A Method to Analyze and Optimize the Load Sharing of Split Path Transmissions

Timothy L. Krantz
Vehicle Propulsion Directorate
U.S. Army Research Laboratory
Lewis Research Center
Cleveland, Ohio

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ABSTRACT
Split-path transmissions are promising alternatives to the common planetary transmissions for rotorcraft. Heretofore, split-path designs proposed for or used in rotorcraft have featured load-sharing devices that add undesirable weight and complexity to the designs. A method was developed to analyze and optimize the load sharing in split-path transmissions without load-sharing devices. The method uses the clocking angle as a design parameter to optimize for equal load sharing. In addition, the clocking angle tolerance necessary to maintain acceptable load sharing can be calculated. The method evaluates the effects of gearshaft twisting and bending, tooth bending, Hertzian deformations within bearings, and movement of bearing supports on load sharing. It was used to study the NASA split-path test gearbox and the U.S. Army’s Comanche helicopter main rotor gearbox. Acceptable load sharing was found to be achievable and maintainable by using proven manufacturing processes. The analytical results compare favorably to available experimental data.

INTRODUCTION
The drive system requirements for a rotorcraft are especially demanding. It must transmit the engine power to the rotor while providing a typical speed reduction of 60 to 1. In addition, the drive system must be safe, reliable, lightweight, and energy efficient while producing little vibration and noise. Rotorcraft transmissions have matured to a high performance level through a combination of analyses, experiments, and application of field experiences. Still, the next generation of rotorcraft will call for drive systems that are even safer, lighter, quieter, and more reliable. These improvements are needed to increase vehicle payload and performance, improve passenger comfort and safety, lower operating costs, and reduce unscheduled maintenance.

The weight of the drive system is especially important. It is significantly influenced by three key features of the configuration: the number of stages, the number of parallel power paths, and the gear ratio of the final stage. By using fewer stages, more parallel power paths, and larger reduction ratios at the final stage, the drive system weight can be reduced. More parallel power paths reduce system weight because a gear is sized by mesh loads, not by the total torque. With the total torque shared among multiple meshes, the gear sizes are reduced. Using a larger reduction ratio at the final stage reduces the system weight because the preceding stages then operate at lower torques.

Helicopters typically use a planetary arrangement (Fig. 1) for the final stage of the geartrain. This arrangement usually has 3 to 18 parallel power paths, with a maximum reduction ratio of about 7:1. A little used but promising alternative for the final stage is the split-torque or split-path arrangement (Fig. 2). With the split-path arrangement, a final-stage reduction ratio of up to 14:1 is possible with two parallel power paths. White (1974, 1983, 1984, 1985, 1989) has studied split-path designs and proposed their use in helicopters after concluding that such designs can offer the following advantages over traditional planetary ones:

1. A high speed reduction ratio at the final stage
2. A reduced number of gear stages
3. Lower energy losses
4. Increased reliability because of separate drive paths
5. Fewer gears and bearings
6. Lower noise levels from gear meshes
7. Lower overall drive system weight

Obviously, depending on the requirements of the vehicle, a split-path design can have significant advantages over the commonly used planetary transmission.

Despite some attractive features, split-path designs have seen little use in rotorcraft, because they have been considered relatively risky. A major risk inherent to these designs is that even gearboxes manufactured to precise tolerances might carry unequal loads in the two parallel paths. To compensate for this, designs proposed for or used in helicopters have featured a load-balancing device. For example, Smirnov (1990) and Cocking (1986) describe split-path designs that feature quill shafts to minimize the torque loading differences between the two parallel load
paths. However, the quill shafts, as do all load-sharing devices, add complexity and weight to the design, thereby offsetting some of the advantages over the proven planetary designs.

Kish (1993a) developed and studied a split-path gearbox that featured a torsionally compliant elastomeric load-sharing device. The gearbox was tested extensively both with and without the load-sharing device, and Kish made the following observations:

(1) Excellent load sharing was obtained when the gearbox was operated under nominal laboratory conditions and with the torsionally compliant load-sharing device installed.

(2) The torsionally compliant load-sharing device that was tested did not meet the requirements for field operation. For example, temperature cycles degraded the function of the device.

(3) Acceptable load sharing can be achieved without a special load-sharing device so long as manufacturing and installation tolerances are adequately controlled. Furthermore, the precision required for manufacture and installation is within the capabilities of available and proven manufacturing processes.

Thus, Kish's research (1993b) indicates that split-path transmissions can be successfully used in rotorcraft and that special load-sharing devices are not necessary. On the basis of this research, a split-path design was selected for use in the U.S. Army's Comanche helicopter. However, the load-sharing properties of such designs are not yet fully understood. For example, Kish (1993a) stated that although acceptable load sharing was demonstrated during the Advanced Rotorcraft Transmission project, the measured load sharing was not as good as had been predicted, considering the precision achieved in the manufacture and installation of the tested gearbox. He suggested that compliances that were not considered in the prediction of the load sharing were, in fact, significant.

The research reported herein was done to help enable the use of split-path transmissions without special load-sharing devices in the Comanche and future rotorcraft. An analytical method was developed and used to study the load-sharing properties of such designs. Here, the clocking angle of the geartrain is defined and shown to be the key design parameter in optimizing an otherwise fixed design for equal sharing of a design load. The load-sharing properties, optimal clocking angle, and effect of manufacturing tolerances are calculated for two gearbox designs—the NASA Lewis split-path test gearbox and the Comanche main rotor gearbox. The analytical predictions are compared to available experimental data. As a companion study, the load sharing of a split-path gearbox was evaluated experimentally. The results of that study are reported separately (Krantz and Delgado, 1996).

SPLIT-PATH CONCEPTS AND DEFINITIONS

In this report, a split path refers to a parallel shaft gearing arrangement, such as that shown in Figs. 2 and 3, where the input pinion meshes with two gears, thereby offering two paths to transfer power to the output gear. Designs that feature a load-sharing device such as an epicyclic torque splitter (White, 1983), balance beam (White, 1989), or quill shaft (Smirnov, 1990; Cocking, 1986) are not considered in this study. This study is limited to split-path designs without a load-sharing device or mechanism.

