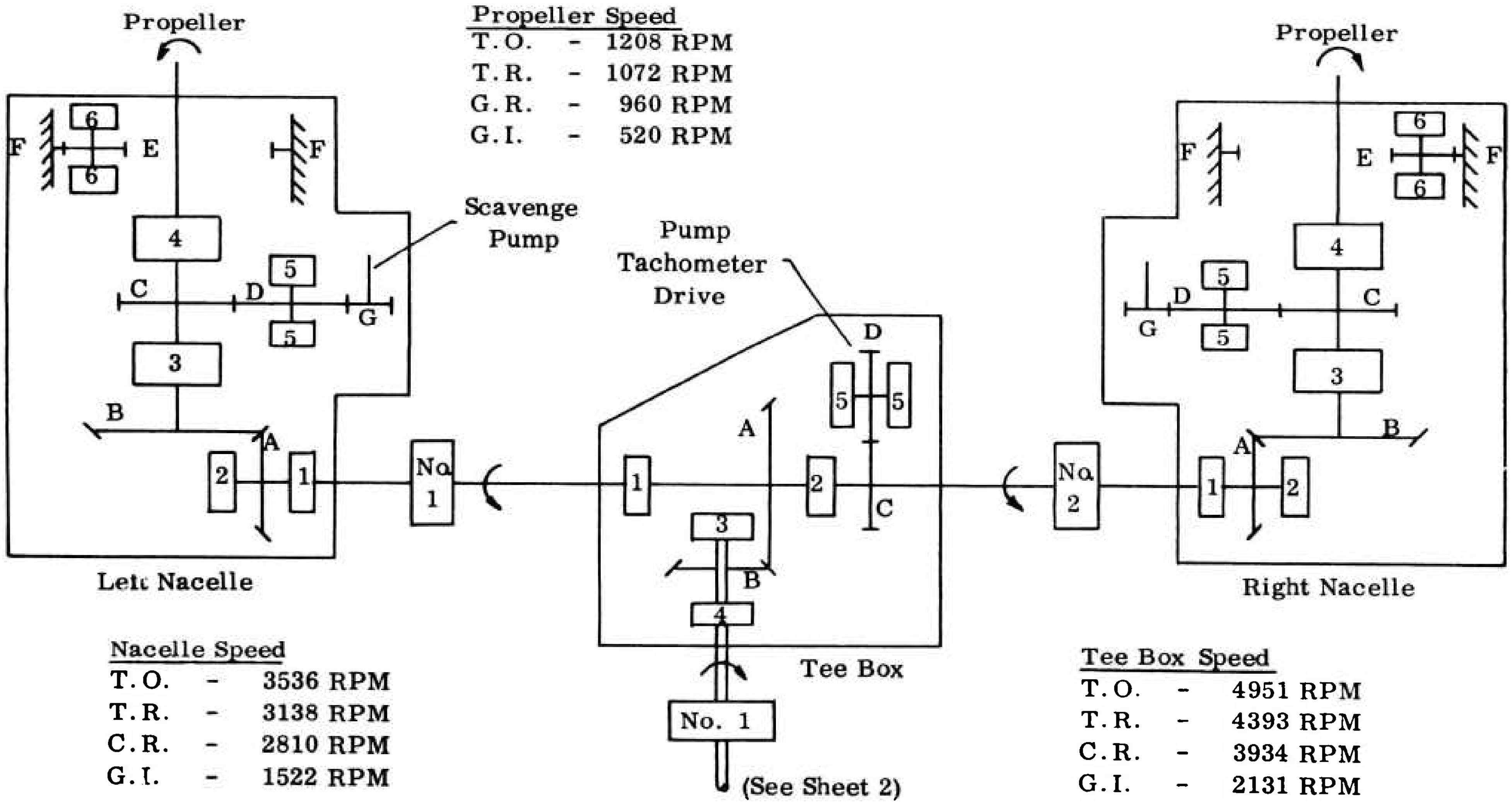
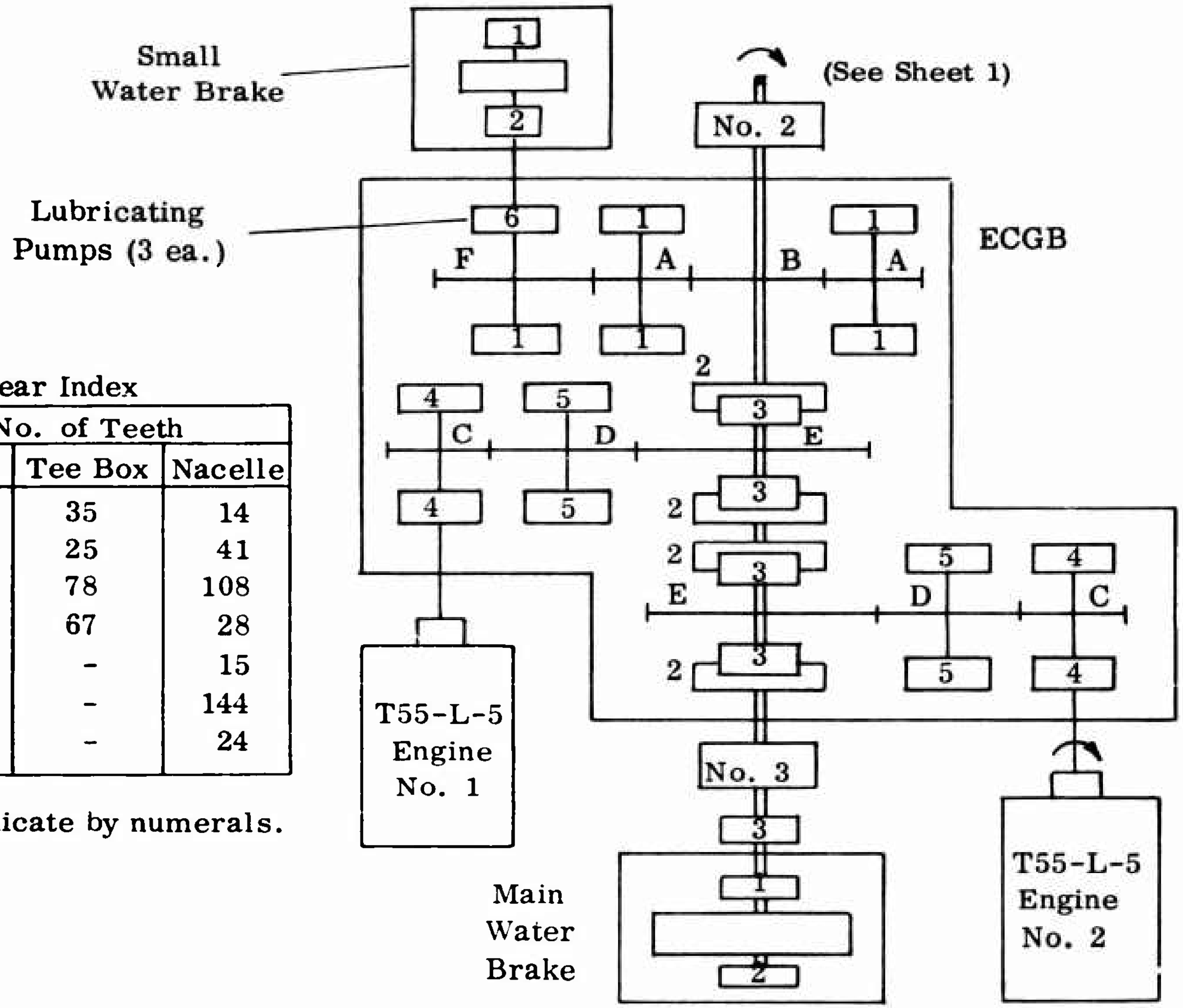


Figure 8. X-19 Half-System Drive Schematic.
(Sheet 1 of 2)



Gear Index

Gears	No. of Teeth		
	ECGB	Tee Box	Nacelle
A	60	35	14
B	72	25	41
C	40	78	108
D	84	67	28
E	122	-	15
F	99	-	144
G	-	-	24

Bearings: Indicate by numerals.

T.O. - 15100 N_2RPM
T.R. - 13400 N_2RPM
C.R. - 12000 N_2RPM
G.I. - 6500 N_2RPM

Figure 8. X-19 Half-System Drive Schematic.
(Sheet 2 of 2)

