NASA Helicopter Transmission System Technology Program

Erwin V. Zaretsky*

Man's goal to achieve flight is recorded in the legends and mythology of the human race. By emulating the flapping of bird's wings, we made our first attempts at flying. The ancient Chinese developed a flying toy which by rotary motion produced lift. This rotary-winged toy eventually found its way to medieval Europe. In the later part of the 15th century, Leonardo de Vinci sketched his concept of a vertical flying machine (fig. 1), probably based on the Chinese rotary-winged toy. De Vinci's proposed powerplant for his rotorcraft was a spring. In 1843, over 300 years after de Vinci, Sir George Cayley sketched his concept of an "Aerial Carriage" (fig. 2), which showed some insight into rotary wing flight, including a mechanical power transmission system (refs. 1 and 2).

On November 13, 1907, nearly 4 years after the Wright brothers achieved man's first powered flight, Paul Cornu achieved the first free flight of a rotary-winged aircraft. The aircraft had twin rotors powered by a 24-horsepower engine. In 1910 Igor Sikorsky attempted, for the second time, vertical flight on his S-2 rotorcraft (fig. 3). He subsequently abandoned efforts on rotorcraft until the 1930's (refs. 1 and 3). In 1925 the first real breakthrough in rotary-wing design was achieved with the invention, by Juan de la Cierva (fig. 4), of the autogyro. Although his aircraft was not a true vertical-lift machine, his contribution to rotor design estabilished the design theory and data which the helicopter industry subsequently adopted (ref. 1).

Because of the success of Cierva, Sikorsky was motivated once again to look at the possibilities of helicopter design. On September 14, 1939, Sikorsky achieved his first successful flight in his VS-300 helicopter powered by a piston engine (fig. 5). The VS-300 became the prototype of all subsequent helicopter designs (ref. 3).

The next dramatic breakthrough was the advent of the turbojet aircraft engine and its application to the helicopter in the mid-1950's. With the higher propulsion power available, much bigger helicopters were practical. The mechanical power transmission system, which interfaces the engine and the rotor, was now subjected to higher loads and speeds. As turbine engine technology improved in the 1960's, the bearing and gearing technology required in the helicopter transmission did not keep pace with the engine technology improvements. As a result, the transmission became a key factor in limiting the life and reliability of the helicopter in the 1970's. It is also important to operating costs. For example, the mechanical drive system can account for as much as half the maintenance cost of the helicopter.

It has been estimated that the free world demand for helicopters in the 1980's will be in excess of 29 000 aircraft worth an estimated 30 billion dollars. Of this amount, the civil market will require approximately 21 000 aircraft worth approximately 14 billion dollars, and the military market will require approximately 8000 aircraft worth approximately 16 billion dollars. United States manufacturers are expected to capture 8 billion dollars of the civilian market and 6 billion dollars of the military market. Hence, the United States should remain the primary marketplace for new helicopters, providing we maintain a technology lead. With the increase in the civil helicopter market, the financial stakes justify a greater effort on part of the United States to capture a greater percentage of the world market.

It has long been a requirement to provide technology to obtain long-life, efficient, lightweight, and compact mechanical power transmissions that are also low-cost and quiet for both commercial and military helicopter applications. In general, current state-of-the-art transmission systems are disturbingly noisy to the pilot and passengers. The maintenance rate on these transmission systems is unacceptably high and, as a result, their reliability for long-life application is relatively low. The time between overhaul (TBO) and mean time between failures (MTBF) on present-day helicopters is much

*NASA Lewis Research Center.

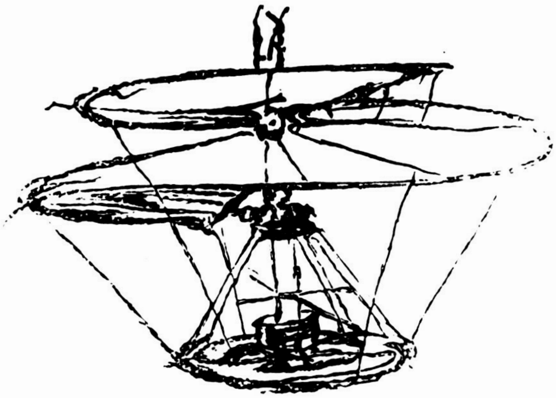


Figure 1. - Leonardo de Vinci's helicopter.

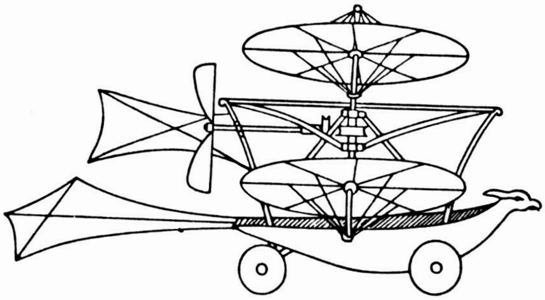


Figure 2. - Sir George Cayley's Aerial Carriage.

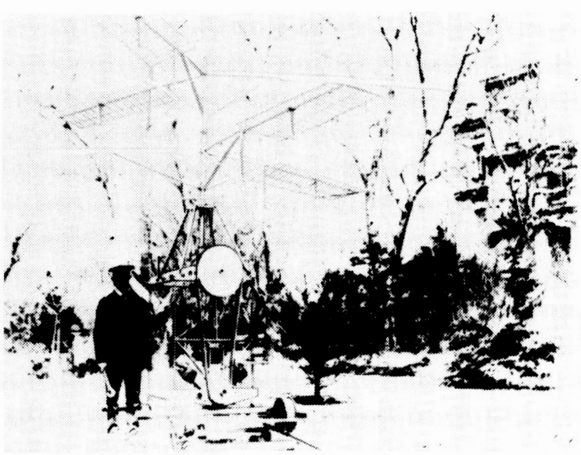


Figure 3. - Igor Sikorsky's S-2 helicopter.

Figure 4. - Juan de la Cierva's autogyro.

Figure 5. - Sikorsky's VS-300 helicopter.

lower than that required for economical commercial operation. The helicopter drive system is generally heavier than desired.

The realization of technological improvements for future helicopter drive systems can only be obtained through advanced research and development. The purpose of the NASA Helicopter Transmission System Technology Program is to improve specific mechanical components and the technology for combining these into advanced drive systems to make helicopters more viable and cost competitive for commercial applications.

Program History

The Bearing, Gearing, and Transmission Section of the NASA Lewis Research Center has had a long history of research in mechanical components technology. The section's genesis dates back to the early 1940's and the National Advisory Committee for Aeronautics (NACA), the predecessor to NASA. In 1970 the section began to act in a consulting capacity to U.S. Army Aviation in the area of mechanical components and transmission systems. Several joint programs were initiated between the U.S. Army Research and Development Command Propulsion Laboratory of the U.S. Army Research and Technology Laboratories, and the Section (refs. 4 to 8). In February 1973 NASA Headquarters suggested that the various research programs that the Section was performing be integrated into a transmission system technology program. By June 1973 the first draft of the proposed program was completed. The program was divided into four basic elements: (1) defining the operating characteristics of current state-of-the-art helicopter transmissions; (2) advancing the state-of-the-art for mechanical components such as rolling-element bearings, gears, and lubrication systems and integrating these components into advanced technology transmissions; (3) investigating the concept of traction and hybrid (combined traction and gear) transmissions for helicopter application, and (4) investigating advanced transmission concepts for helicopter applications. The proposed program was coordinated with the various elements of the Army Aviation Research and Development Command. Based on input from the Army and NASA Office of Aeronautics and Space Technology, the transmissions program focused on two classes of helicopter transmissions. The first was in the 300- to 500-hp range with a single engine input. The second was in the 3000-hp range with two engine inputs.

