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Helicopter Transmission Research at NASA Lewis Research Center

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SUMMARY

A joint helicopter transmission research program between NASA Lewis Research Center and the U.S. Army Aviation Systems Command has existed since 1970. Program goals are to reduce weight and noise and to increase life and reliability. This report reviews significant advances in technology for gears and transmissions and describes the experimental facilities at NASA Lewis for helicopter transmission testing. A description of each of the rigs is presented along with some significant results from the experiments.

INTRODUCTION

NASA Lewis Research Center has had a research program for aircraft mechanical components since the early 1940's. A program for rolling element bearing technology for turbine engine application was built up during the 1950's and 1960's. Since many high-bypass turbine engines have a geared fan, NASA Lewis began a technology program for gear materials endurance in 1969. Meanwhile, during the period from the late 1940's to the 1960's, the helicopter came into wide use as an Army air mobile vehicle. In 1970 the common interest of the Army and NASA Lewis was recognized. The Army had a wide spectrum of helicopters in its inventory and needed to increase their performance; NASA Lewis had established mechanical component research that could be applied to helicopter transmissions. A joint program was undertaken in 1970.

The major goals of this program are to increase the life, reliability, and maintainability; reduce the weight, noise, and vibration; and maintain the relatively high mechanical efficiency of the gear train in helicopter transmissions. The approach is to identify advanced materials and lubrication schemes, as well as advanced design concepts for both transmission components and total transmission systems. In addition, in-house and university grant efforts are developing analytical codes for analysis and design. Unique experimental testing facilities now exist at NASA Lewis for testing mechanical components, materials, and lubrication techniques, as well as demonstrating advanced design concepts and verifying analytical codes.

This report reviews and summarizes the most significant results of the NASA/Army work on helicopter transmission technology. The major advances in technology for gears and transmissions are discussed, and the test rigs that are used to conduct experimental research are described in the appendix.

SIGNIFICANT TECHNICAL ADVANCES

Transmission Data Base Established

An extensive data base was established for two sizes of helicopter transmissions. The 3000-hp stand (see appendix) was used to test the UH-60A (Black Hawk) helicopter transmission. The transmission (fig. 1) is rated at 2110 kW (2828 hp) at an output speed of 258 rpm, and the transmission overall reduction ratio is 81.042:1. Efficiency, vibration, and gear tooth strain data were taken (ref. 1). The transmission's mechanical efficiency at full power was 97.3 and 97.5 percent at inlet oil temperatures of 82 and 99 °C (180 and 210 °F), respectively. The highest vibration reading was 72g rms at the upper housing side wall. The largest stress found was 760 MPa (110 ksi) on the combining pinion fillet. Temperature and deflection data were also taken and are presently being analyzed. Figure 2 shows the measured efficiency as a function of input power, rotor speed, and oil inlet temperature. The information from this data base is being compared with computer code predictions to provide a baseline from which to assess future designs and concepts.

Information of a similar nature and purpose was collected for the OH-58 transmission using the 500-hp test stand. The OH-58 transmission (fig. 3) is a two-stage reduction gearbox with a single spiral bevel mesh as the first stage and a three-planet, fixed-ring gear planetary mesh as the second. The overall reduction ratio of the transmission is 17.44:1. The transmission input is rated for use for an engine output of 201 kW (270 hp) continuous power at 6180 rpm and 236 kW (317 hp) for 5 min at takeoff. Data were collected for bevel-pinion gear tooth strain measurements, bevel gear deflections, component temperatures (bearings, gears, seals, and oil), vibrations, and transmission mechanical efficiencies. The testing consisted of a matrix of speed and load conditions.

The mechanical efficiency was determined by measuring the heat generation due to mechanical losses. Overall transmission efficiency varied from about 98.3 to 98.8 percent at full speed and load conditions and was a function of lubricant type and lubricant temperature. A reasonable correlation of efficiency with lubricant viscosity was made when the viscosities were corrected for temperature and pressure effects in the lubricated contact (ref. 2).

Vibration signals from accelerometers mounted at various locations on the transmission housing were analyzed. The spectra showed vibration amplitude peaks occurring at the spiral bevel gear mesh harmonics and planetary gear mesh harmonics (fig. 4). The highest magnitude of vibration was at the spiral bevel gear meshing frequency (ref. 3). In addition, the highest measured overall broadband acceleration was about 10g rms (occurring at full speed and load and measured on the housing near the ring gear).

Gear Materials Technology

The heavy load and speed conditions of helicopter gearing require that gear materials have high strength and improved fatigue life at elevated temperatures. The standard gear material used in the U.S. aircraft industry today is AISI 9310, a high alloy content steel. The surface fatigue life for a variety of proposed materials have been evaluated (refs. 4 to 9, fig. 5). The results for a few of the materials are as follows.

The standard AISI 9310 gear fatigue life was improved 60 percent by shot peening the gear flanks. Shot peening increased the subsurface residual compressive stress, resulting in increased surface fatigue life.

Three high-temperature materials were evaluated for surface life endurance at heavy test load and moderate speed conditions. The first material, CBS 600, maintains its hot hardness to 260 °C (500 °F) and has a longer fatigue life than AISI 9310. CBS 600 has good fracture toughness and is a good gear material for aircraft use.

The second material, Vasco X-2, retains its hardness to 316 °C (600 °F) and has a longer fatigue life than AISI 9310 when it is heat treated under very closely controlled conditions. Because Vasco X-2 has a high chromium content, it is very difficult to carburize and harden, which means that high standards of quality control are required for aircraft applications. It also has a modest fracture toughness and can be subject to tooth breakage, precipitated at a fatigue spall.

The third material, EX-53, has a much longer fatigue life - more than twice that of AISI 9310 - and has very good fracture toughness. However, EX-53 has a temperature limit of 232 °C (450 °F) which limits its use for some high-temperature applications.

Gear Thermal Behavior

Experimental testing and theoretical analysis were conducted to determine optimum methods for gear lubrication and cooling. High-speed photography (see appendix) was used to study oil jet impingement depths for into-mesh, out-of-mesh, and radial oil jets. The impingement depths measured from the photographs were compared with analytical predictions. The analysis and tests show that impingement depth is limited for into-mesh and out-of-mesh lubrication while radial jet lubrication with adequate oil jet pressure can provide maximum cooling and lubrication for gears (refs. 10 to 13). A thermal analysis was also performed, and experimental verifications were made which show the superior effect of the radial oil jet lubrication and cooling.

