Design Study of Self-Alining Bearingless Planetary Gear (SABP)*

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The ever-present pressure on the aircraft and helicopter power transmission designers to reduce weight, size, and cost of power transmissions has given impetus to many innovations and technological improvements. This pressure is further compounded by the user demand for higher horsepower, improved reliability, improved maintainability, and improved survivability of both military and commercial crafts.

One recent promising development in the area of high performance power transmissions has been the self-alining, bearingless planetary (SABP). This transmission arrangement can be generically classified as a quasi-compound planetary which utilizes a sun gear, planet spindle assemblies, ring gears, and rolling rings.

The SABP transmission concept was first introduced in the mid-1960's. Following the introduction of this new design, numerous studies were undertaken to evaluate the viability of this new arrangement as an advanced helicopter and VTOL aircraft transmission system. The results of reference 1 concluded that this new gear concept offered potential advantages over conventional helicopter planetary gears in the following areas:

1. Eliminating planet bearing power losses and failures
2. Having low planetary weight
3. Permitting high reduction in two compound stages of high efficiency
4. Providing sufficient flexibility and self-centering to give good load distribution between planet pinions
5. Effectively isolating planetary elements from housing deflections
6. Increasing operating time after loss of lubricant, since there were no planet bearings.

In early 1970 this transmission design concept was reduced to practice by manufacturing and testing two 373-kW (500-hp) prototype transmissions (ref. 2). This program demonstrated the technical feasibility of this new transmission. Following the successful completion of the prototype testing, further transmission studies were undertaken (refs. 3 and 4).

These studies concluded that the new transmission concept was in fact superior to the contemporary helicopter epicyclic gears. Both studies recommended that this new transmission be subjected to further work and development testing. The results summarized in this paper are the next step in this evolutionary process and present several preliminary designs of a SABP as applicable to a specific helicopter.

The objective of the study was to evaluate the feasibility of using the SABP transmission in an uprated version of the OH–58 helicopter and to make specific performance comparisons of this new transmission with contemporary helicopter tranmission systems and with the uprated version of the OH–58 power transmission.

Prudence dictates that the introduction of new ideas, materials, designs, etc., into aircraft usage must be preceded by various studies, developments, and testing phases. During this evolutionary process, good ideas advance, and ultimately the advantages and the benefits these new designs offer can be and are incorporated into their respective product lines. To date, the SABP transmission concept has been subjected to several engineering studies, to hardware prototype demonstration programs, and to the study reported herein.

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Symbols

F	fixed ring gear
f	gear clash frequency, cps
Mg	gear ratio
N	number of gear teeth
n	rotational speed of gear, rpm
O	output ring gear
PF	planet/fixed ring gear
PO	planet/output ring gear
PS	planet/sun gear
R	pitch radius (R_1, R_2, . . . , R_N)
RRI	rolling ring internal
RRO	rolling ring external
R_T	total reduction ratio
S	sun gear
V_O	output velocity
V_I	initial velocity
W_O	output angular rate, rad
W_I	input angular rate, rad
WPF	tangential load fixed ring gear
WPO	tangential load output ring gear
W_{RF}	radial fixed force
W_{RO}	radial output force
W_{RS}	radial sun force
WS	tangential load sun mesh
W_{TF}	tangential fixed force
W_{TO}	tangential output force
W_{TS}	tangential sun force

Technical Discussion

Principle of Operation of the SABP

The self-alining, bearingless planetary (SABP) transmission concept covers a variety of planetary gear configurations which share the common characteristic that planet carriers or spiders are eliminated, as are conventional planet mounting bearings. All forces and reactions are transmitted through the gear meshes and through simple rolling rings. In its simplest form this transmission concept is illustrated schematically in figures 1 and 2. These figures show the major components of a SABP type transmission and illustrate the gear tooth balancing principle of this new power transmission arrangement. As can be observed from figure 2, the planet gear faces are so spaced that the tangential gear tooth forces leave the planet spindles in equilibrium. Tooth separating and centrifugal forces are reacted via ID or OD cylindrical rings which are concentric with the sun gear axis. The planet spindles have diameters which freely roll in or on the cylindrical support rings.

