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SUMMARY OF DRIVE-TRAIN COMPONENT TECHNOLOGY IN HELICOPTERS

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ABSTRACT

A review of current helicopters was conducted to determine the technology in the drive-train systems. This paper highlights the design features including reliability, maintainability and survivability characteristics, in transmission systems for the OH-58, UH-1, CH-47 and UH-60 helicopters. In addition, trade-offs involving cost, reliability and life are discussed.

INTRODUCTION

With the advent of the gas turbine engine and its application to helicopters in the late fifties and early sixties, there was a significant change in the design and technology of helicopter transmissions. Drive system input speeds increased from 2500 to 20,000 rpm and power to be absorbed tripled. These challenges were met by the helicopter industry. In the seventies and early eighties there have been other challenges: requirements for reduced weight, reduced noise, increased survivability, increased safety and lower life-cycle costs.

In most cases the technology to meet these challenges has been paced by military interests, in particular the U.S. Army (refs 1 and 2). This being the case, a review was made of the drive system technology in the Army's OH-58, UH-1, CH-47 and UH-60 (Fig. 1). These helicopters represent a range from light observation to medium-lift cargo. With the exception of the UH-60, they became operational in the sixties and have continued in service through several versions (A, B, C and D series) with the latest models expected to be in the Army inventory through 1990. Many are being built under licensee agreements. Their evolution has been characterized by improved range and speed and by constantly improving reliability and safety. New or improved drive systems have been developed for the latest models with the objective of step improvements in maintainability and reliability.

The UH-60 is a relatively new helicopter; first production deliveries began in 1979. It is used extensively by the Army and Navy and is designed primarily to carry eleven fully equipped troops plus a crew of two. The gearbox represents current state-of-the-art design for helicopter transmissions.

DESIGN APPROACH

The design of the transmission system is dictated by the configuration of the helicopter. Two configurations are in general use: (1) a single main rotor with a tail rotor and (2) a tandem configuration with twin contrarotating rotors of equal size and loading so that the torques of the rotors are equal and opposing. A typical drive train configuration for the single-rotor machine is shown in figure 2 with the main variations occurring in the location and configuration of the engines.

In both configurations, single and tandem rotor, the transmission loads are a function of power and speed. The engine power is determined from the maximum performance requirements of the mission, such as hover at 4000 ft (out-of-ground-effect) at 95° F. The input speed to the transmission is fixed by the output speed of the engine, while the rotor speed is determined by the top speed of the rotor blade. Thus the overall drive train reduction ratio can be determined for a given rotor diameter. Trade-off studies are conducted to evaluate different configurations for splitting the reduction ratio among the various transmission components (epicyclic bevel gear set, spur set, etc.) and achieving a design with minimum weight. Consideration also must be given to the transmission housing.

Finally, a thorough aerodynamic analysis is conducted on the helicopter mission in order to obtain complete spectra of the rotor loads and moments as well as the maneuver loads and transients for maximum transmission reliability. This analysis is compared with known load-life relations on similar components to achieve maximum transmission reliability and minimum weight.

OVERALL ARRANGEMENT

Current helicopter main transmission systems have a reduction ratio in the region of 80:1 to 100:1 to reduce the gas-turbine engine speed to the main rotor. This ratio is achieved in either three or four stages of gearing, where each stage is either an epicyclic gear assembly, a spiral bevel gear pair or a helical gear pair. The predominant configuration in current designs is the planetary gear train. The trend to planetary gear trains is well established as it provides maximum torque in a lightweight and compact gear reduction. In the planetary design, practical reductions vary from 2.15:1

to 7:1 for a single stage (sun gear input, ring gear fixed, cage output). In current practice the planetary seldom has a reduction ratio greater than 4.7:1 when fitted with five planet pinions (refs 1 and 2).

There are times when two planetaries are used in series (CH-47 and UH-1) to obtain higher reduction ratios. A wide variety of reduction ratios is available with two planetaries and the designer has the choice of reduction ratio for each stage to attain a specific overall ratio.

TYPICAL CONFIGURATIONS

The OH-58 has a single main rotor transmission which represents current design practice in light helicopters (fig. 3). There are four reduction stages between the engine and main rotor shaft. The engine output speed of 35,350 rpm is reduced in two stages of helical gears to 6060 rpm at the input of the main gearbox. The helical gears provide an offset between the engine and bevel pinion axis and allow power to be extracted from the final helical gear for the tail rotor. The first-stage gearing in the transmission is spiral bevel (19/71 reduction) and provides a speed of 1622 rpm to the sun gear of a fixed-ring planetary unit. The planetary unit provides the final reduction of 4.67:1 and gives a speed of 347.5 rpm to the planet carrier and main shaft.

Noteworthy features of this design include the use of self-aligning bearings in the planet pinions, a radially flexible ring gear and a cantilever support for the bevel gear which was used to reduce the overall height.

Stepping up to the larger size single rotor helicopter, we find the UH-1 and UH-60. Both are in the utility class, however, only the UH-60 will be addressed since the UH-1 drive-train configuration even with an additional planetary stage is similar to the OH-58. The UH-60 main transmission has five separate, interchangeable modules (fig. 4). They are the main module, two engine input modules and two accessory modules. The power train has two spiral bevel gear meshes (17.3:1 reduction and a spur gear planetary system with five pinions (4.67:1 reduction). Three additional spiral bevel meshes provide power take-off for the accessory modules and tail rotor while four spur gear meshes drive the accessories and lubrication pumps. This drive-train configuration provides an overall reduction ratio of 80:1 and reduces the input speed from 20,900 to 258 rpm at the main rotor. The continuous rating of transmission is 2828-hp with a single engine rating of 1560 hp.

While the OH-58 is representative of the single rotor main transmission, the CH-47 has transmissions typical of tandem rotor design. The CH-47 has engine and combining transmissions in addition to forward and aft main rotor transmissions. Each engine gearbox changes the direction of axis from the power plant to the combining transmission and reduces the speed. The gearing is spiral bevel with a reduction ratio of 1.23:1. The power rating of the gearbox is 3750 hp. A clutch is located at the output shaft to allow autorotation without drag from the engine and gearbox.

The combining transmission takes the input from the two engine gearboxes and has two outputs to drive the forward and aft transmissions. The combining transmission has spiral bevel gearing with a reduction ratio of 1.7:1 and a power rating of 6000-hp.

Power from the combining gearbox is transmitted through synchronizing shafts to the forward and aft transmissions, which are similar in design (fig. 5). The first-stage gearing in the transmission is spiral bevel, followed by two simple spur gear planetary units with a common ring gear. This configuration provides a reduction ratio of 30.73 in both the forward and aft transmissions. They are rated at 3600 hp with an input speed of 7465 rpm and 243 rotor rpm.

QUALITY OF MATERIALS

Major advances have been made in the past two decades which improve the quality of bearing and gearing materials for transmissions. These advances involve improved processing and cleanliness and greater control on material chemistry and heat treatment. The largest and most significant improvement is related to the use of double-vacuum-melt steel instead of single-vacuum-melt. This process involves the use of Vacuum-Induction-Melt (VIM) in combination with Vacuum-Arc-Remelt (VAR). The processing techniques provide a very homogenous material with reduced nonmetallic inclusions, entrapped gases, and trace elements.

The first benefit of the improved cleanliness of the material is an increase in fatigue life. An example of the exceptional long fatigue life that can be obtained with VIM-VAR AISI M-50 is presented in reference 3. A group of 120-mm-bore, angular contact ball bearings was endurance tested at three million DN (D is bore diameter in millimeters and N is speed in rpm) and a thrust load of 22,200-N (5000 lb). The ten percent fatigue life obtained was over 100 times the predicted AFBMA life. This long life includes lubrication effects which are beneficial to life at these high speeds, so that the improvement attributed to VIM-VAR AISI M-50 was a factor of 44 (ref. 3).

A second benefit gained through the use of double-vacuum-melt over single-vacuum-melt steel is the improvement in the threshold stress allowables and in fracture toughness characteristics. Tests conducted by Boeing Vertol indicate a substantial improvement in threshold stress as shown in figure 6 (ref. 4). For these reasons, the Army now is specifying VIM-VAR on critical transmission components.

FATIGUE AND RESIDUAL STRESS

In the manufacturing process there are many factors which affect the residual stress in transmission components. Most prominent of these are the type machinery involved in the cutting, speed of the machine, machining lubricants, shape of the part, surface finish, heat-treat processes and handling. The resulting residual stress can be either beneficial or detrimental to the fatigue strength of the part. Parts with surface tension stresses could have shortened life since any applied tension fatigue stress would be additive. Whereas parts with compressive stresses could have beneficial effects as the compressive stress would subtract from applied tension fatigue stresses and inhibit crack initiation or growth.