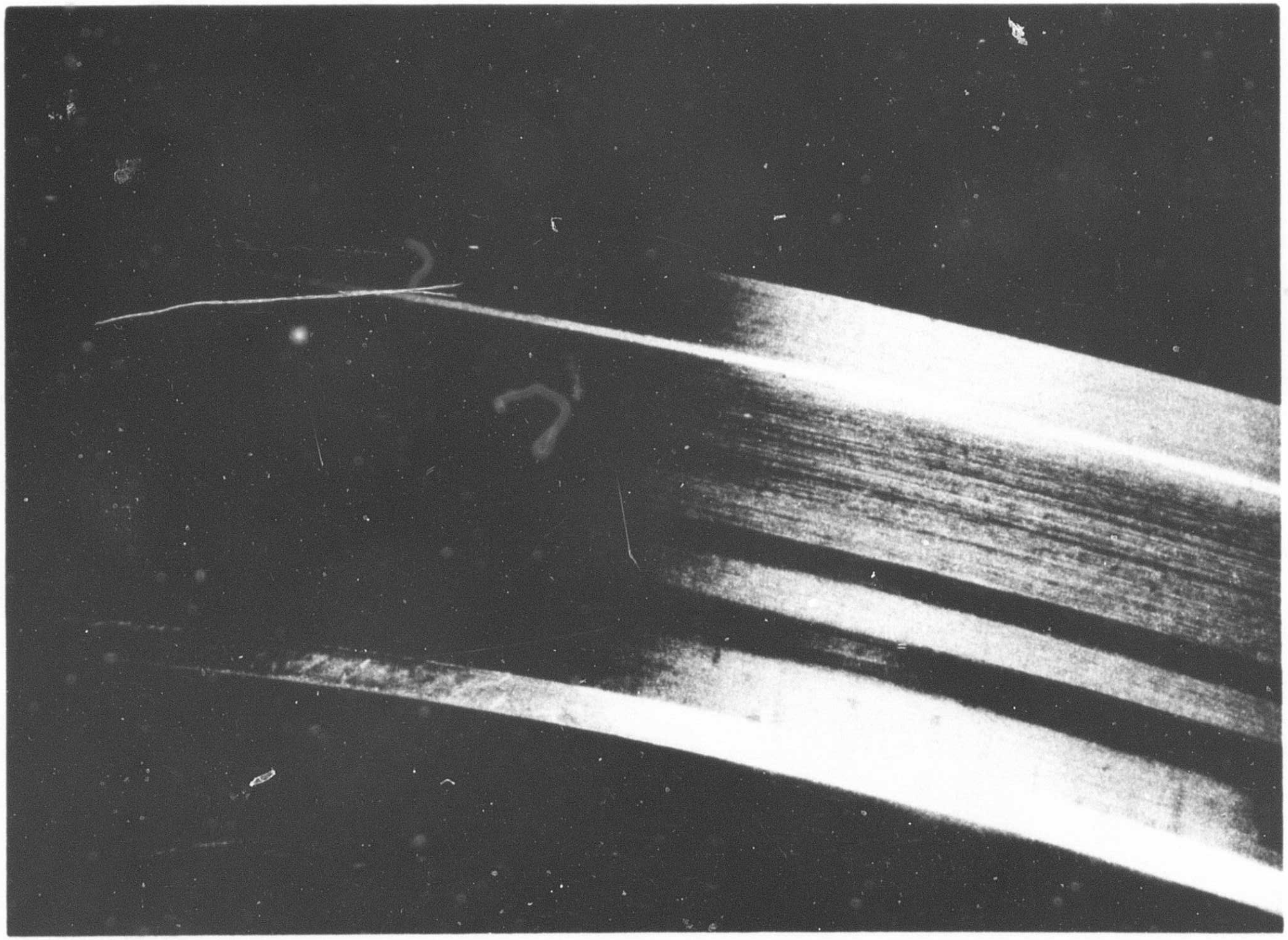


Figure 9. ECGB No. 4 Pinion Gear Bearing - Outer Raceway

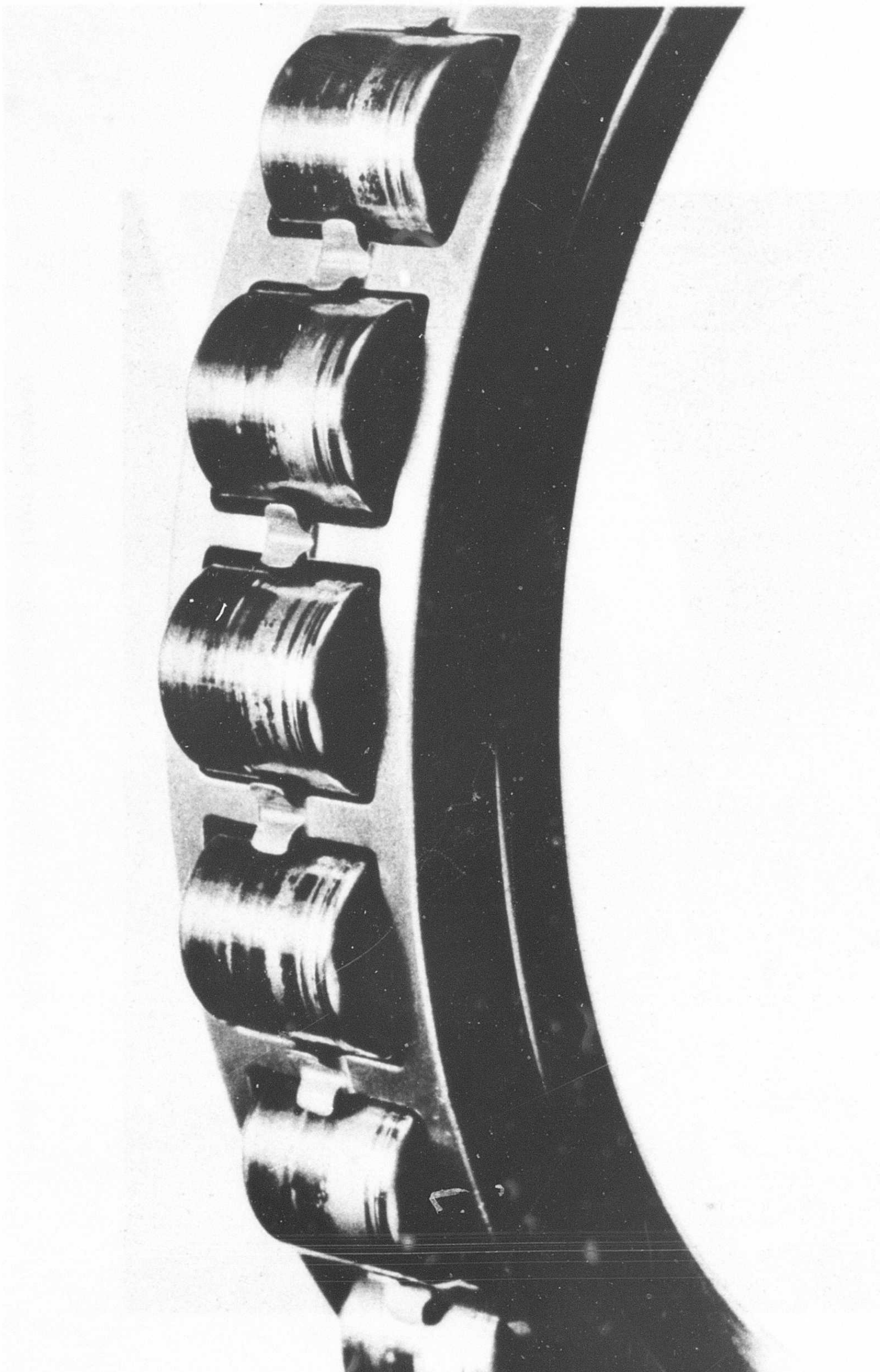


Figure 10. ECGB No. 4 Pinion Gear Bearing - Rollers

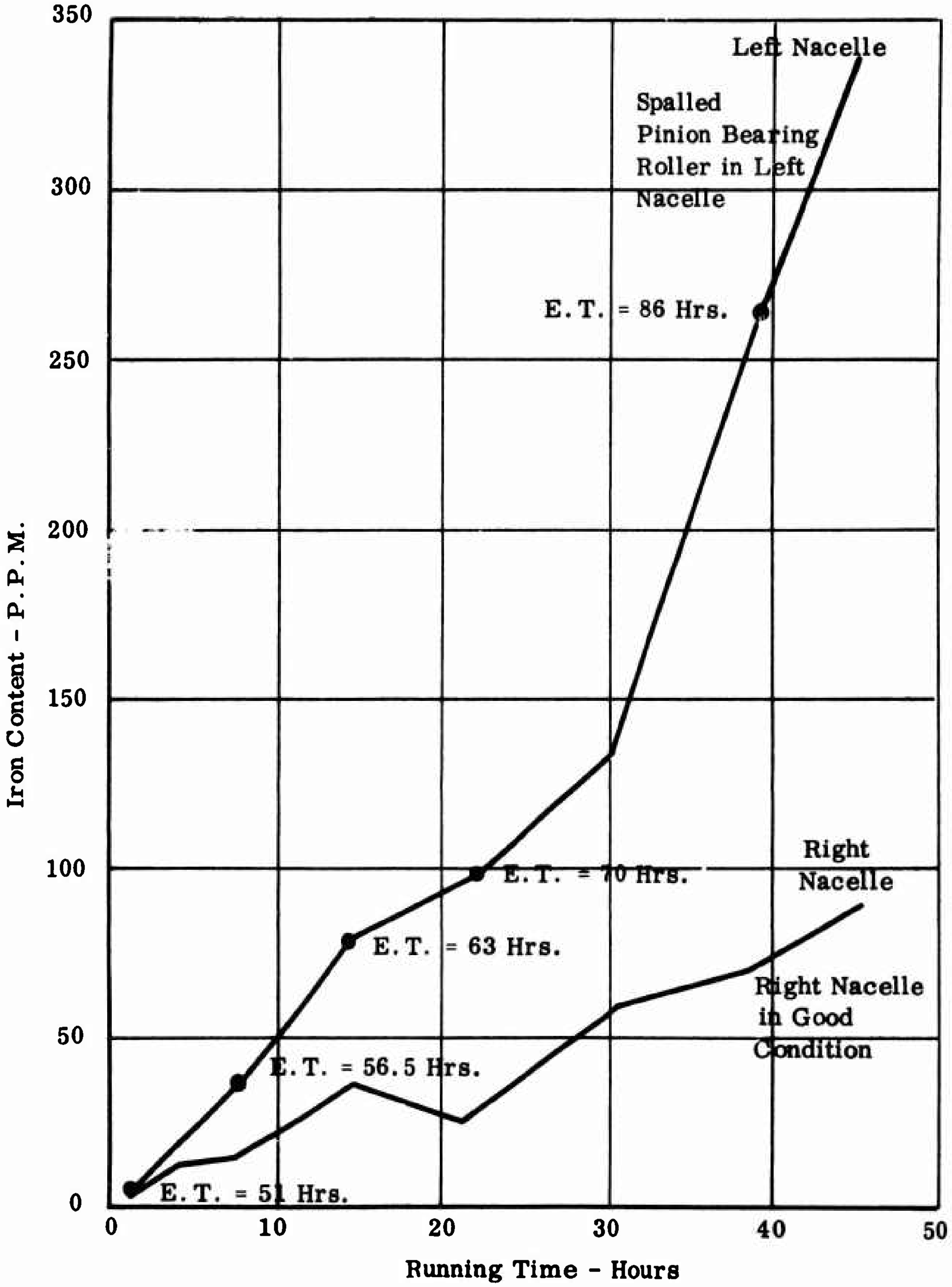


Figure 11. Spectrometric Oil Analysis of Propeller Nacelle Assemblies - X-19 Transmission System.

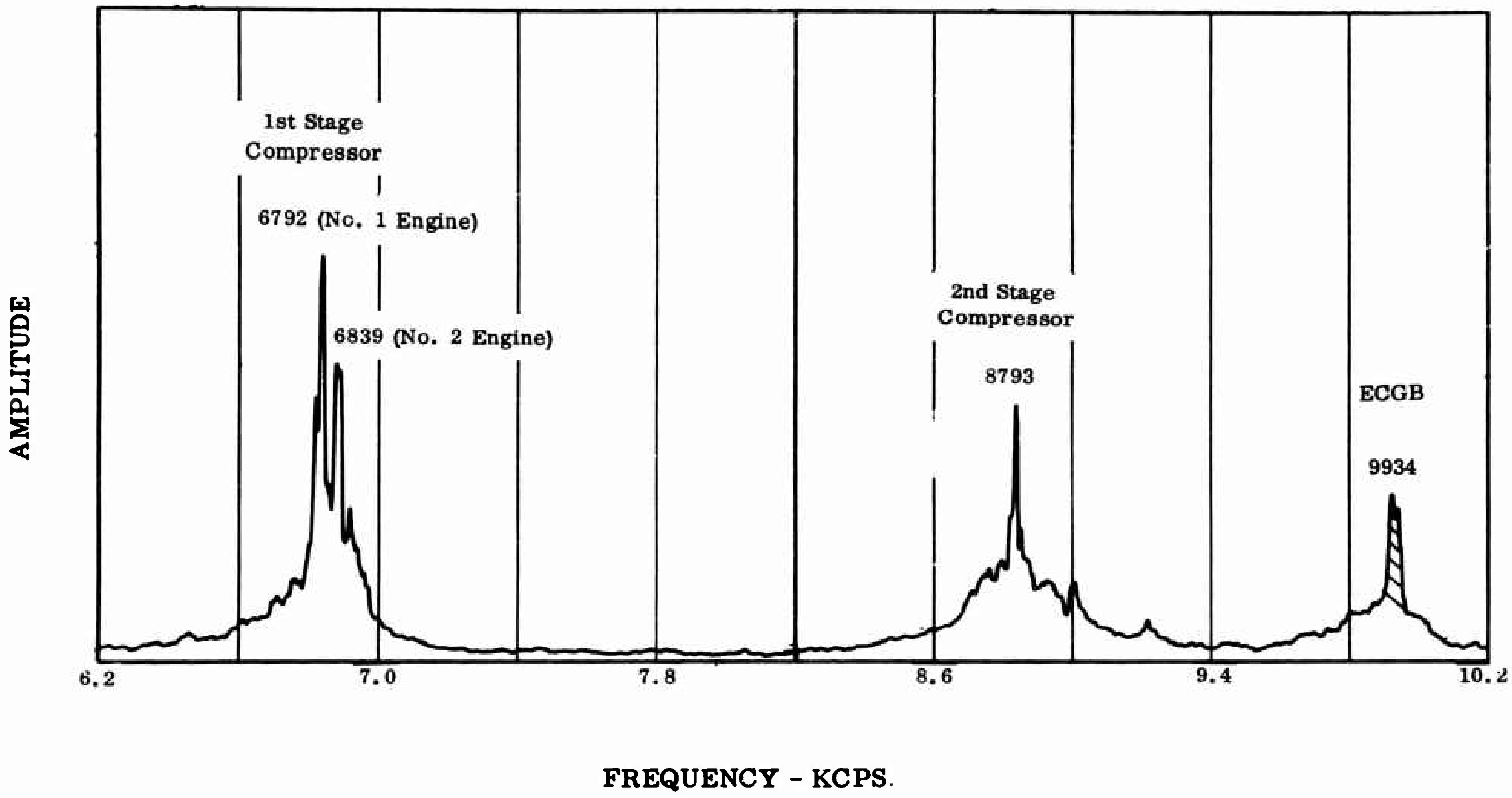


Figure 12. Amplitude vs. Frequency Spectrogram, Recording No. TC5-7B, Microphone No. 1, (Engine Coupling Gearbox), N_2 = 14902 RPM, Total Rig Time = 328:14 Hrs.

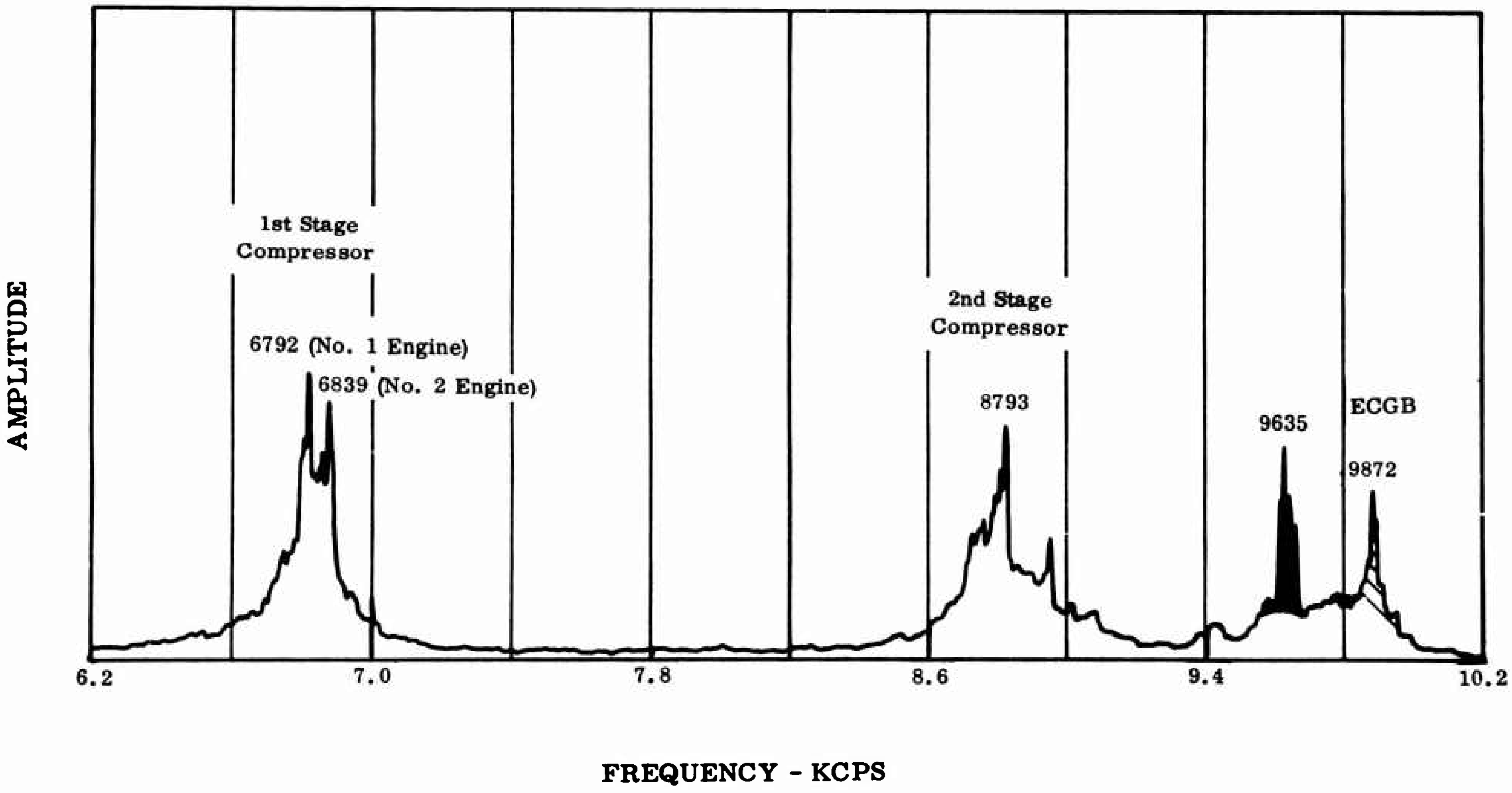


Figure 13. Amplitude vs. Frequency Spectrogram, Recording No. TC5-7B (End), Microphone No. 1, (Engine Coupling Gearbox), N_2 = 14809 RPM, Total Rig Time = 328:14 Hrs.

