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A Sequential Shifting Algorithm for Variable Rotor Speed Control

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Abstract

A proof of concept of a continuously variable rotor speed control methodology for rotorcraft is described. Variable rotor speed is desirable for several reasons including improved maneuverability, agility, and noise reduction. However, it has been difficult to implement because turboshaft engines are designed to operate within a narrow speed band, and a reliable drive train that can provide continuous power over a wide speed range does not exist. The new methodology proposed here is a sequential shifting control for twin-engine rotorcraft that coordinates the disengagement and engagement of the two turboshaft engines in such a way that the rotor speed may vary over a wide range, but the engines remain within their prescribed speed bands and provide continuous torque to the rotor; two multi-speed gearboxes facilitate the wide rotor speed variation. The shifting process begins when one engine slows down and disengages from the transmission by way of a standard freewheeling clutch mechanism; the other engine continues to apply torque to the rotor. Once one engine disengages, its gear shifts, the multi-speed gearbox output shaft speed resynchronizes and it re-engages. This process is then repeated with the other engine. By tailoring the sequential shifting, the rotor may perform large, rapid speed changes smoothly, as demonstrated in several examples. The emphasis of this effort is on the coordination and control aspects for proof of concept. The engines, rotor, and transmission are all simplified linear models, integrated to capture the basic dynamics of the problem.

Notation

Ng	Gas generator speed
N_{GB}	Multi-speed gearbox output shaft speed
N_R	Rotor speed
Np	Power turbine speed
Q_P	Power Turbine Torque
Q_R	Rotor Torque
$T4.5$	Inter-turbine gas temperature
Wf	Fuel flow

Introduction

Continuously variable rotor speed control in rotorcraft is desirable for several reasons including noise reduction and agility. However, because of design limitations of turboshaft engines and constraints placed on the drive train, it has not been feasible to implement. This paper describes a new conceptual approach to continuously variable rotor speed control for rotorcraft. The test bed is a twin engine vehicle such as the Apache or Blackhawk helicopter. To put the problem in context, this section will briefly describe the propulsion/rotor system of these vehicles as an example of a standard constant rotor speed implementation. With this background in place, technologies related to various aspects of rotor speed control will be discussed as a way to introduce the proposed solution.

The Apache and Blackhawk helicopters are each powered by two T700 turboshaft engines. The T700 engine is a 1600 horsepower-class, modular, two-spool engine (fig. 1) consisting of a gas generator section and a free power turbine (ref. 1). The gas generator section is made up of a five-stage axial and a single-stage centrifugal compressor, a low fuel pressure through-flow annular combustion chamber, and an air-cooled, two-stage, axial-flow, high-pressure turbine. The free power turbine is a two-stage, uncooled, axial-flow type. There exists a one-way coupling between the power turbine and the gas generator, i.e., the power turbine extracts work from the gas turbine cycle but does not otherwise affect it. Through mechanical linkages and gears, the power turbine drives the rotor system of the helicopter such that the main and tail rotor speeds are directly proportional to power turbine speed. Thus, in the helicopter application, it seems natural to consider the power turbine as part of the rotor system, to which it is mechanically linked (ref. 2). Turboshaft engines are designed to operate at a constant shaft speed. The shaft is coupled through the transmission to the rotor, which consequently also operates at a constant rotational speed.

The helicopter pilot commands an altitude change by moving the collective stick, which controls the average blade pitch angle and, therefore, the blade lift and average rotor