One method used by the helicopter companies to eliminate the residual stress is through shot peening. Shot peening has long been used as a method for improving the bending strength of gears. However, until recently it had not been considered to be a factor in extending fatigue life. Studies conducted on residual stresses in rolling-element bearings at NASA Lewis Research Center have shown that increased residual compressive stress increases rolling-element (surface) fatigue life (refs. 5 and 6). In addition, an investigation was conducted to determine the effect of shot peening of gear teeth on surface fatigue life (ref. 7). Gear surface fatigue endurance tests were conducted on two groups of carburized and hardened AISI 9310 steel spur gears, manufactured from the same heat of material. One group was subject to an additional shot peening process on the gear tooth surface and root radius. The test results are shown in table I (ref. 7). Basically, the shot peened gears exhibited fatigue lives 1.6 times the life of standard gears without shot peening (ref. 7).

Thus, it can be seen that shot peening provides an increase in fatigue life in addition to improving bending strength.

GEAR STEEL

The most commonly used gear material in U.S. helicopter transmission is AISI 9310. However, the Boeing Vertol Company changed to VASCO X-2, modified in the CH-47D. Other materials such as CBS 600, CBS 1000 and Carpenter X53, are being evaluated by industry and government laboratories. The shift to VASCO X-2 stems from a desire for a steel with improved high-hot-hardness characteristics which would enable gears to carry higher loads without the surface distress that was becoming a limiting factor with AISI 9310. In addition, survivability was of concern to the military and the capability to get home in case of damage to the lubrication system.

Boeing Vertol with support from the Army and Navy developed VASCO X-2 in the early seventies. It now is used on the CH-47D transmission in all the highly loaded gears which had potential for scoring/scuffing using AISI 9310. In comparative tests between VASCO X-2 and AISI 9310, VASCO X-2 has shown superior resistance to scuffing and scoring which limit the load capability under conditions of thin-film lubrication (lightweight synthetic oils), figure 9 (ref. 4). In tests of the bending fatigue endurance limit VASCO X-2 and AISI 9310 were essentially the same (ref. 4). VASCO X-2 has a somewhat improved capacity over AISI 9310 in contact (Hertzian) capacity (ref. 4). In fracture mechanics property tests, AISI 9310 has higher impact strength and fracture toughness, while VASCO X-2 and AISI 9310 have equivalent fatigue crack propagation rates and threshold values (ref. 4). Before this material could be utilized it was necessary to develop a thorough understanding of the material chemistry and heat treatment in addition to the processing variables and quality control. This was accomplished after a great deal of effort by Boeing Vertol and VASCO X-2 now is firmly established as a gear material.

GEAR PARAMETERS

The majority of the current helicopter transmissions have spur-gear contact ratios (average number of teeth in contact) less than two. The contact ratios range from 1.3 to 1.6 so that the number of teeth in engagement is either one or two. Basically, the load is shared by two teeth during the entrance and exit phases of engagement while one pair of teeth carries the load the remaining time. Many gears use a pressure angle of 20 to 25° and operate with a contact ratio of approximately 1.3. Pressure angles up to 28° have been used successfully. This provides improved tooth strength, however, at the same time it increases noise and may cause lower pitting fatigue life.

Allowable stresses vary with gear material to be used and the maximum temperature to be endured. Most designs are based on maximum gear body temperature under 400 K (approx. 250° F). The AGMA (American Gear Manufacturers Association) standards for aircraft gearing are used to calculate both Hertz contact stress and bending stresses. In today's helicopters designs are limited to about 1.1 GPa (160,000 psi) for Hertz Stress, thus allowing for leeway in case of misalignments induced by case flexibility and manuever-imposed loads. Total loads rarely exceed 1.5 GPa (220,000 psi) for Hertz stress in gears. For bending, 0.4 GPa (60,000 psi) is rarely exceeded. Bevel gear limits are lower than for spur and helical gears.

Pitch line velocity in current transmissions for high speed bevel gears is approximately 50 to 100 m/s (10,000 to 20,000 ft/min). These limits were necessary because of the need to limit lubrication churning power loss, as well as to prevent high dynamic loads.

WEIGHT

The specific weights for current main rotor gearboxes range from 0.30 to 0.50 lb/hp. A summary showing the total drive system weight is given in table II. The total drive specific weight ranges from 0.4 to 0.6 lb/hp on the basis of input power to the drive train. The helicopters considered here are plotted with weight trends in figure 8. Housing assemblies are usually made of low density materials such as cast magnesium and forged aluminum for the load bearing members. This is important because housings comprise 20 to 60 percent of total transmission weight in current helicopters. The gears themselves increase in weight according to the square of the ratio. Therefore high ratio reductions in a single stage are not common. The order of weights from lightest to heaviest (for equal gear ratios) is planetary, parallel axis, spiral bevel, and it is beneficial to take higher reductions nearest to the final output. This will trade-off number of stages against overall weight. Current designs reflect this, as the bevel stages usually take the less reduction at the higher speed. These rules may not apply if weight distribution and the effect on helicopter center of gravity are overriding factors.

EFFICIENCY

The current helicopter transmissions transfer power from engine to rotor in an highly efficient manner. Transmission efficiencies range from 97 to 99 percent in today's flying helicopters. The power losses arise from windage losses inside the case, bearing losses, seal sliding friction losses, pumping losses, with the main contributor being the sliding losses in the gear teeth. For a single spiral bevel or a spur mesh there is approximately 0.50 percent loss; for a planetary stage, a 0.75 percent loss. These figures apply only to a fully loaded transmission. At part load, the efficiency decreases significantly. Figure 9 shows a plot of measured efficiency for the OH-58 transmission. Efficiency at maximum speed and torque is 98.4 percent. The effect of decreasing torque is characteristic of all transmissions. The gear teeth need to be loaded to their capacity for the given size and properly lubricated. Also the effect of speed is shown on this figure. As the speed is halved at full torque, a 1/10 percent increase in efficiency is noticed. This is the sensitivity to windage. Efficiency of power transfer is extremely important to the overall operation envelope of the helicopter. For example, in a 3000 hp helicopter, such as the Blackhawk, a one percent decrease in efficiency would consume an additional 30 hp. A medium helicopter suffers a useful payload reduction of 100 to 200 lb with a one percent power loss. In addition, the added 30 hp would have to be dissipated, requiring a larger oil cooler which would be heavier and more vulnerable. Therefore, any new designs, in order to be viable, must be at least as efficient as current designs or they must be much lighter, if not as efficient, in order to compensate for loss of payload and increased cooling system weight.

NOISE

Transmissions are the main source of noise in today's helicopter interiors. The noise is predominantly pure tone multiples of gear mesh frequencies. The frequencies range from several hundred hertz to beyond hearing range. The source of noise is the gear mesh as an impact exciter, with sound transmitted to the listener through structural and airborn pathways. There is currently no universally satisfactory treatment. Current analytical tools are only now being refined and they may be useful to design the next generation of helicopters. Current remedies are spot treatments using damping material around the passenger compartments and friction damping rings on the gear blanks. Sound treatments in use today have the disadvantage of weight and cost penalty and increased maintenance man hours due to the need for removal of noise abatement materials for airframe and component inspection. Moreover, the materials may never be replaced subsequent to an airframe maintenance inspection. Experience has shown that higher frequencies are easier to treat, and that for equal pitch line velocities, helical gears are the most quiet, followed in order by, spur and bevel gears. Generally, higher contact ratio and finer pitch give quieter gears, but fine pitch gears are not as strong as their more course counterparts. This requires a trade-off study.

A study of interior noise levels of current helicopters has been completed recently (ref. 8). The findings, obtained by averaging the measurements from two microphones placed near the pilot's and copilot's heads, were as follows: OH-58A, 107 dB; UH-1H, 113 dB; AH-1S, 120 dB; UH-60A, 115 dB and CH-47C, 118 dB. These measurements are for overall sound pressure levels at cruise conditions. There were significant variations in frequency content from aircraft to aircraft. Costs of noise treatments for cabin interiors have been assessed (ref. 9). For the Bell Jet Ranger III (fig. 10) which is civil version of the OH-58 a speech interference level of 84 dB at cruise conditions can be achieved with a kit supplied by a third party for under $4000. For larger helicopters the costs are proportional to helicopter size and noise severity. Single rotor helicopters have the transmission closer to the passenger compartment, whereas tandem rotor aircraft have the forward transmission very near the cockpit. Transmission location determines the type of noise treatment because of the varied noise paths between the two types of aircraft.