Gear Geometry

High-contact-ratio gears were examined as a means to improve the surface fatigue life and power-to-weight ratio of transmissions. High-contact-ratio (HCR) gears have at least two pairs of teeth in contact at all times, whereas standard- (low-) contact-ratio (LCR) gears have between one and two pairs in contact. Because the transmitted load is shared by at least two pairs of teeth, the individual tooth loading is less for HCR than for LCR designs, thereby enabling a higher power-to-weight ratio. HCR gears, however, require finer pitches or increased working depths, both of which tend to increase the tooth bending stress. In addition, it is expected that HCR gears are sensitive to tooth spacing errors and profile modifications because of the simultaneous tooth contacts. The basic problem to be resolved was whether the lower tooth loads in the HCR design more than offset the effects of the weakened tooth form, especially when run under dynamic load conditions. The investigation revealed that HCR gear designs have twice the fatigue life of LCR designs. Therefore, HCR gears can significantly increase the life, reliability, and power-to-weight ratio for helicopter transmissions (ref. 14).

The contact between spiral bevel gears has been especially difficult to model because there are no equations to represent the contact geometry; it must be developed numerically with a computer, based on the settings of the machine used to manufacture the gears. The contact geometry is essential to predicting the life, lubrication effects, and stress for spiral bevel gears. Kinematic errors have been identified as a contributor to gear mesh vibration. Kinematic errors are the time-varying deviations from a constant gear ratio during gear rotation. A method for eliminating these errors has been developed (ref. 15), but it still needs to be verified by experimental testing. These zero kinematical error gears have potential for reducing gear noise.

Computer Codes

Analyses and/or computer codes have also been developed for gears to provide the following types of calculations: (1) power loss and efficiency, (2) bevel gear contact geometry, (3) gear dynamic analysis, (4) weight minimization, (5) life prediction, (6) lubrication, and (7) temperatures. Several examples follow.

The computer program TELSGE (ref. 16) calculates dynamic loads, lubrication film thickness, stress, and temperature for spur gears. Figure 6 shows a sample calculation produced by TELSGE. The dynamic load is caused by the interaction of the tooth stiffness and the mass of the gear. The figure compares the calculated dynamic load with the static load - the load for very slow gear rotation.

The epicyclic gear program GEARDYNMULT (ref. 17) is a multiple mesh, single stage, gear dynamics program. It is a versatile gear tooth dynamic analysis computer program that determines detailed geometry, dynamic loads and stresses, and surface damage factors. The program can analyze a variety of both epicyclic and single mesh systems with spur and helical gear teeth including internal, external, and buttress tooth forms. The program includes options for flexible carrier or flexible ring gear, a floating sun gear, a natural frequencies option, and a finite element compliance formulation for helical gear teeth. The program can also determine maximum tooth loads as a function of speed, which is useful for critical speed analysis.

Figure 7 shows results for life analysis of a planetary gear transmission. The analysis is based on rigorous statistical methods and is implemented in an interactive computer program, CHOPR (ref. 18). The program can analyze a variety of configurations composed of spiral bevel gear meshes and planetary gear meshes. Spiral bevel reductions may have single or dual input pinions, and gear shafts can be straddle mounted or overhung on the support bearings. The planetary reduction has the sun gear as input, the planet carrier as output, and the ring gear fixed. The planet gears may be plain or stepped, and the number of planets may vary. The program determines the forces on each bearing and gear for a given transmission configuration and loading. The life of each bearing and gear is determined using the fatigue life model appropriate to that component. The transmission system life is determined from the component lives using Weibull statistical methods. The transmission life at a given reliability can then be found as shown in figure 7.

The computer program PLANETSYS (ref. 19) can simulate the thermomechanical performance of a multistage planetary transmission, including spherical roller bearings. SPHERBEAN (ref. 20) can make calculations for outer-ring rotation and misalignment such as found in planetary transmission applications. These programs are useful for helicopter transmission applications where severe performance demands are placed on bearings that require analysis for outer-ring rotation, for nonlubricated operation (dry friction), or for transient thermal performance. SPHERBEAN and PLANETSYS calculations were compared to data from parametric and loss-of-lubricant tests for an OH-58 transmission (ref. 21). Using both programs, calculations of temperatures at the output shaft and transmission case agreed with the data within 1 percent for steady-state operating conditions. Calculations to simulate the loss of lubricant compared well with data from an actual loss-of-lubricant test on an OH-58 transmission.

ADVANCED TRANSMISSION DESIGN CONCEPTS

Based on the experimental, analytical, and design studies conducted under the transmission technology program, some advanced transmission concepts were evolved: The advanced 500-hp transmission, the bearingless planetary transmission, and the split-torque transmission.

Advanced 500-hp Transmission

The design emphasis for the advanced 500-hp transmission (fig. 8) was placed on designing a 500-hp version of the OH-58C (317-hp transmission) that would have a long, quiet life with a minimum increase in the cost, weight, and space (ref. 22). This was accomplished by implementing advanced technology developed during the last decade and making improvements dictated by field experience.

These advanced technology components, concepts, and improvements, and their effect on the 500-hp transmission are

(1) High-contact-ratio planetary gear teeth reduce the noise level and increase life.

(2) Improved spiral bevel gears made of vacuum carburized gear steels, shot peened for increased gear tooth pitting fatigue life as well as gear tooth bending fatigue strength and lubricated with Aeroshell 555 oil, save weight and space and increase transmission life.

(3) Improved bearings made of cleaner steels and designed with improved analytical tools, save weight and space and increase reliability.

(4) Improved design of the planet carrier, a two-piece construction with straddle mounting of the planet gears, improves gear alignment and power capacity.

(5) The cantilever-mounted planetary ring gear has no working spline to generate wear debris, it isolates the meshing teeth from the housing to reduce noise, and it provides a flexible mount for a more uniform load distribution among the planets.

(6) The sun gear now has an improved spline (crown hobbed and hardened) running submerged in a bath of flowthrough oil which prevents the spline from wearing.

(7) The straddle-mounted bevel gear allows higher torque to be transmitted without detrimental shifting of the tooth contact pattern.