The concept can be further illustrated by first studying a simple conventional compound planetary drive (fig. 3). This design requires bearings to react loads in the tangential and radial planes. The forces in the transverse plane are already in equilibrium as a result of the reduction ratio. The bearing load in the tangential plane is approximately 5 to 6 times that in the radial plane.

The SABP design evolved from recognition of the advantages afforded through the elimination of the bearings which react loads in the tangential plane. The bearings could be eliminated by separating the gears in an axial direction. One can verify that all forces and moments add up to zero about any point in or parallel to the three planes.

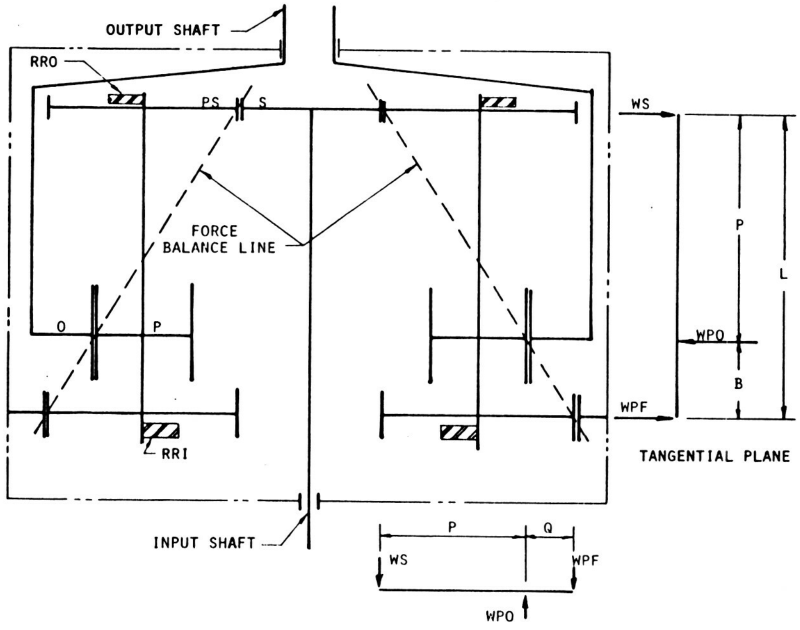


Figure 1. - Schematic arrangement of self-alining, bearingless, planetary gear - tangential plane.

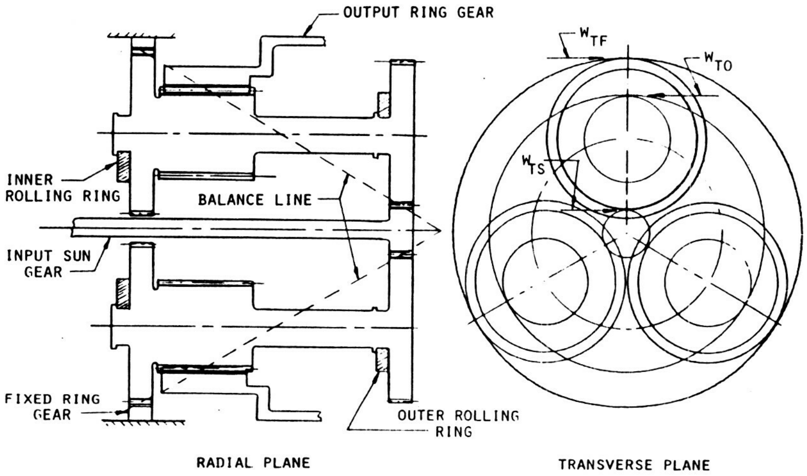


Figure 2. - Schematic arrangement of self-alining, bearingless, planetary gear - radial and transverse planes.