Figure 11 shows that over the past two decades transmissions have steadily become noisier. Figure 12 shows that in the same period the transmissions have steadily become lighter. The result is that in order to meet military noise specification MIL-A-8806A, soundproofing treatments resulted in heavier packages when the combination of main gearbox and sound proofing weights are added together (fig. 12).

LIFE AND RELIABILITY

Achievement of long-lived, reliable power transfer systems can be difficult to achieve and today's helicopters are one of the most severe applications of this technology. Helicopters (sometimes referred to as flying fatigue machines) present the ultimate test of materials and designs for reliability. The many failure mechanisms for bearing and gears must be weighed against anticipated loads which are not know with certainty. In addition to known classical modes of failure, such as pitting, scoring, and bending fatigue, there are unanticipated events that can ground helicopters. Things like sudden leaks producing low oil levels, undetected contamination of lubricant, and poor maintenance practices can severly lower the reliability of the mechanical components of the transmission. There is no way to anticipate the exact effect and typical experience has been that there has to be a suffering through the debugging phase of new designs. Generally, today's flying helicopters have been achieving 500 to 1200 hr time-between-overhaul (TBO) for main transmissions with tail rotor gearbox TBO's up to 1600 hrs. Design calculations often indicate much greater reliability. This is because all the various reasons for failure are not accounted for in those calculations, and there has been no sensible way to calculate the effects of unknown or unanticipated causes. Indeed, it has been found that in overhaul and unscheduled removal operations only about ten percent of failed bearings exhibit classical failure modes. Gears are even less likely to fail, giving rise to the speculation that current gear design practice is more conservative than bearing design practice.

Current practice is to calculate bearing and gear life using AGMA (American Gear Manufacturer's Association) and AFBMA (Antifriction Bearing Manufacturer's Association) standards for pitting fatigue life. Many aircraft companies have established their own data base for bearing and gear reliability from which designs are extrapolated. Experience has shown that subsurface initiated fatigue life is distributed according to the Weibull probability distribution. This holds for gears as well as bearings. As for sensitivity factors, the Weibull slope is one to two for bearings and two to three for gears, where the slope is measured on special coordinates defined by the Weibull distribution. The ordinate is the log-log of the reciprocal of probability of survival graduated as the statistical percent of specimens failed. The abscissa is the log of time to failure or system life. Load also affects life. For gears, life is inversely proportional to the 4.3 power of load and the cube of load for bearings. There are other factors such as material, lubrication, processing and speed which can have an effect and data is in hand (ref. 10) to provide reasonable guidance in estimating surface fatigue life.

There has always been some confusion about the proper relation between individual gear or bearing life and total system life. Moreover, the exact relation that exists between the average system failure rate, TBO, and MTBF has not always been understood. However these figures of merit can and should be rigorously related through proper application of mathematical statistics with an adequate match of circumstances to the basic assumptions of the theory. For example, laboratory measured life distributions for components may determine an average life. But under service conditions in a fleet this circumstance (laboratory condition) does not apply. This is because in a fleet operation, components are repaired or replaced periodically and after a time the fleet is comprised of a mixture of ages for the components. This circumstance fits the classical "renewal theory" assumptions, and the distribution in the limit approaches the exponential distribution instead of the Weibull distribution (ref. 11). It is for the exponential distribution that MTBF is defined. It is precisely this transition of conditions from laboratory to field, with the attendant problems of overhaul and repair record keeping that makes it difficult to correlate the theoretical or design predictions for life with field experience.

Recent publications have documented a life prediction methodology for gears and bearings as applied to an entire transmission (refs. 12 and 13). In reference 12 a current turboprop gearbox (fig. 13) was analyzed using the life prediction methodology developed at the NASA Lewis Research Center. The turboprop gearbox is strikingly similar to a helicopter gearbox if the turboprop input spur gear stage were changed to spiral bevel gear pair. The NASA analysis of the turboprop gearbox is summarized in a Weibull plot (fig. 14). Each gear and bearing life distribution is shown relative to the ten percent life of the entire transmission. The single weakest component, according to the analysis, was the planet bearing.

In reference 13 a similar study was done for a typical planetary gear set such as found in a turboprop or helicopter reduction gear stage. The study was done for a three planet system with an output of 150 kW (200 hp) at 300 rpm. The gears were AISI 9310 Vacuum Arc Remelt steel with face width 51 mm (2.0 in.), module 4.23 mm (diametral pitch 6 in.$^{-1}$), and 20° pressure angle. The tooth numbers were sun, 24; ring, 96; and planet, 36. The planet bearings were 75-02 cylindrical roller bearings with a width of 25 mm (1 in.) and outside diameter of 130 mm (5-1/8 in.). The life distribution of the system and the most critical elements, sun and planet bearing are shown in the Weibull plot (fig. 15). In contrast to the turboprop example, the sun gear is the weakest element according to the analysis.

BEARINGS

In today's Army helicopters many types of bearing are used. Bearings are heavily loaded, the design of these mechanical elements is highly refined, and the design limits are known with reasonable accuracy. Deep groove bearing are used in accessory drives. Spherical double row bearings are used in planetary gear supports for their ability to withstand misalignments imposed by offset loads on the planet carrier posts. Bevel gears, being sensitive to misalignment problems induced by loads and thermal distortions, are rigidly mounted in bearings. Several arrangements are found. Triplex mounted angular contact bearings and a straight cylindrical roller bearing in a straddle mount have been used. Recent step improvements have been made, transitioning to more advanced bearings for gear shaft support. One example is the Boeing-Vertol CH-47A (1960), CH-47C (late 1960's) and CH-47D (mid 1970's). In this application materials evolved from 52100 to CEVM M50 and from standard ball and roller designs to out-of-round (for skidding control) roller bearings with integral spaces (ref. 14). Also there has been a transition to integral bearing raceway/shaft designs in many designs in order to reduce parts count and reduce fretting wear. The Sikorsky UH-60 Blackhawk incorporates tapered roller bearings for gear shaft support for the input main bevels, combining bevel and tail rotor drive take-off.

Ball bearings are used in high speed turbine engine shaft supports and with this severe application as a driving force have achieved very high speed capability: speeds as high as 3×10^6 DN have been demonstrated. The parameter DN is defined as the product of diameter in millimeters and speed in revolutions per minute. Roller bearings are more limited in speed because of higher heat generation. This is partially due to intentional out-of-roundness or "pinch" that is sometimes put on the raceways to control skidding at high speeds and light loads. Tapered roller bearings have good load capacity for combined axial and radial loads such as when reacting spiral bevel gear loads. However tapered roller bearings are used on the slower speed shafts because of heat generation at the roller ends. Conventional (inner cone ribs) tapered roller bearings are limited to 0.5×10^6 DN which is compatible with a cone rib velocity of 36 m/s (7000 ft/min). However, work done in the 1970's (refs. 15 to 18) has improved the high speed performance up to 3×10^6 DN for pure thrust loads and 2.4×10^6 DN for combined thrust and radial loads. Of course, this technology has not yet been input to current helicopter transmissions.

SEALS, CLUTCHES, COUPLINGS

Typically, seals on the input and output shafts are spring loaded lip, elastomeric types. For high speed and more critical requirements spring-loaded carbon type seals may be used.

Clutches most widely used in helicopter free-wheel units are the sprag type (fig. 16) and the roller/ramp type. The OH-58 and the Hueys use the former and the UH-60 the latter. Roller type clutches are somewhat heavier than sprag-types but they do not have a possibility of "rollover" failure. Rollover is where, the torque level being too high, the sprag rolls over and positive engagement is is lost.

A study of the technology of clutches has been made (ref. 19). The overrunning clutches should be on the highest speed shafts, giving lightest weight. A spring type clutch is an attractive candidate for speeds up to 27,000 rpm. Sprags that will not roll over have been developed (fig. 17). The positive continuous engagement type sprag, when overloaded abuts its neighbor sprags, limiting the amount of roll-over. Applications up to 20,000 rpm or 50 m/s (10,000 ft/min) are suitable for sprag clutches. Roller/ramp clutches are limited to 12,000 rpm. The highest Hertz contact stress occurs at the nonconforming inner race contact. Industry practice is to not exceed 3.5 GPa (500,000 psi) contact stress (refs. 1 and 2).