For purposes of discussion, a coordinate system and some concepts are defined as follows (see Fig. 3): A right-hand Cartesian coordinate system is established such that the z-axis is coincident with the output gear shaft, the positive y-axis extends from the output gear center.
To relate the clocking angle to load sharing, we can use the concept of the loaded windup of the geartrain. Envision that the output gear of a geartrain is rigidly fixed from rotating and a torque is applied to the input pinion. As the torque is applied, the input shaft will rotate some amount because of deformations. This rotation of the input pinion relative to the output gear is called the loaded windup. Using the definitions just established, we can see that the loaded windups of the two power paths are related to the clocking angle by

$$\beta = \frac{LWB - LWA}{GR}$$

(2)

where $LWA$ = the loaded windup of power path A; $LWB$ = the loaded windup of power path B; and $GR$ = the reduction ratio of the input pinion and compound shaft gear.

The torque transferred by each load path is a product of the loaded windup multiplied by the net torsional stiffness of that path. Considering this fact along with Eq. (2), we can treat the clocking angle $\beta$ as a design variable. For an otherwise fixed design, the clocking angle can be adjusted to split a design load equally between the two power paths. Of course, as already mentioned, the clocking angle must also allow for assembly of the geartrain.

**ANALYTICAL METHOD**

An analytical method was developed to study split-path load sharing. In so doing, the following assumptions were made:

1. The clocking angle $\beta$ is the only variable dimension; all other dimensions equal the nominal blueprint dimensions.
2. The significant deformations that contribute to the loaded windups are gearshaft torsion and bending, bearing center movement due to Hertzian deformations at rolling element contacts, gear tooth deflection, and bearing support/housing distortions.
3. Forces due to friction, thermal expansion, and inertia effects are negligible.
4. Bearing raceways remain as perfect circles, even under load.
5. For purposes of calculating gearshaft bending, bearings act as pinned connections and, therefore, do not support reaction moments.

In this method the loaded windups of each load path are calculated for a given input torque and a given load split between the two power paths. The calculated loaded windups can then be used in Eq. (2) to find the clocking angle $\beta$. By analyzing an array of input parameters, the relationship between the clocking angle and load sharing can be established for a given input torque. Under the assumptions stated, the gear tooth and bearing reaction force vectors can be calculated by applying gearing kinematics and the methods of statics. Then the deformations within the gearbox, and the windup caused by such deformations, are calculated. In the following paragraphs the calculation of each of the significant deformations is explained.

**Gearshaft Torsion**

To calculate gearshaft torsion, equivalent torsional spring constants for the shafts were determined. The complex shaft shapes were approximated by using a series of sections having constant cross sections. The torsional spring constants for each section were calculated by
where \( L \) is the section length, \( J \) is the polar moment of inertia, and \( G \) is the material's shear modulus. The equivalent torsional spring constants for the shafts were then determined by treating the shafts as a set of torsional springs in series.

**Gearshaft Bending**

To calculate gearshaft bending, the following classical differential equation for bending was used:

\[
E I \frac{d^2 y}{dx^2} = M
\]

where \( y \) is the deflection of the neutral axis, \( x \) is a local coordinate along the shaft length, and \( M \) (the bending moment), \( I \) (the moment of inertia), and \( E \) (Young's modulus) each may be a function of coordinate \( x \). To apply the equation, the complex shaft shapes were approximated as a series of sections, each having either a constant or a linearly varying moment of inertia (Fig. 4, for example). Equation (4) was integrated for each of the shaft sections, and the constants of integration were determined by applying matching boundary conditions for the shaft interior and also by assuming zero deflections and moments at the bearing locations. This procedure yielded a set of algebraic equations that were solved simultaneously by matrix algebra. The beam bending for each shaft was calculated twice, once each in two orthogonal planes; the resulting deflections were summed by vector addition.

**Bearing Deflections**

The force supported by the bearing causes Hertzian deformations at the rolling element contacts and deforms the overall shape of the raceways. In this study, only the Hertzian deformations were considered. The bearing deflections were calculated by an iterative procedure. The first step of the procedure was to guess the radial movement of the bearing center. Then this guess was the input to calculate the total radial deformation of each inner raceway, rolling element, and outer raceway contact. In the third step the radial force that was consistent with the just-calculated radial deformation was calculated for each rolling element contact. This third step was done by trial and error, that is, estimating the radial force on the rolling element and calculating the Hertzian contact deformations. The third step was done by trigonometry. To apply the equation, the complex shaft shapes were approximated as a series of sections, each having either a constant or a linearly varying moment of inertia (Fig. 4, for example). Equation (4) was integrated for each of the shaft sections, and the constants of integration were determined by applying matching boundary conditions for the shaft interior and also by assuming zero deflections and moments at the bearing locations. This procedure yielded a set of algebraic equations that were solved simultaneously by matrix algebra. The beam bending for each shaft was calculated twice, once each in two orthogonal planes; the resulting deflections were summed by vector addition.

**Gear Tooth Deflections**

The gear tooth deflections were calculated by using a spring stiffness equal to the mean of the time-varying mesh stiffness. The mesh stiffness was calculated by using the contact ratio of the gear pair and the method of Cornell (1981) to calculate the stiffness of a pair of contacting spur gear teeth. Cornell's method takes into consideration the effects of the tooth acting as a cantilever beam, the Hertzian contact deformations, the tooth base support, and the contact position. To calculate the mesh stiffness, the helical gears were modeled as an equivalent set of staggered spur gears. The preprocessor of computer program GEARDYNMULT (Boyd, 1989) was used to do the calculations of Cornell's method.

**Bearing Support (Housing) Deflections**

For lack of better information or analytical methods, the housing deformations at the bearing support locations were assumed to be in the direction of the bearing net radial force and to be equal in magnitude to one-half of the calculated bearing center movements due to Hertzian deformations.