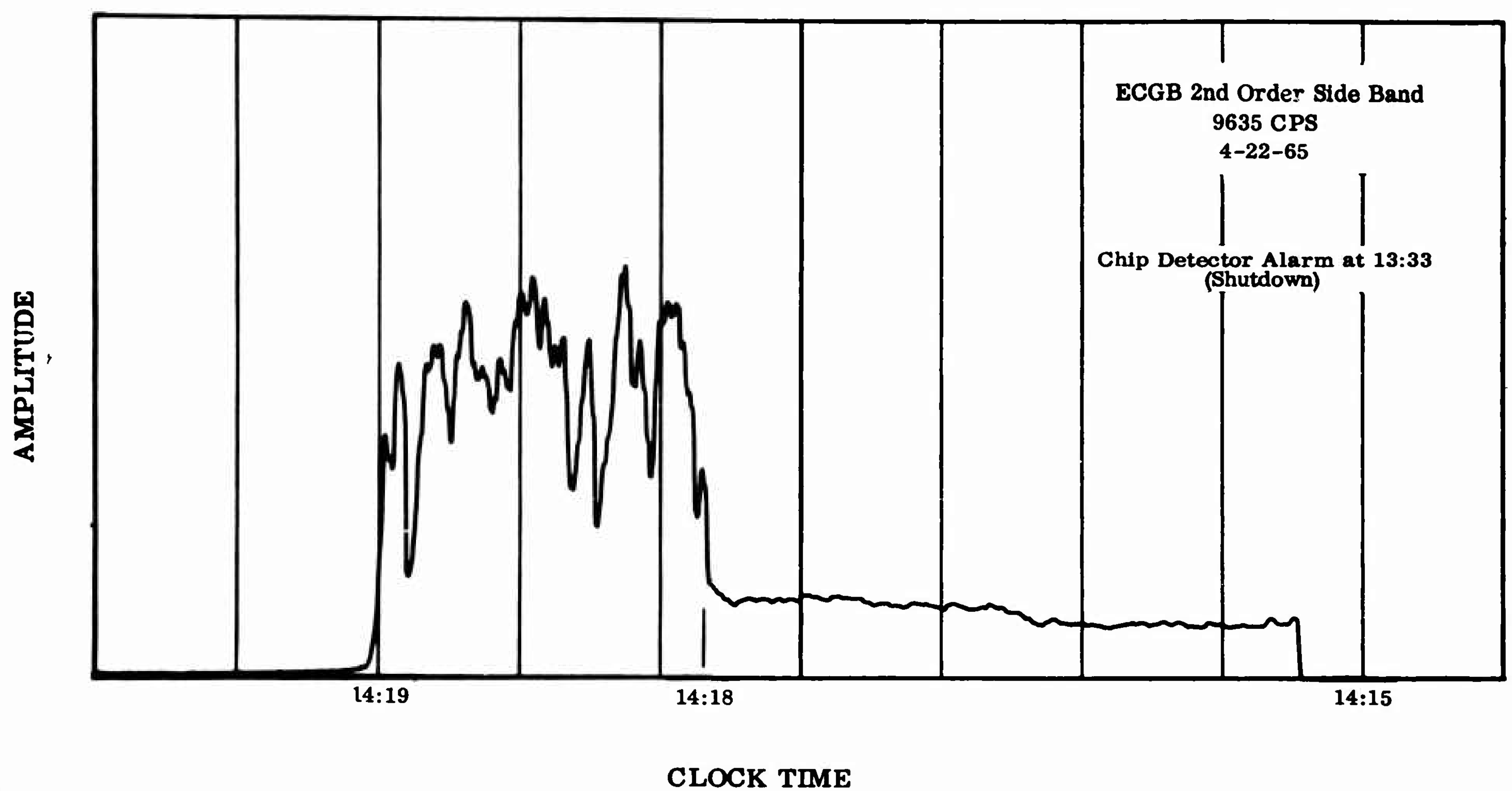


Figure 14. Amplitude vs. Time Spectrogram, Recording No. TC5-7B, Microphone No. 1, (Engine Coupling Gearbox), N_2 = 14809 RPM, Total Rig Time = 328:14 Hrs.

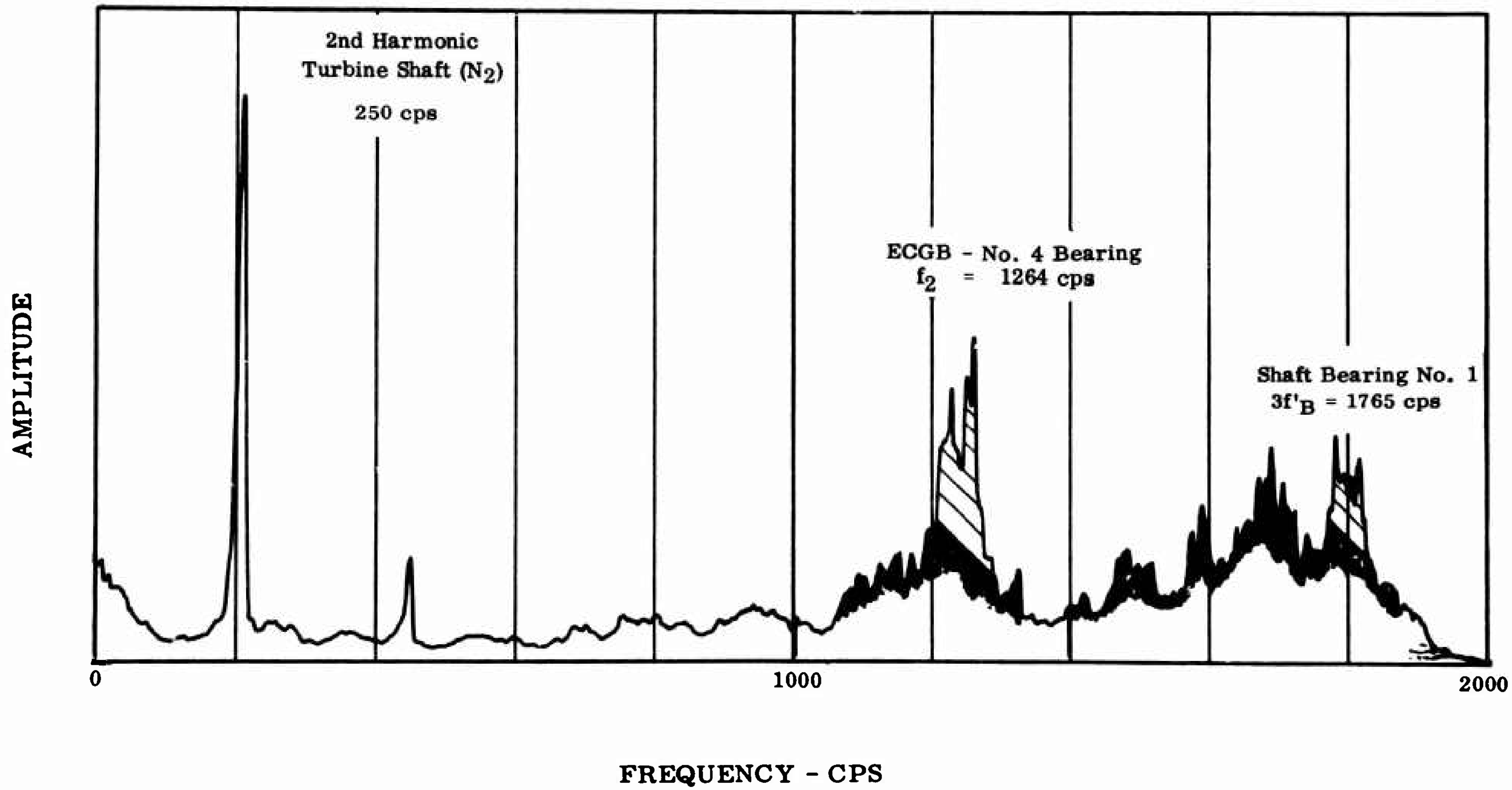


Figure 15. Amplitude vs. Frequency Spectrogram, Recording No. TC19-3A, Microphone No. 1, (Engine Coupling Gearbox), N_2 = 6500 RPM, Total Rig Time = 347:40 Hrs.

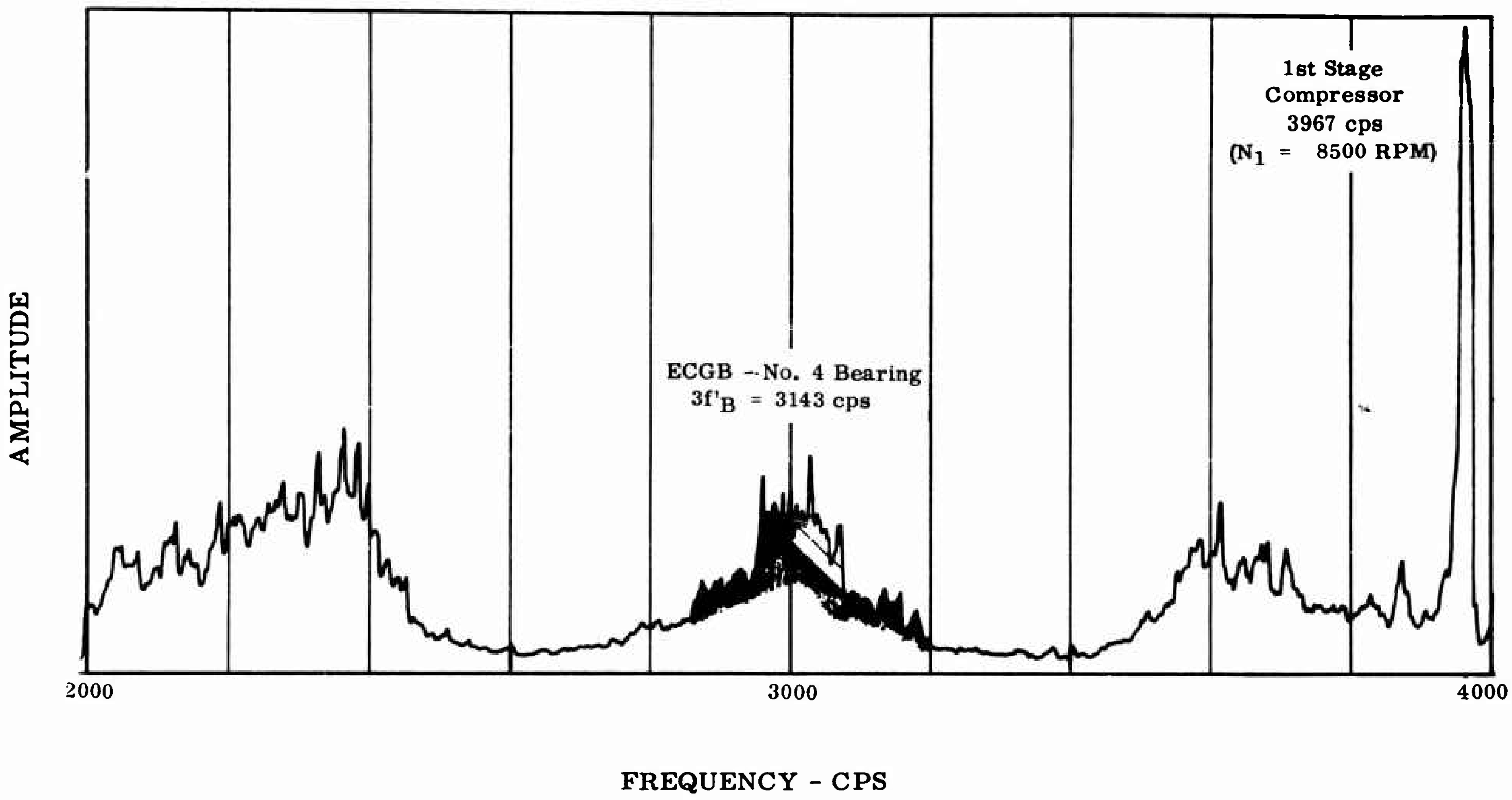


Figure 16. Amplitude vs. Frequency Spectrogram, Recording No. TC19-3A, Microphone No. 1, (Engine Coupling Gearbox), N_2 = 6500 RPM, Total Rig Time = 347:40 Hrs.

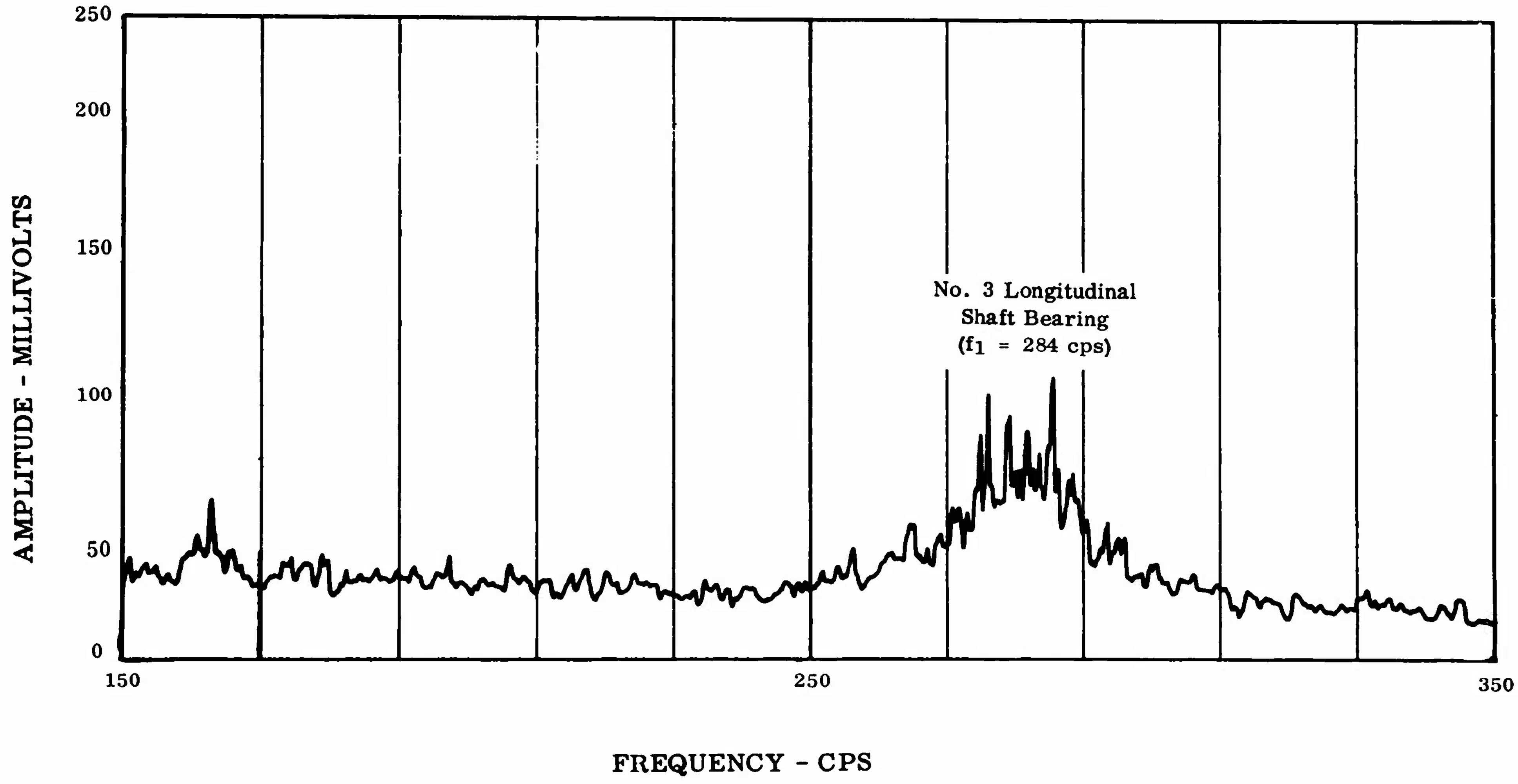


Figure 17. Amplitude vs. Frequency Spectrogram, Recording No. TC39-1A, Engine Coupling Gearbox Microphone, N_2 = 7000 RPM.