The SABP drive concept, as it has evolved, can be summarized as follows:

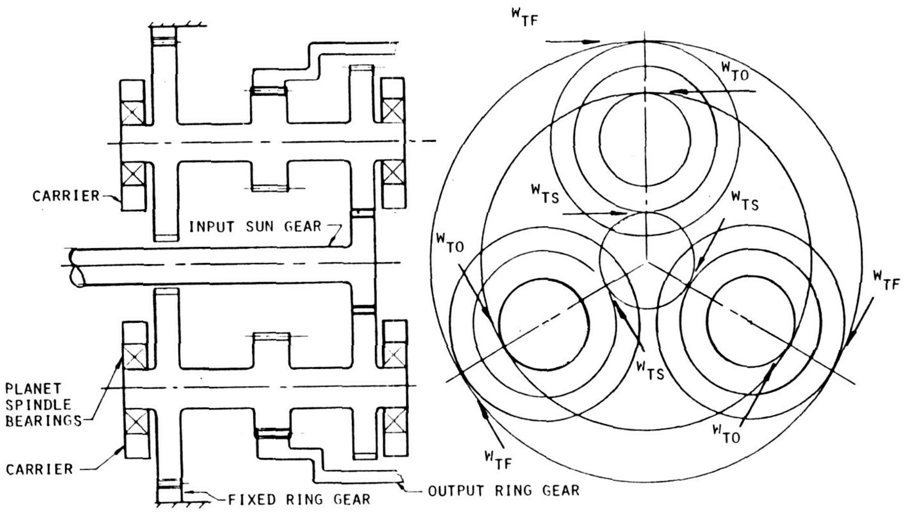
(a) The reduction ratio requirement and maximum diameter define the forces and the geometry in the transverse plane.

(b) Free-floating rings react the loads in the radial plane.

(c) Skewing moments in the tangential plane are eliminated by spacing the gears axially.

Prototype Demonstration and Test Experience

The demonstration of the prototype SABP units was conducted by the Curtiss-Wright Corporation under U.S. Army Air Mobility Research and Development Laboratory sponsorship (refs. 2 and 5).



RADIAL PLANE

TRANSVERSE PLANE

Figure 3. - Conventional compound planetary schematic.

Static Test Results

The prototype units were strain gaged to determine the load distribution among the spindles. Static torque tests indicated good load distribution among the five planet spindles, including good full face gear tooth patterns.

Dynamic Test Results

A 50-hr endurance test was conducted in a back-to-back test arrangement at an input speed of 8000 rpm and at a torque value equivalent to 373 kW (500 hp). The dynamic testing showed that the unrestrained spindles were stable and that, on completion of the endurance test, all hardware was in excellent condition.

Design Study

The objective of the design study was to evaluate the feasibility of using a SABP transmission in an uprated version of the OH-58 helicopter and to make specific comparisons with contemporary OH-58 power transmissions. The table below presents a summary of gearbox specifications used in this study.

Power rating (at 100 %), kW (hp)	335 (450)
Maximum power (at 110 %), kW (hp)	369 (495)
Maximum main rotor speed, rpm	347
Maximum gearbox input speed, rpm	6060
Maximum tail rotor power, kW (hp)	61.8 (83)
Maximum tail rotor output speed, rpm	4130
Angle between rotor and input shaft, deg	95
Power turbine speed	35 000 rpm

Using the above design specifications, three preliminary design layouts were prepared. The first variant, low ratio, has a reduction ratio of 17.46 to 1 and is retrofitable to an OH-58 airframe. The second and third variants, High Ratio and Hybrid, can be coupled directly to the engine's power turbine. All major components have been sized to transmit the rated power at stress levels comparable with those in use in contemporary helicopter transmissions.