Once all of the significant deformations were calculated, the resulting loaded windup of each power path was calculated. The loaded windup due to gear tooth deflections, gearshaft torsion, and gear center displacements can be calculated individually and summed by superposition. The loaded windup due to gear tooth deflections and gearshaft torsion was straightforward. The gear center displacements

\[
K = \frac{L}{JG}
\]

Figure 4.—Cross-sectional geometry, approximate geometry, and sectional properties used to predict gear shaft bending.
were calculated as the vector sum of gearshaft bending, bearing center movement, and housing distortion. Then the windup of each load path due to gear center movements was determined by applying the properties of involute gears. Figure 5 illustrates this idea; detailed equations are given in appendix B.

ANALYSIS OF THE NASA LEWIS SPLIT-PATH GEARBOX

The NASA Lewis split-path gearbox was studied by using the newly developed analysis method. This gearbox (Figs. 2 and 6) has two stages and is designed to operate at 373 kW (500 hp) with an input shaft speed of 8780 rpm. Gear and bearing design data are given in Tables I and II. In a case study, the load sharing was optimized at a selected design torque of 406 N·m (3590 in-lb) at the input shaft. The clocking angle tolerance that would produce acceptable load sharing was also calculated. Load sharing was considered acceptable if the more heavily loaded of the split load paths carried no more than 53 percent of the selected design torque. The results are given in Table III. The analysis predicted that the most heavily loaded split path would carry no more than 53 percent of the design torque so long as the clocking angle was maintained within the range $-0.00146$ to $-0.00060$ rad ($-5.1$ to $-2.1$ min).

To obtain some further insights, the components of the total loaded windup for each load path were calculated for the condition of equal load sharing (Fig. 7). The largest component of the total loaded windup is due to the lateral movements of the second-stage gears. The lateral movements are caused by the combined effects of bearing deformations, housing deformations, and gearshaft bending, and they are very significant because the first-stage gear ratio amplifies their effects. From Eq. (2) we see that since the two power paths have different total loaded windups, the optimal clocking angle deviates from zero. This deviation is entirely due to the lateral movements of the gears; therefore, a torsionally compliant load-sharing device that increases the compliances of both compound shafts by equal amounts would not optimize the load sharing of this gearbox since such a device has no effect on lateral movements.

ANALYSIS OF THE COMANCHE MAIN ROTOR GEARBOX

The Comanche helicopter's main rotor gearbox was analyzed with the newly developed method. This gearbox (Fig. 8) transmits power from two engines to the main and tail rotor shafts. It has three stages: a spiral bevel stage; a spur gear stage, where the load is split; and a double helical stage, where a total of four pinions recombine the power and drive the output gear. The output gear drives the tail rotor shaft through a double helical and bevel mesh. Each engine normally provides power at 820 kW (1100 hp) but can provide 1060 kW (1420 hp) during emergencies (e.g., when one engine is inoperative). Gear and bearing design data are given in Tables IV and V.

The same analytical method that was used to study the NASA Lewis split-path gearbox was used to study the Comanche gearbox, with modifications for calculating the lateral movement of the output gear. For the NASA Lewis gearbox, the movement of the bearing supports was calculated as being in the direction of the net bearing force and equal in magnitude to one-half of the total Hertzian deformations of that bearing. Since results of a finite element analysis of the Comanche gearbox were available (B. Hansen, 1994, Sikorsky Aircraft, personal communication), they were used to model the output gear bearing support stiffness as two springs. (The spring constants used were $16 \times 10^8$ N/m ($9.0 \times 10^5$ lb/ft.).

Figure 5.—Illustration showing windup of input pinion $\theta$ due to lateral movement of output gear. (a) Gears at initial angular orientations with output gear displaced horizontally. (b) Gears at final angular orientations after rigid body rotations to bring teeth into contact.
Input shaft

Shim pack

Output shaft

Figure 6.—Cross-sectional view of NASA split-path test gearbox.
Figure 7.—Total and relative contributions of loaded windups for NASA split-path test gearbox for an input shaft torque of 406 N-m (3590 in.-lb) split equally between the two power paths.

### TABLE I.—Gear Data of the NASA Split-Path Test Gearbox

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of teeth</th>
<th>Pitch diameter, mm</th>
<th>Face width, mm</th>
<th>Normal pressure angle, deg</th>
<th>Helix angle, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-stage pinion</td>
<td>32</td>
<td>51.1</td>
<td>44.5</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>First-stage gear</td>
<td>124</td>
<td>197.9</td>
<td>38.1</td>
<td>20</td>
<td>6</td>
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<tr>
<td>Second-stage pinion</td>
<td>27</td>
<td>68.6</td>
<td>66.0</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Second-stage gear</td>
<td>176</td>
<td>447.0</td>
<td>59.9</td>
<td>25</td>
<td>0</td>
</tr>
</tbody>
</table>

### TABLE II.—Bearing Data of the NASA Split-Path Test Gearbox

<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Inner raceway diameter, mm</th>
<th>Outer raceway diameter, mm</th>
<th>Number of rolling elements</th>
<th>Rolling element diameter, mm</th>
<th>Roller length, mm</th>
<th>Contact angle, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input shaft</td>
<td>Roller</td>
<td>50.0</td>
<td>69.1</td>
<td>13</td>
<td>9.53</td>
<td>13.20</td>
<td>–</td>
</tr>
<tr>
<td>Compound shaft</td>
<td>Roller</td>
<td>87.4</td>
<td>66.5</td>
<td>15</td>
<td>10.67</td>
<td>10.67</td>
<td>–</td>
</tr>
<tr>
<td>Output shaft</td>
<td>Roller</td>
<td>113.0</td>
<td>133.9</td>
<td>23</td>
<td>15.88</td>
<td>10.41</td>
<td>–</td>
</tr>
<tr>
<td>Input shaft</td>
<td>Duplex ball</td>
<td>48.9</td>
<td>71.3</td>
<td>14</td>
<td>11.13</td>
<td>–</td>
<td>29</td>
</tr>
<tr>
<td>Output shaft</td>
<td>Ball</td>
<td>109.1</td>
<td>140.9</td>
<td>14</td>
<td>15.88</td>
<td>–</td>
<td>0</td>
</tr>
</tbody>
</table>
### TABLE III.—Predicted Relationship Between Load Sharing and Clocking Angle for NASA Split-Path Test Gearbox