In summary, the improved 500-hp design has a weight-to-horsepower ratio of 0.26 lb/hp compared to 0.37 lb/hp for the 317-hp, OH-58C transmission.

Bearingless Planetary Transmission

The self-aligning, bearingless planetary (SABP) transmission (fig. 9) can be generically classified as a quasi-compound planetary system that utilizes a sun gear, planet spindle assemblies, ring gears, and rolling rings.

The design study projects a weight savings of 17 to 30 percent and a reliability improvement factor of 2:1 over the standard transmission (ref. 23). The SABP transmission is most beneficial between reduction ratios of 16:1 and 26:1. It permits high reduction in two compound stages of high efficiency, providing sufficient flexibility and self-centering to give good load distribution between planet pinions, while effectively isolating the planetary elements from housing deflections.

This new transmission concept offers advantages over transmissions that use conventional planetary gears: higher reduction ratio, lighter weight, increased reliability, and decreased vulnerability. Since it has no planet bearings, there is a weight savings, and power losses and bearing failures commonly associated with conventional-design transmissions are nonexistent.

In conventional-design transmissions, planet bearings are heavily loaded and are the weak link when the lubricant is interrupted. The SABP transmission has increased operating time after loss of lubricant since there are no planet bearings.

Split Torque Transmission

Advancements in transmissions can come from either components or improved designs of the transmission system. The split torque arrangement is in the second category. Figure 10 shows a split torque design which is compatible with the Black Hawk (UH-60A) helicopter. The fundamental concept of the split torque design is that the power from the engine is divided into two parallel paths prior to recombination on a single gear that drives the output shaft. Studies have shown that replacement of the planetary gear reduction stage with a split torque results in weight savings and increased reliability. There can be many pinions driving the output gear, but for the UH-60A application four pinions gave the optimum design. The basis was least overall weight, reduced power losses, comparable total parts count compared with the existing UH-60 design, and least number (one) of nonredundant gears. The advantage of split torque transmissions over planetary transmissions is greatest for the larger sized helicopters.

The engineering analysis (ref. 24) showed that the following performance benefits can be achieved for a 3600-hp split torque transmission compared to the conventional transmission with a planetary gear stage:

(1) Weight is reduced 15 percent.

(2) Drive-train power losses are reduced by 9 percent.

(3) Reliability is improved and vulnerability is reduced because of redundant power paths.

(4) The number of noise generation points (gear meshes) is reduced.

CONCLUDING REMARKS

The purpose of this report has been to review the most significant developments in gear and transmission technology resulting from the NASA/Army Transmission Research Program of the last two decades. The critical issues that were identified are (1) to achieve significant advances in power-to-weight ratio, (2) to increase reliability, and (3) to reduce transmission noise. New technologies and designs to achieve these goals have been investigated. The advanced 500-hp transmission has an increased power-to-weight ratio using advanced design techniques, component improvements, and advanced materials. The split torque concept offers significant weight savings for large helicopters. The bearingless planetary transmission with helical gears offers advantages in reliability and reduced noise. In addition, an aggressive program to develop computer aided design codes for gears and transmissions is required to replace empirical methods with validated computer codes.

It is reasonable to expect that helicopters will continue to evolve in the future. To achieve the necessary advances in rotary wing flight capability, drive-train technology must keep pace with advances in engines, structures, and rotors.

APPENDIX - TEST STANDS

Six test stands are active for helicopter transmission testing. The rigs provide analytical code verification and a baseline from which to assess the promised advantages of future designs and concepts.

3000-hp Helicopter Transmission Test Stand

The test stand (fig. 11) operates on a torque-regenerative (four-square) principle, where mechanical power is recirculated through a closed loop of gears and shafting, one of which is the test transmission. Power to the test transmission flows through two inputs (simulating two engines) and two outputs (main rotor and tail drive). Power is provided by a constant speed 600-kW (800-hp) induction motor, and speed is controlled by an eddy current clutch. Torque is induced independently in each loop by planetary torque units. The stand is also capable of applying lift, moment, and drag loads on the transmission output shaft.

500-hp Helicopter Transmission Test Stand

The test stand (fig. 12) operates on a torque-regenerative principle. A 149-kW (200-hp) variable-speed motor powers the test stand and controls the speed. Only losses due to friction are replenished by the motor since power is recirculated around the loop. An 11-kW (15-hp) motor provides the torque in the closed loop. This motor drives a magnetic particle clutch that exerts a torque through a speed reducer gearbox and chain drive to a large sprocket on the differential gearbox. The magnitude of the torque in the loop is adjusted by changing the electric field strength of the magnetic particle clutch. The facility is equipped with torque, speed, temperature, oil flow, and oil pressure sensors for health and condition monitoring.

Spur Gear Test Rig

There are four gear-fatigue rigs at NASA Lewis. The spur gear fatigue test apparatus (fig. 13) operates on a four-square principle. One slave gear is equipped with loading vanes, and oil pressure on the vanes produces a torque on the slave gear shaft. The torque is transmitted through the test gears and back to the slave gears. The torque on the test gears, which depends on the hydraulic pressure applied to the load vanes, loads the gear teeth to the desired stress level. A constant-speed motor is connected by a belt to the drive shaft, and various rig speeds are available by changing pulleys. The rig is capable of 75 kW (100 hp) at 10 000 rpm. The standard test gear is a 28-tooth spur gear with a pitch diameter of 8.89 cm (3.50 in.) and a diametral pitch of 8.

Lubricant oil jet tests were performed in the spur gear fatigue test apparatus (fig. 14). A specially designed test gear cover was made for viewing the test gears and photographing the lubrication phenomenon. A high-speed movie camera was used to photograph the oil jet. A high-speed air-cooled stroboscopic system was used to provide flash tube lighting that was synchronized with the high-speed camera. The camera speed was set at one frame per each tooth space movement. A white pigment was added to the gear lubricant, and a

1000-W xenon lamp was used to illuminate the lubricant. The experimentally measured oil impingement depths were used to verify analytical predictions.

Bevel Gear Test Rig

The bevel gear rig (not shown) is similar to the spur gear rig, but it is applied to spiral bevel gears. A torque-regenerative principle is used, and torque is applied by a hydraulic loading device. The rig was designed for capabilities up to 559 kW (750 hp) at a pinion gear speed of 15 000 rpm. The bevel gear apparatus test gears have a 35° spiral angle, a 2.54 cm (1 in.) face width, a 90° shaft angle, and a 22.5° pressure angle. The pinon has 12 teeth, and the gear has 36 teeth. The rig is used for fatigue testing, noise and vibration testing, and lubrication studies.