For the low ratio variant the gearbox envelope constraints were dictated by the design specification and envelope constraints. Preliminary layouts have shown that, in order to tuck the input stage of the planetary gear down and inside the bevel pinion, the bevel gear must be as large as possible. A bevel gear on the order of 0.3048 m (12 in.) in diameter and a bevel ratio of about 3 to 1 were ultimately selected. Since the design specification calls for an overall reduction ratio of 17.45 to 1, the SABP must have a reduction ratio of about 5.8 to 1. Previous parametric studies have shown that a 5.8 to 1 ratio across the SABP, although technically feasible, is low and not in an optimum range. However, since this configuration met the design requirements and envelope constraints, it was selected as a candidate for the preliminary layout.

Since the high ratio variant and the hybrid design did not have the envelope constraints cited above, it was possible to optimize the gear arrangement to favor higher ratios and to take advantage of the high ratio capability of the SABP. In the high ratio variant a reduction ratio of 26.3 to 1 was selected. This selection resulted in a gear unit approximately 0.4572 m (18 in.) high and 0.4826 m (19 in.) in diameter.

An alternative configuration to the high ratio was also evolved (herein called hybrid). In this arrangement a 15.9 to 1 ratio was taken across the SABP, and the remainder was taken across the spiral bevel mesh and a parallel offset mesh. Here, the height of the unit was reduced to 0.3683 m (14.5 in.) from 0.4572 m (18 in.), and the diameter remained unchanged at 0.4826 m (19 in.).

Figures 4 and 5 depict typical results of parametric studies and illustrate the flexibility of this design concept to vary the height or the diameter of the transmission. Figure 6 illustrates a typical velocity diagram for the SABP using the instantaneous center method.

Efficiency

Power losses were calculated using AGMA gear efficiency formulas. The losses ranged from 8.8 to 11.3 kW (11.85 to 15.2 hp) at the 373-kW (500-hp) rated condition. Comparing these losses with those of a single-stage planetary shows the latter to be more efficient. Comparing these losses with those of a two-stage planetary shows the SABP to be more efficient. These results are consistent with other analysis and indicate that at low gear reduction ratios the SABP does not compare favorably with single-stage reduction gears and that at higher ratios the SABP compares favorably with two-stage planetary gear systems.

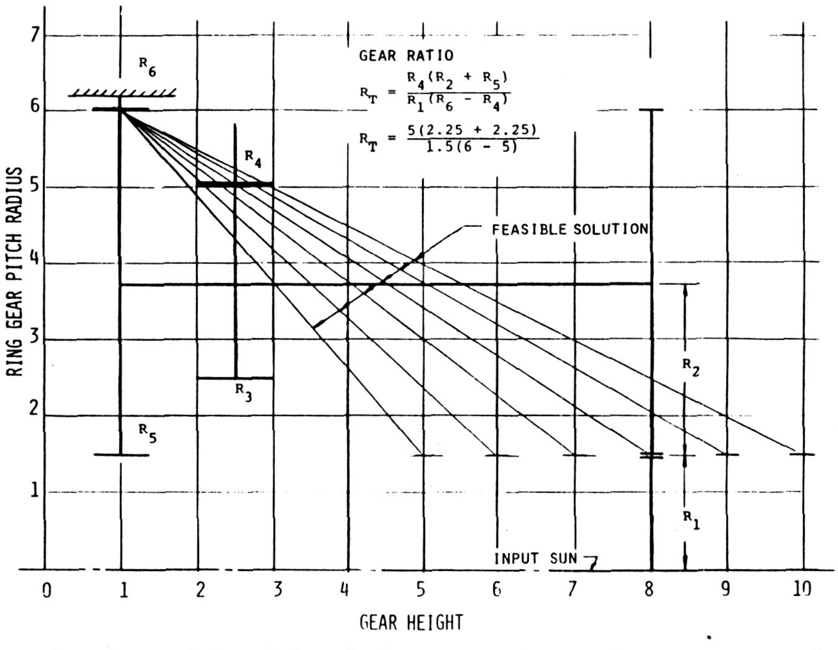
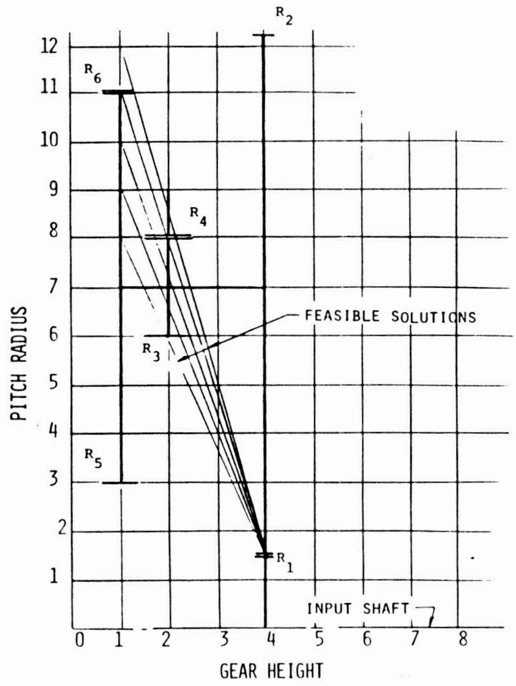


