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Concepts for Variable/Multi-Speed Rotorcraft Drive System

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Abstract

In several recent studies and on-going developments for advanced rotorcraft, the need for variable or multi-speed capable rotors has been raised. A speed change of up to 50 percent has been proposed for future rotorcraft to improve overall vehicle performance. Accomplishing rotor speed changes during operation requires both a rotor that can perform effectively over the operation speed/load range, and a propulsion system that can enable these speed changes. A study has been completed to investigate possible drive system arrangements that can accommodate up to the 50 percent speed change. Several concepts will be presented and evaluated. The most promising configurations will be identified and developed for future testing in a sub-scaled test facility to validate operational capability.

Introduction

Rotorcraft propulsion is a critical element of the overall rotorcraft. Unlike fixed wing aircraft, the rotor/propulsion system provides lift and control as well as forward thrust. As a result, the rotorcraft engine/gearbox system must be highly reliable and efficient. Future rotorcraft trends call for more versatile, efficient, and powerful aircraft, all of which challenge state-of-the-art propulsion system technologies. Variable speed rotors have been identified as having a large impact on many critical rotorcraft issues.

Currently, rotor speed can be varied only a small percentage by adjusting the speed of the engine. This is generally limited by engine efficiency and stall margin permitting speed changes limited to approximately 15 percent maximum (used in current tilt-rotor applications).

The recent NASA Heavy Lift Study (ref. 1) has shown that variable speed propulsion is necessary for all aircraft concepts studied. Variable speed propulsion, without loss of efficiency and torque, is necessary to permit high speed operation with reduced noise. Previous NASA variable speed transmission studies concentrated on 15 percent speed changes (refs. 2 and 3). The heavy lift study suggests that increased speed variations of 50 percent will have a dramatic effect on reducing external noise while increasing rotorcraft performance.

To achieve this large speed variation capability, advanced variable/multi-speed drive system concepts must be developed. This report summarizes an effort to identify viable concepts for both a two-speed and variable speed drive transmission configuration. Efforts will culminate with laboratory testing of a reduced-scale variable/multi-speed drive system to validate system level tools and concepts.

Study Objectives

This report summarizes the results of a study directed at creating multiple variable/multi-speed transmission concepts, identifying the most viable concept(s), and identifying a plan for future development and scale model testing of those concepts. The primary requirement for this endeavor is to identify/create a viable concept for a transmission with a high-range ratio (1:1) and low-range reduction ratio of 50 percent (2:1) through a speed change mechanism. The above transmission concept could be added as an element within the overall drive system resulting in overall ratios of 100:1 to 50:1 in the aircraft. Both discrete two-speed and variable speed configurations are considered herein.

This effort is focused at the concept level in the creation and development of multi/variable speed transmissions. Concepts are created and portrayed using computer aided design (CAD) to provide details such as the introduction of lubrication, sealing requirements, mounting features, and assembly features.

The amount of power and speed required is dependent upon the particular drive concept and device type. The questions to be answered are: How much power and what speeds are required for speed range changes and how much is required for periods of sustained split-power operation, if applicable? The specific speed varying device(s) is not identified at this stage. However, some concepts and ideas are contained within this report.

Concept Creation and Development

A chronology of concept creation, development, and directions pursued is presented below.

Upon starting this study, the initial thought was that any concept(s) to be created should be original. This led to review of some texts in the area of gearing for some basic ideas (refs. 4 to 6). In addition, it was thought that concept creation should begin with a variable speed drive as it seemed better suited to the application. A variety of variable speed devices were reviewed, though none stood out as something being readily accepted for rotorcraft applications. All variable speed configurations employed traction/friction drive or components such as belts and pulleys, which are unacceptable for the power and speeds associated with this application. It was at this point that the realization that a traditional variable drive (traction/friction drive via variable geometry) would not suffice, but perhaps continuous ratio variability could be synthesized.

From the above, an initial variable drive concept emerged based upon a two-engine driven planetary-differential (sun-in, ring-in, and carrier-out) used in a hoisting application, (ref. 6, p. 263). The configuration was thought to be adaptable to a scheme consisting of one engine (input) and the second engine (input) replaced with an external speed controller device. The concept did not seem to have much merit and was rejected at first. Additional factors which discounted the above concept were that it was not a classic continuously variable transmission per se; it had no contour surfaces, nor variable geometry, being comprised of a gear train. Lastly, the second input was surely a weight liability. However, it was retained as a remote possibility due to inherent variable speed output via the differential. The configuration, envisioned as a variable output drive, is shown in figure 1.

Next, a schematic of an inline discrete two-speed transmission was conceived and evolved into a CAD layout. The concept included a clutch, thus requiring an immediate need for a representative scale clutch configuration. Since any two-speed transmission

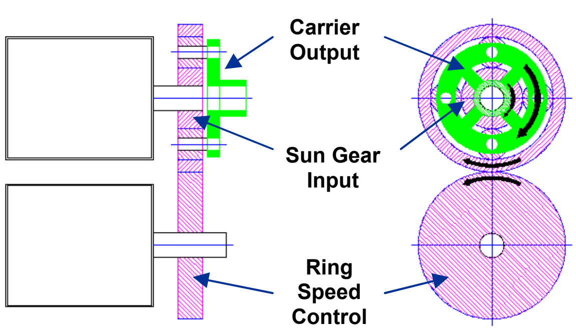

Figure 1.—Differential planetary drive.