It was decided that baseline data were to be obtained with the 317-hp Bell OH-58 helicopter transmissions which has had a long service life. The transmission was derived from the OH-4 helicopter transmission. This helicopter was itself the forerunner of the five-seat civil Bell Jet Ranger, the civilian version of the OH-58. The Army has approximately 2000 OH-58 helicopters in its inventory. This well-proven tranmission is representative of a line of helicopter transmissions which are continually being improved. Three OH-58 transmissions were furnished to the Lewis Research Center by the Army Research and Development Command, Director of Product Assurance.

At the time of program planning, the Army was making its decision to procure a 3000-hp Utility Tactical Transport Aircraft System (UTTAS) helicopter which would incorporate the most current state-of-the-art technology. There were two prototype versions of the UTTAS Helicopter under consideration. One was designed and manufactured by the Vertol Division of the Boeing Co., and the other by Sikorsky Aircraft Division of United Technologies. Baseline research would be performed under the NASA program on the transmission from the aircraft chosen by the Army. This ultimately turned out to be the Sikorsky UTTAS designated the UH-60 Blackhawk.

Funding was approved for the program beginning in October 1977 (fiscal year 1978). The resulting program was a 5-year funded, seven-million-dollar program with 6 years for performance.

A 500-hp transmission test stand, the design and fabrication stage of which began in October 1977, became operational in October 1979 (fig. 6). This test stand is capable of testing both conventional gear and hybrid (traction/gear) transmissions at input speeds of 6000 or 36 000 rpm.

A 3000-hp transmission test stand belonging to the Army Aviation Research and Development Command, on which tests were performed on the Boeing Vertol version of the UTTAS transmission, was transferred to NASA Lewis. The transmission test stand was refurbished by NASA and was put on line at the Lewis Research Center in March 1981 (fig. 7). It is being modified to be a universal test stand capable of accepting two input shaft arrangements of up to 3000 hp with both conventional

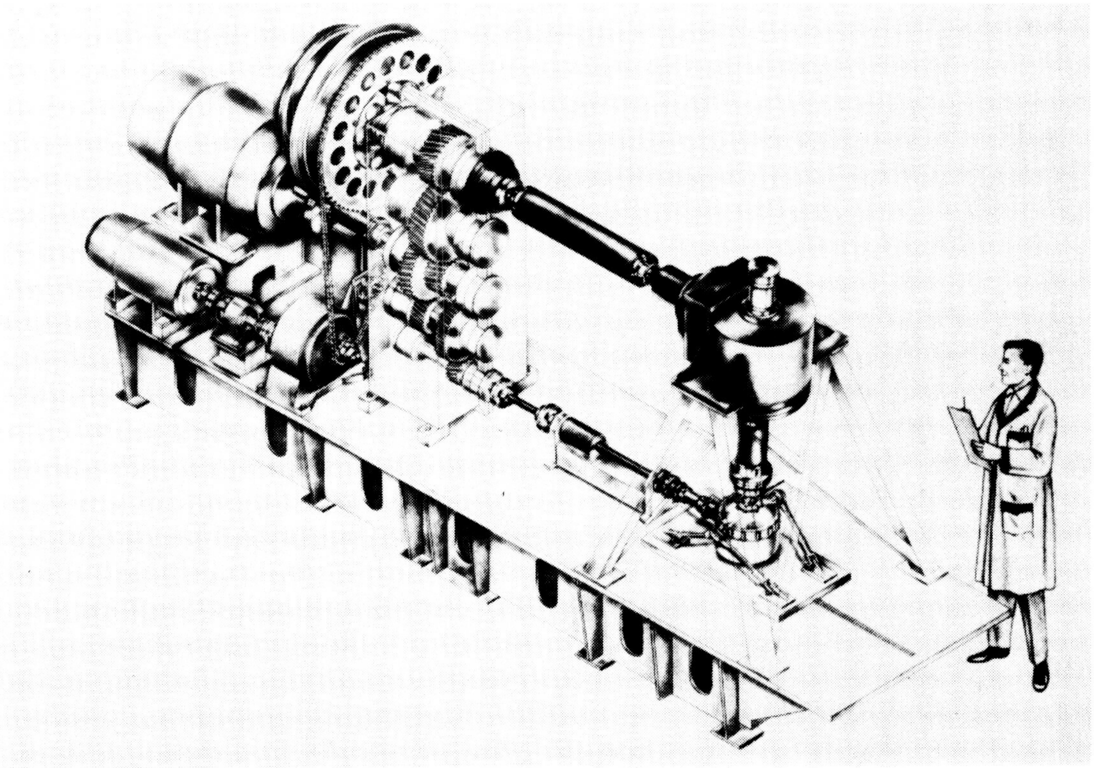


Figure 6. - NASA 500-hp helicopter transmission test stand.

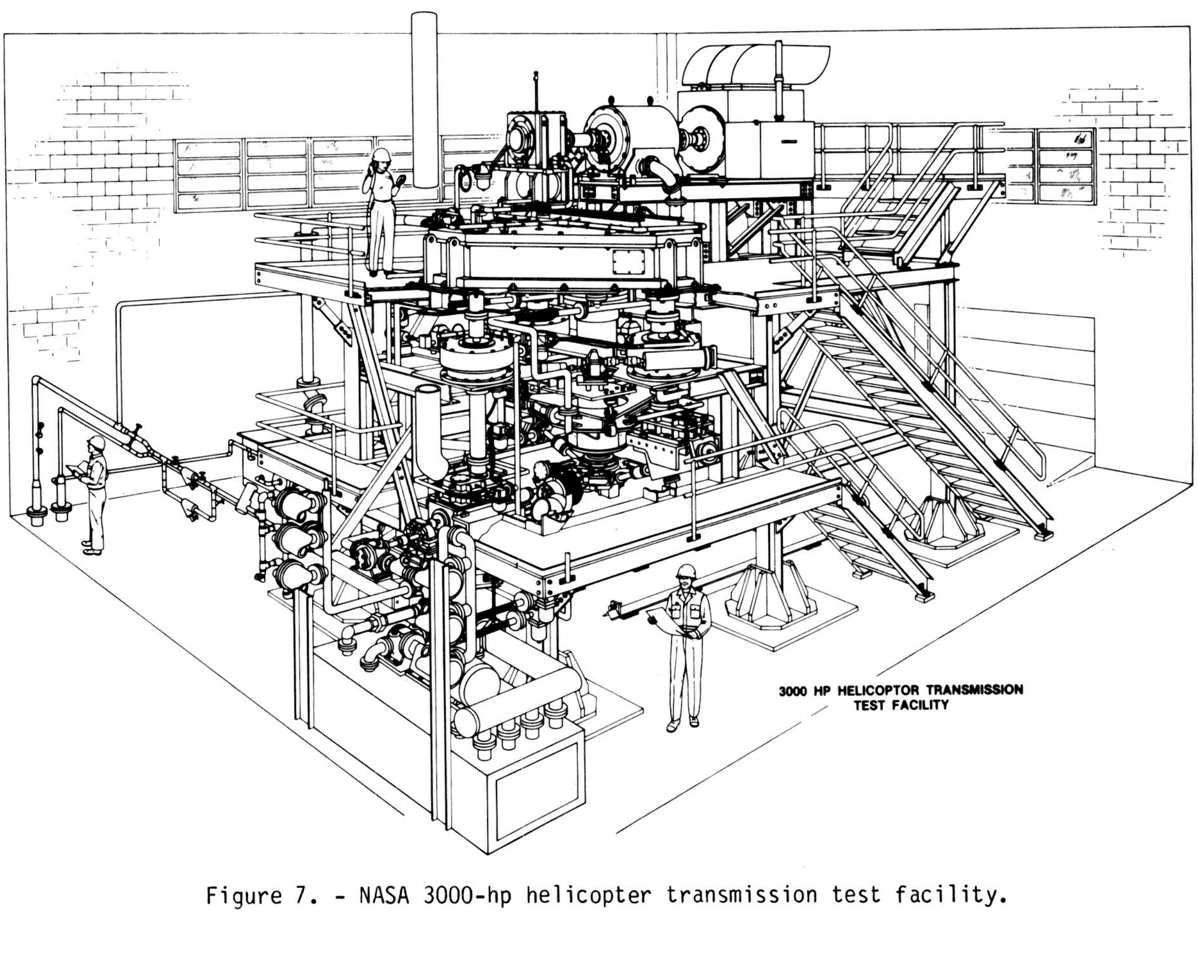


Figure 7. - NASA 3000-hp helicopter transmission test facility.

gear and hybrid traction/gear transmission systems. In addition to the transmission test stands, the other test rigs used for the program are listed in table I.