Figure 4. - Parametric study of ring gear pitch radius versus gear height.



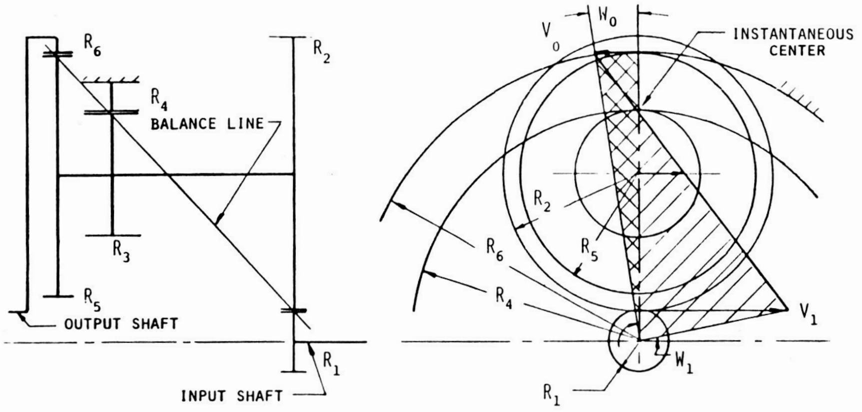
GEAR RATIO

$$R_T = \frac{R_4(R_2 + R_5)}{R_1(R_6 - R_4)}$$

$$R_T = \frac{8(5.5 + 4.0)}{1.5(11 - 8)}$$

$$R_T = 16.8$$

Figure 5. - Parametric study of fixed gear height versus ring gear pitch radius.



GEAR REDUCTION RATIO DERIVATION

Ratio $M_g = \frac{W_1}{W_0}$

$V_1 = W_1R_1;\ W_1 = \frac{V_1}{R_1}$

$V_0 = W_0R_6 \quad W_0 = \frac{V_0}{R_6}$

$M_g = \frac{V_1R_6}{R_1V_0}$

$\frac{V_1}{R_4 - R_1} = \frac{V_2}{R_5 - R_4}$

$V_0 = \frac{V_1(R_6 - R_4)}{R_4 - R_1}$

$M_g = \frac{W_1}{W_0} = \frac{V_1R_6}{V_0R_1}$

$M_g = \frac{V_1R_6(R_4 - R_1)}{V_1R_1(R_6 - R_4)}$

Figure 6. - Velocity diagram.