<table>
<thead>
<tr>
<th>Path A Load, percent</th>
<th>Path B Load, percent</th>
<th>Path A Loaded windup, rad</th>
<th>Path B Loaded windup, rad</th>
<th>Clocking angle, rad</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>53</td>
<td>0.01728</td>
<td>0.02293</td>
<td>-0.00146</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>0.01801</td>
<td>0.02199</td>
<td>-0.00103</td>
</tr>
<tr>
<td>53</td>
<td>47</td>
<td>0.01874</td>
<td>0.02105</td>
<td>-0.00060</td>
</tr>
</tbody>
</table>

### TABLE IV.—Gear Data of the Comanche Main Rotor Gearbox

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of teeth</th>
<th>Pitch diameter, mm</th>
<th>Face width, mm</th>
<th>Normal pressure angle, deg</th>
<th>Helix or spiral angle, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>First stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bevel pinion*</td>
<td>31</td>
<td>115.7</td>
<td>23.0</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>Bevel gear*</td>
<td>63</td>
<td>235.1</td>
<td>23.0</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>Second stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spur pinion</td>
<td>33</td>
<td>92.0</td>
<td>25.7</td>
<td>22.5</td>
<td>0</td>
</tr>
<tr>
<td>Spur gear</td>
<td>95</td>
<td>265.0</td>
<td>25.7</td>
<td>22.5</td>
<td>0</td>
</tr>
<tr>
<td>Third stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double helical pinion</td>
<td>13</td>
<td>58.4</td>
<td>31.6</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>Double helical gear</td>
<td>144</td>
<td>647.2</td>
<td>34.4</td>
<td>20</td>
<td>35</td>
</tr>
</tbody>
</table>

*Bevel mesh has shaft angle of 77°.
*Each half of the double helical members.

### TABLE V.—Bearing Data of the Comanche Main Rotor Gearbox

<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Pitch diameter, mm</th>
<th>Rolling elements per row</th>
<th>Rolling element diameter, mm</th>
<th>Roller length, mm</th>
<th>Contact angle, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-stage bevel pinion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outboard</td>
<td>Spherical roller</td>
<td>67.8</td>
<td>16</td>
<td>11.0</td>
<td>15.0</td>
<td>13.4</td>
</tr>
<tr>
<td>Inboard</td>
<td>Roller</td>
<td>65.4</td>
<td>18</td>
<td>9.0</td>
<td>9.0</td>
<td>0</td>
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<tr>
<td>First/second-stage shaft</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>Roller</td>
<td>77.5</td>
<td>18</td>
<td>11.0</td>
<td>11.0</td>
<td>0</td>
</tr>
<tr>
<td>Lower</td>
<td>Duplex ball</td>
<td>54.0</td>
<td>19</td>
<td>7.9</td>
<td>---</td>
<td>20.0</td>
</tr>
<tr>
<td>Second/third-stage shaft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>Roller</td>
<td>77.5</td>
<td>14</td>
<td>14.0</td>
<td>14.0</td>
<td>0</td>
</tr>
<tr>
<td>Lower</td>
<td>Roller</td>
<td>80.0</td>
<td>10</td>
<td>19.0</td>
<td>19.0</td>
<td>0</td>
</tr>
<tr>
<td>Third-stage output shaft</td>
<td>Tapered roller</td>
<td>381.8</td>
<td>100</td>
<td>8.8</td>
<td>13.2</td>
<td>16.5</td>
</tr>
</tbody>
</table>
along the aircraft centerline and $6.0 \times 10^8$ N/m ($3.5 \times 10^5$ lb/in.) perpendicular to the centerline.) The output gear of the Comanche gearbox is supported by a tapered roller bearing, but the developed analytical method is valid only for straight roller bearings. With the assumption that the deflection of the tapered roller bearing would be equal to that of an “equivalent” straight roller bearing, an equivalent bearing was defined. The cross section geometry of the tapered roller bearing midway along the roller length was used to define the geometry of the equivalent straight bearing for purposes of calculating the bearing deflection.

The optimal clocking angle for each engine load path that would produce equal loads in each split path with both engines operating at normal flight power was calculated. Also, each path’s allowable clocking angle tolerance was determined such that the most heavily loaded split path would carry no more than 53 percent of the power of one engine. The results, presented in Table VI, show that so long as the clocking angles are maintained to within $-0.00070$ to $+0.00176$ rad ($-2.4$ to $+6.1$ min) for engine 1 and to within $+0.00331$ to $+0.00584$ rad ($+6.1$ to $+20.1$ min) for engine 2 the 53-percent-load maximum can be achieved.

![Figure 8.—Split-path design for two engines used for Comanche helicopter.](image)

**TABLE VI.—Predicted Relationship Between Load Sharing and Clocking Angle for the Comanche Main Rotor Gearbox**

<table>
<thead>
<tr>
<th>Path A</th>
<th>Path B</th>
<th>Path A</th>
<th>Path B</th>
<th>Path A</th>
<th>Path B</th>
<th>Path A</th>
<th>Path B</th>
<th>Path A</th>
<th>Path B</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>0.0321</td>
<td>0.0336</td>
<td>+0.00053</td>
<td>0.0261</td>
<td>0.0393</td>
<td>+0.00458</td>
</tr>
<tr>
<td>53</td>
<td>47</td>
<td>53</td>
<td>47</td>
<td>0.0335</td>
<td>0.0315</td>
<td>-0.00070</td>
<td>0.0279</td>
<td>0.0374</td>
<td>+0.00331</td>
</tr>
<tr>
<td>53</td>
<td>47</td>
<td>47</td>
<td>53</td>
<td>0.0343</td>
<td>0.0318</td>
<td>-0.00086</td>
<td>0.0244</td>
<td>0.0416</td>
<td>+0.00600</td>
</tr>
<tr>
<td>47</td>
<td>53</td>
<td>53</td>
<td>47</td>
<td>0.0299</td>
<td>0.0355</td>
<td>+0.00192</td>
<td>0.0278</td>
<td>0.0369</td>
<td>+0.00315</td>
</tr>
<tr>
<td>47</td>
<td>53</td>
<td>47</td>
<td>53</td>
<td>0.0307</td>
<td>0.0358</td>
<td>+0.00176</td>
<td>0.0243</td>
<td>0.0411</td>
<td>+0.00584</td>
</tr>
</tbody>
</table>

(Engines operating at 820 kW (1100 hp) per engine.)