During the first 3 years of the program, 43 NASA technical papers and technical society journal articles were published reporting the results of the work under this program. A bibliography of these publications is in the appendix.

TABLE I.—FACILITIES AND TEST RIGS AT LEWIS RESEARCH CENTER

Event	Dedication date
3000-hp Helicopter transmission test stand, dual input	1981
500-hp Helicopter transmission test stand, single input	1978
Bevel-gear endurance test rigs	1978
200-hp variable speed transmission test stand	1977
EHD lubrication test rig	1977
Ultrahigh-speed ball and roller bearing test rig	1977
300-hp transmission technology test stand	1975
Spur gear endurance test rigs	1972
Flywheel energy storage test rig	1978
High-speed flywheel bearing test rig	1978
Ball and roller bearing torque test rig	1965
Rolling element fatigue testers	1959

Program Goals

If the early pioneers in helicopter design and development were asked to state their goals for their aircraft, no doubt their answers would be

(1) Improve maintainability
(2) Improve reliability
(3) Increase life
(4) Reduce weight
(5) Reduce noise
(6) Reduce vibration
(7) Improve efficiency.

The first three goals basically result in longer mean time between removal (MTBR) of the transmission. Available statistics for military aircraft in the 1970's indicated that transmission removals for repair or overhaul were occurring at a MTBR of between 500 and 1000 hr of operation. A goal of 2500 to 3000 hr was desired. A statistical analysis of both field experience and the stated goal of 2500 hr results in some rather interesting findings. If it is assumed that the transmission is properly designed, lubricated, and maintained, the failure mode of the transmission would be by surface pitting fatigue of the bearing or gear surfaces. Under most conditions, this failure mode should be benign and can be detected by increased transmission vibration, metal partical chip detectors, or spectrographic oil analysis. With this failure mode, it can be expected that from 51 to 63 percent of an original group of transmissions will be removed from service before the MTBR. The probability of the transmission surviving a given time will always be less than the probability of the shortest lived component in the transmission surviving to that given time. Hence, the transmission life or reliability is a function of the individual lives of the components and of the number of components. As a simplified example, if a transmission having 20 components of equal life must have an MTBR of 2500, then each component must have a mean life of approximately 50 000 hr (20×2500). Individual attention must then be given to the bearing and gearing technology to insure individual long lives.

Transmission weight as a function of power is shown in figure 8. Reduced weight can be achieved by a variety of means. These are improved structure and composite materials for the transmission case, longer life bearing and gear materials, reduced lubrication volume, and improved mechanical component design including reduced structure. However, the reduction of weight does not come without its penalities. These may include increased bending deflections of the gears and support structures, higher bending stresses, shorter component lives, increased noise levels, and higher operating temperatures. As a result, design trade-offs must be made to assure minimum weight at maximum life and reliability. Analytical tools must be developed to achieve this optimization as well as higher temperature gear materials.

Lower weight may also mean higher input speed. Hence, high-speed, rolling-element-bearing technology can become essential. Alternatively, transmission concepts that minimize the need for high-speed bearings, such as the bearingless planetary concept, become of interest. Also, traction transmission concepts that eliminate or minimize the need for gears and bearings become attractive. Split torque transmissions can also reduce weight.

Reduced noise and vibration are related. Representative noise levels in state-of-the-art transmissions are shown in figure 9. The primary noise generators within the transmission are the gears. While the use of high-contact-ratio gearing and gear profile modifications may reduce noise, the amount of noise reduction is not expected to be more than 10 dB from current noise levels. Hence, the elimination of the gears with traction rollers becomes attractive. Work performed by General Motors (ref. 9) with a single row planetary-roller traction drive and an equivalent geared planetary drive resulted in a reduction in noise level with the traction drive of approximately 30 dB. Whether the traction technology applied to helicopter transmissions systems will result in this magnitude of noise reduction is a question which remains to be answered.

Improving the efficiency of helicopter transmissions beyond their nominal 97.0 to 98.5 percent, at first blush, appears to be a more difficult task. It is doubtful that much can be done to the design of the bearings or gears that will decrease their power loss. However, it is well known that lubricant type, rheology, chemical and physical properties, as well as the amount and method of insertion into the transmission components affect efficiency. As a result, a key element to improve efficiency is to define the behavior of the lubricant both within the bearing and gear as well as in the transmission system. The effects of lubricant on transmission efficiency and on bearing and gear life must be defined. A lubricant that can provide for good efficiency can result in low component life. Hence, it becomes vital to select those lubricants that provide for both high efficiency and long life.

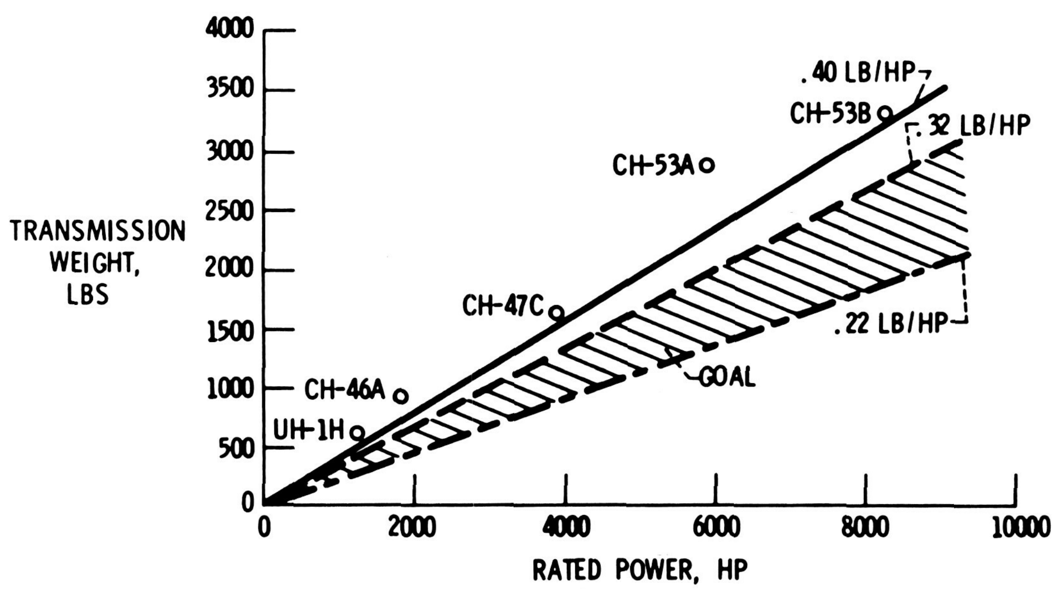


Figure 8. - Transmission weight as function of rated power.

In view of the aforementioned, it has become the purpose of the NASA Helicopter Transmission System Technology Program to make helicopters more cost competitive for commercial applications through improved transmission and mechanical component technologies. The program objectives are to (1) develop technology for the design of advanced transmission systems for helicopter applications; (2) extend bearing, gearing, and lubrication concepts to achieve lightweight, compact, low noise, long-life, low-cost, mechanical power transmission systems for advanced commercial helicopters; and (3) evaluate new concepts in component and transmission tests.