Weight Analysis

Numerous studies have been undertaken to quantify helicopter transmission weights and to plot the weights of specific helicopter transmissions against various design parameters. References 6 and 7 present the results of two such studies. In these reports the respective authors have compiled actual helicopter transmision weights and have plotted these weights against such parameters as helicopter gross weight, rotor output torque, the time period in which the transmission was designed, etc.

One of the plots in each report is a curve depicting the weight of the main power transmission as a function of rotor shaft output torque. It is interesting to note that a logarithmic plot of these data produces a straight-line relationship between the weight of a helicopter transmission system and rotor torque. Figure 7 was replotted from reference 5 and depicts this relationship. This plot is very useful in estimating transmisssion weights of new helicopters and in studying the desirability of new or proposed transmission concepts.

Using the average line drawn through the points plotted in figure 7 and assuming the original power rating of the OH-58 helicopter to be 201 kW (270 hp), the estimated weight of the main power transmission is 56.8 kg (125 lb). This estimate compares favorably with the actual transmission weight of 50.8 kg (112 lb).

Using the average line from figure 7 and uprating the OH-58 gearbox to 335 kW (450 hp), the projected transmission weight is 81.6 kg (180 lb). Using the same slopes established by the average lines in these figures and correcting for the actual transmission weight of 50.8 kg (112 lb), the projected weight of a 335 kW (450 hp) transmission is approximately 74.8 to 77.1 kg (165 to 170 lb). These projected weight values now can be compared with the 62.1 kg (137 lb) calculated weight of the SABP.

These results were also compared with the results and conclusions presented in references 3 and 4. The conclusions of references 3 and 4 are in agreement with the results obtained during this study.

Cost Considerations

In considering producibility of the SABP, the question was analyzed from two points of view: (a) ability to manufacture the required components using current gear manufacturing processes, and (b) cost comparison of the major components of the SABP with the major components of conventional helicopter transmissions.

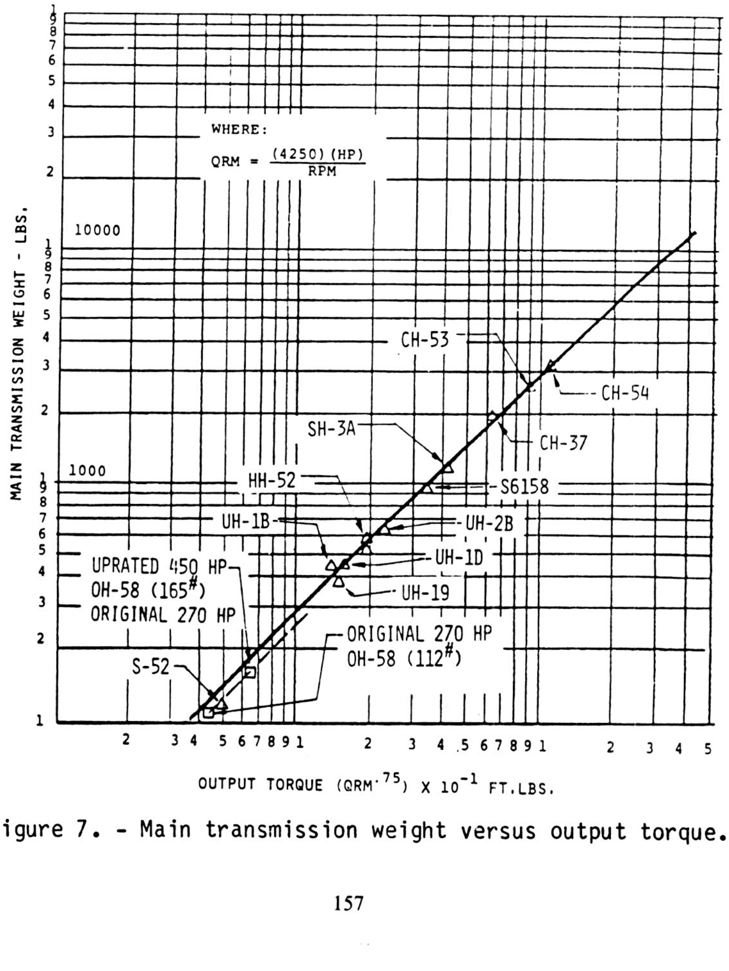


Figure 7. - Main transmission weight versus output torque.