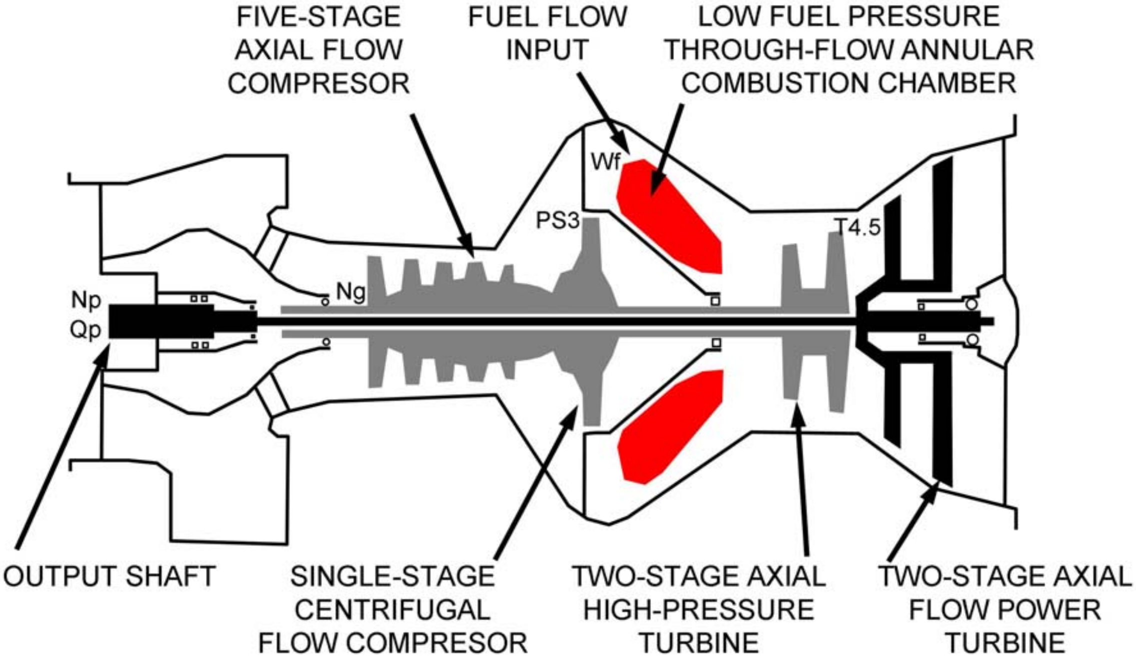

Figure 1.—Cross-section of a turboshaft engine showing the rotating components and sensor locations.

thrust. A change in the blade pitch angle causes a change in load as lift is increased or decreased. The standard T700 control system regulates power turbine speed with fuel flow to accommodate variations in the load. The power turbine shaft is designed to operate at a constant 20,900 rpm. Momentary changes in this power turbine speed are induced by disturbances such as collective pitch changes, wind gusts, etc. The control system returns the power turbine speed to its design point as the engine approaches a steady state condition.

As seen in figure 2, T700 engines are used in pairs, employing a torque-sharing arrangement so that each engine participates equally in turning the rotor system. In each engine, the power turbine's shaft is connected to the main gearbox through a nose box (a small reducing gearbox which redirects the torque by 90°) and a freewheeling clutch. The main rotor is driven by a shaft projecting from the gearbox. The clutch is a mechanically-activated device that allows the turbine to drive the rotor system but not vice versa. The tail rotor is driven by a shaft extending from the transmission which is turned though a gear mechanism powered by the main rotor. Thus, it spins as long as the main rotor is spinning, even if the engines are disengaged. If both engines are engaged and one is delivering less torque than the other, a load sharing arrangement modifies the demand to the lower torque-producing engine until the torques balance. When the helicopter tries to climb, the load increases, inducing transient excursions in the engine variables, and the control system increases the fuel flow to the engines to boost their torque output. The rotor applies a load to the turbines as long as they are engaged. A command to descend causes the control system to reduce fuel flow, thereby reducing the torque applied to the rotor from the shaft. If the load is reduced enough, the rotor will spin freely and will only be driven when friction and aerodynamic damping begin to slow it down.

Because the rotor is controlled to a constant speed, rotorcraft flight control systems are typically designed with a constant rotor speed assumption. However, load disturbances cause the rotor speed to vary up to a few percent transiently during flight operation. The engines attempt to maintain rotor speed at 100 percent, but they can only react to rotor speed droop by applying torque when it gets too low. If the rotor speed gets too high, the power turbines disengage by means of the freewheeling clutches that allow the engines to drive the rotor, but not the other way around. This means that the overspeeding rotor is spinning freely while the engines idle, waiting for the rotor speed to drop to the commanded level. Once the rotor speed drops to 100 percent, the engines re-engage and spool up, but the rotor speed droops before the engines are able to hold it constant and they must bring it back up. Pilots consider this rotor droop and resulting lack of power indications of poor handling qualities (ref. 3). To address this, adaptive fuel control laws have been developed to anticipate the rotor droop and spool up the gas generator as the rotor speed starts to decay (refs. 4 and 5). An alternate, more formal approach has been to design a *decentralized* or *partitioned* integrated flight/propulsion control system that has the potential to eliminate some of the undesirable coupling between the propulsion system and the airframe/rotor (refs. 6 and 7).