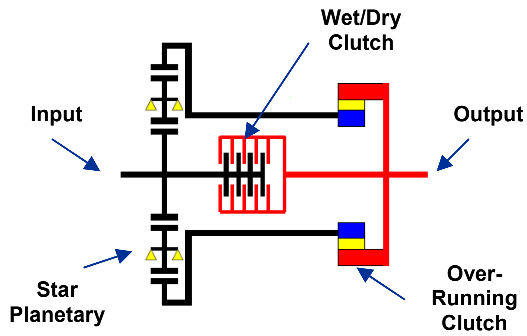

Figure 2.—Initial inline two-speed concept schematic.

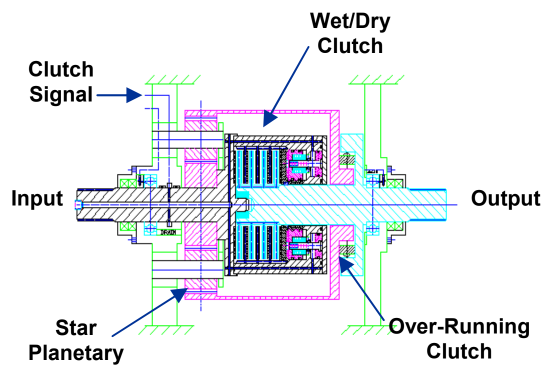

Figure 3.—Initial inline two-speed concept CAD concept corresponding to above schematic.

configuration intended to change speed range during power transfer requires a means of disengaging power during ratio change, conceptualization focused toward a clutch (presented later in the Concept Descriptions section). The schematic and corresponding CAD configuration is shown in figures 2 and 3.

During development of the initial two-speed transmission concept above, a short coming relative to the output direction of rotation between the two ratios emerged. The concept employs a planetary gear system with fixed star gears where the sun gear is the input and the ring gear is the output. Powering in low speed range causes the ring gear to rotate in a direction opposite to that of the sun gear, and opposite to the output of the high speed range which is direct coupled via the clutch. To make this basic concept viable, the immediate challenge was to determine the best approach to reverse low range output rotation. It was this shortcoming that became the impetus for the creation of several reversing concepts that are presented later.

With a few two-speed concepts underway, attention returned to pursue a variable speed configuration. Though a specific candidate CV (continuously variable) element had not been identified, a CV element of some variety was thought to be needed since a discrete multi-speed transmission was not perceived as the best configuration for the given application for a variety of reasons to be discussed later. As the project advanced, an unspoken direction emerged; power transmission via fluid traction would not be well received. A dilemma of "what to do" became a dominant theme. Focus shifted toward capitalizing on desirable aspects of a CV element thorough synthesizing CV. The above pointed to a variable direct-mechanical drive such as the differential or planetary gear system with some to-be-determined outside control device (externally powered or internally driven). This was the initial concept.

As mentioned earlier, the initial basic concept based on a two-input geared differential was almost dismissed. It was retained due to its inherent power transmission via gears while having variable output. From the perspective of power transfer, there is a lack of acceptance of flight being powered via fluid-traction or fluid-impulse power transmission in lieu of power transmission by mechanical means (i.e., gearing). Desires of "positive drive" and "continuously variable ratio" originate from within the various entities of the aeronautics industry, civil, and government stakeholders which manufacture or use rotary wing aircraft. The above being in direct conflict pose a difficult challenge.

Another possible direction/solution resulting from the above dichotomy is a two-speed transmission with a CV speed-matching element. This may be a better operational configuration for this application than a true CV transmission. The hybrid configuration overcomes some undesirable aspects of both the discrete two-speed transmission and the variable speed transmission while capitalizing on positive aspects from both. The idea of adapting the two-speed concepts to include a variable element was realized thus resulting in plausible quasi-variable speed drive configurations. Concepts for two such drives, which include either a controller or variator, were configured and are presented later. Although it has been stated that power transmission via traction fluids is not perceived as desirable for quasi-full-time operation in either the high or low speed ranges, a CV element may be suitable to take on full power requirements for short duration, or perhaps the lesser power requirement of matching speeds, during speed range transition. Another area in which a CV element might excel is in a split-power transmission configuration where the CV element is only required to transmit a portion of the required power during a range transition.

Since the focus of this study is the overall transmission configuration, not detailed examination of any specific components, the selection, or design of a specific CV element within the various concepts is to be addressed during the next stage of development. Design of such a device would be a formidable task in itself as evidenced by the number of configurations and contributors pursuing their development. However, if employed in this application a mechanical take-off driven toroidal based variator configuration is thought to be the best.

An alternative to using a take-off driven variator as a CV element is to employ a speed controller (internal/external powered). This led to an idea of adapting the two-speed concepts to also include a variable speed controller to render a quasi-variable speed drive configuration. Concepts for two such drives were configured and are presented later. Both power and speed requirements for the specific application and configuration will need to be reviewed to determine if a suitable candidate device can be identified.

The above adaptations of the two-speed basis concepts to include variable speed output were then configured to be modular units. All of the above are presented later in the Concept Descriptions section.

System Considerations

The controllability and system dynamics aspects of discrete versus continuous variable speed control are significant design considerations. Each configuration has both merits and liabilities. The discrete ratio drive is the most straight forward, reliable, cost effective (initial manufacture), and can be based on current state of the art technologies with respect to design, manufacture, and maintenance. However for application to a flight vehicle, the two-speed transmission is less desirable than a transmission which can provide continuous variable speed range with smooth and continuous power transmission. Such a transmission would not possess the potentially harsh dynamics as those of a discrete two-speed transmission.