High-Speed Gear Test Stand

The high-speed gear test stand is used to study lubrication techniques, noise, and vibration at very high spur gear pitch line velocities. The test stand (fig. 15) has a power capacity of 2234 kW (3000 hp) with a pitch line velocity of 152 m/sec (30 000 ft/min). The pinion test gear has a 27.94-cm (11-in.) pitch diameter, a 4-diametral pitch, and a 25° pressure angle. The pinion meshes with a 33.02-cm (13-in.) pitch diameter gear.

Planetary Gear Test Rig

The planetary gear test rig is used to study performance characteristics of planetary gear assemblies. The rig uses a regenerating torque loop where two OH-58 planetary systems are mounted back-to-back with a drive motor on one end and a rotating torque actuator on the other end (fig. 16). The torque actuator loads the test planetary gear section with respect to the slave planetary gear section. The drive motor provides the speed and also supplies the power to overcome friction losses. The rig is capable of 373 kW (500 hp) at 1620 rpm sun gear speed.

The test and slave planetary systems have separate lubrication systems. Each system is comprised of 14 oil jets for lubrication of different areas of the planetary. The oil flow through each jet can be individually controlled. This makes possible an extensive study of the effect of lubrication on planetary gear performance.

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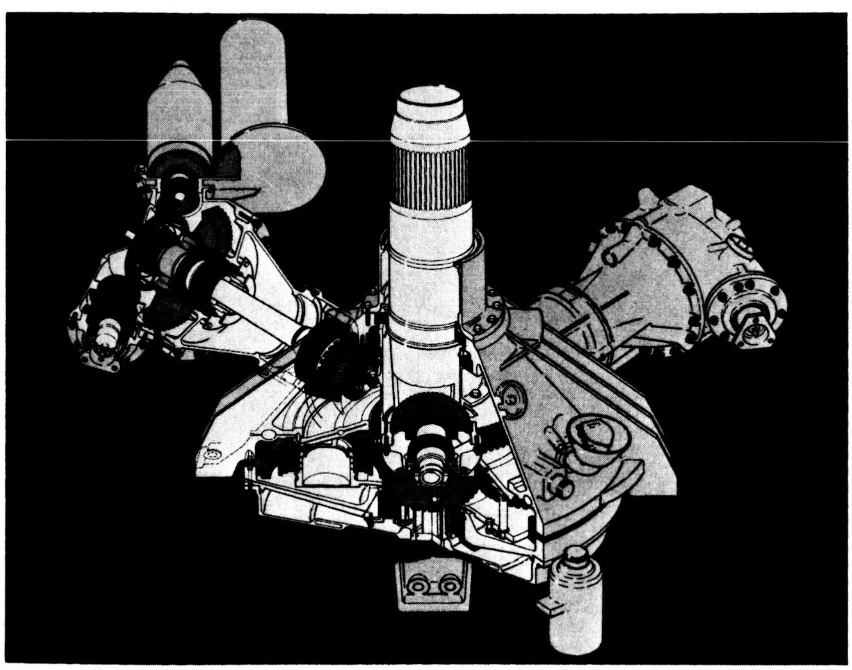

FIGURE 1. - UH-60A HELICOPTER TRANSMISSION.

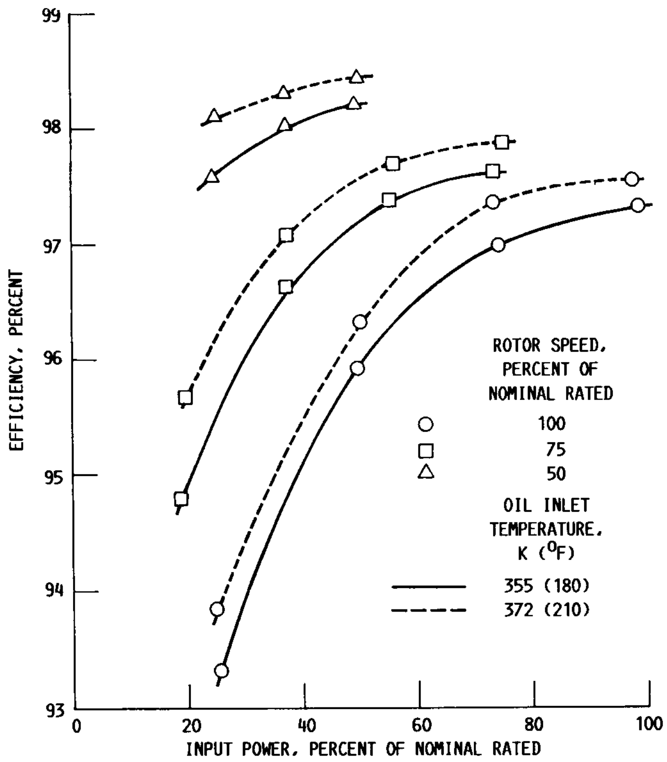

FIGURE 2. - MEASURED MECHANICAL EFFICIENCY.

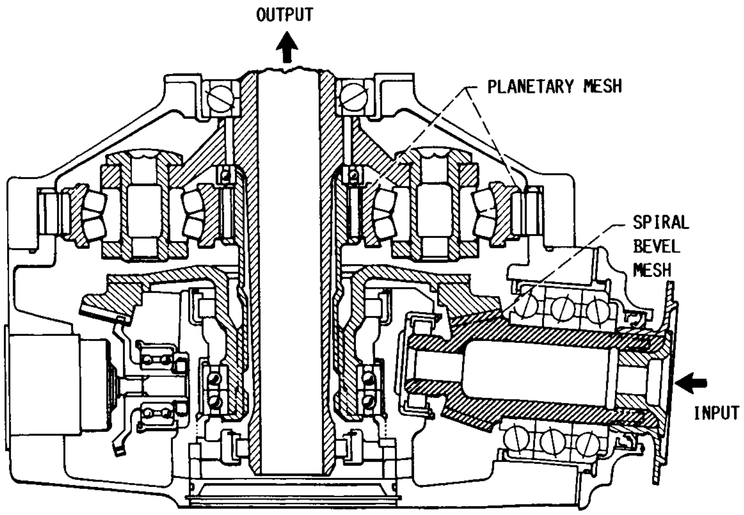

FIGURE 3. - OH-58A HELICOPTER MAIN ROTOR TRANSMISSION.