Program Elements

The NASA Helicopter Transmission System Technology Program is divided into four basic areas of research. These are

(1) Components technology
(2) State-of-the-art transmissions
(3) Advanced transmission concepts
(4) Hybrid and traction transmissions

Components Technology

Components technology research is concentrated in the field of rolling-element bearings, gearing, lubricants, and lubrication systems. Because of the requirement for higher temperature transmission applications, new materials are being used for gears with a minimal data base and limited experience. In addition, heat-treat specification and control can significantly affect the life and reliability of a gear system. Experimental definition of the relative life of gear materials and their heat treatment can aide in the selection of potential gear materials and in determining life-adjustment factors for life-prediction methods. Materials can rationally be selected for longer life application.

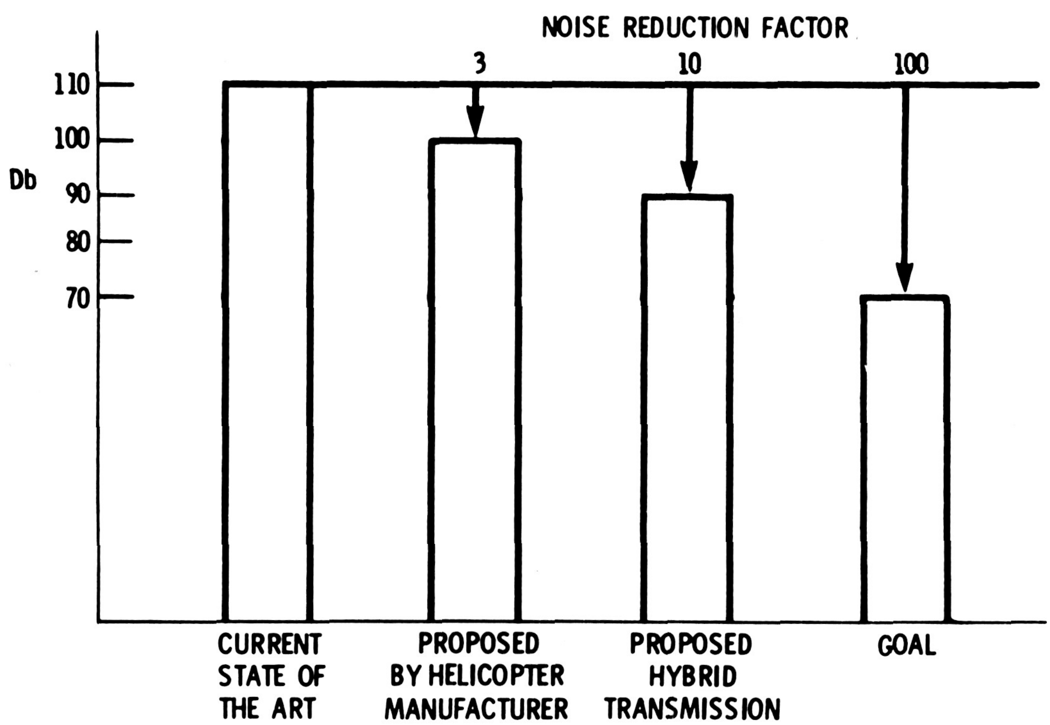


Figure 9. - Representative noise levels in state-of-the-art transmissions.

Proper gear lubrication and cooling has been basically an art. In general, the choice of lubricant flow, pressure, nozzle position, and type has been based on experience and trial-and-error methodology. Equations are being developed whereby the optimum position of the oil jets and lubricant flow rate can be predicted with reasonable certainty to obtain efficient lubrication. Oil volume and gear operating temperatures can be optimized for a given transmission design.

The application of elastohydrodynamic (EHD) lubrication analysis to gear design and operation will enhance gear life and operation. The effect of EHD film thickness in determining transmission life and reliability has, for the most part, been ignored by the transmission designer. Furthermore, lubricant temperature affects film thickness and gear tooth temperature. Hence, cooling analysis of the gear must be integrated with the EHD analysis. Selection of a lubricant affects both parameters and can affect the efficiency of a gearbox as well as its life.

Accurate dynamic stress predictions for tooth bending in the contact zone of gear teeth are very important factors in transmission design. Finite-element techniques for both spur and bevel gears will greatly improve stress predictions. This would allow the designer to more fully utilize the greater load capacity of advanced transmission systems and at the same time minimize transmission weight.

Tooth profile modifications and high-contact-ratio gearing offer the potential of higher transmission loads for a given transmission weight. Similarly, for a given transmission load, reliability and life should improve.

Rolling-element bearings operating under conditions that fall within the state-of-the-art will generally meet or exceed the predicted life, provided the bearing is properly handled and lubricated and providing load conditions have been correctly analyzed. For helicopter transmission applications, four types of rolling-element bearings are generally used:

(1) Cylindrical roller bearings
(2) Angular-contact ball bearings
(3) Tapered roller bearings
(4) Spherical roller bearings

Before the initiation of the transmission program, analytical methods that could reasonably predict the performance of cylindrical roller bearings and angular-contact ball bearings were fairly well established and had been experimentally verified. However, both tapered roller bearing and spherical-roller bearing analyses were limited. Tapered-roller bearings are being used in some helicopter transmissions to carry combined radial, thrust, and moment loads and, in particular, those loads from bevel gears such as high-speed input pinions. For this application tapered-roller bearings have a greater load capacity for a given envelope or for a given weight than the more commonly used ball and cylindrical roller bearings. The speed of tapered-roller bearings is limited to approximately 0.5 million DN (a cone-rib tangential velocity of approximately 36 m/sec (7000 ft/min) unless special attention is given to lubricating and designing this rib/roller-end contact. At higher speeds centrifugal effects starve this critical contact of lubricant. Moreover, the tapered bearing is sensitive to lubricant interruption at the rib/roller-end contact, making the bearing susceptible to early failure. Developing the design methodology to solve these problems could contribute to improved transmission life and load capacity.

Spherical roller bearings are advantageous for applications where misalinement can be expected such as in the planet gears of a helicopter transmission (fig. 10). Contemporary design of spherical roller bearings relies on "rules," hand calculations, and some modest computerized simulations. Operating speed has been restricted to maximum DN values of approximately 4.5×10^5. Higher speed transmission systems may require a bearing speed of approximately 1×10^6 DN. Both analytical and experimental verification are required to advance the technology of these bearings.

Improved analytical methods to predict bearing power loss and operating temperature would greatly aide in optimizing transmission efficiency. Unfortunately, the bearing is not an isolated component functioning independent of the other bearings and gears within the transmission system. Proper modeling of the bearing within its operational environment is a condition precedent to the proper prediction of the bearing's operational characteristics.

State-of-the-Art Transmissions

Current design methodology for transmission systems uses relatively standard stress calculations and methods dictated by AGMA standards. These methods for the most part have proven

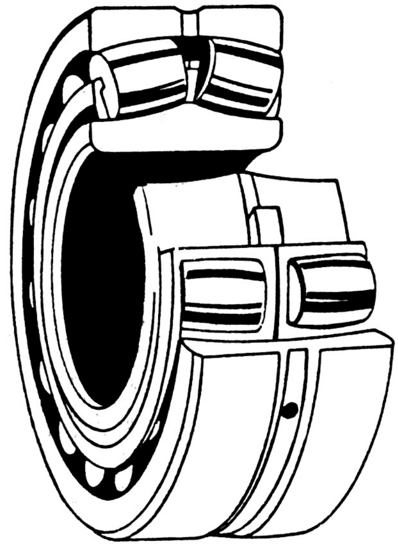


Figure 10. - Spherical roller bearing.

satisfactory for current applications. However, transmission life prediction methods are inadequate and, for the most part, inconsistent from one design group to another. Transmissions can be sized not only for stress, speed, and speed ratio but also for life. The traditional assumption of an infinite gear pitting life is not technically acceptable.

Analytical methods to accurately predict transmission noise is another potential design tool. While life and reliability as well as efficiency are prime design considerations, alternative designs of equal merit may result in significantly different noise amplitudes. Proven analytical methods for predicting noise would aide in the proper design, selection, or modification of gear systems whereby noise can be minimized while mechanical performance can be optimized.