Couplings are used in helicopter drive lines to accommodate shaft misalignments which are caused by airframe flexibilities. Past experience has shown that, for reliable operation, much attention should be given to the coupling design. One important parameter is the torsional stiffness. This affects drive line dynamics. Space and weight considerations are also important and affect the selection of coupling type. There are two main types of coupling in use. The gear coupling is most prevalent (fig. 18). The UH-1 and OH-58 use this type. It is able to carry the torque loads with 3 degrees of continuous misalignment and transient conditions up to 6 degrees of misalignment. Speeds up to 20,000 rpm are possible. Grease with an extreme pressure additive is used as lubricant for lower speeds, and forced oil flow for better cooling at high speeds. Rotor/transmission/pylon systems with soft mounts require the large misalignment capability of gear type couplings. The gear coupling is normally limited by its thermal capacity. The usual failure mode is overheating followed by plastic shearing of the gear teeth and/or local welding of the gear teeth.

Another popular coupling is the flexible element type. There are several similar types in this category: the flexible ring type or Thomas Coupling (fig. 19); the flexible diaphragm type or Bendix Coupling (fig. 20); and the axially loadable straight element type (Kaman K-Flex Coupling), (fig. 21). The first two need to be used in conjunction with a spline for axial motions. These types of coupling are usually found on the larger helicopters where they have a weight advantage over geared couplings. They are simple, light, and don't require lubrication. However the Thomas and Bendix types may carry only up to 1 degree misalignment. The Kaman type may carry up to 0.5 degree per plate element. With these types, the failure problems are flexural fatigue and

fretting at the bolted connections. The Thomas type is used on the UH-60 Blackhawk main transmission input, the CH-47 synchronizing shaft, and the OH-58 tail rotor drive. An advantage is that when failure occurs by flexural fatigue in one of the flexible elements, it is easily seen and the failure is progressive so that catastrophic breakage is not the case. So far, the Kaman coupling has been given experimental trials on UH-1's at Ft. Rucker. Based on that experience, the Army is now retrofitting the K flex couplings on UH-1's.

CONCLUDING REMARKS

This has been an overview of some of the current drive train concepts that are used in the U.S. Army helicopters that are flying today. The history of rotary wing aircraft has seen evolutionary change in component technology that has brought in lightweight reliable drive trains. The current concepts have been reviewed for bearings, gears, seals, clutches, materials and overall design arrangements. The implications of materials and treatments have been reviewed. Performance indices such as power to weight relations, efficiency, and reliability have been discussed. Indeed, in the past 30 years several generations of rotary wing aircraft have been brought into the military scene, and it is certainly expected that more refinements and new concepts will be introduced.

Trends for future developments that are expected will be in the areas of improved reliability, quieter drive trains, better materials for high temperature components, better materials for corrosion resistance and high fracture toughness. Mean time between overhaul and/or removal will increase and operating envelopes will be extended in the future as a result of component technology that is being researched, developed, and experimentally verified at the present time. Better design techniques will be brought in with the advent of modern computer analysis techniques that will enable design optimizations to be run by the transmission designers. Finite element analyses will become cheaper and faster to run because of work that is being done on pre- and post-processors that are being developed especially for gears.

It has been the intention of this paper to briefly, review current technology and to provide some background from the U.S. Army's viewpoint for the papers that follow in this symposium. The following papers will add more detail to the topic of drive trains for rotary wing and turboprop aircraft, and the pertinent research and developments that can be factored into the next generation of flying aircraft. Today's, rotary wing aircraft are wonders of technology, and the challenge is to make tommorrow's even better.

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A1

TABLE I. - FATIGUE RESULTS WITH AISI 9310 STANDARD
AND SHOT-PEENED TEST GEARS

Gears	10-Percent life, cycles	50-Percent life, cycles	Slope	Failure index[a]	Confidence number,[b] percent
Standard	19×10^6	46×10^6	2.1	18/18	----
Shot peened	30	68	2.3	24/24	83

[a]Indicates number of failures out of total number of tests.
[b]Probability, expressed as a percentage, that the 10-percent life with the baseline AISI 9310 gears is either less than, or greater than, that of the particular lot of gears being considered.

TABLE II. - WEIGHTS FOR CURRENT DRIVE SYSTEMS

Helicopter type	Engines	Drive train			
		Input, hp	Gearboxes rotor shafts, lb	Drive shafts, lb	Total weight, lb
Bell OH-58A "KIOWA"	1-ALLSION 25-C18A	300	153	21	174
Bell UH-1H "HUEY/IROQUIS"	1-LYCOMING T53-L-13	1400	512	66	578
Bell AH-1J "HUEY/COBRA"	1-PRATT WHITNEY T400 CP 400	1250	576	69	645
HUGHES AH-64 "APACHE"	2-GENERAL ELECTRIC T700's	3000	1175	92	1267
SIKORSKY UH-60 "BLACKHAWK"	2-GENERAL ELECTRIC T700's	3000	1366	97	1463
BOEING-VERTOL CH-47C "CHINOOK"	2-LYCOMING T55-L-11C's	6000	3403	282	3685
BOEING-VERTOL CH-47D "CHINOOK"	2-AVCO LYCOMING T55-L-712's	7500	4078	281	4359

(a) OH-58.

(b) UH-1.

(c) UH-60.

(d) CH-47.

Figure 1. - Representative US Army helicopters.

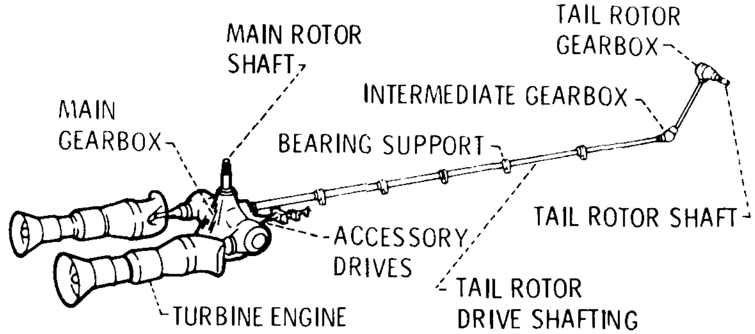
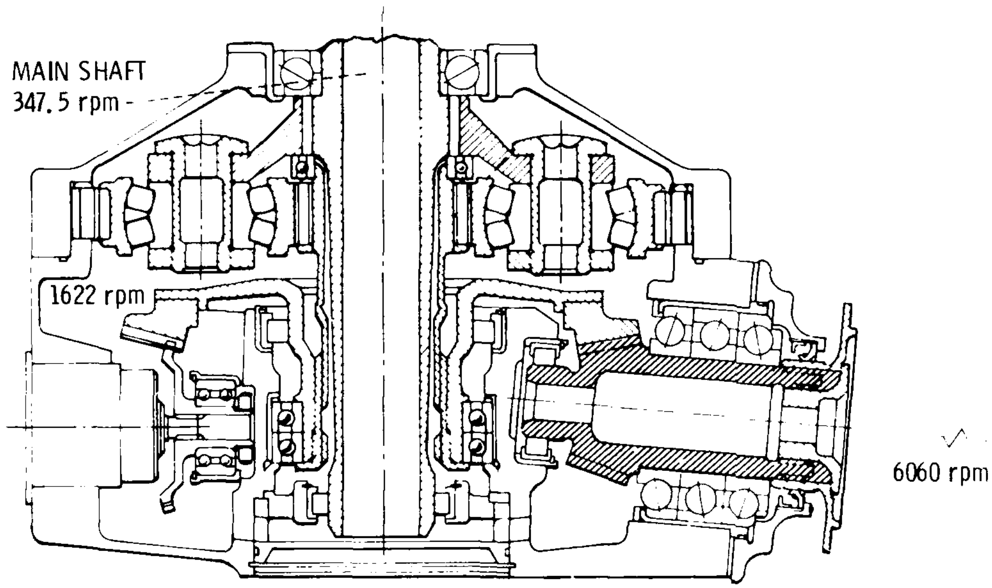
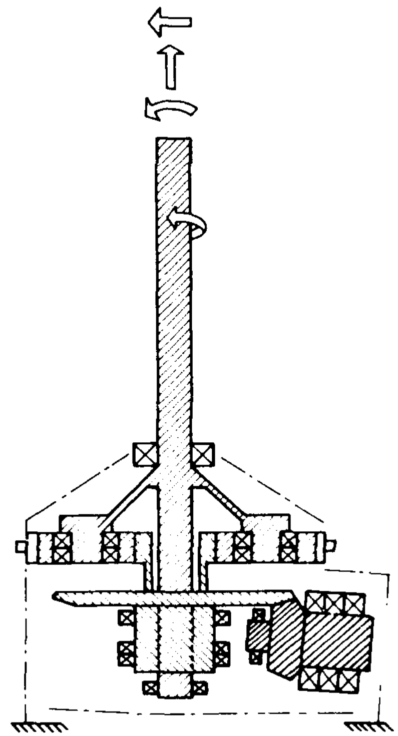


Figure 2. - Typical transmission system in single-rotor helicopter.