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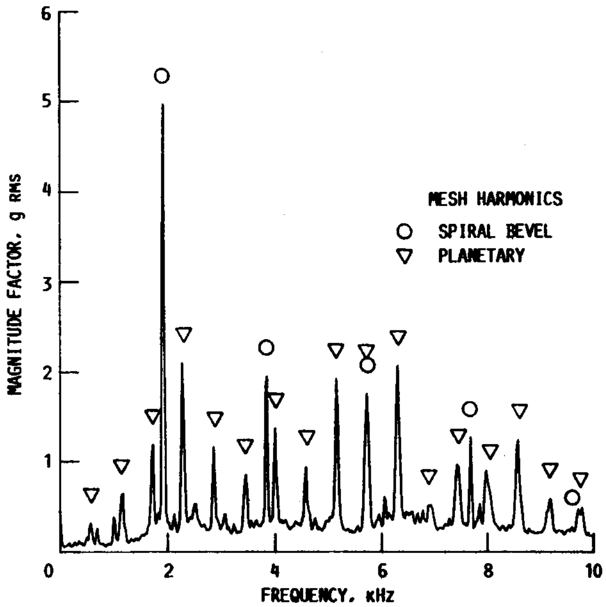

FIGURE 4. - OH-58A TRANSMISSION VIBRATION SPECTRUM.

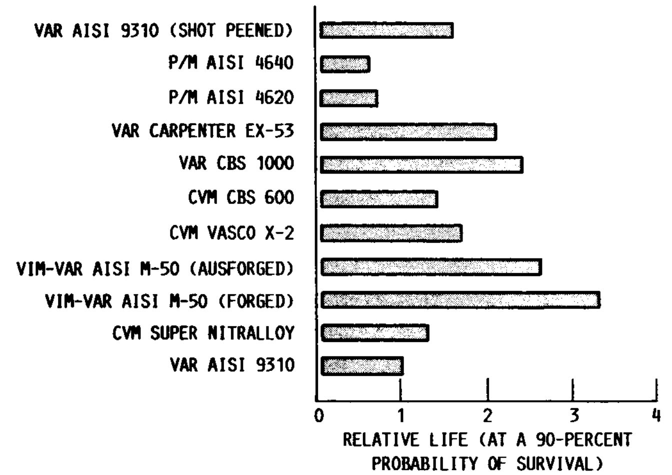

FIGURE 5. - PITTING FATIGUE LIVES OF VARIOUS AIRCRAFT QUALITY GEAR STEELS (VACUUM ARC REMELTED (VAR); CONSUMABLE ELECTRODE VACUUM MELTED (CVM); VACUUM INDUCTION MELTED, VACUUM ARC REMELTED (VIM-VAR)).

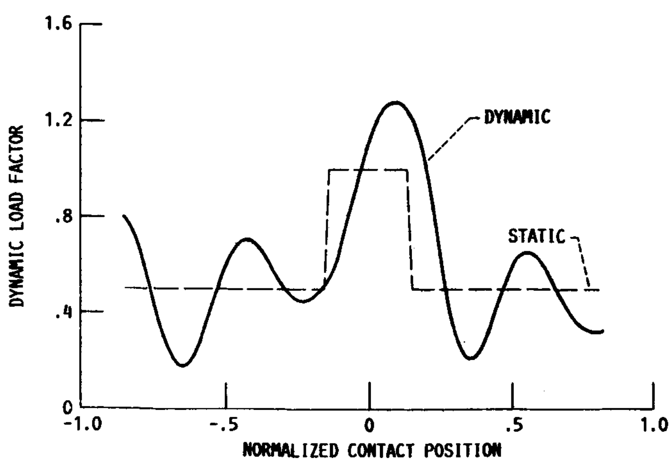

FIGURE 6. - GEAR TOOTH DYNAMIC LOAD COMPARED TO STATIC LOAD.

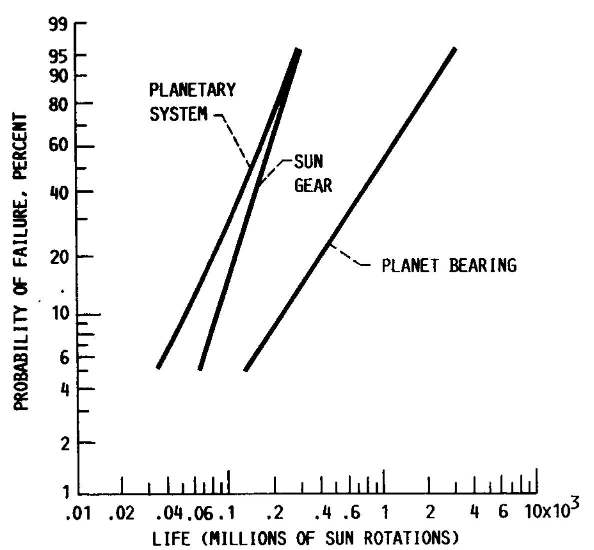

FIGURE 7. - CALCULATED WEIBULL DISTRIBUTIONS FOR PLANETARY SYSTEM AND COMPONENTS.

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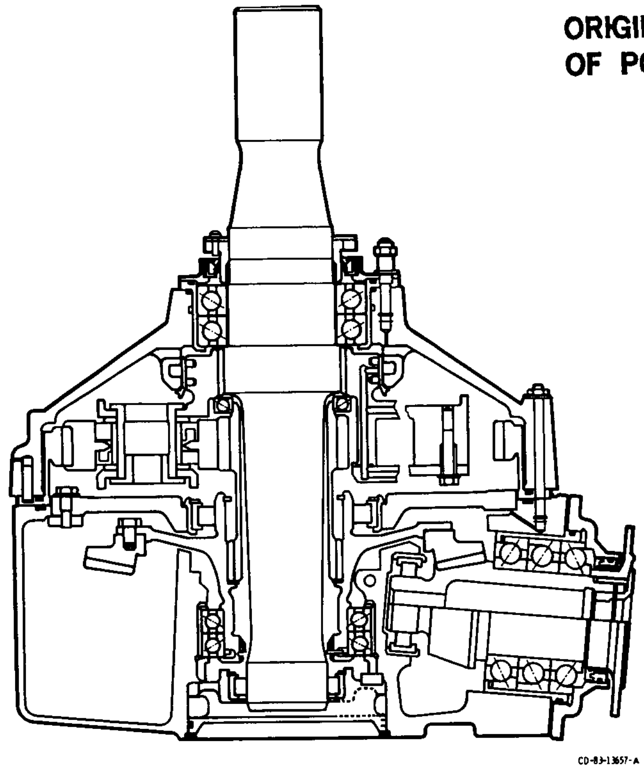

FIGURE 8. - 500-HP ADVANCED TECHNOLOGY TRANSMISSION.