Dynamics and Operation of Two-Speed Transmission Concepts

Just the thought of shifting a transmission in a rotorcraft during flight suggests a seemingly perilous operation whether shifting from hover to cruise or the converse. The degree of difficulty for each transition is different, as well as a function of the urgency of the maneuver. That is, is the speed range change a planned routine operation, or, is it required to occur during an emergency condition? Initiating a change in any situation should be equally easy and of second nature to the operator (pilot), if not fully automated.

Down shifting a two-speed transmission from hover to cruise mode is seemingly the easier of the two range transitions since the rotorcraft speed is nearing the point where the fixed-wing takes over the entire function of providing lift, and the engine/driveline only has to provide the power necessary to support forward thrust and control. One can envision throttling down the engine to a lower power level, shifting the transmission, followed by throttling up the engine speed, though at a lower power level. It is the converse of the above, transition from cruise to hover, which is more challenging. In this situation, rotorcraft speed is being reduced with fixed-wing lift diminishing to negligible magnitude. During this transition, the rotor must quickly take on providing thrust AND lift as well as directional control requiring full-power and speed, a 2X increase in rotor speed from 50 to 100 percent output speed!

System dynamics of speed changes within a fixed multi-speed transmission are a significant concern based on the high speeds and horsepower being transmitted and the resultant shock loads which may occur due to unsynchronized speeds during transitions between the discrete speeds. At high power and speed, even a small speed mismatch can introduce significant shock loads within the driveline as well as the engine and/or rotor(s). Although increasing the transition period may tend to improve smoothness, it is must still be done quickly to maintain airframe forward velocity, as well as minimize internal heat generation within the transmission.

Should an unforeseen emergency situation arise during an in-progress speed range change, it may be required to return abruptly to the initial condition. Such a scenario might be transitioning from hover to cruise during which time the aircraft is operated in an emergency condition requiring conversion back to hover. In a discrete speed transmission, such a situation would result in an abrupt change in torque transfer or mismatch in speed which ultimately results in an abrupt loading or unloading condition due to the required flight mode and power demands. Such a condition is created in the discrete two-speed transmission because something mechanical or hydraulic must be engaged or disengaged to initiate or permit the change in ratio and something must be synchronized to continue power transfer. Operation during an emergency situation is in direct contrast to normal operation striving to obtain a smooth transition. Any event that disrupts the disengagement-reengagement periods will undoubtedly result in abrupt change in power flow and heat generation in a discrete speed configuration.

From the above one may surmise that the best approach to employing a two-speed configuration might be to employ a CV element or controller as a ratio-changing device and to only use the CV element for up-shifting (cruise to hover) and to use the clutch for down shifting (hover to cruise). Operation of the CV element and clutch in this manner would serve to reduce the required duty service of both the CV element and the clutch.

Dynamics and Operation of Variable Speed Transmission Concepts

For a continuously variable transmission configuration, engine speed can be maintained nearly constant while the transmission output speed is decreased or increased based upon power demand. Thus the engine may be operated at maximum power or maximum efficiency conditions as required. In addition, the period, or time, for a speed range change is dramatically more flexible and controllable compared to that of a discrete two-speed transmission where the smoothness of the speed change and heat generation is a strong function of the transition period.

A CV transmission, with fully synchronized speeds throughout the operable speed range, results in the smoothest range changes with little or no driveline shock due to speed mismatch between driving and driven elements since they are always in contact. However, for a traction drive configuration, speed mismatch may potentially result from a condition such as driveline or rotor load/inertia thus overrunning traction capacity. Any realized speed mismatch could result in internal slippage and heat generation within the traction fluid and drive surfaces. Traction fluid properties are generally a function of their temperature. Any significant temperature rise could result in unstable fluid properties as well as low reliability in the traction coefficient (ref. 7). Such a condition has the potential to deteriorate to a point of total instability or loss of traction. While not desirable for any power transmission, this could be catastrophic on an airframe application. For the above reasons, full power transmission through fluid traction/friction is not foreseen as viable for future rotary wing applications.

The above discussions suggest that neither discrete multi-speed transmissions, nor CV transmissions utilizing power transmission via fluid-traction, are the best configuration for the given application. Just what type of transmission is best suited? Another aspect to consider is “transition cycle life” (i.e., operation life of the transitioning element). The major portion of any mission is comprised of operation that is primarily in either the upper or lower speed range, not transitioning between them. Transitioning ranges is thought to be an extremely low percentage of any flight missions.

Considering the above, the best approach for this application is thought to be a split power transmission with CV element (variator), or externally powered controller transition between two fixed ratio positive-drive (direct drive or geared) speed ranges. Whether the drive configuration is a fixed or CV ratio design, the primary control is foreseen to be both engine and transmission shaft-speed instrumentation based where shaft-speed signals are used to synchronize relative speeds prior to and during the shifting or transition period to assure continuous and smooth power transfer.

Assessment of Concepts and Selection

Concepts developed within this study were reviewed and ranked to identify the most viable. An initial ranking process was planned which included specific metrics against which the concepts would be evaluated. During real-time concept selection, several key points were recognized within the concepts and the proposed concept evaluation metrics/selection process. Evaluation metrics evolved during the above ultimately leading to a favorable strategy for driveline development, which is summarized later.