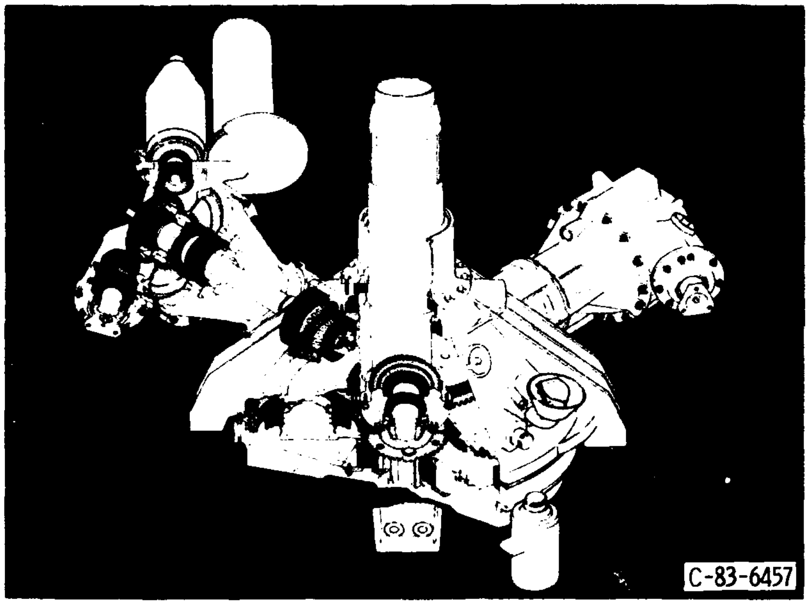


(a) Detail.

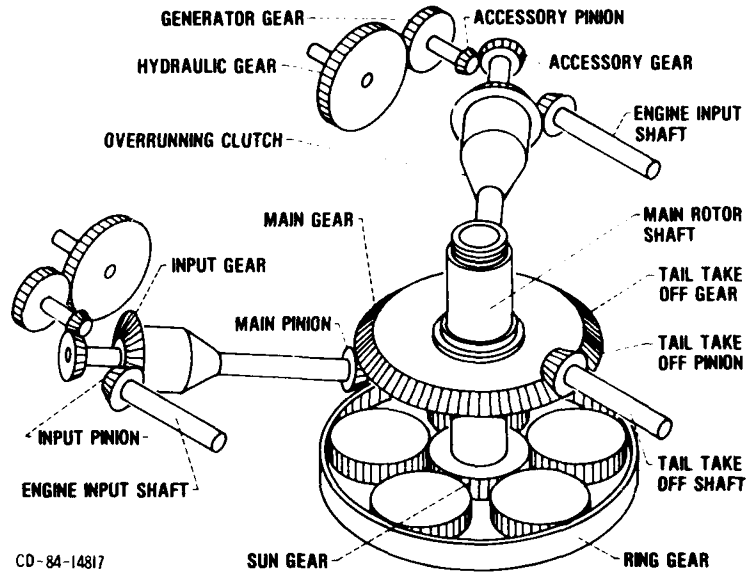


(b) Schematic.

Figure 3. - OH-58 main transmission.

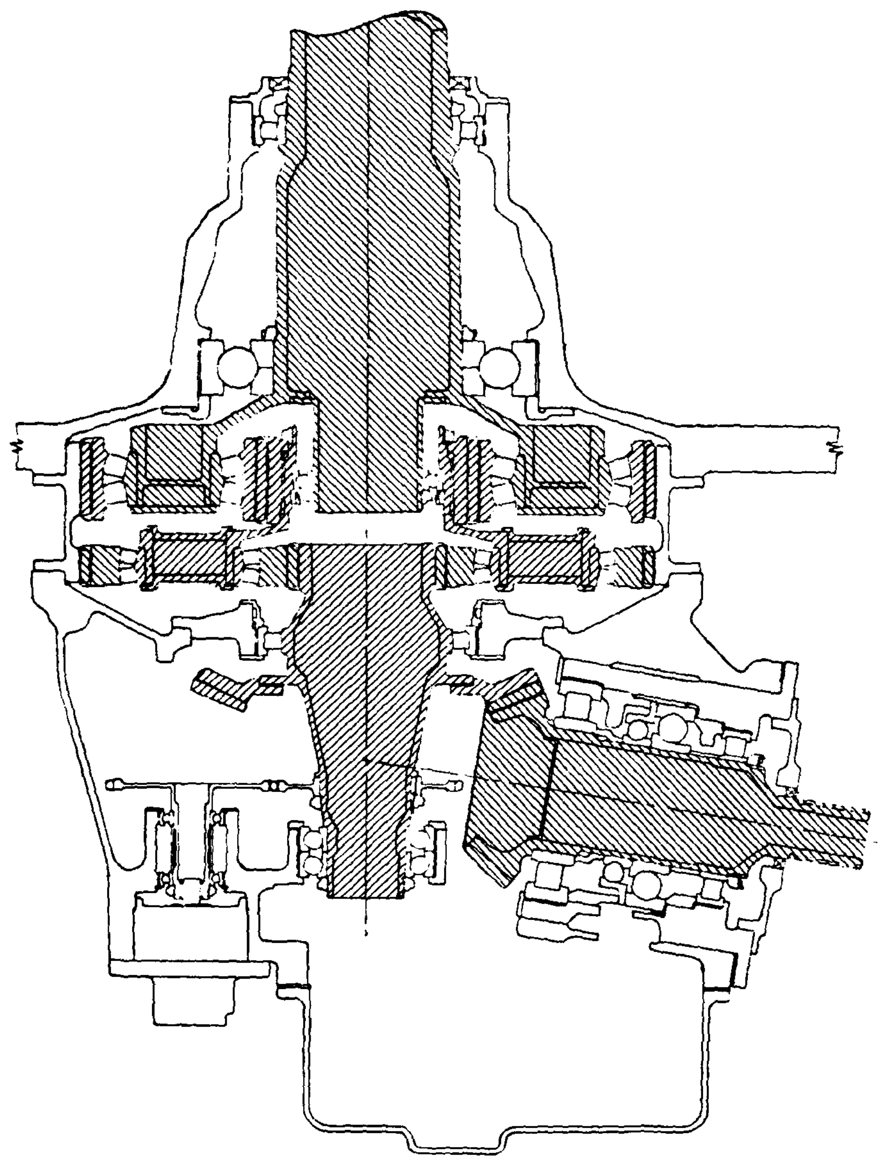


(a) Detail.



(b) Schematic.

Figure 4. - UH-60 Blackhawk main transmission.


(a) Detail

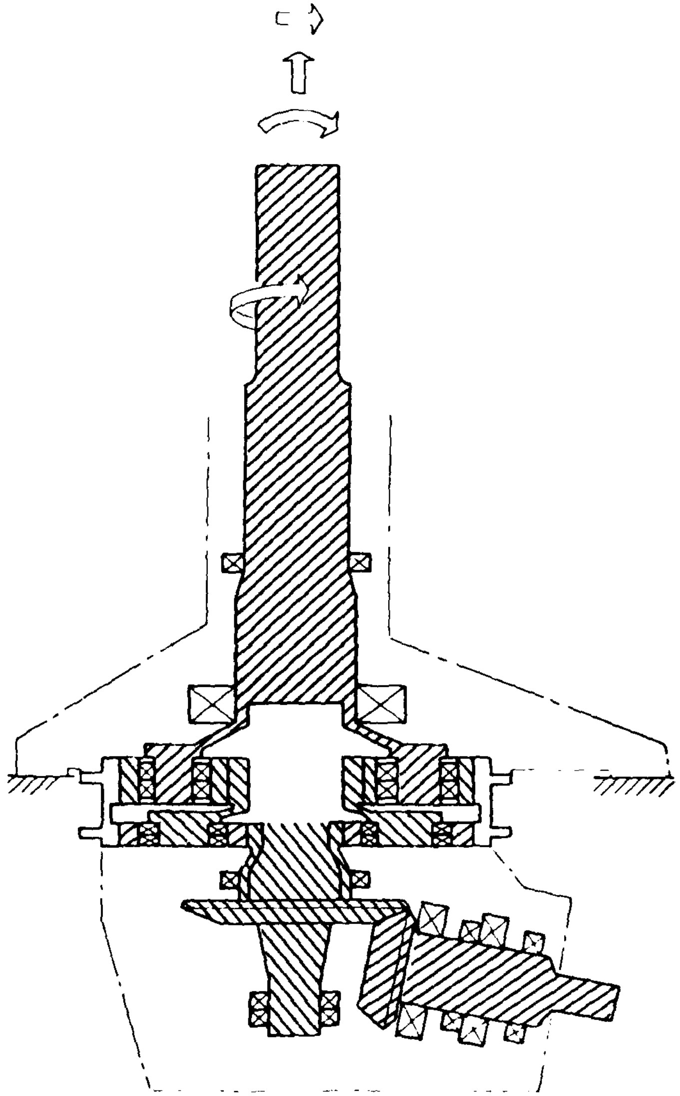

(b) Schematic

Figure 5. CH47 forward transmission.