While deviations in rotor speed have been portrayed as negative from the point of view of power loss, rotor speed variations during maneuvers such as the bob-up have also been shown in simulation to provide benefits in agility such as reduced time-to-climb (by exchanging rotor speed for

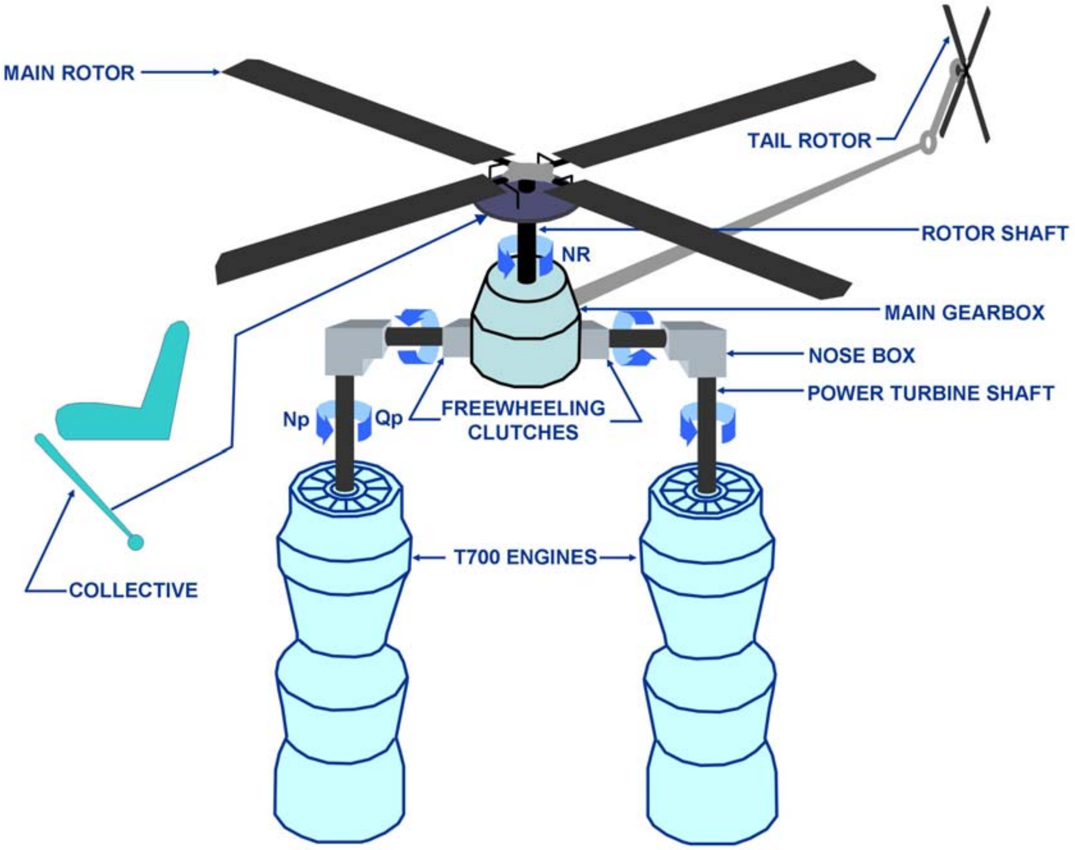

Figure 2.—Twin engine/rotor system in a helicopter.