When concepts were reviewed on a detailed component level some concepts may appear seemingly similar though they may possess very important differences. Some examples of these differences are considerations such as whether power is transferred through a gear train or if it is directly coupled through a clutch, how many gears and different relative sizes are required to achieve the specific low range reduction ratio (i.e., single or two-stage reduction), how many bearings are required, overall system operation, etc.

In contrast, reviewing concepts from a higher level, the many differences and details seem less important with respect to comparisons based solely on meeting the application requirements and apparent simplicity. Although details such as those above and many more are very important in identifying the best concepts with respect to function in the application, simplicity, and weight emerged as the dominant determining factors in the selection of the most viable concepts. This is suggestive that the fine details of the many concepts are of lower significance when compared to the overall concept capacity to meet the objective—a multi/variable speed transmission capable of 50 percent reduction and being simple, light weight, and robust. The ultimate metric of concept value is an overall assessment of which concept(s) has the highest potential to be realized within a flight application.

Evolution of Concept Evaluation Metrics

Initially proposed evaluation metrics evolved as the study progressed into the following:

Weight	combined below
Complexity/parts count	→ Simplicity
Noise/dynamics	dismissed
Risk—rolled up into	→ simplicity
Cost—rolled up into	→ simplicity
Performance/efficiency	dismissed

From the preceding, the primary metric became simplicity.

Primary Metric → Simplicity - Weight

It is thought that simplicity will result in the lightest possible configuration and also result in a driveline element that can be more easily integrated as a module into the overall driveline system.

Upon comparing all of the concepts, a very distinct demarcation of simplicity versus complexity emerged; the simplicity of the discrete two-speed configurations and planetary differentials in contrast to the complexity of the multi-shaft split-power and variable speed configurations (not presented herein).

Looking at the concepts from a top level perspective, the concepts naturally flow into three basic groups:

(1) Inline discrete two-speed configurations
(2) Dual input planetary differential (quasi-variable)
(3) Variable-speed multi-shaft split-power configurations

A simple design containing well developed configurations, those with field service heritage, can be easily made to be very robust with inherent high reliability. A good basic design with the combination of simplicity and robustness leads to most other desirable traits such as ease of manufacture, ease of assembly and maintainability, high reliability, and high efficiency.

Concept Selection and Development

Ultimately, concept ranking based on the "simplicity" metric combined with collaborative and synergistic discussion lead to a plan which is expected to advance the consideration and design of multi/variable-speed transmissions for rotary wing application through the development and testing of multiple test articles applicable to a broader range of aircraft resulting in a wider array of study than initially thought possible.

The resulting plan, outlined below, calls for parallel development of both discrete two-speed and variable-speed adaptable configurations leveraged from basic simple design concepts along with parallel study and development of controller/variator devices/systems able to be incorporated into the above driveline concepts making them quasi-variable ratio. This plan thus assures support of the NASA SRW/Subsonic Rotary Wing Program basis of fundamental research.

Concept Development and Testing Strategy

(1) Develop and test simple two-speed configurations. Identify the best configuration based on scale test models and actual hands-on experience as opposed to paper studies and intuition.

(2) Develop variations of the above two-speed configurations that are variable output capable (employing modular controller/variator devices).

(3) Develop and test concepts for variable control devices/systems, both take-off driven variator, internally/externally powered controller. Integrate both types into item 2 configurations for direct comparison.

(4) Test a basic two-input differential planetary drive to determine power levels required for speed range of 100 to 50 percent and compare to two-speed variable input capable configurations (item 3) to identify the best driveline configuration for end development and further testing.

(5) Combine the results from items 1 to 4 above into the overall best configuration and test.

The outcome of these development steps is intended to yield both a discrete two-speed and a variable-speed configuration either of which may be the basis for incorporation into specific airframe applications based upon overall system requirements. The strategy is presented in the development and testing matrix shown in figure 4. Concepts depicted in the matrix below are described in the following section.

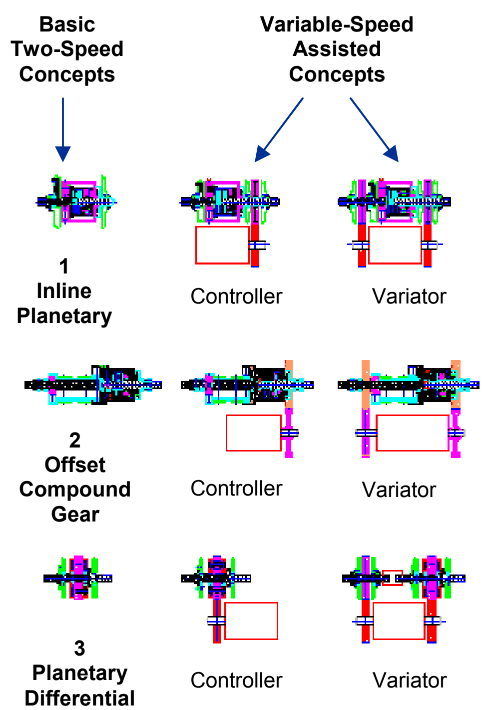

Figure 4.—Modular two-speed and variable speed configuration development and testing matrix.

Concept Descriptions

The three primary two-speed concepts and their respective variable-speed assisted variations as shown in figure 4, are presented in detail in the following text.