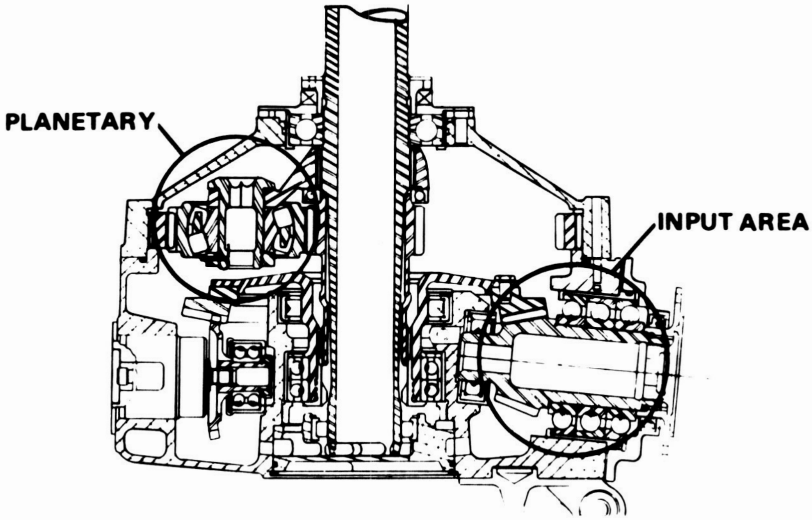
The data in the open literature defining current state-of-the-art transmission technology, supported by tests under carefully controlled conditions, are virtually nonexistent. If changes are to be made in gear and bearing technology as applied to transmission systems, the effect of this technology must be assessed. Hence, the operating parameters of current state-of-the-art transmissions must be evaluated. This knowledge would allow improvements in components and new transmission concepts to be quantified with respect to noise, vibration, efficiency, stresses, and thermal gradients.

Four state-of-the-art transmissions will be evaluated under this program: (1) the 317-hp OH-58 three-gear planetary transmission (fig. 11(a)), (2) the 317-hp OH-58 four-gear planetary transmission (fig. 11(b)), (3) the 3000-hp Sikorsky UH-60A transmission (fig. 12), and (4) the 3000-hp Boeing UTTAS transmission (fig. 13).

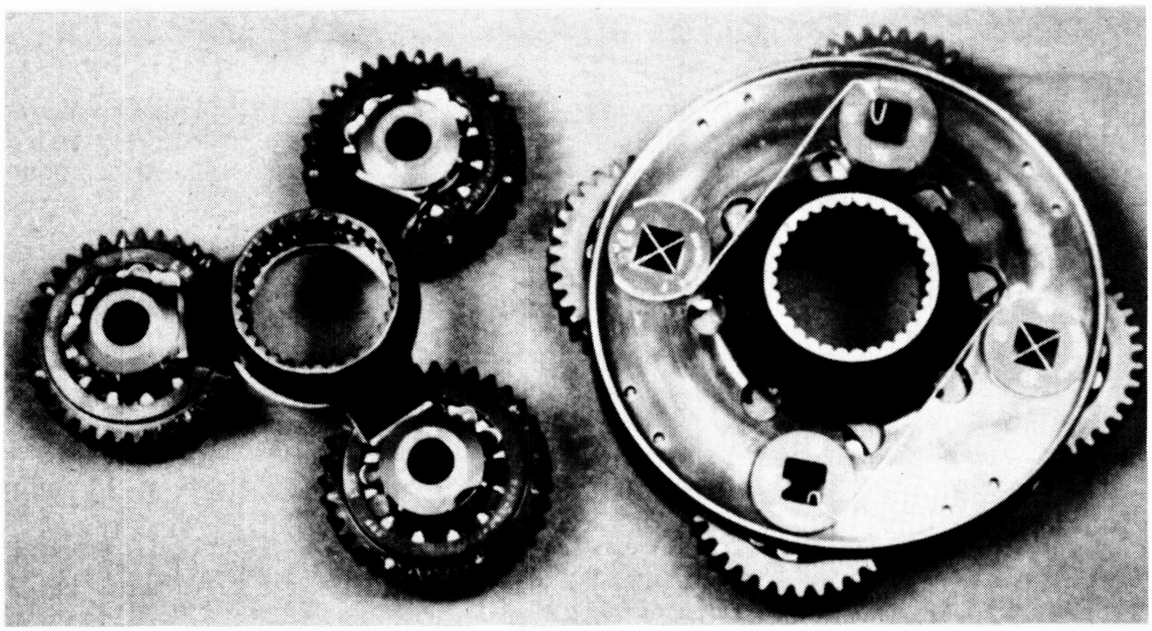
Advanced Transmission Concepts

Three advanced geared transmission concepts are being investigated under this program: (1) advanced components transmission (fig. 14), (2) bearingless planetary transmission (fig. 15), and (3) split-torque transmission (fig. 16). Of the three, the advanced components transmission and the bearingless planetary transmission will be fabricated under the current NASA Lewis program.

Advanced components transmission. – Based on fundamental research performed in mechanical components, an advanced 500-hp transmission has been designed (fig. 14(a)). The concept is a high-contact-ratio four-gear planetary transmission for improved load capacity and life. The high-contact-ratio gears are expected to result in lower noise and reduced dynamic loads. The main bevel gear has been straddle mounted to improve deflection of the gear mounting, thereby improving load sharing in the gear mesh. This, too, is expected to result in lower noise and improved life. The planetary ring gear has been cantilever-mounted to relieve problems inherent in the ring-gear-to-case-spline interface. Rolling-element bearings will be manufactured from vaccum-induction-melted, vacuum-



(a) Three-planet configuration.

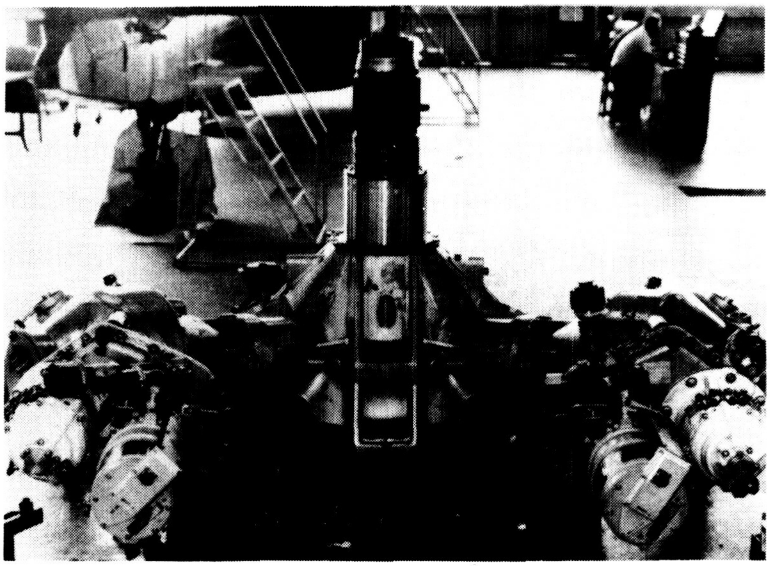


(b) Planetary arrangements.
Figure 11. - 317-hp OH-58A transmission.