increased available collective) (ref. 8), and there is evidence that experienced pilots purposely allow rotor speed droop in order to improve performance (ref. 9). Thus despite the previously mentioned drawbacks (lack of power resulting in poor handling qualities), the idea of variable rotor speed for rotorcraft is attractive in certain situations because of its ability to improve responsiveness. However, because of high pilot workload and the complexity of performing aggressive maneuvers in a near-optimal manner, automation of the optimal control law has been investigated (ref. 10). This automated control law generates optimal trajectories for specific variables based on the maneuver, which are used to modify the pilot's commands, thus optimizing the control commands. The trajectories are subject to the same constraints as those a pilot could generate because the optimizer is working within the traditional flight and propulsion control framework. In contrast, by allowing large (30 percent of nominal) rotor speed variations, dramatic improvements have been demonstrated through simulation in agility and maneuverability during a 180°, maximum performance decelerating turn (ref. 11). A cost function was defined that captures the important features of this maneuver, and a rotor speed versus airspeed curve was optimized to minimize it. In several examples this variable speed approach significantly outperformed the baseline control on multiple criteria (the individual terms of the cost function).

Assuming that the rotor does not disengage, thus avoiding the undesirable temporary loss of power, high speed maneuvers are greatly enhanced through the use of variable rotor speed. But variable rotor speed is important for other reasons as well. For instance, a 15 percent rotor speed reduction can result in as much as 5 dB noise-reduction (ref. 12), and variable speed propulsion is considered a necessary technology for both heavy lift and high speed rotorcraft to be successful (refs. 13 and 14). Unfortunately, turboshaft engines are designed to operate at a fixed power turbine speed, and performance significantly degrades for off-design operation. In fact, engine speed variation is restricted to a maximum of about 15 percent because of fuel efficiency and stall margin considerations (ref. 15). Thus, in order to achieve useful variable rotor speed control over a significant range, either engine operability range needs to be expanded (ref. 16), or some of the speed variability must be accounted for though the transmission. A study of several competing approaches incorporating a combination of engine and transmission modifications concluded that the baseline turboshaft engine coupled with a variable speed transmission is the best configuration. It would be able to produce nearly constant output power with good fuel consumption characteristics over a 100 to 50 percent output speed range with little technology risk (ref. 17).

Continuously variable transmissions (CVT) have been developed that allow speed variation over a wide range while providing continuous power. However, they are usually based on a traction drive or friction drive, where the power is transferred though non-positive engagement frictional contacts. These drives are relatively large and heavy, and their efficiency and reliability are poor compared to those of gearboxes (ref. 18). Two-speed transmissions are common in tilt rotor concepts, which often employ two-speed operation, one for vertical mode and one for forward flight. Two-speed transmissions were utilized even in the earliest experimental models from the 1950s, the Transcendental Model 1-G and the Bell XV-3, each of which had a two-speed reduction gearbox. The Transcendental never fully converted to airplane mode in flight; the XV-3 did, but the complex gear shifting process for reducing rotor speed in airplane mode required an unacceptably high pilot workload (ref. 19). Even if the shifting process were automated, transmissions designed for two discrete speeds do not provide continuously variable rotor speed. Additionally, while two-speed transmissions that use gears to transmit torque and power are very efficient, shifting from one speed to another could cause a momentary loss of output power, and the large power changes can damage the transmission or drive train (ref. 18). However, if a multi-speed transmission (similar to the dual speed tilt rotor arrangement already in service) is used in combination with a sequentially shifting controller (which will be described in the next section), large magnitude rotor speed variations can be made to be completely continuous throughout the designated range of operation.

To summarize the main points of this section, continuously variable rotor speed is desirable but the turboshaft engine has too small a speed range to accommodate it through power turbine speed variation. Variable speed transmissions that could be used to extend the speed range are either too unreliable for this application or cannot provide continuous power. Thus, to achieve continuously variable rotor speed, the problem can be turned from one of design (or redesign) to one of control. A control solution can utilize existing hardware such as the Apache or Blackhawk engines and drive train, and gearboxes similar to the type already used in tilt rotor vehicles in a coordinated way to enable large smooth variations in rotor speed. The following section describes the conceptual sequential shifting approach taken to address the overall problem of continuously variable rotor speed control, accounting for the practical issues just mentioned. This is followed by examples of the algorithm applied to variable rotor speed in a rotorcraft, and then a discussion of issues and potential improvements.