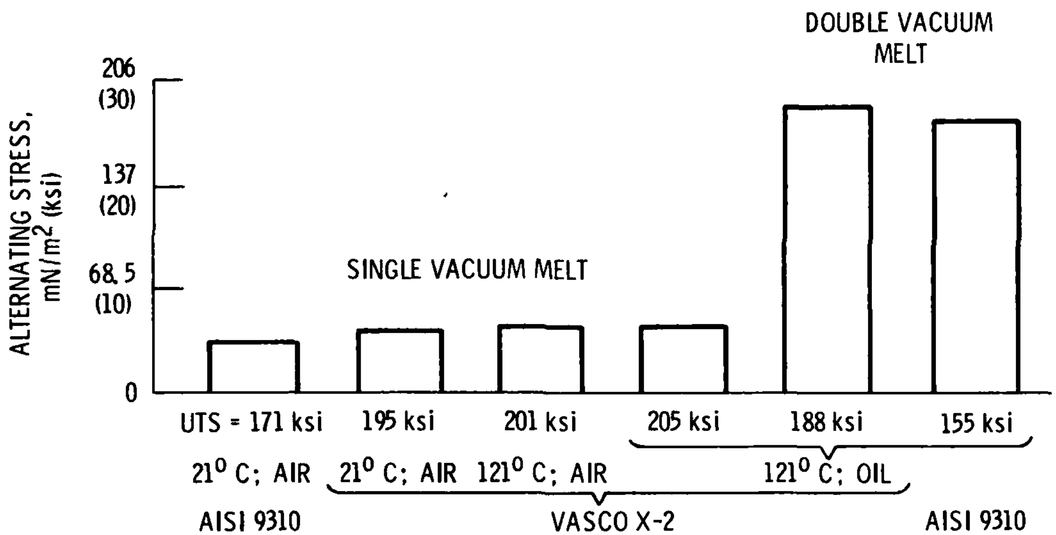
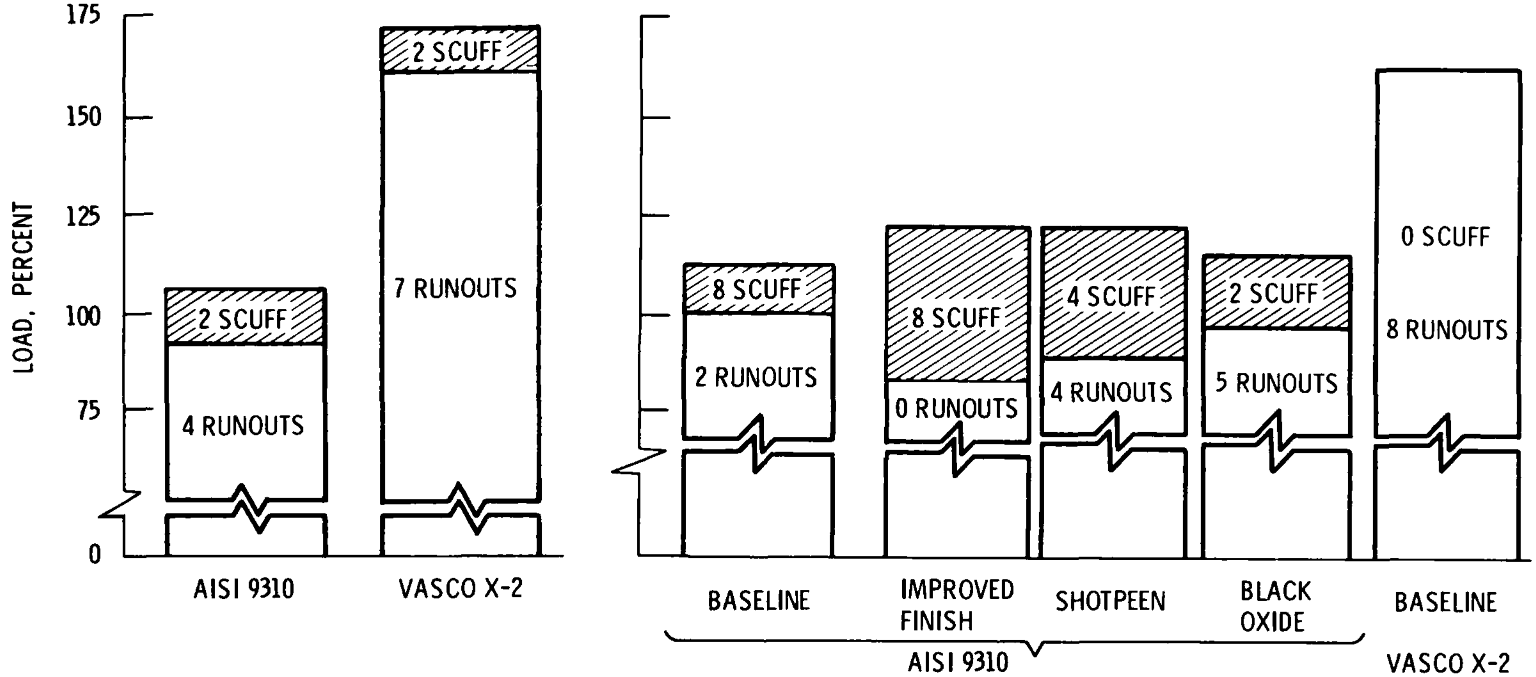


Figure 6. - Effect of multiple remelting (ref. 4).



(a) Spiral bevel test results.

(b) Spur gear test results.

Figure 7. - Scoring and scuffing tests indicate improvement in load capacity (ref. 4).

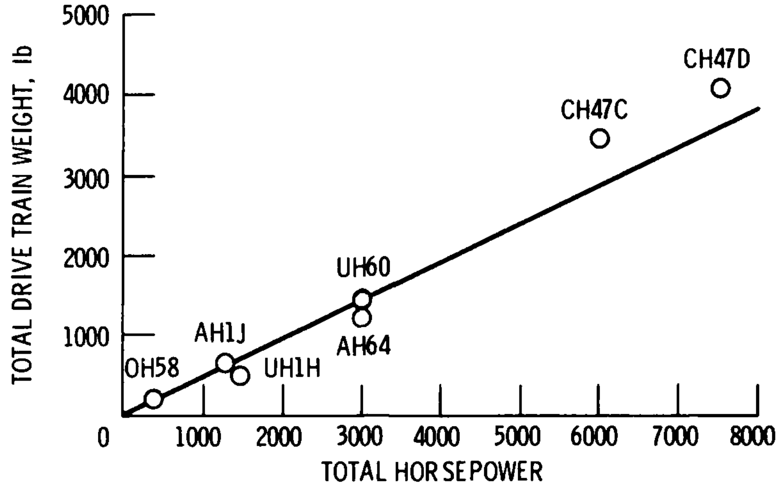


Figure 8. - Weight trends for current helicopter drive trains.

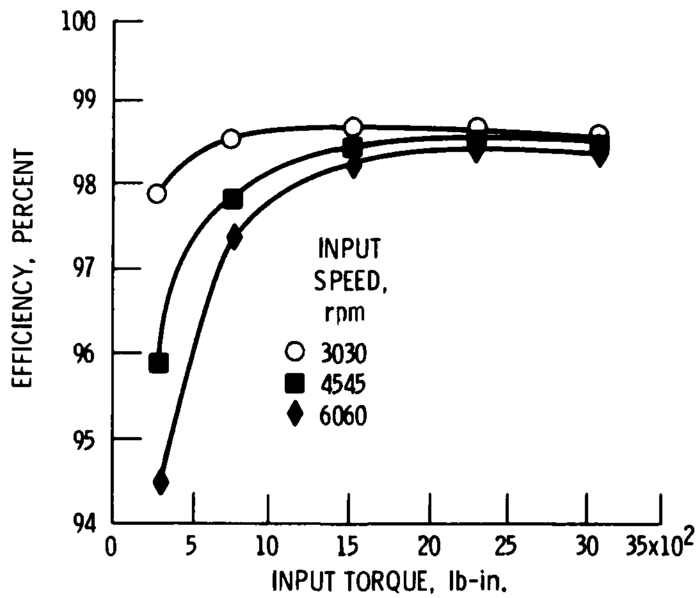


Figure 9. - OH 58 helicopter transmission efficiency, 3-planet assembly, Mobil Jet II (180° F oil inlet).