(1) Two-speed (double star idler reverser)
(2) Two-speed (offset compound gear)
(3) Planetary differential
(4) Variable transition assisted variations of (1, 2, and 3)

As previously mentioned, concepts were created in two-dimension (2–D) CAD using a commercially available CAD drafting design tool (ref. 8). Concepts are all depicted in the same scale (detail gearing analysis may indicate otherwise), employ many standard configurations, and also contain representative bearing/shafting sizes. Gear pitch diameters depicted are based on employing a nominal diametral pitch of twelve and 25° pressure angle (ref. 2). Gearing depicted in the original concepts within this paper are limited to consideration of spur tooth, helical, or double-helical.

Concept 1—Inline Two-Speed Planetary (Modified With Addition of Double Star/Idler)

The initial inline two-speed planetary drive concept, discussed earlier and shown again below in figure 5, was the earliest two-speed configuration conceived during this effort. The configuration uses one clutch, one sprag, and a star planetary gear train to achieve the 50 percent speed reduction for the low speed cruise mode.

The major shortcoming of the above concept was the rotational direction for low speed range being opposite to that of the high speed range (as discussed earlier). Several concepts were considered to remedy the reverse rotation issue. The lightest and most viable methods are presented in the two concept descriptions that follow.

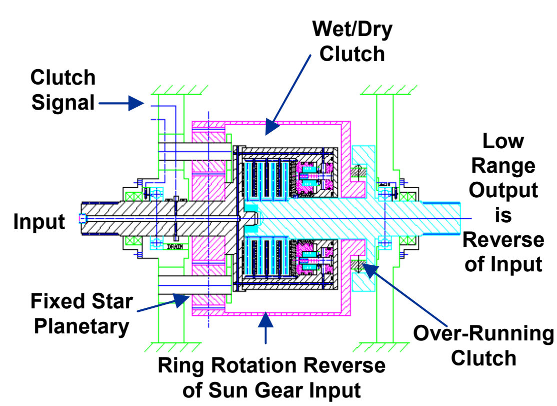

Figure 5.—Initial inline two-speed planetary drive (concept discounted due to reverse rotation—see text).

The most basic method to reverse output rotation for two gears in mesh is through the placement of an idler gear between the original gear set. An idler reverses rotation across the first mesh and then re-reverses it across the second mesh without changing the speed ratio of the original two gears.

For the planetary train above, this means an addition of a second star gear to act as an idler. With the addition of a second star gear, serving as an idler (i.e., a reversing element), the direction of rotation of the output ring is reversed. The second star gear is mounted in an unconventional manner allowing it to act as an idler gear between the first star gear and the output ring gear. This configuration is shown in figure 6.

The double star idler configuration, seemingly simple, is a highly restrictive design. It is difficult to achieve the desired overall ratio between the sun gear and the ring gear, simultaneously obey diametral pitch constraints, limit star gear speeds, obtain an entire set of gears that mesh properly, and which can be assembled. When one is fortunate enough to obtain a design satisfying the above constraints, this configuration is a very light weight method for reversing output rotation of this form of planetary gear train.

The revised driveline configuration, which includes the addition of the above double star idler reversing gear set, is shown in figure 7.

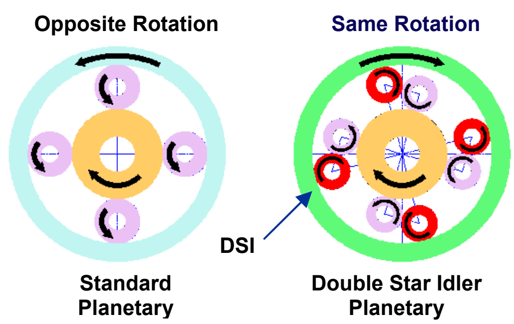

Figure 6.—Double-star-idler reversing concept.

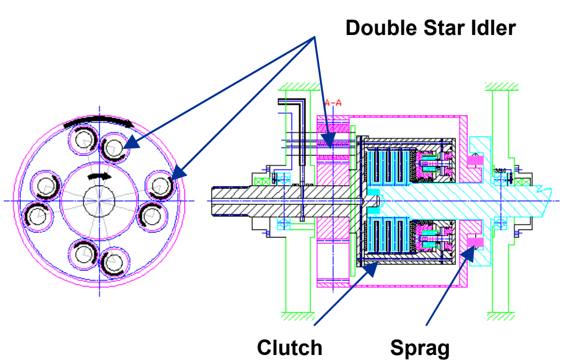

Figure 7.—Final version concept 1—inline two-speed planetary drive (modified with addition of double-star-idler reversing concept).

Power flow during high speed output mode is straight-thru with the main clutch engaged and the output ratio is 1:1. The planetary gear train free-wheels and overruns the over-running clutch (sprag). The power flow during low speed operation is directed thru the star planetary gear train into an over-running clutch (sprag) by disengaging the main clutch. With the clutch disengaged, transfer of power thru the planetary is directed to the sprag, which is now the driving element. The star planetary achieves a 2:1 output ratio. The power requirement for high speed range is full power with reduced power being required for the low speed range, thus power routing is optimally directed.

As discussed earlier, the two-speed concept can be made to be a quasi-variable configuration with the addition of a variator or controller. The quasi-variable speed off-shoot configurations of the above two-speed concept are shown in figures 8 and 9.