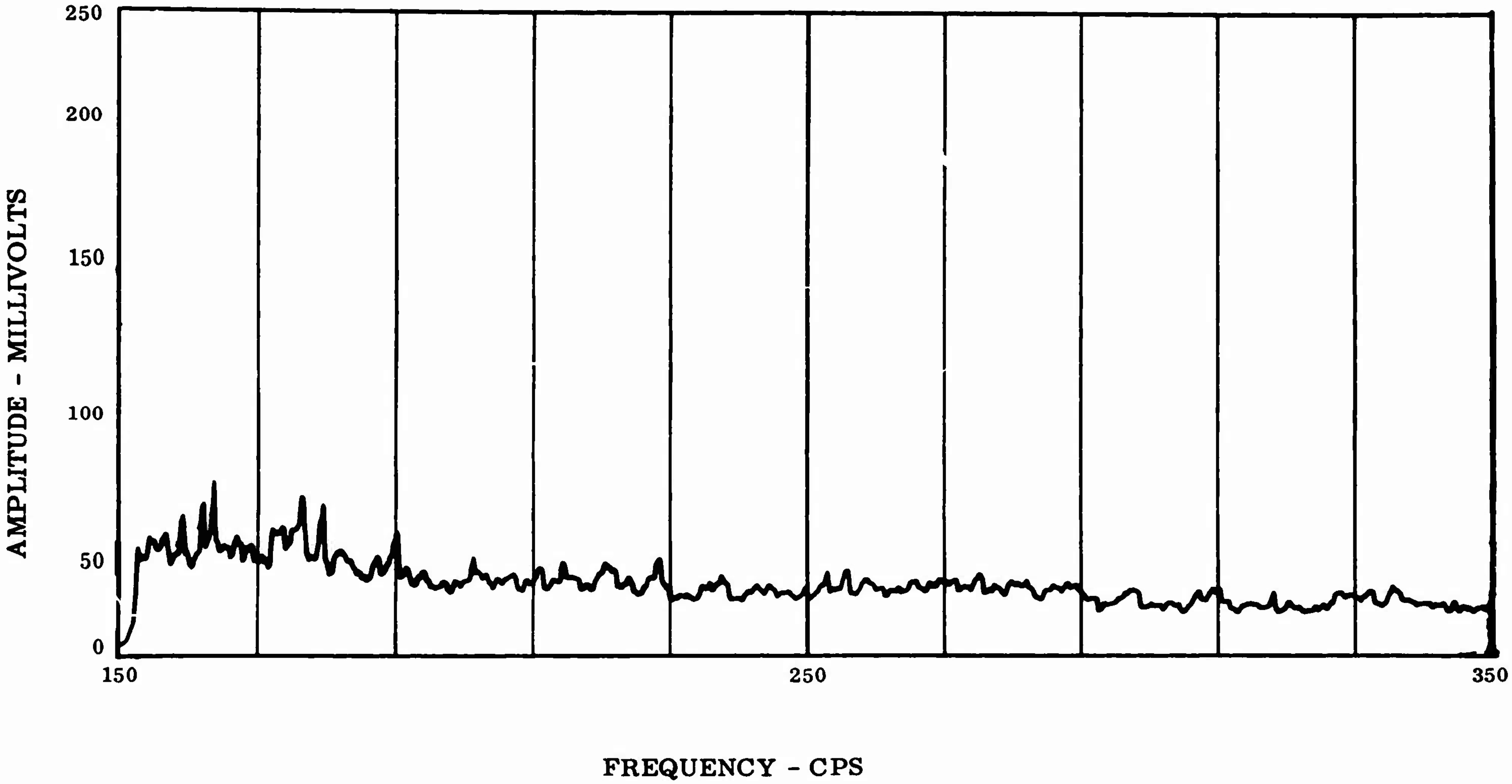


Figure 18. Amplitude vs. Frequency Spectrogram, Recording No. TC38-1A, Engine Coupling Gearbox Microphone, N_2 = 7000 RPM.

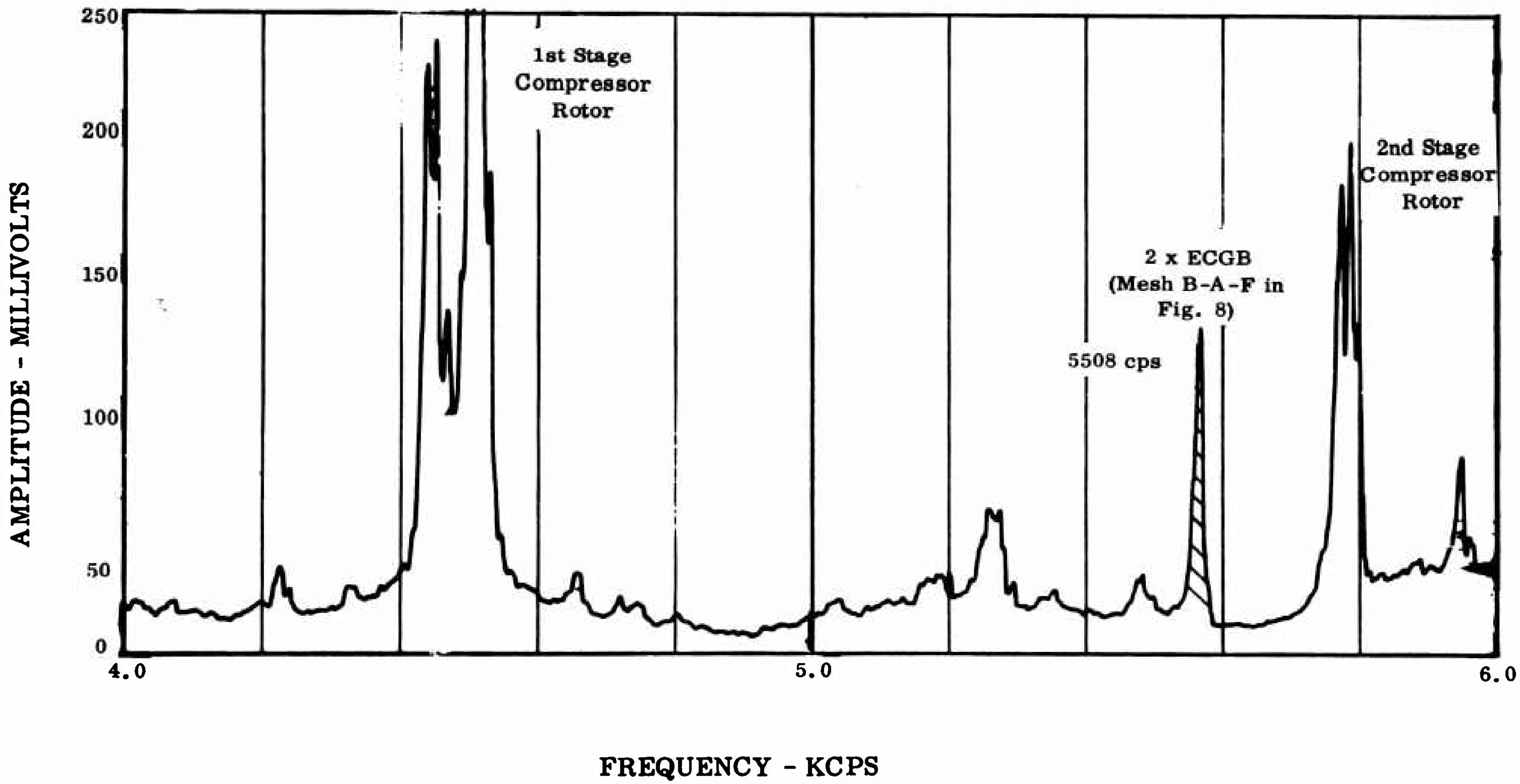


Figure 19. Amplitude vs. Frequency Spectrogram, Recording No. TC25-5A, Engine Coupling Gearbox Microphone, N_2 = 7000 RPM.

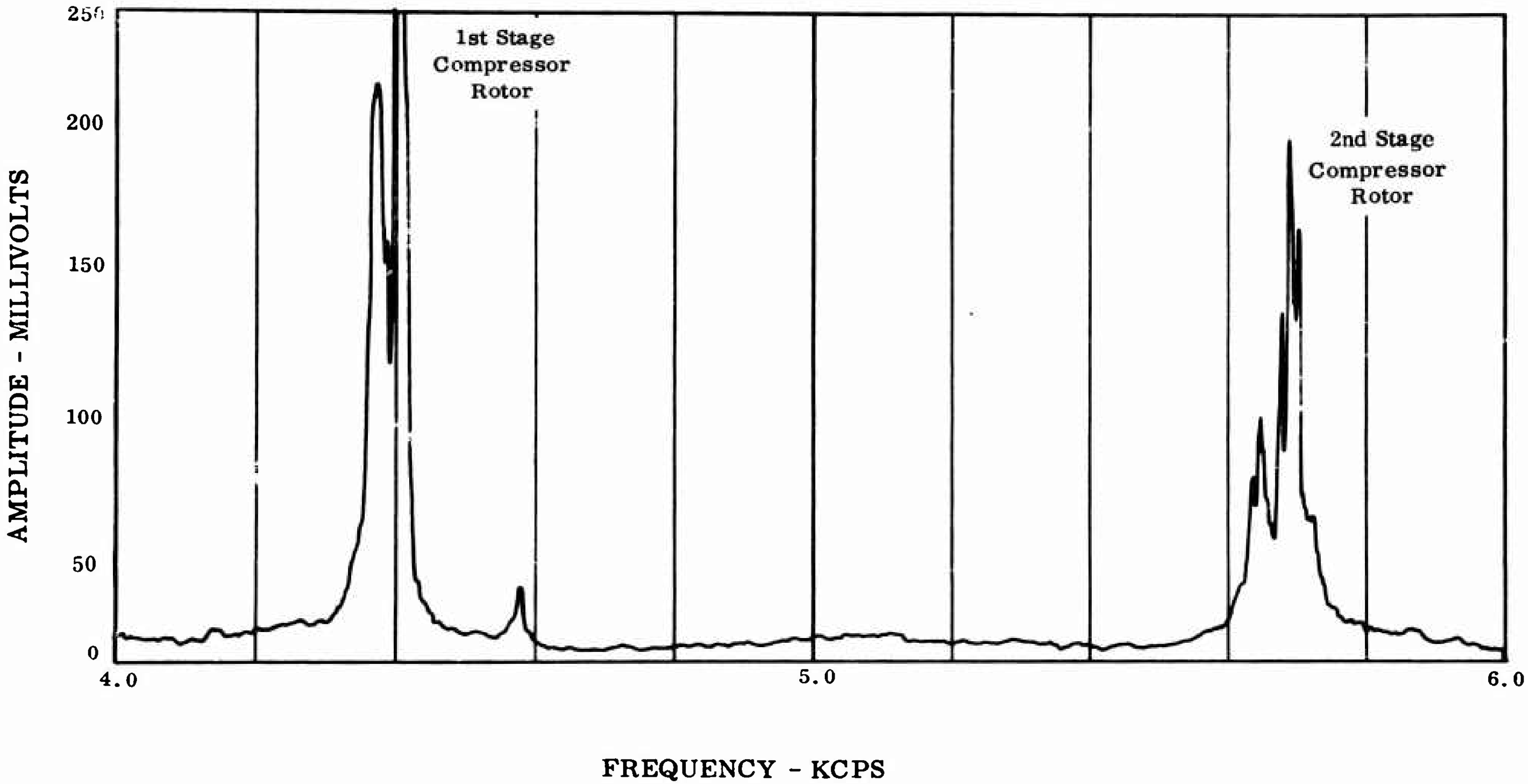


Figure 20. Amplitude vs. Frequency Spectrogram, Recording No. TC35-1A, Engine Coupling Gearbox Microphone, N_2 = 7000 RPM.

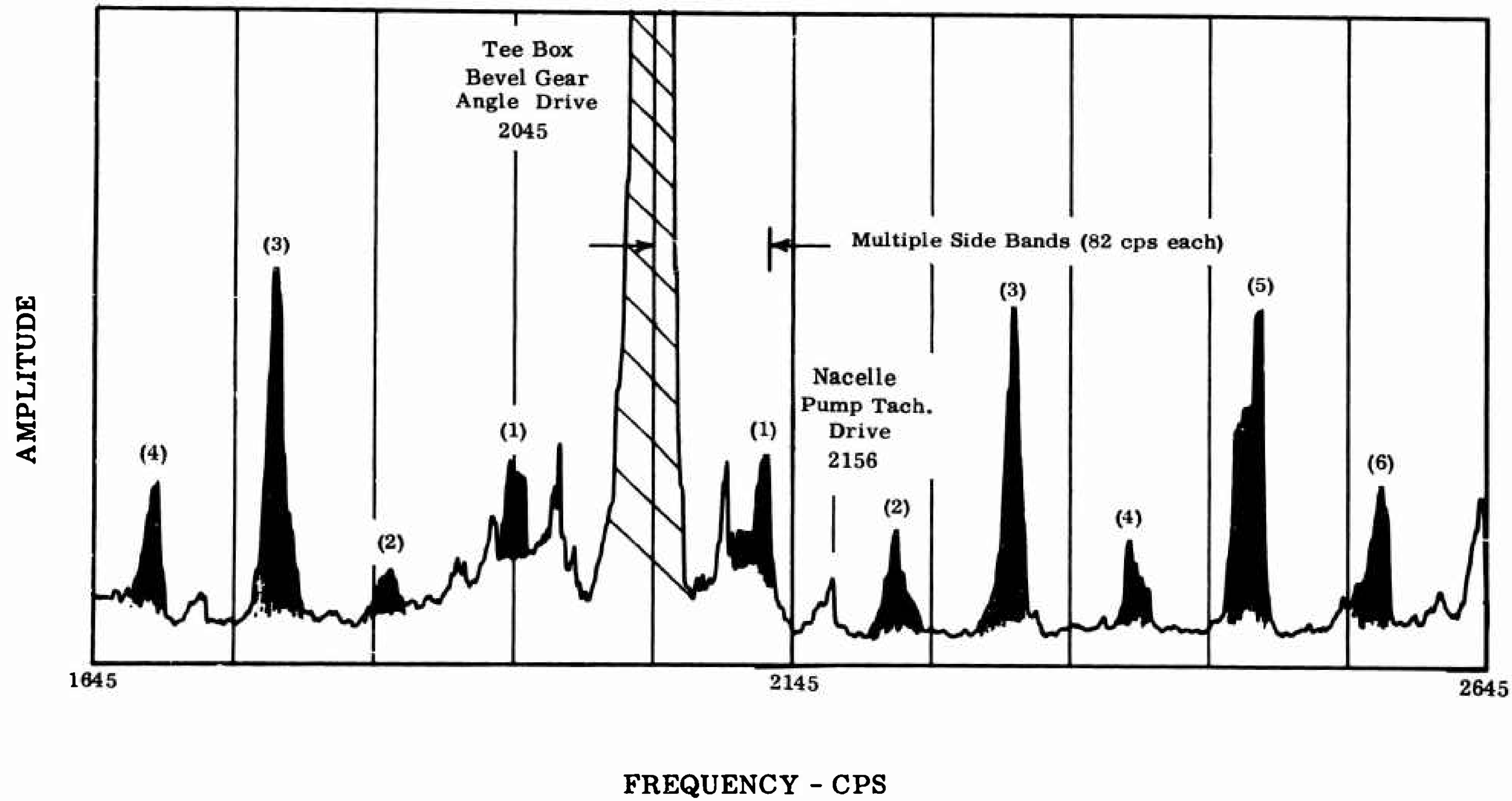
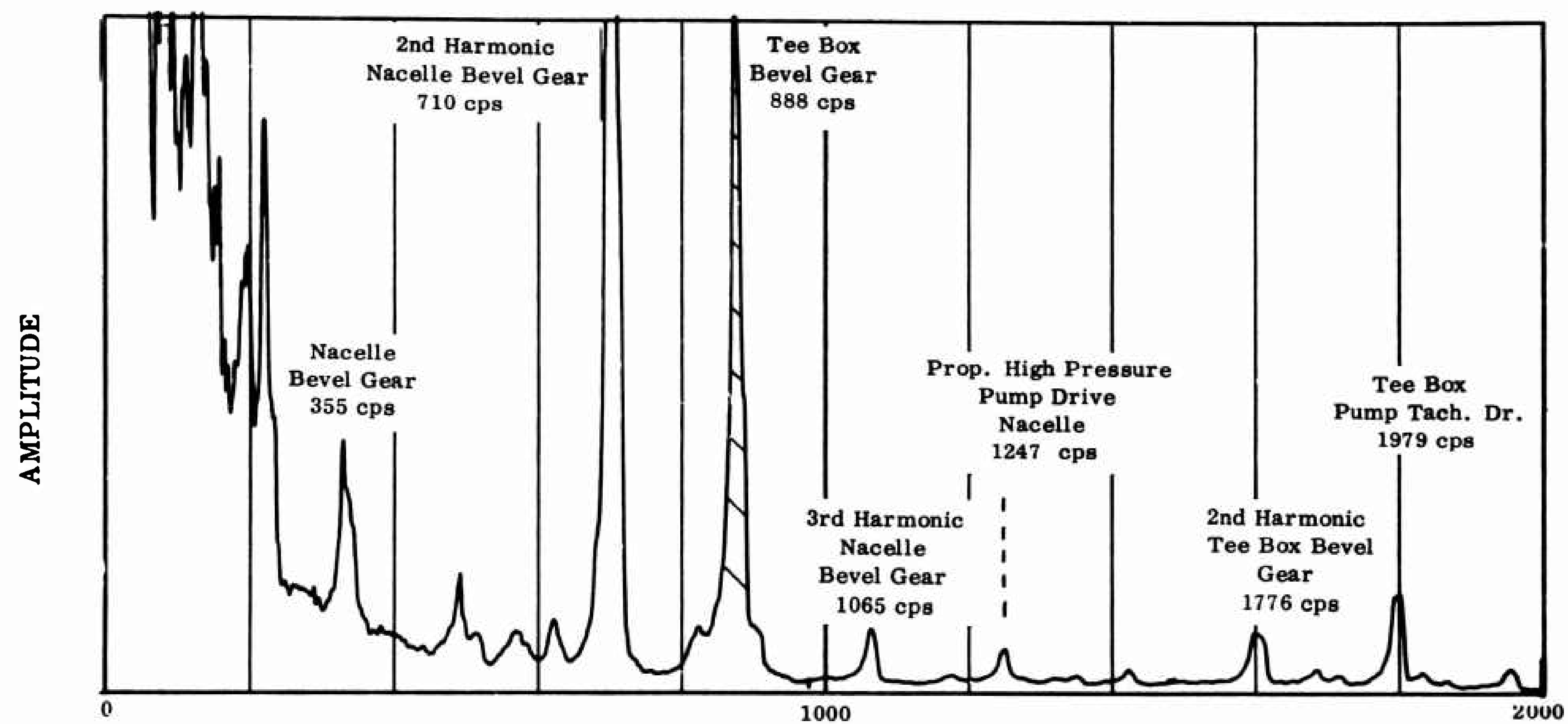