Figure 10. - Bell Jet Ranger.

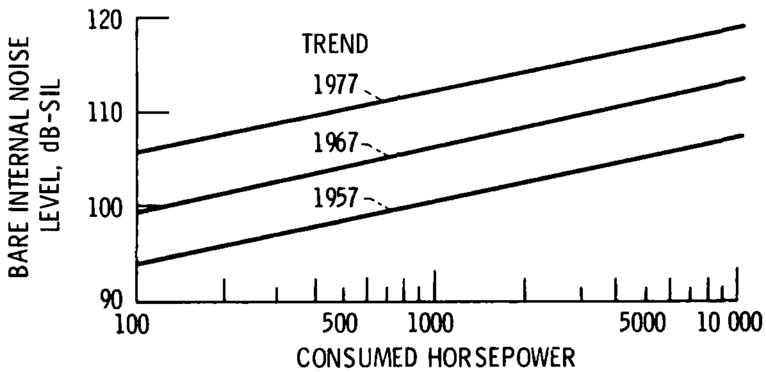


Figure 11. - Transmission noise has increased 6 dB per decade.

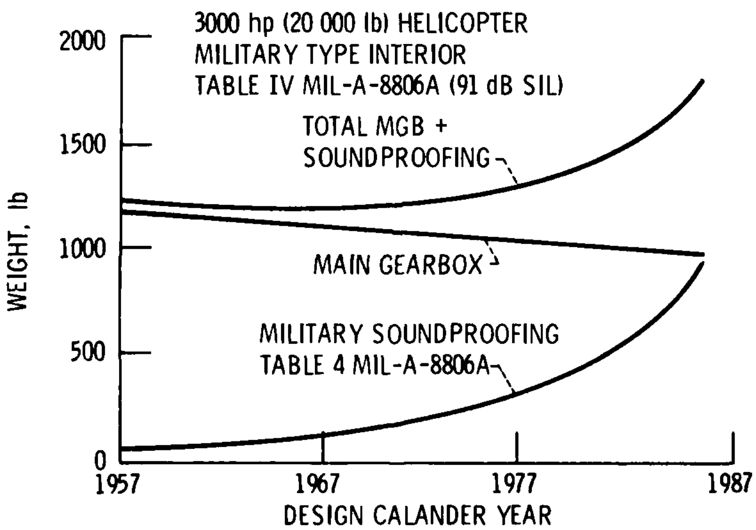


Figure 12. - Gearbox weight technology gain offset by acoustic treatment weight penalty.

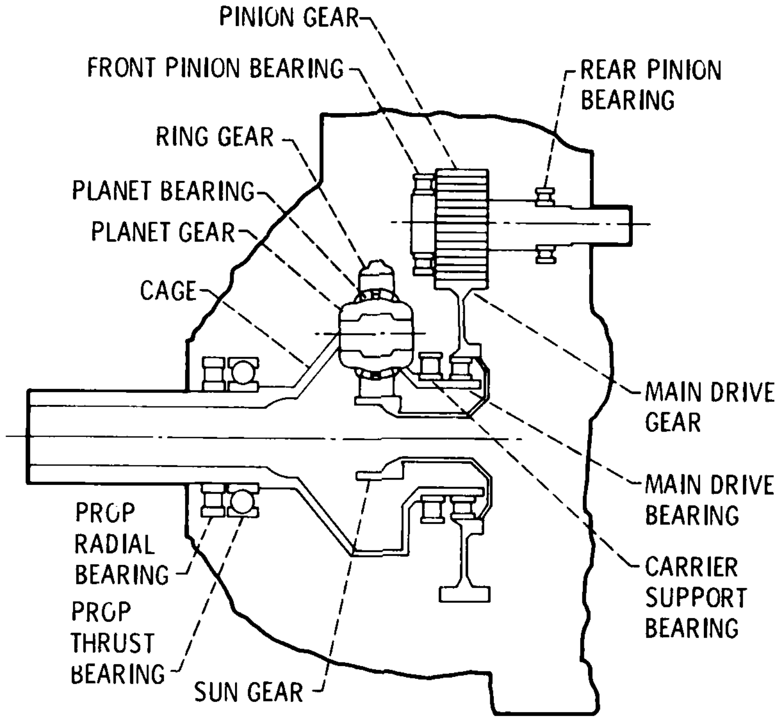


Figure 13. - Typical turboprop reduction gearbox (ref. 12).

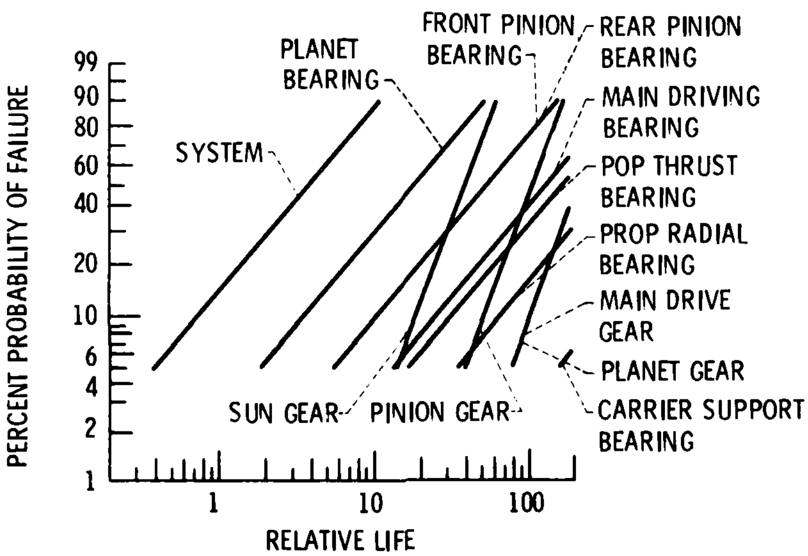


Figure 14. - Calculated theoretical system and component pitting fatigue mission lives (ref. 12).

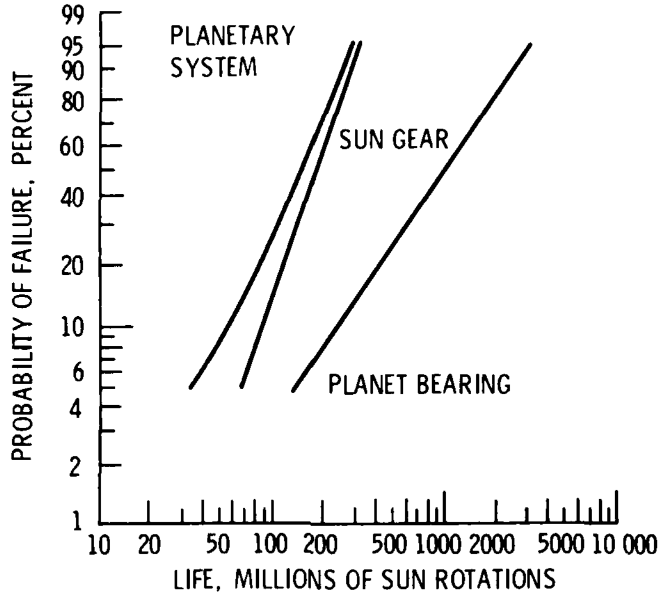


Figure 15. - Calculated theoretical life distributions for planetary drive (ref. 13).