Approach to Continuously Variable Rotor Speed Control

The goal of the effort described in this paper is to prove the feasibility of a new approach to continuously variable rotor speed in a dual-engine helicopter. Based on the results and issues already presented, a conceptual sequential shifting control (SSC) approach with baseline turboshaft engines is proposed. It requires the addition of two multi-speed gearboxes to a standard drive train. The approach taken consists of two engines working together to vary the rotor speed over a range much larger than either could achieve individually. They are coordinated to vary their power turbine speeds sequentially, synchronized with the gear shifting, to produce smooth, continuous rotor speed variations over a wide operating range. The development here is applied to the T700 propulsion/rotor system (fig. 2), but this approach is applicable for other configurations as well.

The approach for SSC is illustrated in figure 3. There are two engines, each with a multi-speed gearbox inserted between the nose box and freewheeling clutch. Any approach to large rotor speed variations must meet the following requirements: 1) power turbine speed variation must be limited to about 15 percent, and 2) continuous torque must be applied to the rotor. The SSC meets the first by dividing the rotor speed range up into speed bands, each corresponding to about 15 percent of power turbine speed times the gear ratio. A small amount of overlap with the neighboring speed bands at each end allows one engine to “hand off” the rotor to the other engine during the synchronized gear shifting process. If 50 percent speed variation is specified, six overlapping speed bands are required to implement the algorithm. The second requirement is met by always having one engine engaged while the other is shifting (unless the rotor is overspeeding, when neither is engaged). This way the rotor speed can vary over a wide range while the engines each remain within their smaller speed band. Since the highest rotor speed band includes the nominal rotor speed, the engines do not have to work as hard in the other speed ranges. This addresses the issue of available power and the ability of a single engine to drive the rotor while the other is shifting—if the procedure can be accomplished in the highest gear, it can be accomplished in lower gears where less torque is required. In fact it is anticipated that there would be shifting constraints into high gear that are related to power and life, but procedures such as the maximum power check that are performed with only one engine operating at full power indicate that the SSC approach is feasible.

As shown in figure 3, the SSC requires a high level of coordination between the propulsion system and the gearboxes. Conceptually, a command (presumably from a pilot) to vary rotor speed from one speed band to another would result in a

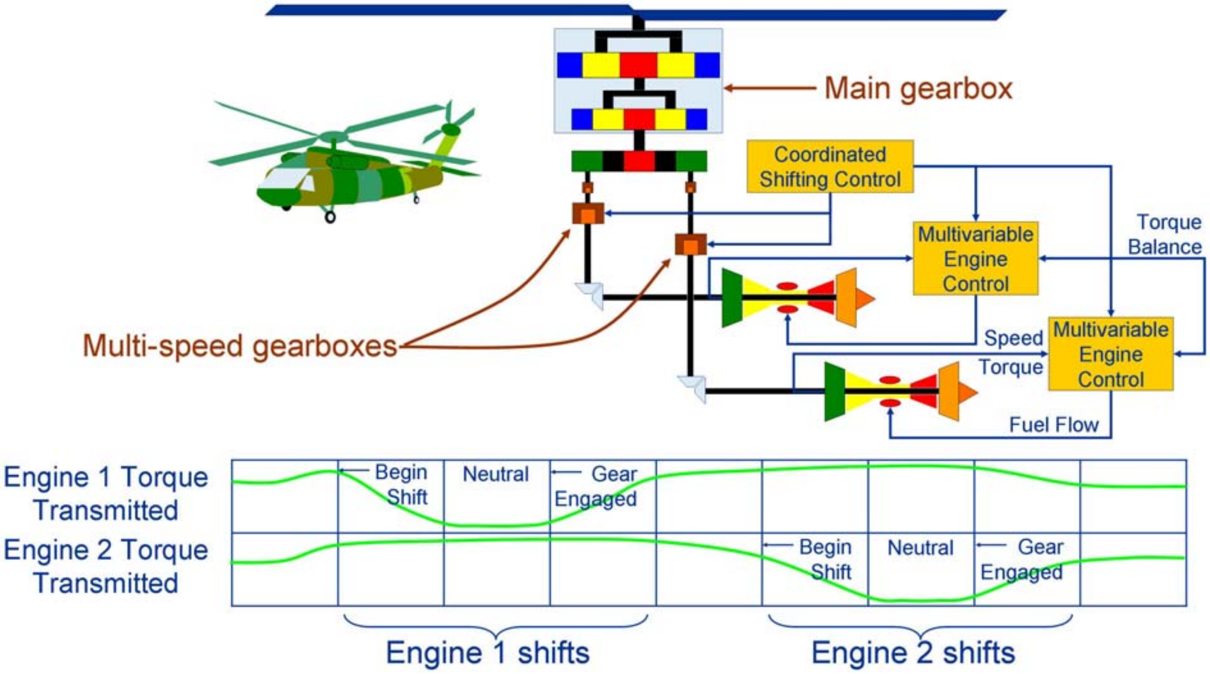

Figure 3.—Overall concept of the sequential gear-shifting strategy.