Figure 21. Amplitude vs. Frequency Spectrogram, Recording No. TC4-3A, Microphone No. 2, (Tee Box), N_2 = 14969 RPM, Total Rig Time = 324:58 Hrs.



FREQUENCY - CPS

Figure 22. Amplitude vs. Frequency Spectrogram, Recording No. TC19-3B, Microphone No. 2, (Tee Box), N_2 = 6500 RPM, Total Rig Time = 347:40 Hrs.

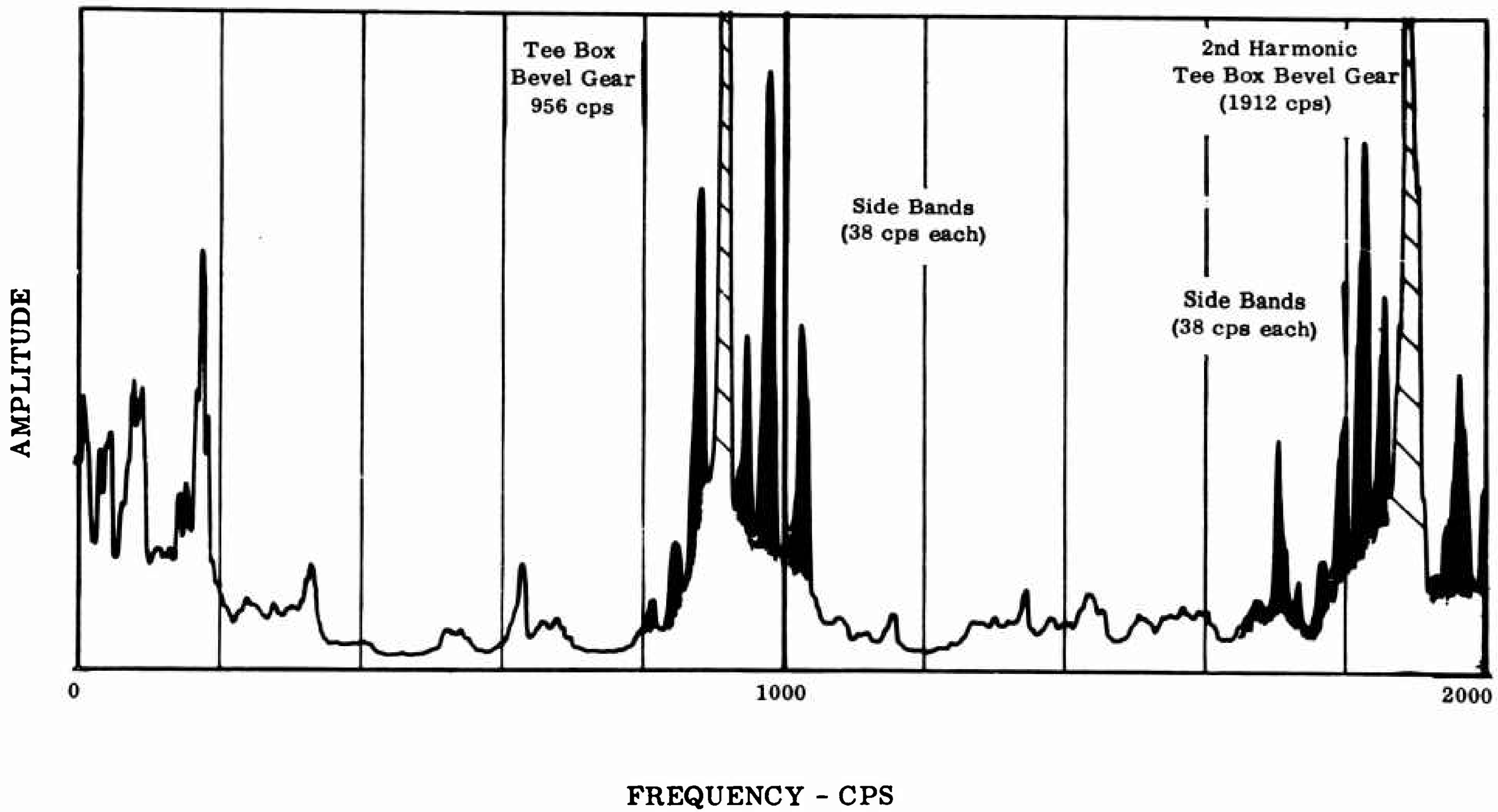


Figure 23. Amplitude vs. Frequency Spectrogram, Recording No. TC22-1B, Microphone No. 2, (Tee Box), N_2 = 7000 RPM, Right Nacelle Not Installed, Total Rig Time = 355:49 Hrs.

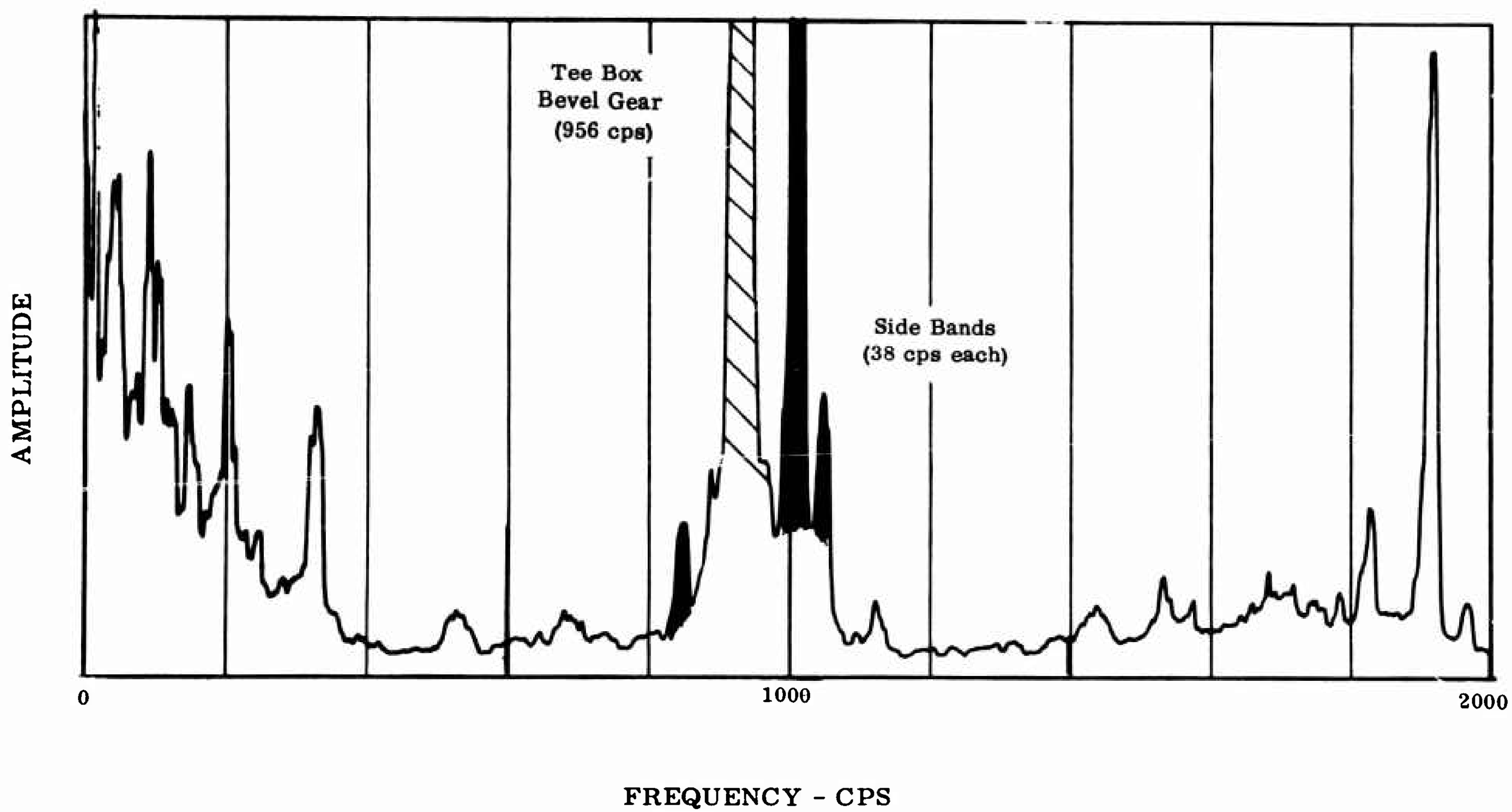


Figure 24. Amplitude vs. Frequency Spectrogram, Recording No. TC26-1B, Microphone No. 2, (Tee Box), N_2 = 7000 RPM, Total Rig Time = 384:55 Hrs., Endurance Time = 21:15 Hrs.

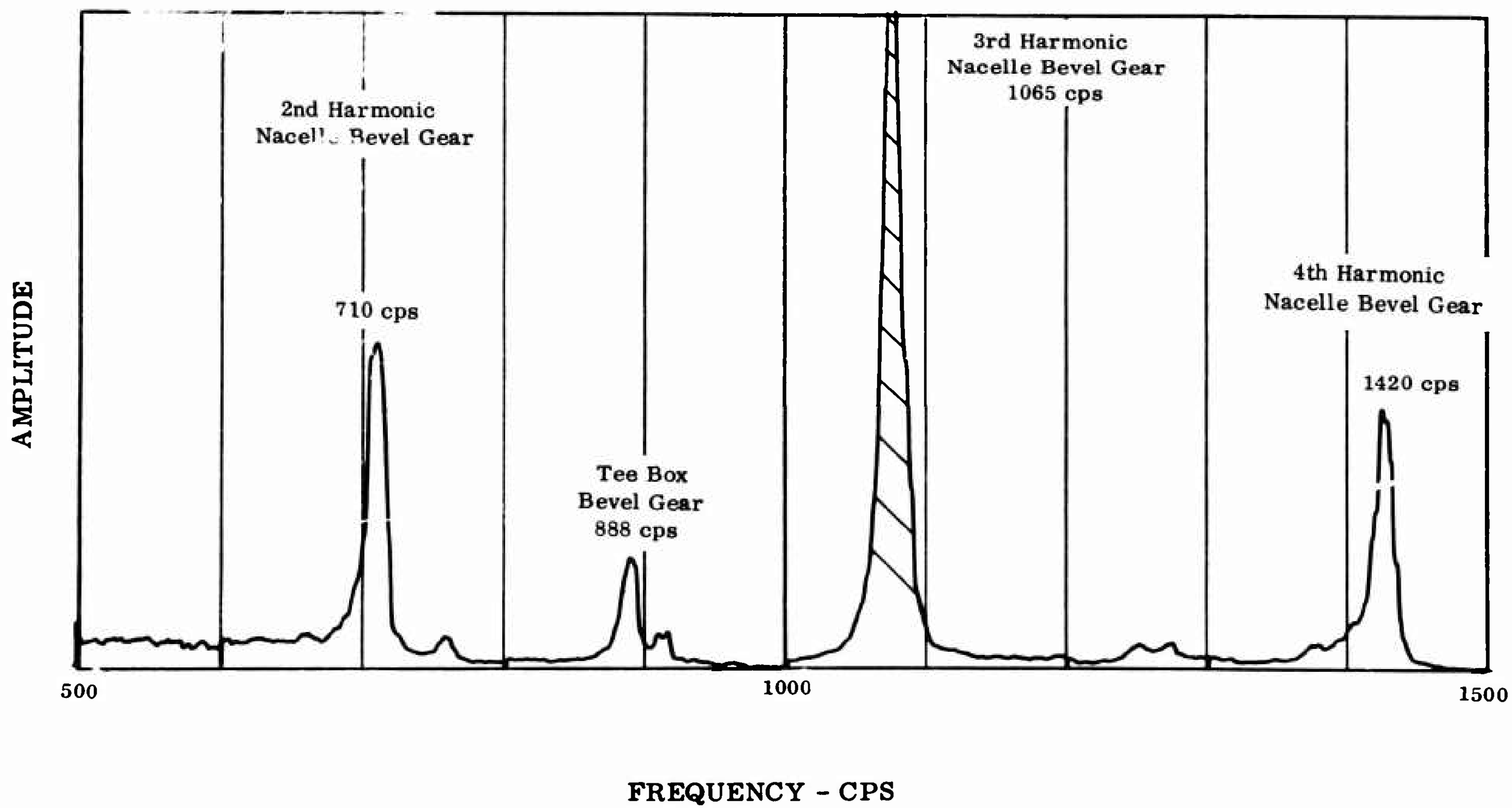


Figure 25. Amplitude vs. Frequency Spectrogram, Recording No. TC19-4A, Microphone No. 3, (Left Nacelle), N_2 = 6500 RPM, Total Rig Time = 347:43 Hrs.