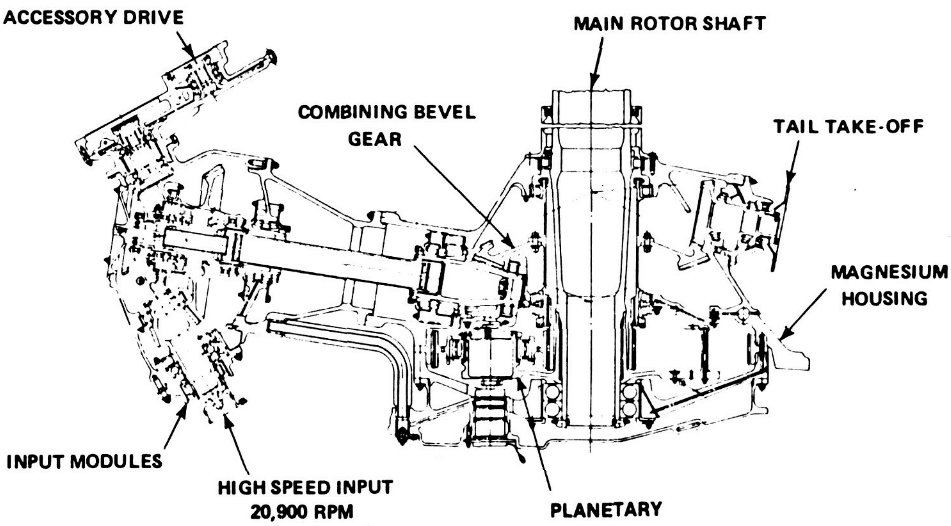
arc-remelted (VIM–VAR) AISI M–50 material. The VIM–VAR AISI M–50 will result in longer bearing life. The bevel gearset will be manufactured from VIM–VAR AISI 9310. The lubrication system will use the latest technology of positive radial-jet lubrication to the sun gear and spline. This will reduce wear and increase the load-carrying capacity of the gearset.

This advanced transmission will have a weight-to-power ratio of 0.24 lb of transmission weight per horsepower, as compared with the standard 317-hp OH–58 transmission of 0.34 lb/hp. A life analysis of the transmission will be conducted to assess its theoretical life. The transmission, which is being fabricated under the current NASA Helicopter Transmission Program, will be tested on the NASA 500-hp test stand.

The transmission design has been modified to allow for the replacement of the ball bearings with tapered-roller bearings (fig. 14(b)). Tapered-roller bearings on the ouput and input transmission shafts offer greater load capacity and longer life than the ball bearings. The modification also required some change to the existing housing and a new output shaft.



(a) Main gearbox.



(b) Main transmission.
Figure 12. - Black Hawk main transmission.

Bearingless planetary transmission. —The self-alining bearingless planetary transmission (fig. 15) covers a variety of planetary-gear configurations, which share the common characertistic that the planet carrier, or spider, is eliminated, as are conventional planet-mounted bearings. The bearings are eliminated by load balancing the gears, which are separated in the axial direction. All forces and reactions are transmitted through the gear meshes and contained by simple rolling rings. The concept was first demonstrated by Curtis Wright Corp. under sponsorship of the U.S. Army Aviation Research and Development Command (ref. 10). The 500-hp bearingless planetary transmission for the NASA program is being designed to be comparable with the OH-58 baseline transmission. The transmission weight-to-power ratio is approximately 0.27 lb/hp. A transmission life analysis will also be performed. The transmission will be tested on the NASA 500-hp transmission test stand.

Split-torque transmission. —A means to decrease the weight-to-power ratio of a transmission or to decrease the unit stress of gear teeth is by load sharing through multiple power paths. This concept is referred to as the split-torque transmission (refs. 11 and 12). As part of the NASA Helicopter Transmission System Technology Program, feasibility studies are being conducted on two variants of

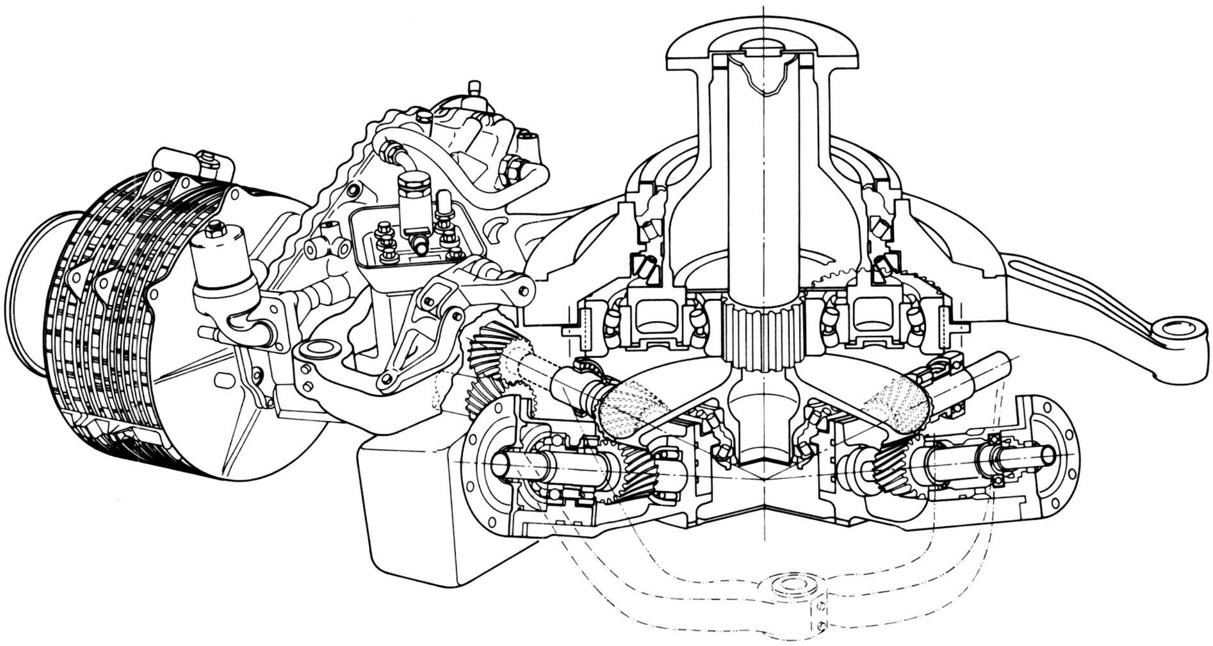
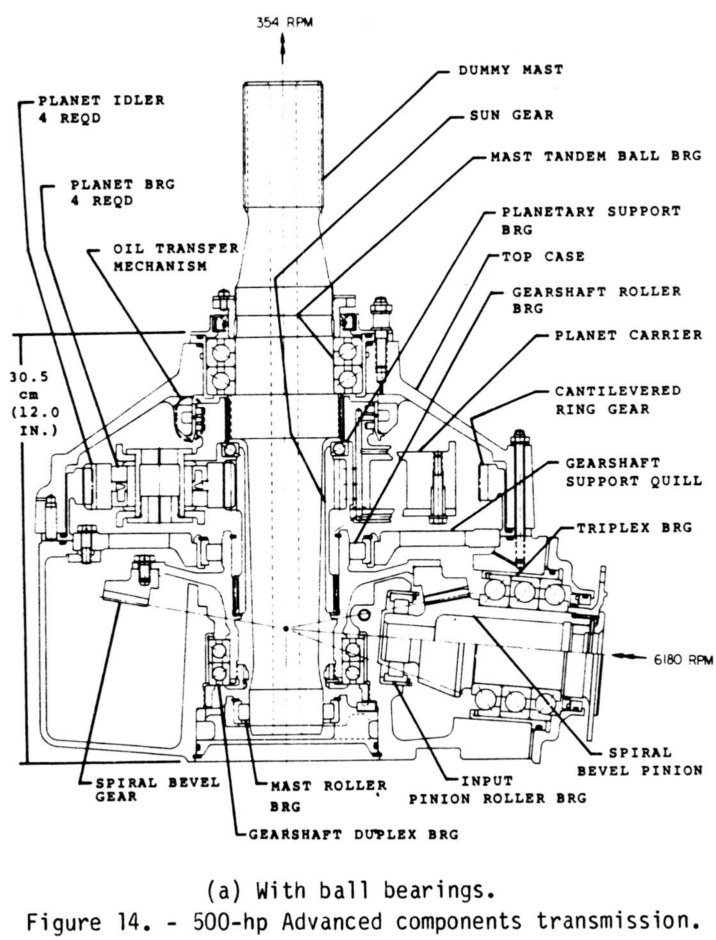
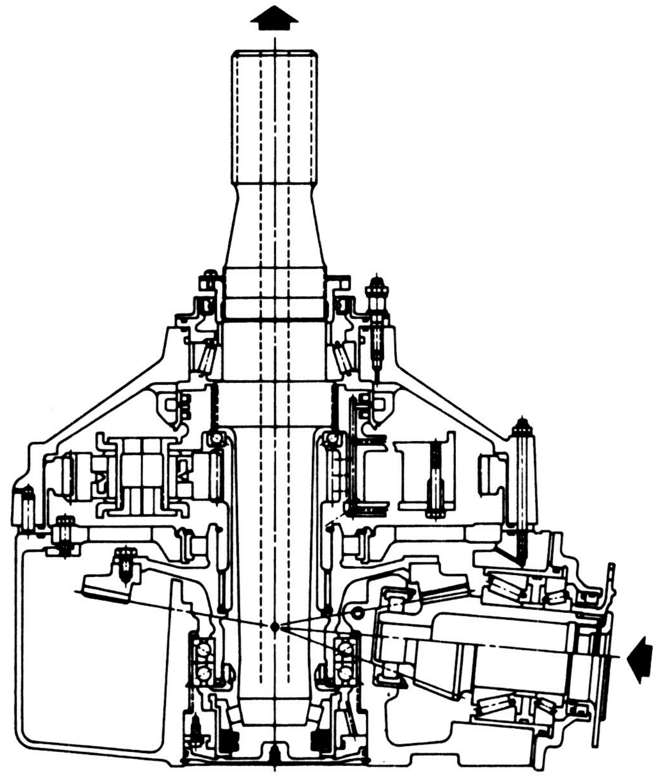