9
TABLE VII.—Predicted Load Sharing for the Comanche Main Rotor Gearbox Operating Under Emergency* Conditions for Clocking Angles That Maintain a 53- to 47-Percent Load Split Under Cruise Conditions

<table>
<thead>
<tr>
<th>Clocking angles in assembled configuration, rad</th>
<th>Engine 1 power to path A, percent</th>
<th>Engine 2 power to path B, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine 1</td>
<td>Engine 2</td>
<td></td>
</tr>
<tr>
<td>At cruise condition</td>
<td>At one engine inoperative</td>
<td></td>
</tr>
<tr>
<td>At nominal clocking angles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0.00053 -0.00458</td>
<td>50.0</td>
<td>53.5</td>
</tr>
<tr>
<td>At maximum clocking angles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0.00176 -0.00584</td>
<td>47.0</td>
<td>51.2</td>
</tr>
<tr>
<td>At minimum clocking angles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.00070 +0.00331</td>
<td>53.0</td>
<td>55.7</td>
</tr>
</tbody>
</table>

*Emergency condition is defined as one engine inoperative.

TABLE VIII.—Experimentally and Analytically Determined Power Distribution Among Split Paths of Comanche Main Rotor Gearbox

<table>
<thead>
<tr>
<th>Ranking by load level</th>
<th>Engine number</th>
<th>Power path</th>
<th>Engine power transmitted by split path, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Experiment</strong></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>A</td>
<td>58</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>A</td>
<td>53</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>B</td>
<td>47</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>B</td>
<td>42</td>
</tr>
</tbody>
</table>

The load sharing of the Comanche gearbox operating under emergency conditions (with one inoperative engine) was studied. The clocking angles considered in this part of the study were those that provided acceptable load sharing under normal operating flight power. Results of the calculations are presented in Table VII. Under normal flight power and with the clocking angles at maximum acceptable dimensions, the most heavily loaded split path will carry 435 kW (583 hp) or 53.0 percent of an engine's normal flight power. For the same clocking angles and with only engine 2 operating, the most heavily loaded split path will carry 597 kW (801 hp) or 56.4 percent of emergency condition power. During the emergency power condition, the power output of the operating engine increases by 29 percent over the normal flight condition, but the power carried by the most heavily loaded split path may increase by as much as 37 percent. Thus the load sharing of a split-path gearbox under normal two-engine conditions can be very different from the load sharing for emergency, one-engine-inoperative power conditions.

It is reasonable to expect that these tolerances can be maintained during manufacture. Therefore, split-path transmissions without load-sharing devices can be built so as to maintain acceptable load sharing by using proven manufacturing capabilities. This is encouraging evidence that these transmissions could be successfully used for rotorcraft.
COMPARISON OF ANALYTICAL AND EXPERIMENTAL Results

The results of this analytical study were compared to the results of the companion experimental study (Krantz and Delgado, 1996). Results describing the percentage of the total torque carried by power path A as a function of the clocking angle are compared in Fig. 9. Both the analyses and experiments indicate that power path A will carry the desired 50 percent of the total torque at a clocking angle of approximately _0.001 rad. For a given clocking angle deviation from the optimal value, the analysis predicts a somewhat greater deviation from equal load sharing than was measured experimentally. For example, if 53 to 47 percent of the total torque is considered the acceptable load for equal load sharing than was measured experimentally. For example, if 53 to 47 percent of the total torque is considered the acceptable load for power path A, the analysis suggests a tolerance for the clocking angle of about _0.0004 rad, whereas the experiments suggest the tolerance was about _0.0007 rad.

Analyses were also conducted to predict the results of experiments done to measure the load sharing of the prototype main rotor gearbox for the Comanche helicopter. The prototype gearbox was designed for nominal clocking angles of zero for both engines. The results of the experiment indicate that the clocking angles of the tested gearbox were indeed near zero (experimental work done by J. Kish, 1995, Sikorsky Aircraft; personal communication). Experimental and analytical results are compared in Table VIII. The analytically predicted rankings of the split paths (from highest to lowest loads) are confirmed by the experiments. The measured and predicted loads for the individual split paths match to within about 3 percent of one engine’s power. For both gearboxes studied, the analytical predictions compare favorably to the experimental results.

The differences between the analytical and experimental results presented here are probably due to the net effects of several assumptions made in developing the analytical method. One significant assumption was that the bearing races remained as perfect circles, even under load. A second significant assumption was that the magnitude of the housing deformations at the bearing supports equaled one-half of the bearing center movements due to rolling element and raceway deformations. If a more precise analysis is desired, perhaps the validity of these two assumptions should be assessed.

SUMMARY

This investigation was done to better understand split-path transmissions without load-sharing devices and to support their use in the Comanche and in future rotorcraft. An analytical method was developed to calculate the effects of deformations on load sharing. This method was applied to both the NASA split-path gearbox and the Comanche main rotor gearbox. The following results and conclusions were obtained:

1. The clocking angle can be considered a design variable for split-path gearboxes. For an otherwise fixed design, the clocking angle can be adjusted to split a design load equally between the two power paths.

2. For the NASA split-path gearbox, the analysis predicts that the most heavily loaded split path will carry more than 53 percent of the design torque so long as the clocking angle is maintained within the range _0.00146 to _0.00060 rad (_5.0 to _2.1 min).

3. For the Comanche main rotor gearbox, the most heavily loaded split path will carry no greater than 53 percent of one engine power so long as the clocking angles are kept to within _0.00070 to _0.00176 rad (_2.4 to 6.1 min) for engine 1 and to within _0.00331 to _0.00584 rad (_11.4 to _20.1 min) for engine 2.