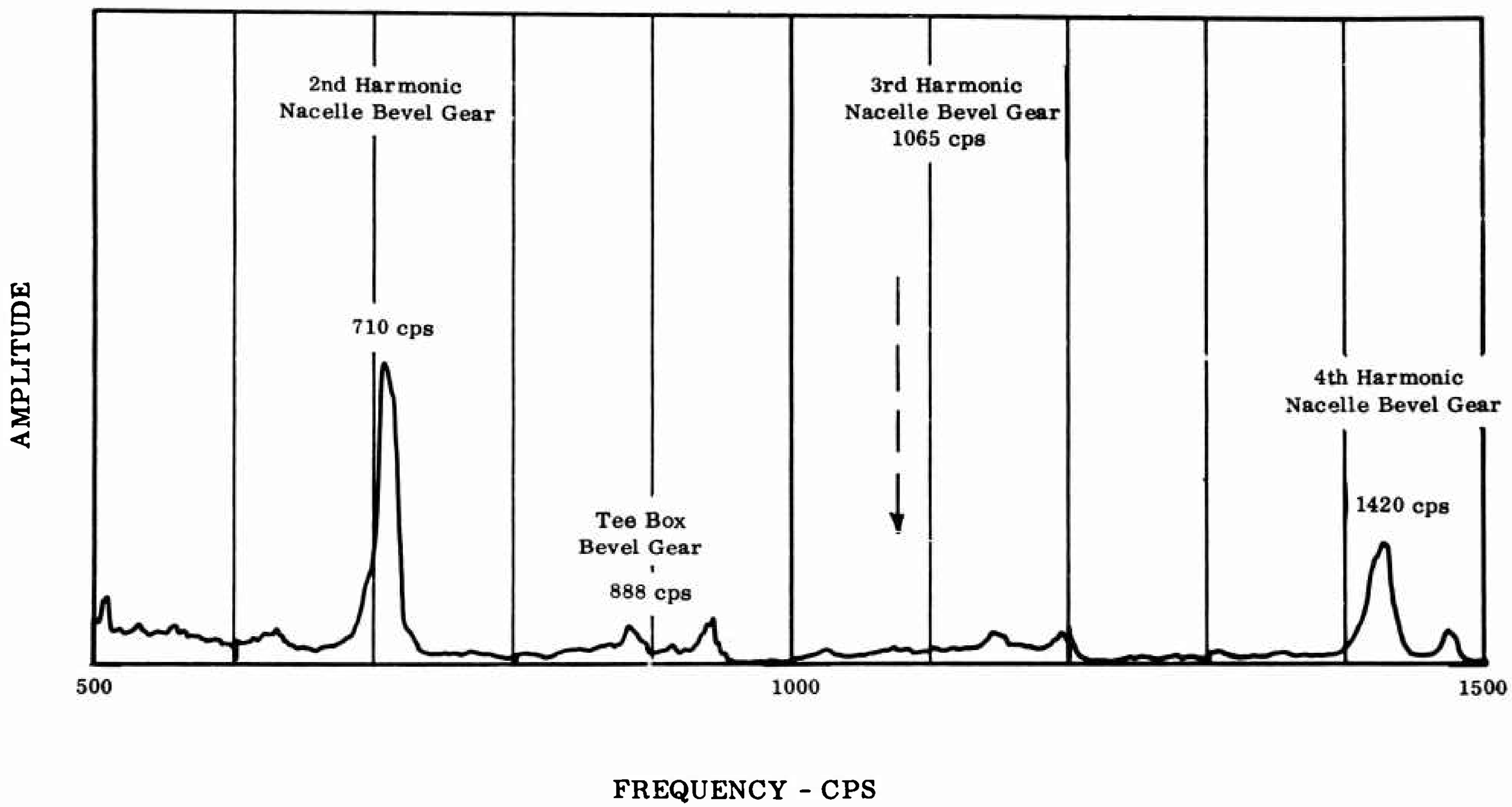


Figure 26. Amplitude vs. Frequency Spectrogram, Recording No. TC19-4B, Microphone No. 4, (Right Nacelle), N_2 = 6500 RPM, Total Rig Time = 347:43 Hrs.

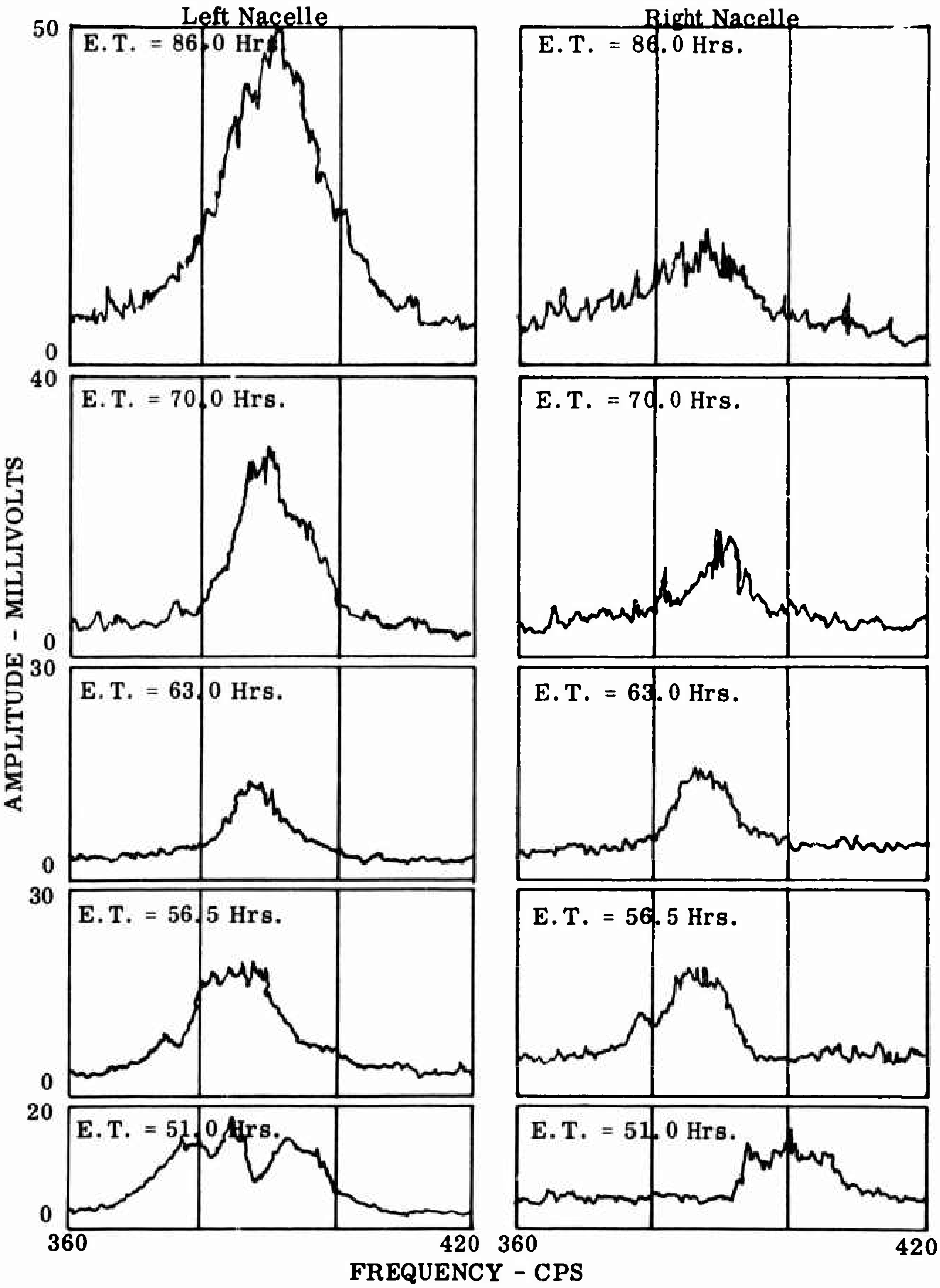


Figure 27. Amplitude vs. Frequency Spectrograms of the Nacelle Bevel Gear and No. 1 Pinion Bearing at Various Time Intervals

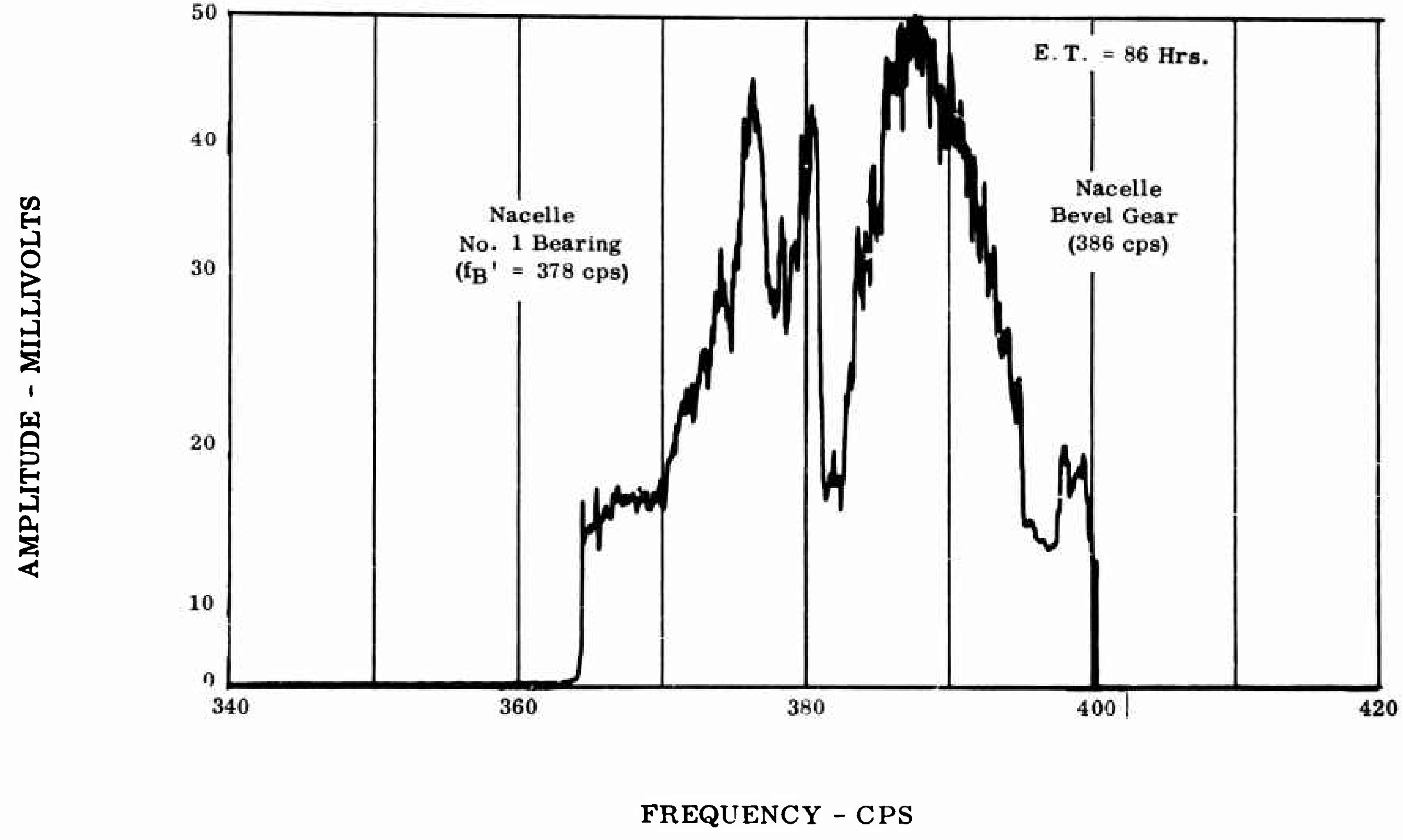


Figure 28. Amplitude vs. Frequency Spectrogram, Recording No. TC39-2A, Microphone No. 3, (Left Nacelle), N_2 = 7074 RPM.