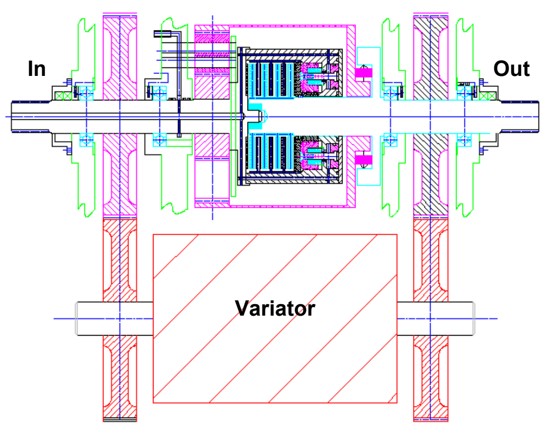

Figure 8.—Inline two-speed planetary drive (double-star-idler)—variator configuration.

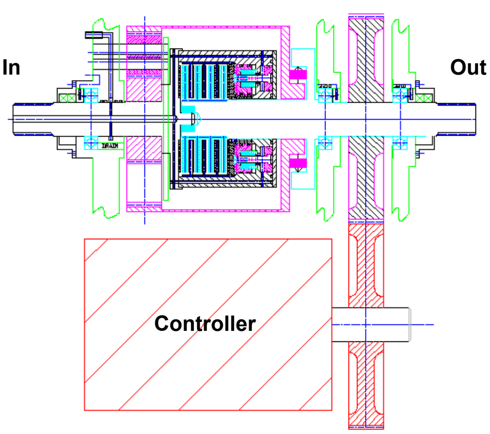

Figure 9.—Inline two-speed planetary drive (double-star-idler)—controller configuration.

Concept 2—Offset Compound Gear

This configuration is based on a novel approach of off-setting and embedding a gear mesh. The heart of the concept is the offset compound gear which uses identical pitch diameter for both internal gear teeth on the input end and external gear teeth on the output end, thus allowing it to mesh with both a smaller external gear and a larger internal gear in series. This results in a simple in-line reduction gear set.

The basis of this concept is shown in figure 10. Input gear 1, Intermediate gear 2, and Output gear 3. This concept directly evolved from the double reversing idler concept described above (refer to fig. 6).

The above geometry permits the intermediate compound gear to be offset and mesh with the input gear and the output gear, both of which are on the same centerline. The configuration provides 50 percent reduction in two stages, or meshes, utilizing only three gears replacing multiple gears of a conventional planetary stage. The concept will require very robust and ultimately wide gears. Although the concept is simplistic from the gearing perspective, the challenge will be how to best support the offset compound gear on bearings.

The Offset Compound Gear Drive concept as shown in figure 11 was initially conceived as an in-line discrete two-speed device and is similar in operational basis to the previous concept. This concept was directly evolved

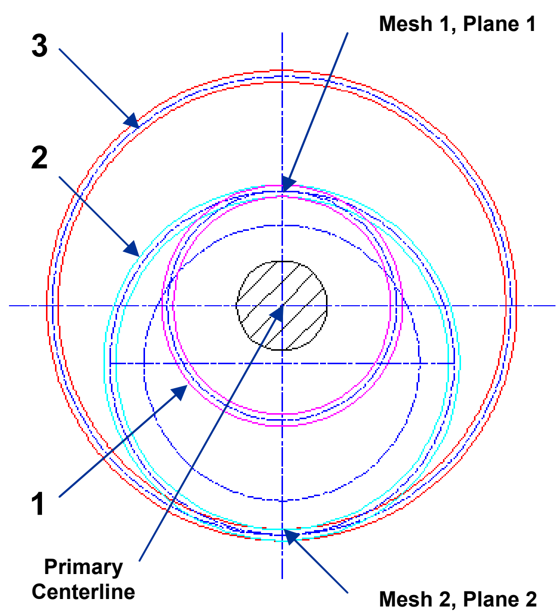

Figure 10.—Offset compound gear concept basis.

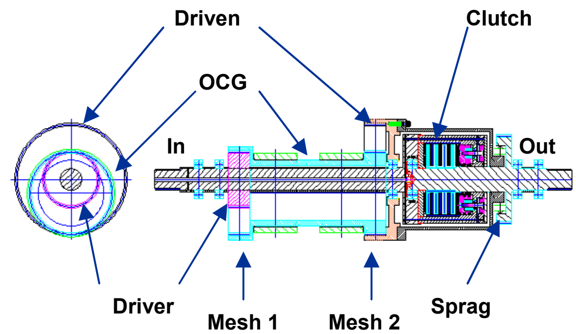

Figure 11.—Concept 2 offset compound gear drive.

from the double reversing idler concept described above in resolving the reverse rotation issue.

In this concept layout, low speed operation is accomplished in two meshes: a 5.0-in. pitch diameter input gear to 7.50-in. pitch diameter intermediate gear (0.667 reduction mesh) and a 7.50-in. pitch diameter intermediate gear to a 10.00-in. pitch diameter output gear (0.750 reduction mesh). The resultant low speed ratio is 2:1, (output speed = 0.500 = 0.667 stage one reduction × 0.750 stage two reduction). Note that nominal diameter sizes are specified above to depict relative sizes. Detailed analysis may dictate an increase in gear width and/or diameter. The input and output shafts spin on rolling element bearings while the intermediate gear shaft (the offset compound gear) spins on fluid film journal bearings. Power transferred through the gear train drives a sprag. During this low range mode of operation, the main clutch is disengaged.

The high speed, 1:1 ratio, is direct drive through the primary clutch. During this mode of operation, the gear train free-wheels an overrunning sprag. A slight reduction in input speed is required to overrun the sprag. The above gear train always spins. An alternative to spinning these gears in both speed ranges might employ the sprag at the forward end of the gear mesh allowing the gear train to quasi-idle when not transferring power.