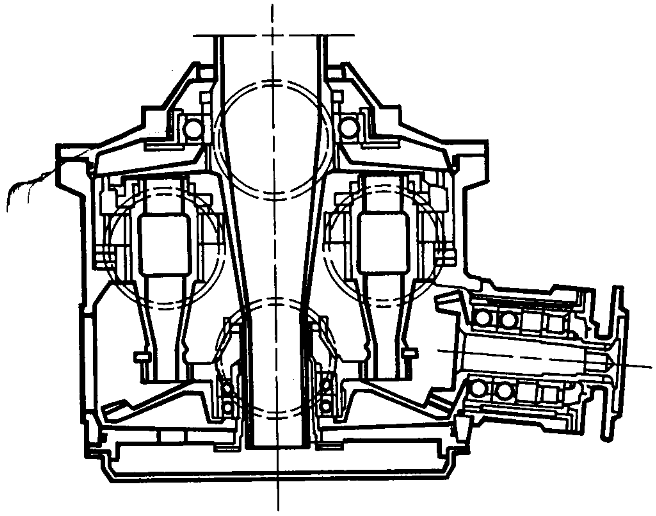

FIGURE 9. - SELF-ALIGNING, BEARINGLESS PLANETARY TRANSMISSION.

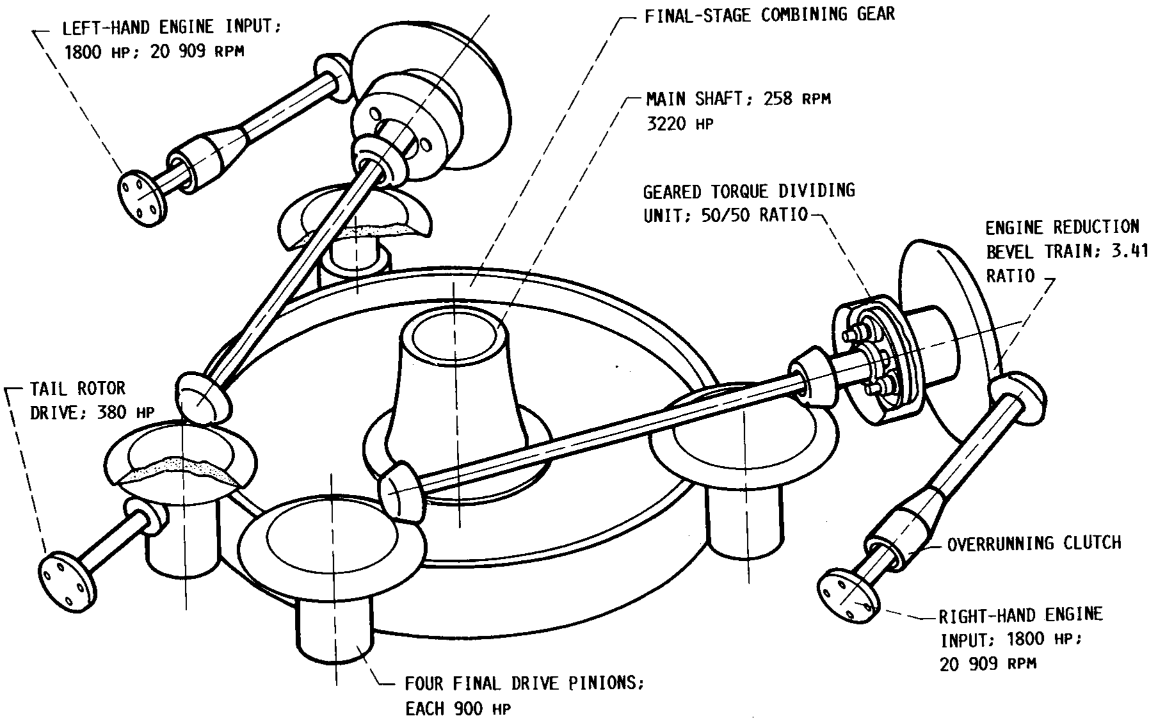

FIGURE 10. - SPLIT-TORQUE TRANSMISSION.

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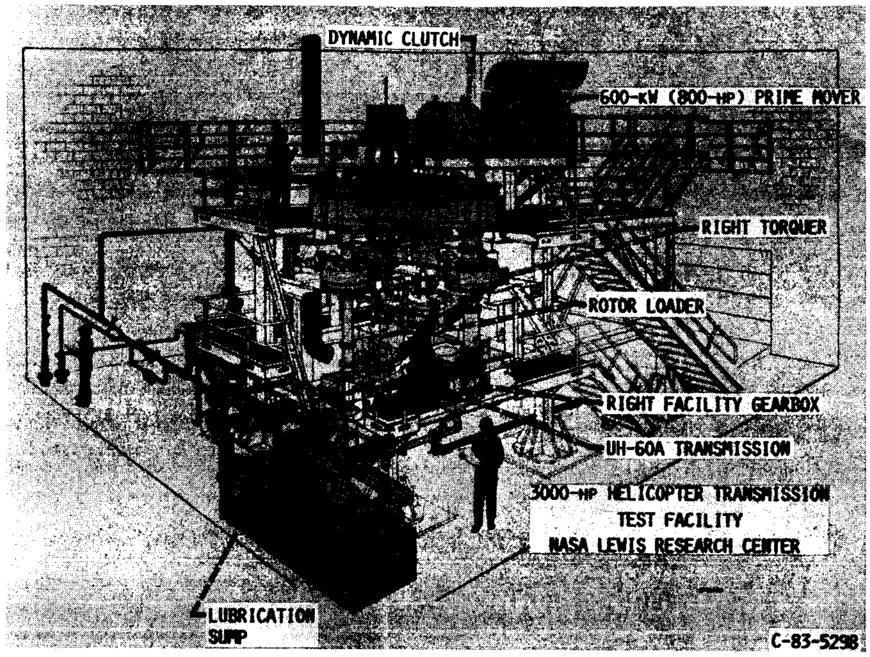

FIGURE 11. - 3000-HP HELICOPTER TRANSMISSION TEST STAND.