4. The load sharing of a split-path gearbox with two engines operating under normal flight conditions can be very different from the load sharing for emergency (one-engine-inoperative) power conditions.

5. The analytical predictions compare favorably to experimental data.

6. Split-path transmissions without load-sharing devices can be built to maintain acceptable load sharing by using proven manufacturing capabilities. This is encouraging evidence that these transmissions could be successfully used for rotorcraft.

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REFERENCES


APPENDIX A
CALCULATION OF THE DEFORMATIONS OF ROLLING ELEMENT AND RACEWAY CONTACTS

The methods presented by Hamrock (1991) were used to calculate the deformations of rolling element and raceway contacts. The equations that follow are approximate solutions of the classical Hertzian theories. Material properties are introduced into the calculations by defining an effective elastic modulus $E'$ as

$$E' = \frac{2}{\frac{1}{E_1} + \frac{1}{E_2} - \nu_1^2 - \nu_2^2}$$

where $E$ = Young’s modulus, $\nu$ = Poisson’s ratio, and the subscripts 1 and 2 indicate the rolling element and raceway materials, respectively. For cylindrical roller bearings, the curvatures of the bearing geometry are introduced into the calculation by

$$R_x = \frac{r_{bx}r_{ax}}{r_{bx} - r_{ax}}$$

where $r_{bx}$ is the raceway radius, $r_{ax}$ is the roller radius, the plus sign designates an inner raceway, and the minus sign designates an outer raceway. The dimensionless load $W'$ is defined as

$$W' = \frac{F}{E'R_xl}$$

where $F$ is the load on a single rolling element and $l$ is the rolling element’s effective length. The contact semiwidth $b$ is calculated by

$$b = R_x \left\{ \frac{8W'}{\pi} \right\}^{1/2}$$

The maximum deformation of a roller raceway contact $\Delta_{roll}$ is then calculated by

$$\Delta_{roll} = \frac{2W'R_x}{\pi} \left\{ \frac{2}{3} + \ln\left( \frac{2r_{ax}}{b} \right) + \ln\left( \frac{2r_{bx}}{b} \right) \right\}$$

For ball bearings, the conformity of the geometry is introduced into the calculations by

$$f = \frac{r}{d}$$

where $r$ is the raceway groove radius and $d$ is the ball diameter (Fig. 10). The curvatures of the ball bearing geometries are calculated by

$$R_y = \frac{fd}{2f - 1}$$

where $d_o$ is the outer raceway diameter (the inner diameter of the outer race), $d_i$ is the inner raceway diameter, $d$ is the ball diameter, $\gamma$ is the bearing contact angle, the plus sign designates an outer raceway contact, and the minus sign designates an inner raceway contact. The curvature sum $R$ is defined as

$$R = \left\{ \frac{1}{R_x} + \frac{1}{R_y} \right\}^{-1}$$

The curvature ratio $\alpha$ is defined as

$$\alpha = \frac{R_y}{R_x}$$

The Hertzian contact ellipticity parameter $K$ is then calculated as

$$K = \alpha^{(2\pi)}$$

and the elliptical integral terms $C$ and $A$ as

$$C = 1 + \frac{\pi}{2} - 1 \right\} \ln \alpha$$

$$A = \frac{\pi}{2} + \frac{\pi}{2} - 1 \right\} \ln \alpha$$
The maximum deformation in a ball and raceway contact $\Delta_{ball}$ can then be calculated as

$$\Delta_{ball} = A \left( \frac{9}{2CK} \left( \frac{F}{\pi KE} \right)^2 \right)^{1/3}$$

where $F$ is the load carried by a single ball. These methods were used to calculate the load carried by each rolling element of the bearing, and all of the load vectors were summed to calculate a net bearing load. The relation between the net radial load and radial deformation for a rolling element bearing is typically nonlinear, as illustrated by Fig. 11. The following FORTRAN subroutines were used to do the calculations for this study:

FORTRAN subroutine for roller bearing deflections:
```fortran
subroutine rolldf, tl, dr, di, do, rl, er, ppr, ei, pri, eo, pro, ao, ao
subroutine to calculate the deflection for a single roller element, inner race, outer race conjunction for roller bearings

version 1.0 6/22/93 tim krontz
version 1.1 12/27/93 changed name to 6 letters to keep within standard FORTRAN convention
version 1.2 2/7/94 changed coefficients within log expressions from 4 to 2, per NASA RP-1126


required inputs
t = total load
dr = roller diameter
di = inner raceway diameter
do = outer raceway diameter
rl = roller length
er = Young's modulus for roller
ppr = Poisson's ratio for roller
ei = Young's modulus for inner race
pri = Poisson's ratio for inner race
eo = Young's modulus for outer race
pro = Poisson's ratio for outer race

outputs

total deformation
inner race deformation
outer race deformation

calculate elastic coefficients
inner race & roller
eroll=(1.-ppr*ppr)/er
eirac=(1.-pri*pri)/ei
epi=2./(eroll+eirac)

outer race & roller
eorac=(1.-pro*pro)/eo
epo=2./(eirac+eorac)
```

FORTRAN subroutine for ball bearing deflections:
```fortran
subroutine balldf(tl, di, do, fi, fo, del)
subroutine to calculate the deflection for a single rolling element, pure radially loaded inner race-ball outer race conjunction-to be used for calculating ball bearing deflections
```

Figure 11.—Example of typical nonlinear function relating radial deflection of rolling element bearing to radial load.

**required inputs**
- \( tl \) = total load (lb)
- \( d \) = ball diameter (in.)
- \( di \) = inner raceway diameter (in.)
- \( do \) = outer raceway diameter (in.)
- \( fi \) = inner race conformity * see notes
- \( fo \) = outer race conformity * see notes

**outputs**
- \( \text{del} \) = total deformation in direction of applied load

---

Notes:

1. It is assumed that the material is steel with \( E = 380 \times 10^6 \) and Poisson's ratio = 0.29.

2. The race conformities (f) are often not available in bearing catalogs. By definition, the race conformity is greater than or equal to 0.5. Most bearings are in the range 0.51 < f < 0.54, with f = 0.52 the most common value. Often, the outer race conformity is smaller than the inner race conformity in order to equalize the contact stresses of the inner and outer races. The difference in conformities usually does not exceed 0.02.