Using the preliminary layouts evolved during this study, a detailed review of all major components was made from manufacturing and processing points of view. This study showed that the processes required to produce the SABP gear units were similar to those required to produce conventional helicopter transmission systems. The SABP design does require that the three gears which form a spindle subassembly be indexed to each other. The tolerance for indexing is on the order of 0.0254 to 0.0762 mm (0.001 to 0.003 in.). This level of accuracy is considered to be readily achievable and is not expected to have an adverse influence on the cost of the spindles. Elimination of the planet carrier and close tolerances associated with the manufacturing of this component on the order of 0.00508 to 0.0127 mm (0.0002 to 0.0005 in.), however, does have a favorable implication on the cost of manufacturing the SABP. Combining the elimination of the planet carriers (one of the most expensive components in the helicopter transmission system) with the reduced number of components in the SABP results in a projected reduction in the overall manufacturing cost of 16.5 to 28 percent when compared with the manufacturing cost of a conventional two-stage helicopter transmission system. There is good agreement between the results of this study and the results of cost studies reported in references 1 and 3.

Survivability and Vulnerability

Assessment of survivability characteristics indicates that the SABP offers improved operation after loss of lubricant when compared with conventional helicopter transmissions. One of the most important of these improvements is the elimination of planet gear bearings which have been found to be the major source of failure after loss of lubricant (ref. 8). The second improvement worth noting is that the gears themselves appear to be more tolerant of loss of oil. The fewer number of parts within the transmission itself means fewer sources of heat—another potential improvement. The mechanical efficiency of the SABP transmission is higher than that of a comparable two-stage planetary; thus, less heat is generated. The SABP transmission density is lower than that of a functionally comparable two-stage helicopter transmission; thus, more cooling air is available.

Reliability

Past experience with helicopter power transmission systems dealing with the subject of reliability and maintainability (R&M) indicates that rolling contact bearings represent one of the major R&M problem areas. If these elements could be eliminated from the helicopter power transmission or if their use could be minimized, the R&M of these units could be improved significantly. It should be noted that one of the inherent characteristics of the SABP is the elimination of planet bearings and carriers (spiders). This characteristic is ranked as one of the most striking features of the SABP and has favorable implication on the projected reliability.

Reliability of the SABP was addressed during the studies reported in references 2 to 4 (as well as during the current effort). These studies considered this question from three points of view:

(a) Quantitative comparison of the number of major components in the SABP versus contemporary helicopter transmissions (ref. 2)
(b) Previously established reliability index for critical transmission components (ref. 4)
(c) Reliability analysis based on over 300 000 flight hr at operating stress levels (ref. 3).

In reference 3 the reliability of the SABP was compared with that of a conventional two-stage planetary transmission. The analysis indicated a 2 to 1 improvement in reliability of the SABP.

Gear Noise

The subject of gear noise has been addressed by numerous investigators, researchers, and practitioners of the art. There is good agreement among the various gear experts that noise is a product of many factors and many design parameters. One of the primary causes of gear noise is the clashing of loaded gear teeth caused by various tolerances, tooth deflections, and vibrations. Gear noise can be correlated with gear clash frequencies and component resonances. Ordinarily, gear clash noise dominates and can be heard as a combination of distinct tones. Gear clash frequency can be calculated from

$$f = \frac{nN}{60}$$

where f is the gear clash frequency in Hz, N is the number of teeth on a gear, and n is the rotational speed of a gear in rpm.

Gear clash noise is caused by the vibration resulting from two types of impulses which stem from tooth engagement forces. The two types of impulses are pitch circle impulse and engagement impulse.