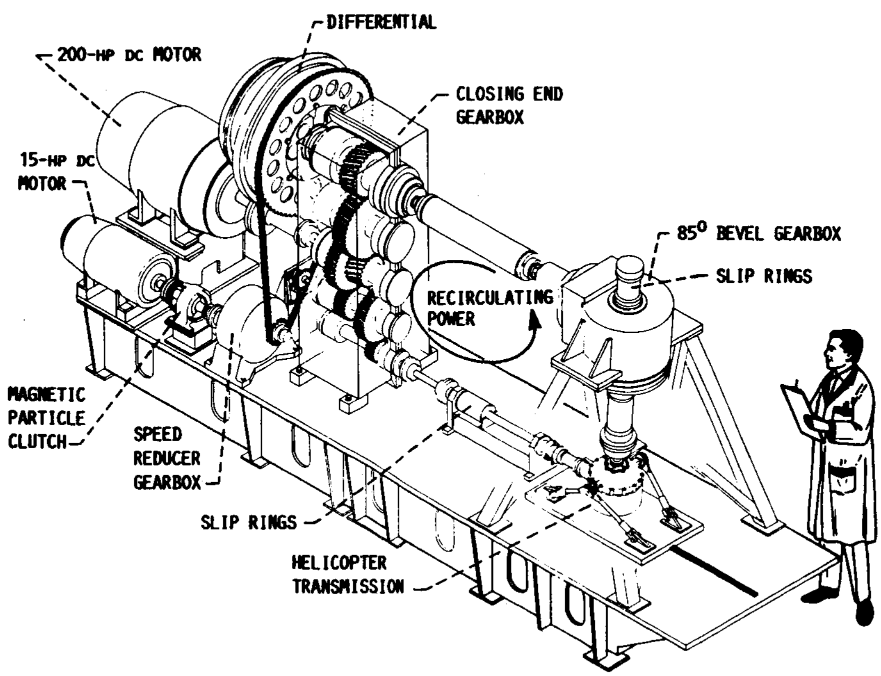

FIGURE 12. - 500-HP HELICOPTER TRANSMISSION TEST STAND.

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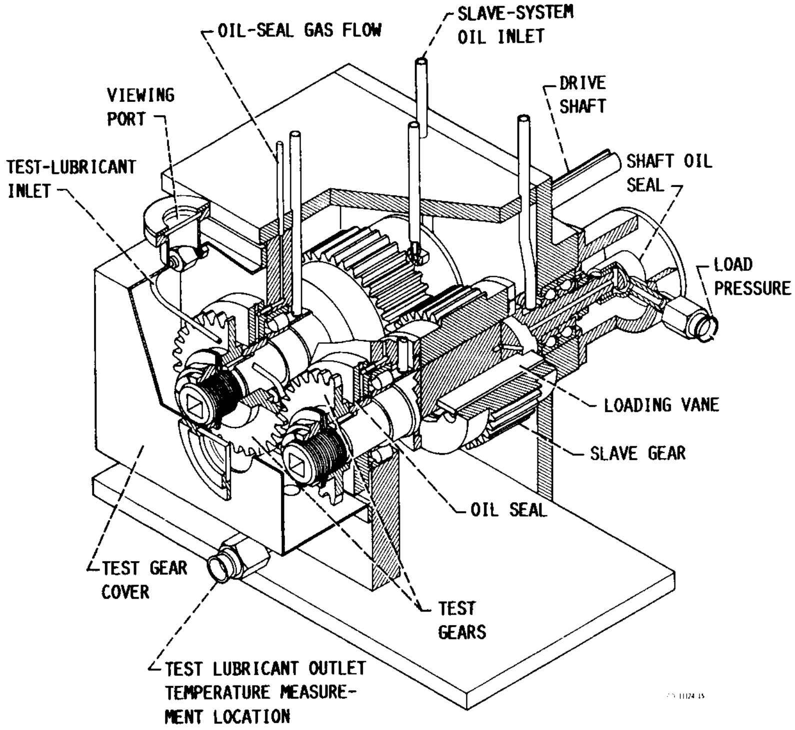

FIGURE 13. - SPUR GEAR TEST RIG.

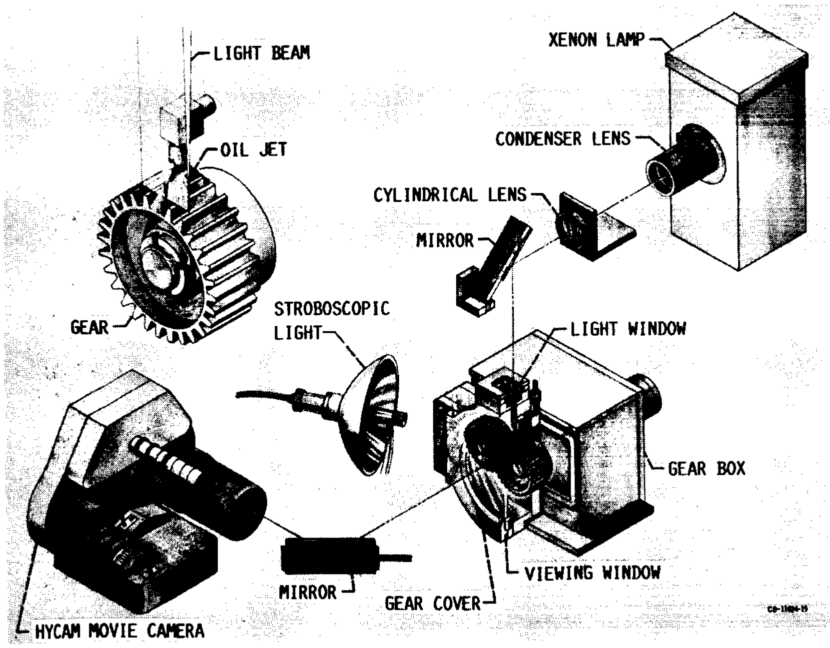

FIGURE 14. - TEST APPARATUS FOR OIL JET PENETRATION STUDIES.