While this concept was initially conceived as a discrete two-speed device, it is adaptable to a quasi-variable speed drive using a speed synchronizer to power/speed up the output shaft to match the speed of the input shaft. With some minor modifications the above configuration can be explored as a Variable Speed Transmission. The proposed configuration is depicted in figure 12.

Also, the basic configuration is adaptable to controller assist (externally powered) shown in figure 13.

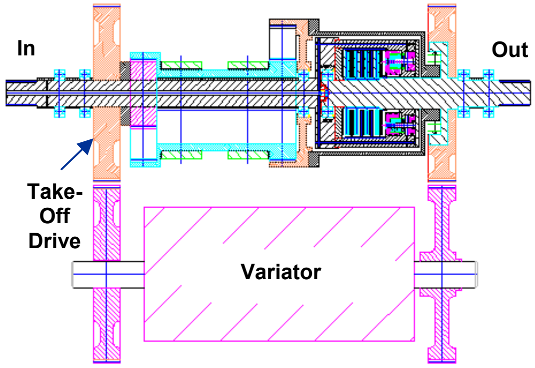

Figure 12.—Offset compound gear drive with variator.

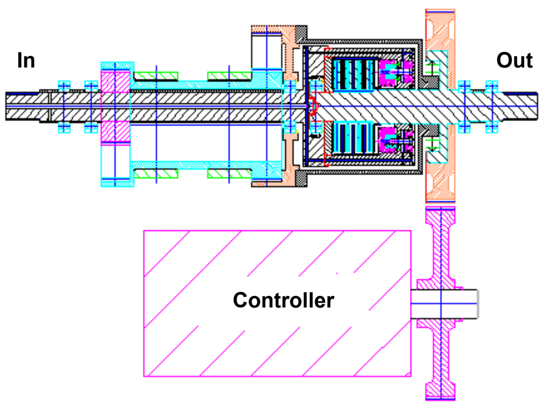

Figure 13.—Offset compound gear drive with controller.

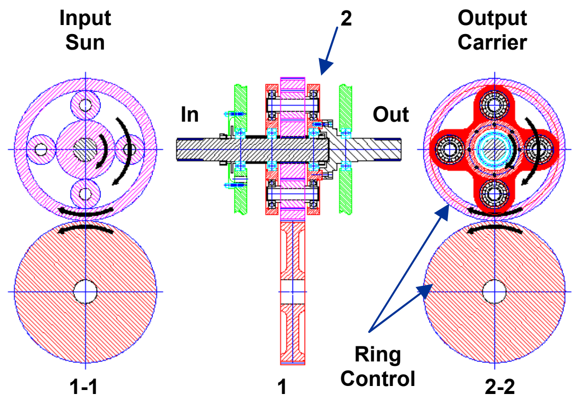

Figure 14.—Concept 3 differential planetary drive.

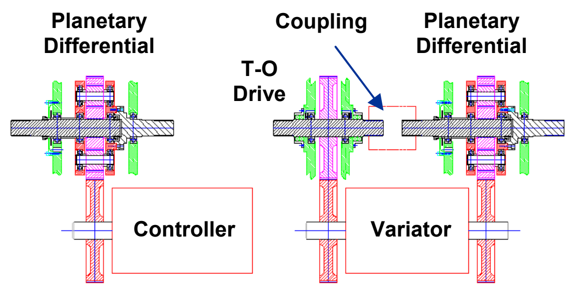

Figure 15.—Planetary differential drive (CV control).

Concept 3—Planetary Differential Drive (Basic)

The Differential Planetary Drive, shown in figure 14, capitalizes on the output variability of a dual-input to single-output planetary differential using one input to serve as a controller. Primary power is input to the sun gear, output power is transferred thru the carrier, and speed variation is achieved by varying the speed of a special ring gear from zero speed to full speed with a variable speed controller device/system.

The ring gear is special in that it has both an internal pitch diameter and an external pitch diameter contained within an integral ring. As depicted, ring gear speed is varied from zero to full engine speed by a speed controller driving the external pitch diameter. The controller ratio may be varied in design permitting selection of the optimal power and speed range. As depicted, the controller rotates in the opposite direction of the primary input but may be the same if an idler is employed. The speed controller may be a variety of possible devices either externally powered and controlled or take-off driven from the transmission power input shaft. The power take-off may be a continuously variable speed device as suggested elsewhere for the other configurations. A configuration for a planetary differential drive with integral CV control is presented in figure 15.

A primary advantage of the two-input planetary differential configuration is that it is a variable speed device with power transferred via gear teeth. The main disadvantage is the power loss to spin/control the ring speed. Unknowns at this point are the optimal power and speed requirements for the controller. Through testing, controller speed and power requirements can be established identifying either a separate externally powered speed controlling device or an internal gear takeoff driven variable speed device as the most viable. The concept as shown has 3:1 ratio output when ring gear is at rest; one can obtain 50 percent speed output with the controller rotating at 16.67 percent of the sun input speed.

Multi-Plate Clutch (Employed in Concepts 1 and 2)

As stated earlier, any multi-speed transmission configuration intended to change speed range during power transfer requires a means to disengage power during ratio change, thus a suitable clutch is needed. Availability of clutches for the required speeds which incorporate a compatible means of actuation would probably be very limited resulting in a custom design. Thus, a conceptual clutch was needed that could be incorporated into the various transmission concepts.