---

```c
real ki, ko
pi=atan(1.)*4.
eprim=32.755e+06

calculate curvature terms

dc=0.5*(do-di)
rci=dc*(dc-di)/(2.*dc)
rco=dc*(dc-di)/(2.*dc)
ryi=fi*dc/(2.*fi-1.)
ryo=fo*dc/(2.*fo-1.)
ri=1./(1./rci+1./ryi)
ro=1./(1./rco+1./ryo)
alpha=ri/ryi
alphao=ryo/rci
ki=alpha**2/(2./pi)
ko=alphao**2/(2./pi)
q=pi/2.-1.
ei=1+(q/alpha)
eo=1+(q/alphao)
ffi=(pi/2.)*q*log(alpha)
ffo=(pi/2.)*q*log(alphao)
t1=9./(2.*ei*ri)
t2=t1/pi*ki*eprim
del1=ffi*t1*t2**(1./3.)

t1=9./(2.*eo*ro)
t2=t1/pi*ko*eprim
delo=ffo*t1*t2**(1./3.)

del=del1+delo
return
end
```
Appendix B
Calculation of Pinion Windup Resulting From the Movements of Gear Centers

The properties of the involute were used to calculate the pinion windup resulting from the movements of the gear centers. These movements occur because of gear support forces that arise when torque is carried by the gear pair. In the description that follows, a gear's angular orientation is defined as the polar angle, in the global coordinate system, of the vector originating at the gear center and ending at the intersection of the gear's base circle and the involute curve of interest. If we use the gear member as a reference, the pinion windup is the difference between the pinion's angular orientations when the geartrain is loaded and that when the geartrain is unloaded.

To calculate the angular orientation of the gear under no load, we use the known radii of the base circles, the global X-Y Cartesian coordinates of the gear centers, and the radial distance from the gear center to the contact point along the line-of-action (Fig. 12). We also establish a local X'-Y' coordinate system such that the Y' axis is coincident with the line-of-centers. Further, we assume that the driving member rotates clockwise (see Eqs. (B 16) to (B 18) in this appendix for the case of the driving member rotating counterclockwise). The angle $\Omega_1$ that relates the global and local coordinate systems is given by

$$\Omega_1 = \arctan \frac{Y_{pl} - Y_{Gl}}{X_{pl} - X_{Gl}} - \frac{\pi}{2} \quad (B1)$$

The installed center distance and pressure angles are

$$MN = \sqrt{(X_{pl} - X_{Gl})^2 + (Y_{pl} - Y_{Gl})^2} \quad (B2)$$

$$\eta_1 = \arccos \left( \frac{t\rho + r}{MN} \right) \quad (B3)$$

Next, the length of line segment AB may be calculated from the properties of right triangle ABM, since the length of line segment BM is known to be equal to the radius to the contact point:

$$AB = \sqrt{(BM)^2 - r_{pl}^2} \quad (B4)$$

By the properties of the involute, the length of line segment AB equals arc length AC. Therefore, angle $\lambda_1$ may be calculated as

$$\lambda_1 = \frac{AB}{r_{pl}} \quad (B5)$$

In Fig. 12, we see that $\Omega_1$ is positive counterclockwise, so the gear angular orientation angle $\sigma_g$ can be calculated by

$$\sigma_g = \frac{\pi}{2} + \eta_1 - \lambda_1 + \Omega_1 \quad (B6)$$

Equations (B1) to (B6) establish a general procedure for calculating the gear angular orientation angle.

Equations (B7) to (B15) establish a general procedure to calculate the pinion angular orientation angle if the gear centers' coordinates, the radii of the base circles, and the gear angular orientation angle $\sigma_g$ (Fig. 13) are known. A local X'-Y' coordinate system is established such that the Y' axis is coincident with the line-of-centers. The angle $\Omega_2$ that relates the local and global coordinate systems is given as

$$\Omega_2 = \arctan \frac{Y_{p2} - Y_{G2}}{X_{p2} - X_{G2}} - \frac{\pi}{2} \quad (B7)$$

The operating center distance and pressure angles can be calculated as
The length of line segment EF can be found by subtraction 

\[ \overline{EF} = \overline{DF} - \overline{DE} \]  

(B13)

By the properties of the involute, arc length FH equals the length of line segment EF, so angle \( \Lambda \) can be calculated from 

\[ \Lambda = \frac{\overline{EF}}{r_p} \]  

(B14)

Finally, the pinion angular orientation angle \( \sigma_p \) can be calculated from 

\[ \sigma_p = \frac{3\pi}{2} + \eta_2 - \Lambda + \Omega_2 \]  

(B15)

To apply the just-described procedure to calculate loaded windup, we assume that the gear train is unloaded and (without loss of generality) that the gear pair is operating at the pitch point. Then Eqs. (B1) to (B6) may be used to calculate the gear angular orientation angle. Equations (B7) to (B15) may then immediately be applied to calculate the pinion’s angular orientation angle under zero load. Next, we use new values for the gear centers’ locations (the deformed locations after load is applied) and, keeping the same value for the gear angular orientation angle, again apply Eqs. (B7) to (B15) to calculate the pinion angular orientation angle with load applied. Subtracting the pinion angular orientation angles (the loaded angle minus the zero load angle) yields the pinion loaded windup.