trajectory being generated (potentially by an automated system). This trajectory would involve the synchronized operation of the two engines and gearboxes to adjust the rotor speed while maintaining rotor torque. Thus the rotor trajectory would be decomposed into an individual speed profile for each engine's power turbine that takes into account the constraints associated with the shifting procedure. The actual procedure involves a sequence of events to make the transition, taking advantage of the existing freewheeling clutches to disengage the power turbines from the main gearbox to facilitate the shifting process. Figure 4 shows the logical flow of the process for a change from one speed band to another; the parallel nature is clear. The two power turbines and the two multi-speed gearboxes all operate in a coordinated manner to facilitate the wide speed range operation of the rotor. First, Np of engine #1 is commanded to drop below that of engine #2, and engine #1 disengages from the transmission, at which point the gear shifts; then engine #1 speeds up and re-engages, all while engine #2 drives the rotor toward the next speed band. The re-engagement must take place within the overlap band so that engine #1 can begin to drive the rotor before engine #2 disengages. The process is then repeated, allowing engine #2's gear to shift. Once engine #2 shifts to the same gear ratio as engine #1, it can re-engage at the appropriate place within the speed band. Because the engines are individually controlled, torque sharing is turned off during the rotor transient. From a controls perspective, the challenges include defining the power turbine speed trajectories that enable re-engagement within the overlap band, and maintaining the desired rotor speed transient despite controller limits.

For the T700, the transmission reduces the speed (Np to N_R) by a factor of about 81. For the SSC example application, the highest gear ratio of the multi-speed gearboxes is 1. This gives a speed range of 92.5 to 107.5 percent. For the next lowest speed band, the only change is that the gearbox reduces down to say, 0.87, giving a speed range of 80 to 93.5 percent, and an overlap of 1% with the speed range above. Table 1 shows the potential gear ratios and corresponding speed ranges enabled by the multi-speed gearboxes.

TABLE 1.—MULTI-SPEED GEARBOX GEAR RATIOS AND CORRESPONDING ROTOR SPEED RANGES

Range	Gear ratio	Lowest speed, %	Highest speed, %
1	1.0	92.5	107.5
2	0.87	80	93.5
3	0.75	69	81
4	0.65	60	70
5	0.57	53	61
6	0.50	46	54