Having some familiarity with a commercial single-plate clutch that shares common design basis with a

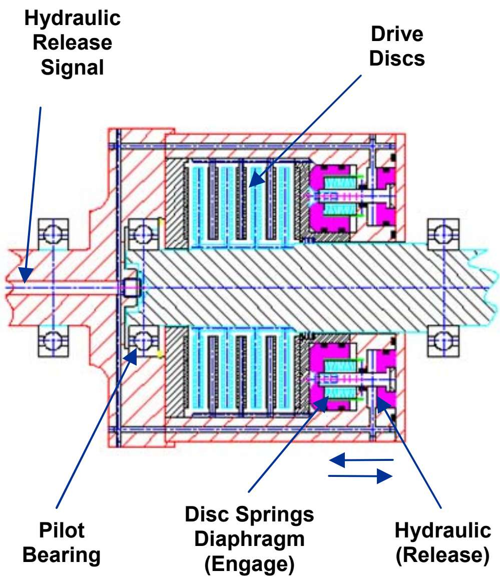

Figure 16.—Multi-plate hydraulic-actuated-release mechanical-spring-activation clutch concept.

product line of multi-plate configurations, a basic familiarity with the multi-plate clutch configuration and its benefits existed. The multi-plate aspect and associated high power density contained within the reduced diameter compared to the larger diameter of an equivalent capacity single-plate configuration is the key element that is capitalized upon.

An earlier multi-plate basis clutch concept conceived for rotorcraft application based on multi-plate automotive racing clutch configurations is described in reference 2). The above clutch concept is a hydraulic over mechanical spring configuration with fail-safe condition being the load provided by mechanical spring(s). A failure (e.g., loss of hydraulic signal) will fail to the high-range or hover mode (i.e., loss of hydraulic pressure would engage the clutch resulting in the high-range power path operation).

Hydraulic actuation seemed preferable over mechanical linkage. Driveline concept development also concluded hydraulic actuation to be the exclusive method. Within the concepts presented in this paper, the clutch is surrounded by other rotating structures making access for mechanical linkage impossible.

In the above clutch concept (ref. 2), the hydraulic release signal passes through a face seal arrangement (passage transition between the stationary and rotating components). In the new concept, this function is intentionally reconfigured to be at the lowest practical face-seal element. The basis is to minimize peripheral speed at the point of sealing, improve fluid movement, utilize a reliable seal configuration, as well as allowing for the potential advantage of utilizing centrifugal forces in the eventual design of the actual sealing unit.

Based on the above, a hydraulic over mechanical spring clutch was configured. Several clutch configurations were created to meet specific design requirements for a number of different transmission concepts. However, only one clutch relevant to driveline concepts described herein is included and is shown in figure 16.

Conclusions and Recommendations

Observations and Conclusions

Variable speed propulsion is determined to be necessary for all advanced rotorcraft concepts. Currently, rotor speed can be varied only a small percentage by adjusting engine speed, which is generally constrained by engine efficiency and stall margin, limiting speed changes to approximately 15 percent maximum. Advanced rotorcraft concepts offering dramatic effects of reduced external noise and increased rotorcraft performance require speed variations of 50 percent, but increased speed variation must be done without loss of efficiency and torque. To achieve 50 percent speed variation capability, advanced variable/multi-speed drive system concepts must be developed. This report summarizes an effort to identify viable concepts for both two-speed and variable speed drive transmissions that can provide the required 50 percent speed change. Several concepts were developed with the most promising identified for future testing in a sub-scaled test facility to validate operational capability and system level tools and concepts. Based on the work presented in herein, the following conclusions are made:

(1) Two-speed designs are less complex compared to variable speed designs but possess inherent power interruptions during speed ratio transition.

(2) Rotorcraft application requires positive and continuous power transfer and variable speed.

(3) The major portion of a flight mission is hover and cruise. Transition between the above operation points is a minor portion of the flight mission.

(4) Two-speed designs can be adaptable to be quasi-variable through variable transition assist which may be either external powered (controller) or internally take-off driven (variator - traction drive or power electronics motor-generator system).

(5) A positive drive continuously variable speed configuration is achievable via a two-input planetary differential (second input controlled).

(6) The optimal configurations for advanced development are simple gear based drives:

(a) Discrete two-speed with variable transition

(b) Planetary differential with variable transition

(7) Speed range changes need to be computer controlled sensing both transmission and engine speed/power.

Recommendations

Development and testing for a variable/multi-speed transmission system should be based on the basic step and variable transition assisted configurations below:

1. Two-speed (double star idler reverser)
2. Two-speed (offset compound gear)
3. Planetary differential (two-input)
4. Variable transition assisted variations of (1, 2, and 3)

Variable transition shift assist (externally powered and take-off driven) configurations should consider:

1. Motor (second input)
2. Controller (power electronics)
3. Variator (toroidal drive)

Combine the results from the above developmental configurations to configure final design(s) with potential flexibility to pursue multiple applications/requirements.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
In several recent studies and on-going developments for advanced rotorcraft, the need for variable or multi-speed capable rotors has been raised. A speed change of up to 50 percent has been proposed for future rotorcraft to improve overall vehicle performance. Accomplishing rotor speed changes during operation requires both a rotor that can perform effectively over the operation speed/load range, and a propulsion system that can enable these speed changes. A study has been completed to investigate possible drive system arrangements that can accommodate up to the 50 percent speed change. Several concepts will be presented and evaluated. The most promising configurations will be identified and developed for future testing in a sub-scaled test facility to validate operational capability.

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