The procedure just developed is valid for the driving member rotating clockwise. For the case of the driving member rotating counterclockwise, the same procedure may be used if the following three changes are made:

1. Substitute the following equation for Eq. (B6):
   \[ \eta_2 = \frac{\pi}{2} + \eta_2 + \Omega_2 - \sigma_g \]  

2. Substitute the following equation for Eq. (B10):
   \[ \lambda_2 = \sigma_g - \Omega_2 - \left( \frac{\pi}{2} - \eta_2 \right) \]  

3. Substitute the following equation for Eq. (B15):
   \[ \sigma_p = \frac{3\pi}{2} + \eta_2 + \Lambda + \Omega_2 \]  

In this study, the following FORTRAN subroutines, which are valid for the case of the driving member rotating clockwise, were used to calculate pinion loaded windup due to movements of the gear centers. A companion routine called ANGLE is also listed.
FORTRAN subroutines used for loaded windup calculations

subroutine gearao(xp, yp, rp, xg, yg, rg, rcpg, thetag)
  gearao - FORTRAN subroutine to calculate the GEAR Angular Orientation (GEARAO) in the global coordinate system. The angular orientation is defined by the angle from the global X-axis to the vector originating at the gear center and ending at the intersection of the base circle and the involute curve. The returned angle is positive for counterclockwise.

written by Tim Krontz
Version 1.0 11/29/93

C list of arguments
C inputs
xp, yp = global coordinates of pinion center
xg, yg = global coordinates of gear center
rp = base radius of pinion
rg = base radius of gear
rcpg = radius to contact point on gear
C outputs
thetag = angular location of intersection of gear base circle with involute curve
values of input variables not changed upon return

C Notes:
1. This method ASSUMES that the center distance cd between the gears is larger than the sum of the inputs for the base radii rg and rp. There is no error checking !
2. This method assumes that the pinion is the driver rotating clockwise; it is valid for the gear driving counterclockwise.
3. This subroutine calls another routine-ANGLE.
4. Angle thetag is calculated within the range of [-pi/2 < thetag < 3*pi/2].

pi = 4.*atan(1.)
call angle(xg, yg, xp, yp, gamma)
gamma = gamma - pi/2.
calpha = acos((rp+rg)/
  * sqrt((xp-xg)*(xp-xg)+(yp-yg)*(yp-yg)))
tau = (sqrt((rcpg*rcpg)-(rg*rg))/rg)

thetag = pi/2. + alpha - tau + gamma
restrict the output to -pi/2 < thetag < 3*pi/2
if (thetag .gt. (3.*pi/2.)) thetag=thetag-2.*pi
if (thetag .lt. (-1.*pi/2.)) thetag=thetag+2.*pi
return
end

subroutine pinao(xp, yp, rp, xg, yg, rg, thetag, thetap)
  pinao - FORTRAN subroutine to calculate the PINion Angular Orientation (PINAO) in the global coordinate system. The angular orientation is defined by the angle from the global X-axis to the vector originating at the pinion center and ending at the intersection of the base circle and the involute curve. The returned angle is positive for counterclockwise.

written by Tim Krontz
Version 1.0 11/29/93 Original
Version 1.1 11/30/93 Revised: Added if statement to restrict variable tau—involute angle of gear—to be less than pi

C list of arguments
C inputs
xp, yp = global coordinates of pinion center
xg, yg = global coordinates of gear center
rp = base radius of pinion
rg = base radius of gear
thetag = angular location of intersection of gear base circle with involute curve
C outputs
thetap = angular location of intersection of pinion base circle with involute curve
values of input variables not changed upon return

C Notes:
1. This method ASSUMES that the center distance cd between the gears is larger than the sum of the inputs for the base radii rg and rp. There is no error checking !!
2. This method assumes that the pinion is the driver rotating clockwise; it is valid for the gear driving counterclockwise.
3. This subroutine calls another routine-ANGLE.
4. Angle thetap is calculated within the range of [-pi/2 < thetap < 3*pi/2].

pi = 4.*atan(1.)
call angle(xg, yg, xp, yp, gamma)
gamma = gamma - pi/2.
alpha = acos((rp+rg)/
            sqrt((xp-xg)*(xp-xg)+(yp-yg)*(yp-yg)))
tau = pi/2. + alpha + gamma - thetag
if (tau .gt. pi) tau = tau-2.*pi
omega = (((rp+rg) * tan(alpha)) - (tau * rg))/rp
thetap = 3.*pi/2. + alpha - omega + gamma
restrict output to range -pi/2 < output < 3*pi/2
if (thetap .gt. (3.*pi/2.)) thetap = thetap-2.*pi
if (thetap .lt. (-1.*pi/2.)) thetap = thetap+2.*pi
return
end

subroutine angle(x0,y0,x1,y1,zeta)
angle - FORTRAN subroutine to calculate the angular
orientation of a vector.
The origin of the vector is at x0,y0.
The end of the vector is at x1,y1.
The angle is located from the X-axis with angles
measured positive counterclockwise.
written by Tim Krontz
Version 1.0 11/22/93

pi=4.*atan(1.)
dy=y1-y0
dx=x1-x0
if (dx) 10,20,10
10 zeta=atan2(dy,dx)
   if ( zeta .lt. 0.) zeta=zeta+pi-pi
   return
20 zeta=pi/2.
   if (dy, .lt. 0.) zeta=zeta+pi
   return
end
# A Method to Analyze and Optimize the Load Sharing of Split Path Transmissions

**6. AUTHOR(S)**

Timothy L. Krantz

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

NASA Lewis Research Center  
Cleveland, Ohio 44135-3191  
and  
Vehicle Propulsion Directorate  
U.S. Army Research Laboratory  
Cleveland, Ohio 44135-3191

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**13. ABSTRACT (Maximum 200 words)**

Split-path transmissions are promising alternatives to the common planetary transmissions for rotorcraft. Heretofore, split-path designs proposed for or used in rotorcraft have featured load-sharing devices that add undesirable weight and complexity to the designs. A method was developed to analyze and optimize the load sharing in split-path transmissions without load-sharing devices. The method uses the clocking angle as a design parameter to optimize for equal load sharing. In addition, the clocking angle tolerance necessary to maintain acceptable load sharing can be calculated. The method evaluates the effects of gearshaft twisting and bending, tooth bending, Hertzian deformations within bearings, and movement of bearing supports on load sharing. It was used to study the NASA split-path test gearbox and the U.S. Army’s Comanche helicopter main rotor gearbox. Acceptable load sharing was found to be achievable and maintainable by using proven manufacturing processes. The analytical results compare favorably to available experimental data.

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