Figure 13. - Boeing 3000-hp UTTAS transmission.



(a) With ball bearings.
Figure 14. - 500-hp Advanced components transmission.



(b) With tapered roller bearings.
Figure 14. - Concluded.

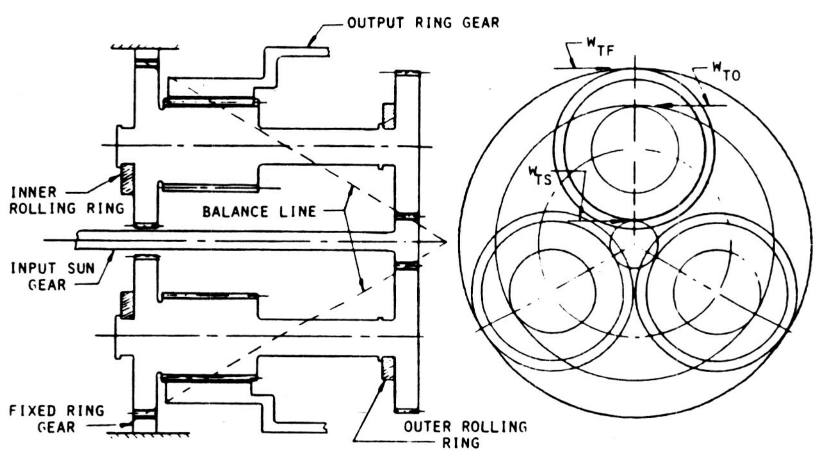


Figure 15 - 500-hp Bearingless planetary transmission.

this concept (fig. 16). The first variant is in the 500-hp range with a single-engine input (fig. 16(a)); the second is in the 3000-hp range with a two-engine input (fig. 16(b)). Instead of a planetary-gear arrangment, the input power is split into two or more power paths and recombined in a bull gear to the output power (rotor) shaft.

There has been no commitment to fabricate a drive of this type under the current program. Preliminary weight estimates indicate that the weight-to-power ratio is approximately 0.24 lb/hp. Life estimates of this concept have not been made. This concept appears to offer weight advantages over conventional planetary concepts without high-contact-ratio gearing. The effect of incorporating

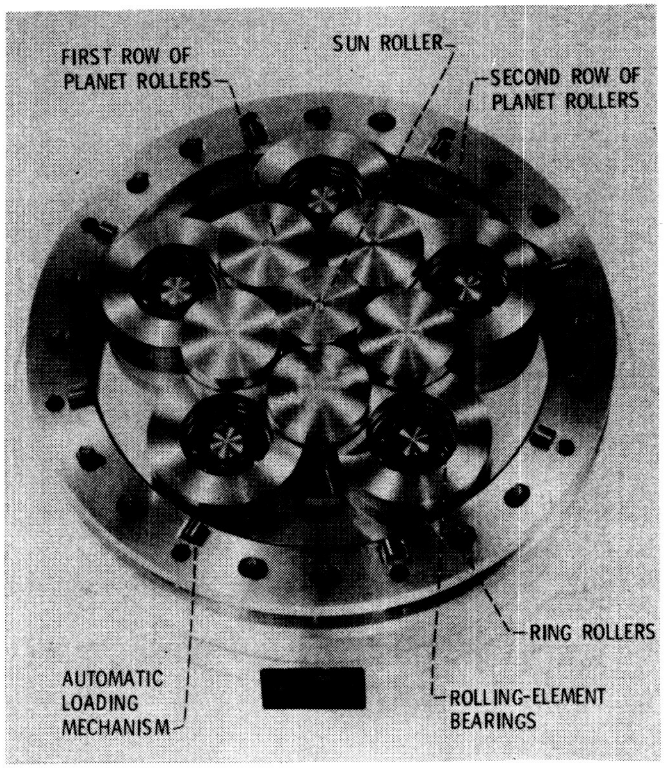


Figure 17. - Multiroller planetary traction drive.

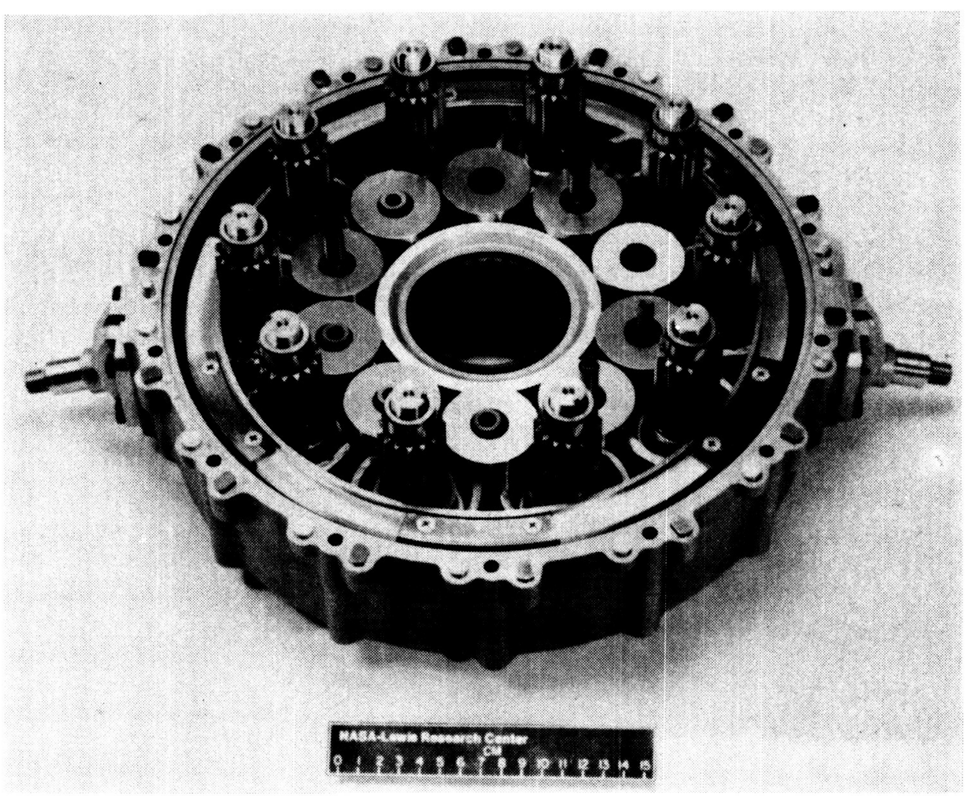
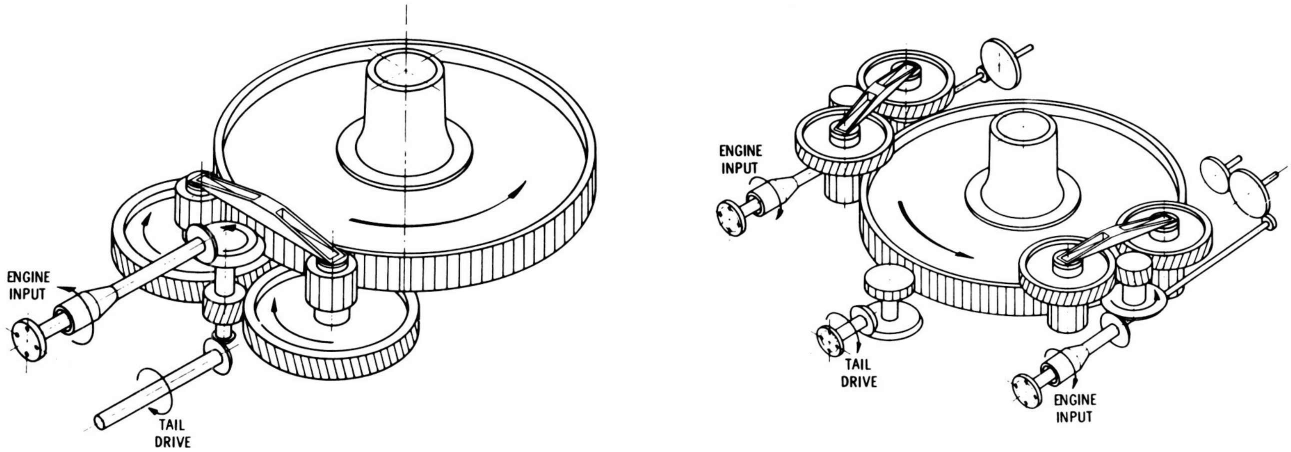