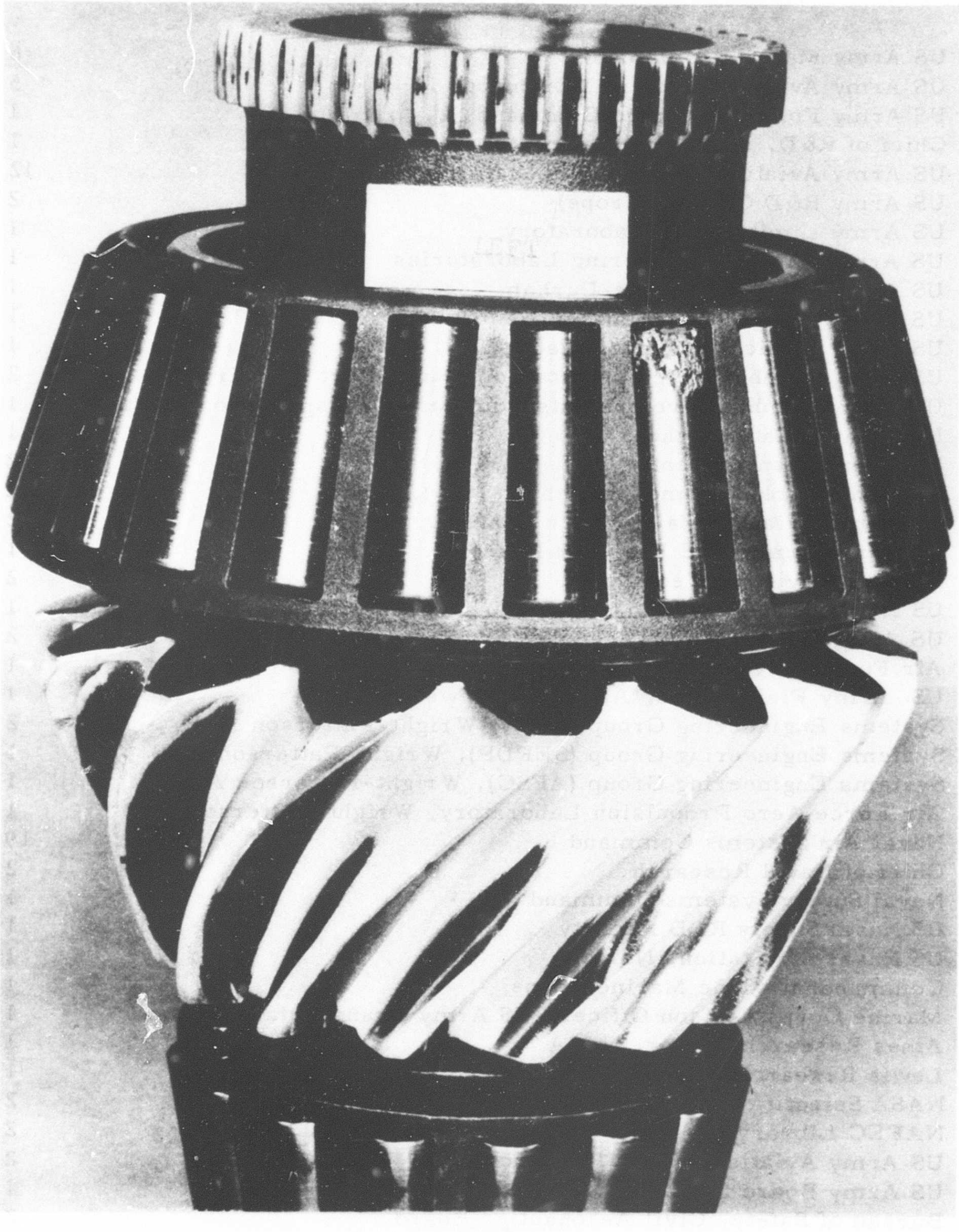


Figure 29. Left Nacelle No. 1 Pinion Bearing Showing Spalled Roller

DISTRIBUTION

US Army Materiel Command	6
US Army Aviation Materiel Command	5
US Army Forces Southern Command	1
Chief of R&D, DA	1
US Army Aviation Materiel Laboratories	12
US Army R&D Group (Europe)	2
US Army Limited War Laboratory	1
US Army Human Engineering Laboratories	1
US Army Research Office-Durham	1
US Army Test and Evaluation Command	1
US Army Medical R&D Command	1
US Army Combat Developments Command, Fort Belvoir	2
US Army Combat Developments Command Transportation Agency	1
US Army Aviation School	1
US Army Infantry Center	2
US Army Tank-Automotive Center	2
US Army Aviation Maintenance Center	2
US Army Armor and Engineer Board	1
US Army Aviation Test Board	2
US Army Transportation Engineering Agency	1
US Army Aviation Test Activity, Edwards AFB	2
Air Force Flight Test Center, Edwards AFB	1
US Army Field Office, AFSC, Andrews AFB	1
Systems Engineering Group (RTD), Wright-Patterson AFB	2
Systems Engineering Group (SEFDP), Wright-Patterson AFB	1
Systems Engineering Group (AFSC), Wright-Patterson AFB	1
Air Force Aero Propulsion Laboratory, Wright-Patterson AFB	1
Naval Air Systems Command	19
Chief of Naval Research	2
Naval Supply Systems Command	1
US Naval Supply R&D Facility	1
US Naval Air Station, Norfolk	1
Commandant of the Marine Corps	1
Marine Corps Liaison Officer, US Army Transportation School	1
Ames Research Center, NASA	1
Lewis Research Center, NASA	1
NASA Scientific and Technical Information Facility	2
NAFEC Library (FAA)	2
US Army Aviation Human Research Unit	2
US Army Board for Aviation Accident Research	1
Bureau of Safety, Civil Aeronautics Board	2
US Naval Aviation Safety Center, Norfolk	1

The Surgeon General	1
Defense Documentation Center	20
US Government Printing Office	1
Federal Aviation Agency, Washington, D. C.	1

APPENDIX I

SAMPLE CALCULATIONS

FUNDAMENTAL FREQUENCIES @ 6500 N_2RPM AND 7500 N_1RPM

1. Compressor

(a) Fundamental rotational frequency

$$f_R = \frac{\text{RPM of compressor rotor, } N_1}{60}$$

(b) Compressor rotor rotational frequency

$$f_C = f_R \times \text{no. of rotor blades}$$

Example: 1st stage = 28 blades, N_1 = 7500 RPM

$$f_R = \frac{7500}{60} = 125 \text{ rps}$$

$$f_C = 125 \times 28 = 3500 \text{ cps}$$

2. Engine Coupling Gearbox

(a) Rotational frequency

$$f_{gear} = \frac{\text{RPM of gear shaft}}{60} \times \text{no. of gear teeth}$$

Example: Gear C = 40 teeth, N_2 = 6500 RPM

$$f_{gear} = \frac{6500}{60} \times 40 = 4333 \text{ cps}$$

(b) Gear RPM (ref. Figure 8)

$$\text{RPM of driven gear} = \frac{\text{no. of teeth on driver gear}}{\text{no. of teeth on driven gear}} \times \text{RPM of driver}$$

Example: gear E = 122 teeth, gear C = 40 teeth,
gear D = 84 teeth, N_{driver} = 6500 RPM

$$N_{gear\ E} = \frac{40}{84} \times \frac{84}{122} \times 6500 = 2131 \text{ RPM}$$

3. <u>Bearing Formulae</u>

(a) Fundamental rotational frequency

$$f_R = \frac{\text{RPM of shaft}}{60}$$

(b) Frequency caused by irregularity on inner race

$$f_1 = f_R \; m \; D_2$$

(c) Frequency caused by irregularity on outer race

$$f_2 = f_R \; m \; D_1 \text{ or } f_1 \frac{d_1}{d_2}$$

(d) Frequency caused by spin of rolling element

$$f_B = f_R \frac{d_2}{d_B} D_1$$

(e) Frequency caused by rough spot on rolling element

$$f_B' = 2 \; f_B$$

(f) Frequency due to rotation of train of rolling elements

$$f_T = f_R D_1 \quad \text{or} \quad \frac{f_2}{m}$$

where m = no. of rolling elements

D_1 = $d_1/(d_1 + d_2)$

D_2 = $d_2/(d_1 + d_2)$

d_1 = inner race diameter

d_2 = outer race diameter

d_B = diameter of rolling element

Example: ECGB No. 4 bearing on gear C

d_1 = 3.7992", d_2 = 4.6654", m = 26, d_B = .433"

N = 6500 RPM

(a) $f_R = \frac{6500}{60} = 108.33$ rps

(b) $D_2 = \frac{d_2}{d_1 + d_2} = \frac{4.6654}{8.4646} = .5512$

$f_1 = 108.33\ (26)\ .5512 = 1552.5$ cps

(c) $D_1 = \frac{d_1}{d_1 + d_2} = \frac{3.7992}{8.4646} = .4488$

$f_2 = 108.33\ (26)\ .4488 = 1264.1$ cps

(d) $f_B = 108.33\ \frac{(4.6654)}{.433}\ .4488 = 523.8$ cps

(e) $f_B' = 2 \times 523.8 = 1047.6$ cps

(f) $f_T = \frac{1264.1}{26} = 48.62$ cps

APPENDIX I

SUMMARY LOG OF ACOUST

Recording Number	Date	Time	Components	Test Rig	Speed
TC1-1	2-16-65	0856	Tee Box	Lube Rig	G.I.
TC1-2	"	0904	"	"	Cruise
TC1-3	"	0910	"	"	Trans.
TC1-4	"	0915	"	"	T.O.
TC1-5	"	1012	None	"	G.I.
TC1-6	"	1015	None	"	Cruise
TC1-7	"	1018	None	"	Trans.
TC1-8	"	1020	None	"	T.O.
TC2-1	3-10-65	1501	ECGB	X-19 Half System	Cruise
TC2-2	"	1531	"	"	Trans.
TC2-3	"	1537	"	"	T.O.
TC2-4	"	1545	"	"	G.I.
TC3-1	3-25-65	1456	ECGB, Tee Box & Nacelles	"	G.I.
TC3-2	"	1459	"	"	G.I.
TC3-3	"	1504	"	"	Cruise
TC3-4	"	1507	"	"	Cruise
TC3-5	"	1544	"	"	T.O.
TC3-6	"	1600	"	"	T.O.
TC3-7	"	1608	"	"	T.O.
TC4-1	4-22-65	0908	"	"	T.O.
TC4-2	"	0914	"	"	T.O.
TC4-3	"	1034	"	"	T.O.
TC4-4	"	1041	"	"	T.O.
TC5-5	"	1136	"	"	T.O.
TC5-6	"	1144	"	"	T.O.
TC5-7	"	1415	"	"	T.O.

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APPENDIX II

LOG OF ACOUSTIC RECORDINGS

	Speed	Power Condition	Microphone Number	Comments
	G.I.	No Load	1, 2	
	Cruise	"	1, 2	
	Trans.	"	1, 2	
	T.O.	"	1, 2	
	G.I.	"	1, 2	Test rig alone. Tee Box uncoupled.
	Cruise	"	1, 2	Test rig alone. Tee Box uncoupled.
	Trans.	"	1, 2	Test rig alone. Tee Box uncoupled.
	T.O.	"	1, 2	Test rig alone. Tee Box uncoupled.
em	Cruise	"	1	ECGB alone.
	Trans.	"	1	ECGB alone.
	T.O.	"	1	ECGB alone.
	G.I.	"	1	ECGB alone.
	G.I.	-	1, 2	
	G.I.	-	3, 4	
	Cruise	160 HP/Prop	1, 2	
	Cruise	"	3, 4	
	T.O.	500 HP/Prop 600 HP Water Brake	1, 2	
	T.O.	"	1, 2	
	T.O.	"	3, 4	
	T.O.	200 HP, Left 240 HP, Right	1, 2	
	T.O.	"	3, 4	
	T.O.	300 HP/Prop 300 HP Water Brake	1, 2	
	T.O.	"	3, 4	
	T.O.	400 HP/Prop 400 HP Water Brake	1, 2	
	T.O.	"	3, 4	
	T.O.	"	1, 2	

Recording Number	Date	Time	Components	Test Rig	Speed
TC5-8	4-22-65	1419	ECGB, Tee Box & Nacelles	X-19 Half System	T.O.
TC6-1	4-23-65	-	172980 (wide face) gear from ECGB	-	-
TC6-2	"	-	167875 (narrow face) gear from ECGB	-	-
TC6-3	"	-	172981 pinion gear from ECGB	-	-
TC6-4	"	-	172984 clutch drive gear from ECGB	-	-
TC7-1	5-3-65	1000	ECGB, Tee Box	"	G.I.
TC7-2	"	1029	"	"	G.I.
TC8-1	5-4-65	1342	ECGB, Tee Box & Nacelles	"	G.I.
TC8-2	"	1417	"	"	G.I.
TC8-3	"	1431	"	"	G.I.
TC8-4	"	1435	"	"	G.I.
TC8-5	"	1505	"	"	G.I.
TC8-6	"	1507	"	"	G.I.
TC8-7	"	1512	"	"	T.O.
TC9-1	5-10-65	0852	ECGB	Lube Rig	G.I.
TC9-2	"	0855	"	"	Cruise
TC9-3	"	0858	"	"	Trans.
TC9-4	"	0901	"	"	T.O.
TC10-1	5-25-65	1548	ECGB, Tee Box & Nacelles	X-19 Half System	T.O.
TC10-2	"	1553	"	"	T.O.
TC10-3	"	1600	"	"	T.O.

eed	Power Condition	Microphone Number	Comments
O.	400 HP Prop 400 HP Water Brake	3, 4	P/N 172980 gear failure noted on inspection of gearbox.
-	-	-	Ringing test.
-	-	-	Ringing test.
-	-	-	Ringing test.
-	-	-	Ringing test.
I.	-	1, 2	Removed ECGB (chip detector on). Inspection revealed ECGB to be OK.
I.	-	1, 2	Removed ECGB (chip detector on). Inspection revealed ECGB to be OK.
I.	-	1, 2	
I.	-	1, 2	
I.	-	1, 2	Removed ECGB due to high bearing temperature and low lube pressure.
I.	-	3, 4	Removed ECGB due to high bearing temperature and low lube pressure.
I.	-	1, 2	Removed ECGB due to high bearing temperature and low lube pressure.
I.	-	3, 4	Removed ECGB due to high bearing temperature and low lube pressure.
O.	500 HP/Prop 600 HP Water Brake	1, 2	
I.	-	1	
uise	-	1	
ans.	-	1	
O.	-	1	
O.	300 HP/Prop 360 HP Water Brake	1, 2	ECGB has new wide face idler gears.
O.	"	3, 4	
O.	"	1, 2	

Recording Number	Date	Time	Components	Test Rig	Speed
TC11-1	5-25-65	1619	ECGB, Tee Box & Nacelles	X-19 Half System	T.O.
TC11-2	"	1625	"	"	T.O.
TC11-3	"	1630	"	"	T.O.
TC11-3	"	1635	"	"	T.O.
TC11-4	"	1640	"	"	T.O.
TC11-5	"	1644	"	"	T.O.
TC12-1	5-26-65	1028	"	"	G.I.
TC12-2	"	1030	"	"	G.I.
TC12-3	5-27-65	1012	"	"	T.O.
TC12-4	"	1017	"	"	T.O.
TC13-1	5-27-65	1055	"	"	T.O.
TC13-2	"	1101	"	"	T.O.
TC13-3	"	1105	"	"	T.O.
TC13-4	"	1110	"	"	T.O.
TC13-5	"	1114	"	"	T.O.
TC13-6	"	1118	"	"	T.O.
TC13	"	-	-	-	-
TC14-1	6-7-65	1121	"	"	G.I.
TC14-2	"	1126	"	"	G.I.
TC14-3	"	1133	"	"	G.I.
TC14-4	"	1137	"	"	G.I.

Power Condition	Microphone Number	Comments
400 HP/Prop 400 HP Water Brake	1, 2	
"	3, 4	
Changed N_1 RPM on No. 1 & No. 2 engines (one at a time) while holding N_2 constant.	1, 2	Examined Tee Box to search for source of high noise level. No apparent discrepancies noted.
400 HP/Prop 400 HP Water Brake	1, 2	
"	3, 4	
"	1, 2	
"	1, 2	Warm up.
-	1, 2	
600 HP/Prop 800 HP Water Brake	1, 2	After reinstalling Tee Box high noise level practically disappeared.
"	3, 4	
700 HP/Prop	1, 2	
800 HP/Prop	1, 2	
900 HP/Prop	1, 2	
-	1, 2	No. 1 engine at idle, No. 2 at takeoff.
-	1, 2	No. 1 engine at idle, No. 2 at takeoff.
600 HP/Prop 600 HP Water Brake 2000 HP No. 2 engine	1, 2	No. 2 engine at idle, No. 1 at takeoff.
-	-	Finished break-in run of ECGB and nacelle bevel gear sets. Inspection revealed No. 2 ECGB intermediate gear to be cracked. Found left nacelle gear set slightly scuffed. Built up ECGB using narrow face idler and output gears (from previous endurance test).
-	3, 4	Nacelle microphones relocated and attached to nacelles.
-	1, 2	Nacelle gear run-in.
300 HP L.P., 200 HP R.P., 500 HP Tee Box, 400 HP Water Brake	3, 4	Nacelle gear run-in.
"	1, 2	Nacelle gear run-in.