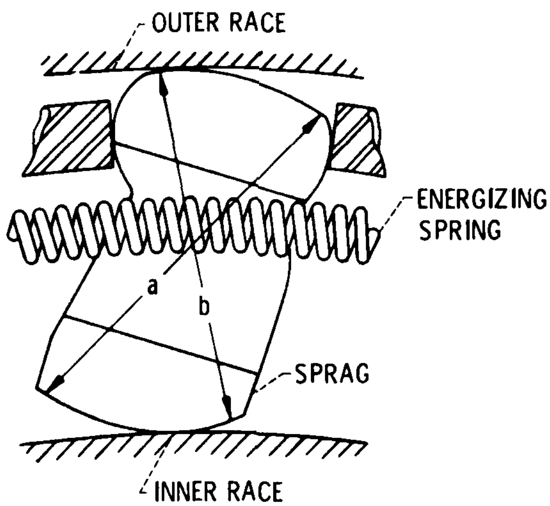
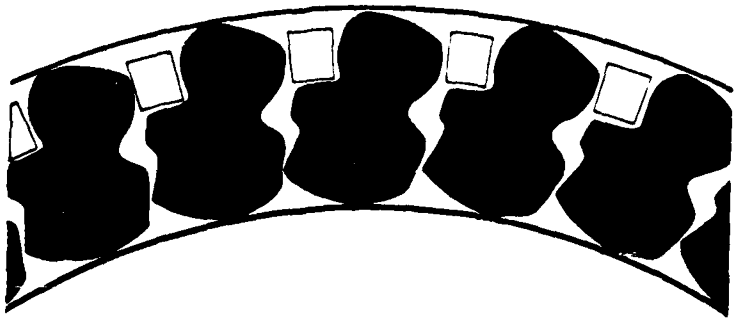
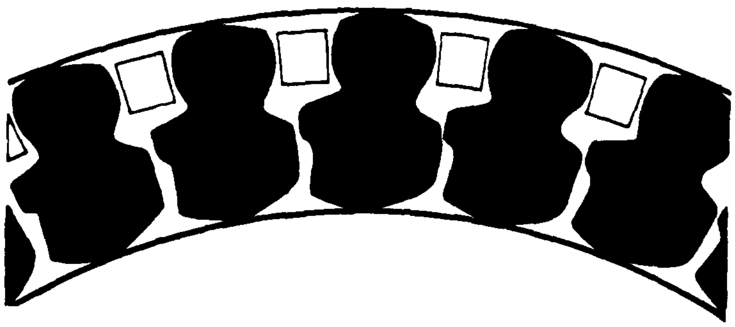


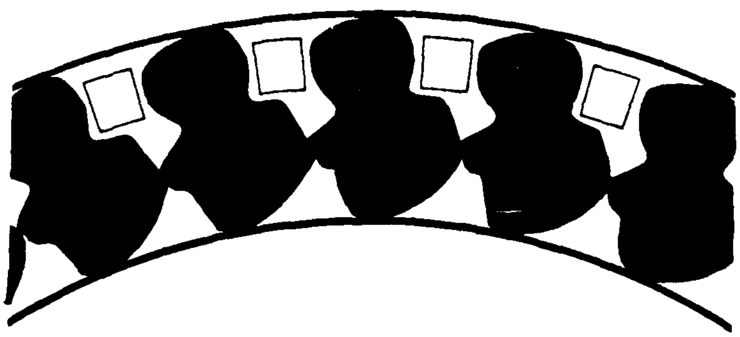
Figure 16. - Sprag overrunning clutch detail (ref. 1).



(a) Normal overrunning position.



(b) Driving under normal load.



(c) Driving with extreme overload.

Figure 17. - Sprags resistant to roll over (ref. 1).

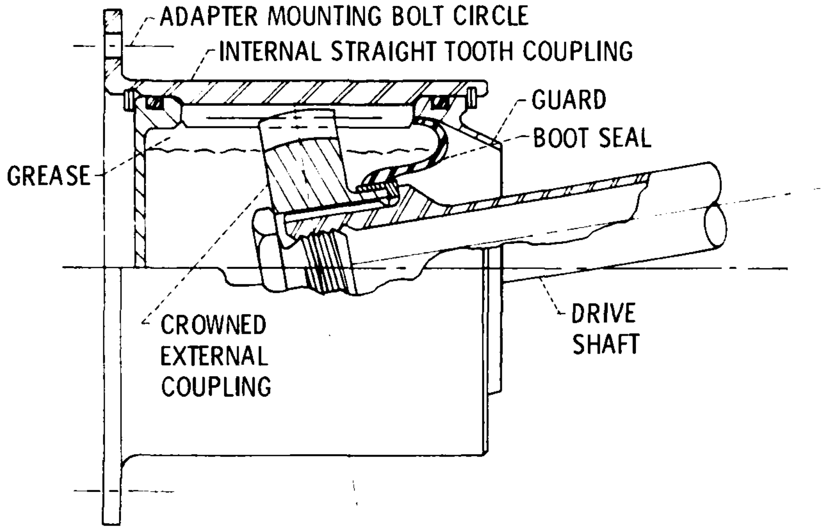


Figure 18. - Gear coupling (ref. 2).

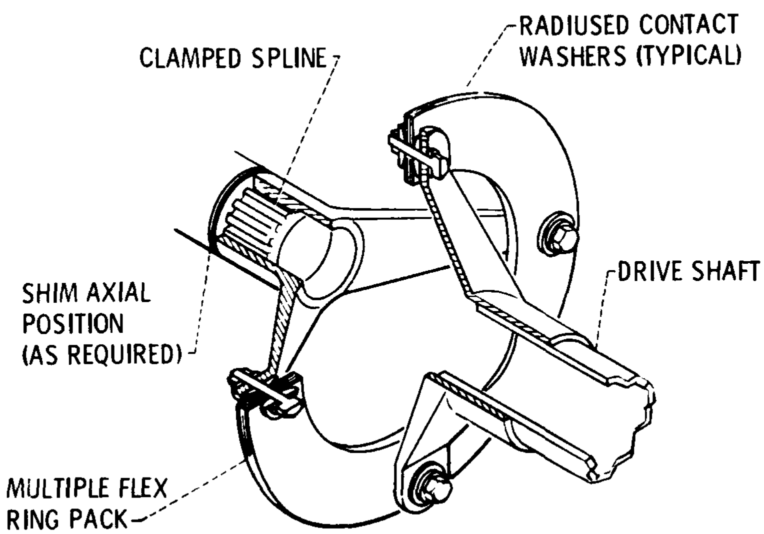


Figure 19. - Typical laminated ring coupling (ref. 1).

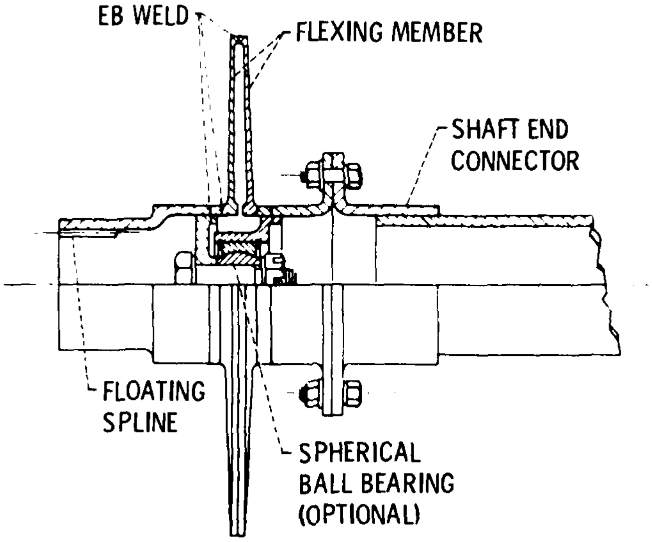


Figure 20. - Typical flexible disk coupling (ref. 1).

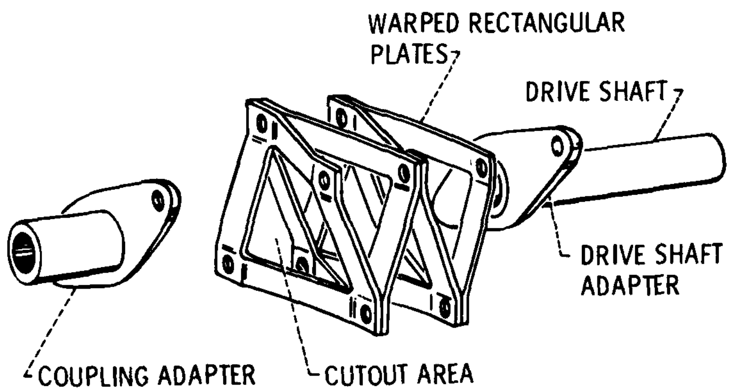


Figure 21. - Kaman Kaflex coupling (ref. 2).

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16. Abstract
A review of current helicopters was conducted to determine the technology in the drive-train systems. This paper highlights the design features including reliability characteristics, in transmission systems for the OH-58, UH-1, CH-47, and UH-60 helicopters. In addition, trade-offs involving cost, reliability and life are discussed.

17. Key Words (Suggested by Author(s))
Helicopters; Transmissions; Gearing; Bearings; Seals; Clutches; Design

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