Figure 18. - Hybrid stage of 500-hp hybrid helicopter transmission.



(a) Single input. (b) Dual input.

Figure 16. - Conceptual sketch split torque transmission.

high-contact-ratio gearing into the split torque concept is expected to further reduce transmission weight.

Hybrid and Traction Transmissions

Early traction drives were not competitive in size and weight with gear systems. There are several reasons for this. First, unlike a simple gear mesh, in order to prevent slip, the normal load imposed on a traction contact must be at least an order of magnitude larger than the transmitted traction force. Second, the steels used in early traction drives had a significantly lower fatigue life than today's metallurgically cleaner bearing steels. Third, the earlier traction drives did not benefit from the use of modern traction fluids which can produce up to 50 percent more traction than conventional mineral oils for the same normal load. In addition, recent advancements in the prediction of traction-drive performance and fatigue life have added a greater degree of reliability to the design of these drives.

To achieve high power density, the traction drive must be constructed with multiple, load sharing roller elements that can reduce the contact unit loading. For traction drives with a simple, single-row planet-roller format, the number of load sharing planets is inversely related to the speed ratio. For example, a four-planet drive would have a maximum speed ratio of 6.8 before the planets interfered with each other. A five-planet drive would be limited to a ratio of 4.8, and so on.

A remedy to the speed-ratio and planet number limitations of simple, single-row planetary systems was devised by A.L. Nasvytis (ref. 13). His drive system used the sun and ring-roller of the simple planetary traction drive, but replaced the single row of equal diameter planet-rollers with two or more rows of stepped, or dual diameter, planets (fig. 17). With this new, multiroller arrangement, practical speed ratios of 250 to 1 could be obtained in a single stage with three planet rows. Furthermore, the number of planets carrying the load in parallel could be greatly increased for a given ratio. This resulted in a significant reduction in individual roller contact loading with a corresponding improvement in torque capacity and fatigue life.

To further reduce the size and the weight of the drive for helicopter transmission applications, NASA incorporated with the second row of rollers, pinion gears in contact with a ring gear (fig. 18). The ring gear is connected through a spider to the output rotor shaft. The number of planet-roller rows and the relative diameter ratios at each contact are variables to be optimized according to the overall speed ratio and the uniformity of contact forces. The traction-gear combination is referred to as the hybrid transmission.

Three variants of the hybrid transmission have been studied and will be fabricated in the current NASA program. A 500-hp low-ratio variant has been fabricated (fig. 18) and will be tested. The transmission, which has a weight-to-power ratio of 0.27 and a speed reduction ratio of 17:1, could retrofit the OH–58 helicopter. The second variant of the hybrid transmission is referred to as the 500-hp high-ratio variant. This transmission has a speed reduction of 101:1. The low-ratio hybrid is designed for a speed input of approximately 6020 rpm, and the high-ratio variant is designed for an input speed of approximatly 36 000 rpm. Because the transmission can accommodate the higher input speed, the 40-lb, 6:1 reduction gearbox on the engine can be eliminated. Hence, the power train weight-to-power ratio is approximatley 0.20 lb/hp.

Life estimates of both the low- and high-ratio variants were made. For the low-ratio variant the mean fatigue life is estimated to be approximately 3000 hr at a 70-percent prorated load. Under similar conditions the high-ratio variant has a mean fatigue life of approximately 50 000 hr.

The third variant of the hybrid transmission is a 3000-hp, two-engine input variant having a reduction ratio of 81:1 with an input speed of 20 000 rpm. The transmission, which is under design and which will be fabricated under the NASA program, could be compatible with the Army's UH–60 helicopter. It is expected to have a weight-to-power ratio of 0.25 lb/hp. Preliminary life calculations indicate that this transmission will have a mean fatigue life of approximately 47 000 hr at 70 percent prorated load and 16 000 hr at a continuous 100-percent load. Testing of this transmission will be on the NASA 3000-hp helicopter transmission test stand.

Summary of Results

The NASA Helicopter Transmission System Technology Program began October 1977. The purpose of the program is to make helicopters more feasible and cost competitive for commercial application. The program objectives are (1) to develop technology for the design of advanced transmission systems for helicopter applications; (2) to extend bearing, gearing, and lubrication concepts to achieve lightweight, compact, low-noise, long-life, low-cost, mechanical power transmission systems for advanced commercial helicopters; and (3) to evaluate new concepts in component and transmission tests.

The program is divided into four basic areas of research. These are (1) components technology, (2) state-of-the-art transmission, (3) advanced transmission concepts, and (4) hybrid and traction transmissions. The area of component technology is concentrated in the fields of rolling-element bearings, gearing, lubricants, and lubrication systems. The state-of-the-art transmissions to be evaluated are the (1) 317-hp OH–58 three-gear planetary tranmission, (2) 317-hp OH–58 four-gear planetary transmission, (3) 3000-hp Sikorsky UH–60 transmission, and (4) 3000-hp Boeing UTTAS transmission. Three advanced gear transmission concepts are being investigated. These are the (1) advanced components transmission, (2) bearingless planetary transmission and (3) split-torque transmission. The advanced components transmission and bearingless planetary transmission are being fabricated in a 500-hp single-engine input version. The split torque is being studied for a single-engine-input 500-hp and a 3000-hp two-engine-input version. However, the split-torque transmission will not be fabricated under the current program. Three variations of the hybrid transmission will be fabricated and tested: (1) 500-hp single-engine-input low-ratio hybrid transmission, (2) 500-hp single-engine-input high-ratio hybrid transmission, and (3) 3000-hp dual-engine-input hybrid transmission. These transmissions are expected to have longer lives and significantly lower noise than state-of-the-art transmissions and the other advanced-concept transmissions being evaluated.

The NASA Program will contribute technology towards quieter and more efficient transmission systems having higher power-to-weight ratios at lives and reliabilities greater than state-of-the-art systems. Further, the use of improved mechanical components, such as gears and bearings, advanced materials and lubricants and design methodology should improve transmission maintainability and mean time between removal.

Appendix
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