Recording Number	Date	Time	Components	Test Rig	Speed
TC15-1	6-8-65	0905	Tee Box and Nacelles	X-19 Half System	T.O.
TC15-2	"	0914	"	"	T.O.
TC15-3	"	0920	"	"	T.O.
TC16-1	"	-	"	"	15100
TC16-2	"	-	"	"	14000
TC16-3	"	-	"	"	13000
TC16-4	"	-	"	"	12000
TC16-5	"	-	"	"	Accel
TC16-6	"	-	"	"	15100
TC16-7	"	-	"	"	12000
TC16-8	"	-	"	"	12000
TC16-9	"	-	"	"	12000
TC16-10	"	-	"	"	Decel
TC17-1	6-11-65	1550	ECGB, Tee Box & Nacelles	"	G.I.
TC17-2	"	1554	"	"	G.I.
TC17-3	"	1605	"	"	Cruise
TC17-4	"	1610	"	"	Cruise
TC18-1	"	2000	Left & Right Nacelle	"	Cruise
TC18-2	6-14-65	0940	"	"	Cruise
TC18-3	"	1900	"	"	Cruise
TC19-1	6-15-65	0900	ECGB, Tee Box & Nacelles	"	Cruise
TC19-2	"	0907	"	"	Cruise
TC19-3	"	1052	"	"	G.I.
TC19-4	"	1055	"	"	G.I.
TC20-1	7-16-65	1009	ECGB, Tee Box & Left Nacelle	X-19 Half System*	15100
TC20-2	"	1037	"	"	7000

* Right nacelle not installed on rig.

Speed	Power Condition	Microphone Number	Comments
T.O.	600 HP L.P., 110 HP R.P., 400 HP Water Brake	3, 4	Nacelle gear run-in.
T.O.	"	2, 3	Nacelle gear run-in.
T.O.	"	3, 4	Nacelle gear run-in.
15100	-	2, 3)	
14000	-	2, 3)	
13000	-	2, 3)	
12000	-	2, 3)	These runs made to determine source and frequency of high noise level.
Accel	-	2, 3)	
15100	-	2, 3)	
12000	-	2, 3)	
12000	-	2, 3)	
12000	-	2, 4)	
Decel	-	2, 4)	
G.I.	-	1, 2	Start endurance.
G.I.	-	3, 4	Continuing endurance.
Cruise	-	1, 2	Continuing endurance.
Cruise	-	1, 2	Continuing endurance.
Cruise	563 HP/Prop 1126 HP Water Brake	3, 4	Continuing endurance.
Cruise	"	3, 4	Continuing endurance.
Cruise	"	3, 4	Continuing endurance.
Cruise	-	1, 2	Continuing endurance.
Cruise	-	3, 4	
G.I.	-	1, 2	
G.I.	-	3, 4	Continuing endurance.
15100	200 HP/L.P.	1, 2	
7000	No Load	1, 2	

Recording Number	Date	Time	Components	Test Rig	Speed
TC21-1	7-16-65	1429	ECGB, Tee Box & Left Nacelle	X-19 Half System*	7000
TC21-2	"	1432	"	"	7000
TC21-3	"	1439	"	"	15100
TC21-4	"	1442	"	"	15100
TC22-1	7-28-65	1505	"	"	7000
TC22-2	"	1508	"	"	7000
TC22-3	"	1540	"	"	15100
TC22-3A	"	1543	"	"	7000
TC22-4	7-29-65	-	"	"	15100
TC22-5	"	0920	"	"	15100
TC22-6	"	1435	"	"	15100
TC22-7	"	1635	"	"	15100
TC22-8	7-30-65	1015	"	"	7000
TC22-9	"	1020	"	"	15100
TC23-1	"	-	"	"	15100
TC23-2	"	-	"	"	7000
TC23-3	"	-	"	"	12000
TC23-4	"	-	"	"	7000
TC23-5	8-12-65	1105	ECGB, Tee Box & both Nacelles	X-19 Half System	7000
TC23-6	"	1309	"	"	7000
TC23-7	"	1311	"	"	7000
TC23-8	"	1340	"	"	15100
TC23-9	"	1343	"	"	15100
TC23-10	8-13-65	0854	"	"	15100
TC23-11	"	0856	"	"	15100
TC23-12	"	0923	"	"	15100

* Right nacelle not installed on rig.

Speed	Power Condition	Microphone Number	Comments
7000	No Load	1, 2	
7000	No Load	2, 4	
15100	200 HP L.P. 600 HP Water Brake	2, 4	
15100	"	1, 2	Removed left nacelle gear set on 7-17-65. Found nacelle gears scuffed. Installed another gear set.
7000	No Load	1, 2	
7000	No Load	1, 3	
15100	200 HP L.P.	1, 3	
7000	No Load	1, 3	
15100	400 HP L.P.	1, 3	
15100	600 HP L.P.	1, 3	
15100	800 HP L.P.	1, 3	
15100	1000 HP L.P.	1, 3	
7000	No Load	1, 3	
15100	2000 HP No. 2 Engine	1, 3	
15100	1250 HP L.P.	1, 3	
7000	No Load	1, 3	
12000	563 HP L.P.	1, 3	
7000	No Load	1, 3	Prepare to run 2 hours at Max. Cruise.
7000	No Load	1, 2	
7000	No Load	1, 2	
7000	No Load	3, 4	
15100	200 HP/Prop 300 HP Water Brake	1, 2	
15100	"	3, 4	
15100	600 HP/Prop 330 HP Water Brake	1, 2	
15100	600 HP/Prop 330 HP Water Brake	3, 4	
15100	800 HP/Prop 370 HP Water Brake	1, 2	

Recording Number	Date	Time	Components	Test Rig	Speed
TC23-13	8-13-65	0925	ECGB, Tee Box & both Nacelles	X-19 Half System	15100
TC23-14	"	1504	"	"	15100
TC23-15	"	1506	"	"	15100
TC23-16	"	1516	"	"	15100
TC23-17	"	1517	"	"	15100
TC24-1	8-16-65	1553	"	"	7000
TC24-2	"	1556	"	"	7000
TC24-3	8-17-65	1552	"	"	7000
TC24-4	"	1555	"	"	7000
TC24-5	8-19-65	1600	"	"	7000
TC24-6	"	1600	"	"	7000
TC25-1	8-24-65	1631	"	"	7000
TC25-2	"	1633	"	"	7000
TC26-1	8-25-65	1619	"	"	7000
TC26-2	"	1621	"	"	7000
TC27-1	10-15-65	1340	"	"	7000
TC27-2	"	1342	"	"	7000
TC28-1	11-4-65	1042	"	"	7000
TC28-2	"	1045	"	"	7000
TC28-3	"	1051	"	"	15100
TC28-4	"	1054	"	"	15100
TC28-5	"	1058	"	"	15100
TC28-6	"	1101	"	"	15100
TC29-1	11-4-65	1435	"	"	7000
TC29-2	"	1437	"	"	7000
TC29-3	"	1442	"	"	15100
TC29-4	"	1446	"	"	15100
TC29-5	"	1449	"	"	15100

ed	Power Condition	Microphone Number	Comments
)0	800 HP/Prop	3, 4	
	370 HP Water Brake		
)0	1000 HP/Prop	1, 2	
	350 HP Water Brake		
)0	"	3, 4	
)0	1250 HP R.H. Prop	1, 4	
	700 HP L.H. Prop		
)0	1250 HP L.H. Prop	1, 3	End of gear tooth profile development program
	700 HP R.H. Prop		
)	No Load	1, 2	Start 50 hour endurance program.
)	No Load	3, 4	
)	No Load	1, 2	Endurance time 5:00 hours.
)	No Load	3, 4	
)	No Load	1, 2	
)	No Load	3, 4	End of 10 hour endurance cycle.
)	No Load	1, 2	Endurance time 16:30 hrs.
)	No Load	3, 4	Endurance time 16:30 hrs.
)	No Load	1, 2	Endurance time 21:15 hrs.
)	No Load	3, 4	Endurance time 21:15 hrs.
)	No Load	1, 2	Green runs.
)	No Load	3, 4	Green runs.
)	No Load	1, 2	Green runs on tee box gears.
)	No Load	3, 4	Green runs on tee box gears.
)0	430 HP/Prop	1, 2	Green runs on tee box gears.
)0	"	3, 4	Green runs on tee box gears.
)0	"	1, 2	Green runs on tee box gears.
)0	"	2, 3	Green runs on tee box gears.
)	No Load	1, 2	Green runs on tee box gears.
)	No Load	3, 4	Green runs on tee box gears.
)0	650 HP/Prop	1, 2	Green runs on tee box gears.
)0	"	3, 2	Green runs on tee box gears.
)0	"	4, 2	Green runs on tee box gears.

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Recording Number	Date	Time	Components	Test Rig
TC30-1	11-5-65	0917	ECGB, Tee Box & both Nacelles	X-19 Half System
TC30-2	"	0920	"	"
TC30-3	"	0926	"	"
TC30-4	"	0930	"	"
TC30-5	"	0935	"	"
TC31-1	11-10-65	1555	"	"
TC31-2	"	1604	"	"
TC31-3	"	1614	"	"
TC32-1	11-11-65	0900	"	"
TC32-2	"	0905	"	"
TC33-1	11-16-65	0833	"	"
TC33-2	"	0842	"	"
TC34-1	12-14-65	0938	"	"
TC34-2	"	0941	"	"
TC35-1	12-16-65	0902	"	"
TC35-2	"	0905	"	"
TC36-1	12-16-65	1553	"	"
TC36-2	"	1556	"	"
TC37-1	12-20-65	0926	"	"
TC37-2	"	0930	"	"
TC38-1	12-21-65	1123	"	"
TC38-2	"	1127	"	"
TC39-1	12-22-65	0915	"	"
TC39-2	"	0919	"	"
TC40-1	12-31-65	-	ECGB Housing	-
TC40-2	"	-	No. 1 ECGB Pinion Gear	-
TC40-3	"	-	No. 1 ECGB Intermediate Gear	-

em

Speed	Power Condition	Microphone Number	Comments
7800	No Load	1, 2	Green runs on tee box gears.
7800	No Load	3, 4	Green runs on tee box gears.
15100	860 HP/Prop	1, 2	Green runs on tee box gears.
15100	"	2, 3	Green runs on tee box gears.
15450	"	2, 4	Green runs on tee box gears.
7000	No Load	1,2,3,4	Endurance.
15100	860 HP/Prop	1,2,3,4	Endurance.
-	No. 2 engine at idle	1,2,3,4	Endurance.
7000	No Load	1,2,3,4	Endurance.
15100	-	1,2,3,4	Endurance.
7000	No Load	1,2,3,4	Endurance.
15100	-	1,2,3,4	Endurance.
7000	Idle	1, 2	Endurance time 51:00 hrs.
7000	Idle	3, 4	
7000	Idle	1, 2	Endurance time 56:30 hrs.
7000	Idle	3, 4	
7000	Idle	1, 2	Endurance time 63:00 hrs.
7000	Idle	3, 4	
7000	Idle	1, 2	Endurance time 70:00 hrs.
7000	Idle	3, 4	
7000	Idle	1, 2	Endurance time 78:00 hrs.
7000	Idle	3, 4	
7000	Idle	1, 2	Endurance time 86:00 hrs.
7000	Idle	3, 4	
-	-	-	Ringing test.
-	-	-	Ringing test.
-	-	-	Ringing test.

Speed
7800
7800
15100
15100
15450
7000
15100
-
7000
15100
7000
15100
7000
7000
7000
7000
7000
7000
7000
7000
7000
7000
7000
7000
-
-
-

Recording Number	Date	Time	Components	Test Rig	Speed
TC40-4	12-31-65	-	No. 1 ECGB Bull Gear	X-19 Half System	-
TC40-5	"	-	No. 2 ECGB Intermediate Gear	-	-
TC40-6	"	-	No. 2 ECGB Pinion Gear	-	-
TC40-7	"	-	No. 2 ECGB Bull Gear	-	-
TC40-8	"	-	No. 2 ECGB Pinion Gear *	-	-
TC40-9	"	-	No. 2 ECGB Intermediate Gear *	-	-
TC40-10	"	-	No. 2 ECGB Bull Gear *	-	-
TC40-11	"	-	No. 1 ECGB Pinion Gear *	-	-
TC40-12	"	-	No. 1 ECGB Intermediate Gear *	-	-
TC40-13	"	-	No. 1 ECGB Bull Gear *	-	-

* Back lash out - slight torque on quill shafts.

Test Rig	Speed	Power Condition	Microphone Number	Comments
9 Half System	-	-	-	Ringing test.
-	-	-	-	Ringing test.
-	-	-	-	Ringing test.
-	-	-	-	Ringing test.
-	-	-	-	Ringing test.
-	-	-	-	Ringing test.
-	-	-	-	Ringing test.
-	-	-	-	Ringing test.
-	-	-	-	Ringing test.
-	-	-	-	Ringing test.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Curtiss-Wright Corporation Curtiss Division Caldwell, New Jersey	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

DIAGNOSTIC NOISE STUDY OF POWER TRANSMISSION SYSTEMS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final

5. AUTHOR(S) (Last name, first name, initial)

Locklin, Robert G.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1966	85	None

8a. CONTRACT OR GRANT NO. DA 44-177-AMC-249(T) b. PROJECT NO. c. Task 1M121401D14414 d.	9a. ORIGINATOR'S REPORT NUMBER(S) USAAVLABS Technical Report 66-55 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) C-2979

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	US Army Aviation Materiel Laboratories Fort Eustis, Virginia

13. ABSTRACT

The purpose of this investigation was ~~to make a diagnosit~~c noise ~~study of~~ the X-19 power transmission system to demonstrate the feasibility of using the diagnostic sonic technique to determine the mechanical condition of the internal gearing and bearings.

The method employed in monitoring the transmission system utilizes the noise generated by gears and bearings to determine the mechanical integrity of the system. The condenser type microphone system was utilized to record these signals on magnetic tape, and the recorded data were then analyzed using the panoramic sonic analyzer. In addition to the diagnostic sonic concept, a spectrometric oil analysis of the system was also made.

The diagnostic sonic analysis of the X-19 power transmission system was successful in detecting the majority of the system anomalies including a gear fatigue failure, several bearing failures, and gear tooth scuffing conditions. Correlation between acoustic and spectrometric oil analysis was also achieved.

The results of this investigation indicate the ability of the diagnostic sonic analysis technique in determining the mechanical integrity of the X-19 power transmission system. Although spectrometric oil analysis cannot indicate fatigue failures which may occur between sampling periods and obviously cannot detect nonlubricated components, in many cases additional information is obtained by the correlation of the oil sampling and sonic methods. Therefore, it is recommended that in a complete maintenance monitoring system, both the spectrometric oil sampling and the diagnostic sonic analysis techniques be utilized.

DD FORM 1 JAN 64 1473

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Sonic Analysis Sonic Analysis - Gears Sonic Analysis - Bearings X-19 Power Transmission System						

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