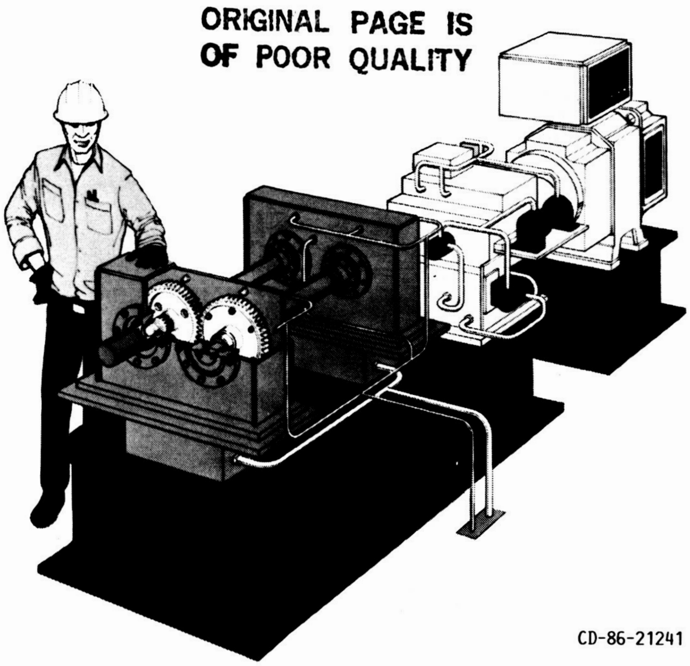

FIGURE 15. - HIGH-SPEED GEAR TEST STAND.

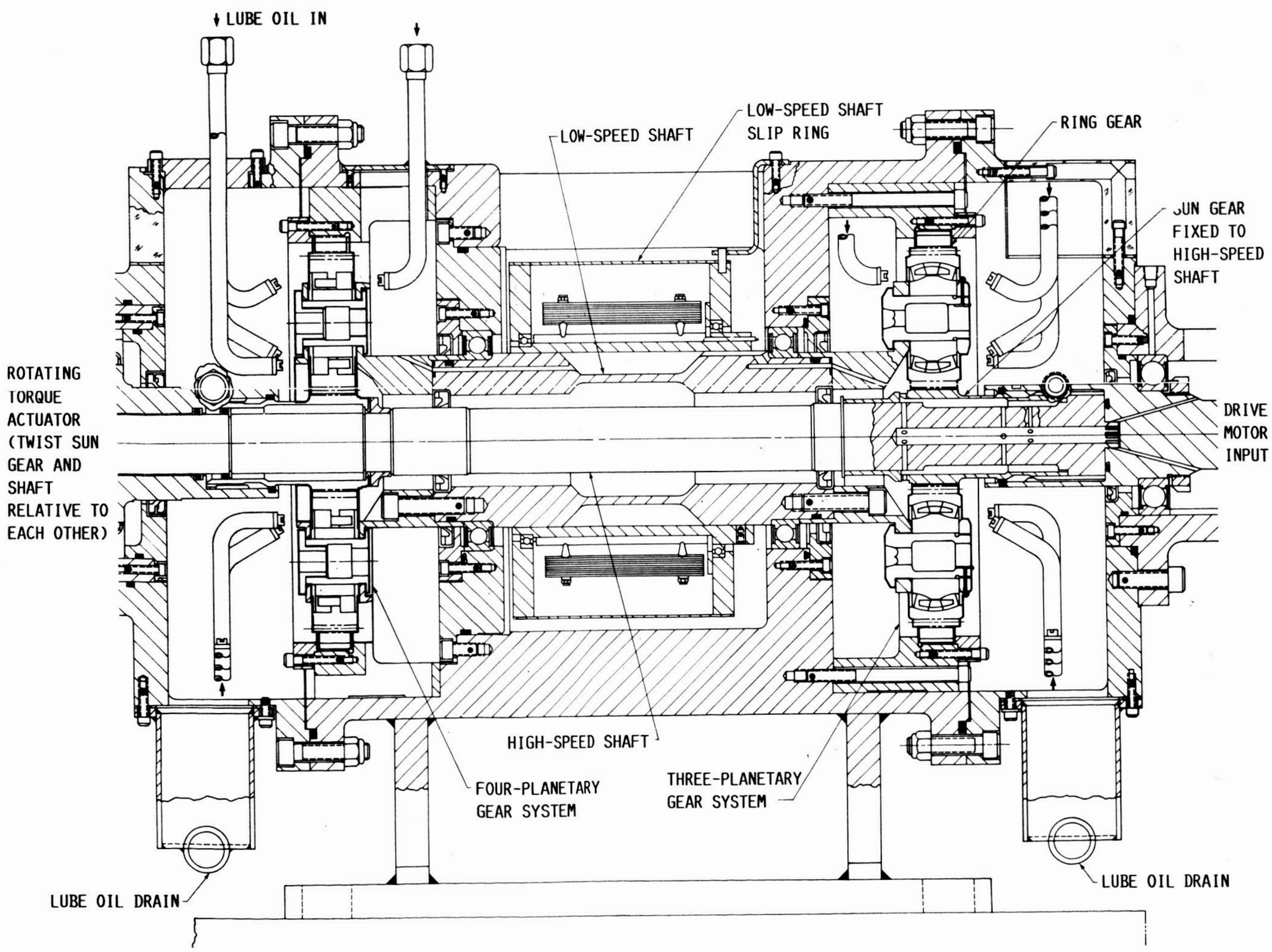

FIGURE 16. - PLANETARY GEAR TEST RIG.

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15. Supplementary Notes

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16. Abstract

A joint helicopter transmission research program between NASA Lewis Research Center and the U.S. Army Aviation Systems Command has existed since 1970. Program goals are to reduce weight and noise and to increase life and reliability. This paper reviews significant advances in technology for gears and transmissions and describes the experimental facilities at NASA Lewis for helicopter transmission testing. A description of each of the rigs is presented along with some significant results from the experiments.

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