The magnitude of these factors is controlled by a number of design parameters; the more important of which are diametral pitch, contact ratio, pressure angle, backlash, face width, type of gear, tooth profile, finish, web thickness, material, and natural frequencies.

Pitch Circle Impulse

While undergoing an engagement cycle, gear teeth do not have perfect rolling contact. In the transmission of circumferential force between gears, the point of pressure application travels from the root of the driving gear to its tip and from the tip of the driven gear to its root. As a result of this load variation through an engagement cycle, deflection of the teeth contributes to sliding between them. At the beginning and end of engagement, sliding velocity is maximum, and at the pitch cycle, it is zero. At the pitch circle the direction of sliding reverses, thus reversing the direction of sliding force between the mating teeth and thereby causing the pitch circle impulse. The direction of this impulse is perpendicular to the line of action, and its sense depends on which side of the pitch point the action is taking place.

Engagement Impulse

Whenever a tooth engages, it picks up part of the load carried by the previously engaged tooth. The reduction in loading on the original driving teeth causes them to deflect toward their unloaded positions; thus, imparting tangential acceleration to the gear body. Since the previously engaged teeth are deflected slightly due to loading, the incoming engaging tooth cannot make the smooth contact that it should. Instead, it impacts its mate on the meshing gear and sends an impulse through the bodies of both gears.

Noise Transmission

Gear noise is transferred from its source at the tooth in action to the atmosphere in a number of ways. The direct sound wave radiation from the gear teeth accounts for only a small percentage of the gear noise emitted. The largest amount of transmitted noise is that caused by ringing of the gear bodies and by radiation from other components, including bearings and gear casings.

Gear Noise Design Trends

Over the years, the gear industry has identified parameters which lead to the reduction of gear noise. The voluminous amount of literature available on the subject of gear noise suggests that a gear designer now has sufficient data to design quiet gear trains.

Upon detailed examination of the characteristics required for quiet gears, it can be readily seen that there is a conflict between these design parameters and such considerations as cost of the gear train, envelope constraints, weight constraints, etc. Accordingly, a properly designed gear train must achieve a balance which will satisfy both the design requirements as well as the constraints of cost, performance, weight, size, etc.

Analysis of the SABP shows that many design parameters such as gear size, accuracy, pitch line velocity, gear materials, etc., are comparable to contemporary helicopter transmissions. Therefore, it can be anticipated that the noise intensity of the SABP would be comparable to contemporary helicopter transmissions. Results of hardware testing of prototype SABP type gear units support the above observation. Since comparable quantitative data are not available at this time for the SABP, specific noise levels cannot be cited nor can comparisons be made.

Conclusion

The subject study concluded that the SABP offers significant potential weight and reliability advantages over the contemporary two-stage helicopter power transmissions. Weight savings of 17 to 30 percent have been projected during this study, and a reliability improvement by a factor of 2 to 1 has been calculated. Considering other design parameters such as efficiency, vulnerability, maintainability, and cost, the SABP achieved in all areas a higher rating than conventional two-stage helicopter transmissions. For lower gear reduction ratios, the SABP does not compare favorably with a single-stage planetary.

The potential for weight and size reduction of this new transmission concept appears to lie in its ability to transmit higher torques in a given size due to improved load distribution among the planets and due to the elimination of the planet carriers and planet bearings. These improvements can have significant implications when space and weight limitations are imposed on the transmission designer.

Considering the failure modes and vulnerability of contemporary helicopter transmissions and of the SABP, the new concept should be more tolerant to the loss of lubricant and loss of bearings. The study concluded that for the same output torque and approximately the same gear sizes, the SABP has lower operating gear tooth stress levels, higher mechanical efficiency, and lower heat rejection rates.

The most promising arrangements of the SABP studied are where the reduction ratios ranged from approximately 16:1 to 26:1.

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