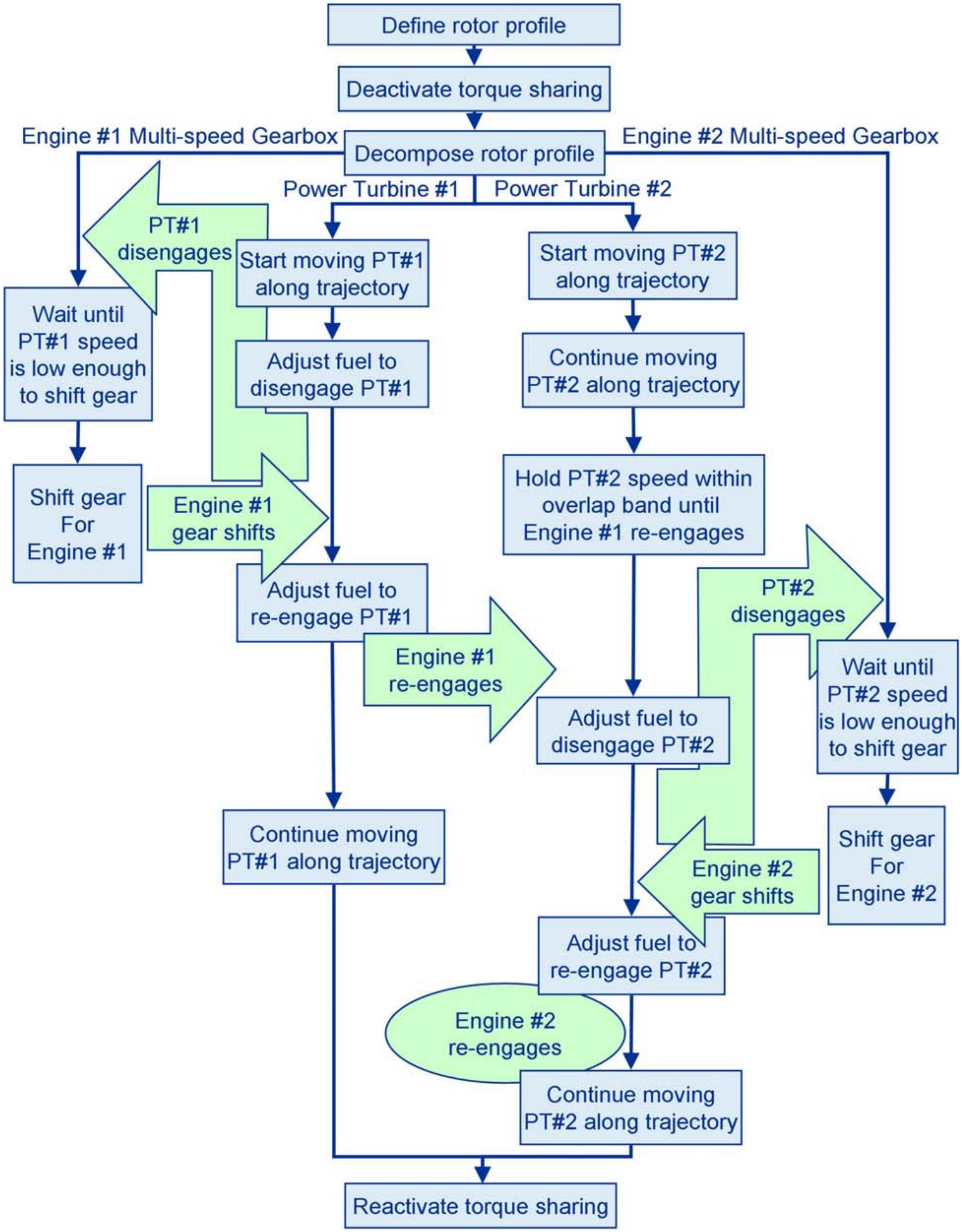

Figure 4.—Logical flow diagram of the SSC process for variable rotor speed operation involving a gear shift. The desired rotor speed trajectory is decomposed into commands for the two engines' power turbines (PT) and the two multi-speed gearboxes. The diagram shows the parallel nature of the process.

The T700 model used in this effort consists of a set of piecewise linear models from the literature (ref. 20). The linear engine models had been obtained through system identification of a high-fidelity nonlinear engine model at discrete operating points between flight idle and intermediate rated power (IRP). The model of the rotor, which consists of rotor inertias and friction, as well as aerodynamic damping, was derived from the same source. As a check, the frequency responses of the linear models were validated against transfer functions included in reference 20 for the case where both engines are coupled to the rotor. The freewheeling clutches were modeled as instantaneous release/engagement devices that allow the models of the power turbine dynamics to be coupled or decoupled from the rotor dynamics. Hence the power turbine speeds can be simulated realistically, independent of the rotor speed when decoupled from the rotor. The freewheeling clutches were modeled simply to disengage from the transmission shaft when the output shaft torque exceeds the torque provided by the power turbine shaft (i.e., at the point where the rotor begins to drive the engines). The clutches then re-engage when the power turbine speeds again increase to the output shaft speeds. The model is intended to mimic the operation of a grip-roller freewheeling clutch. The multi-speed gearboxes are represented as a set of gear ratios that are assumed to shift instantaneously, and the main gearbox is a single gear ratio. The components are all rigidly connected. The helicopter loads are modeled after the Lewis dynamometer, which provides a relationship for rotor torque at any given values of collective pitch input and rotor speed (ref. 21). Due to the lack of an airframe model, a constant external torque was applied to the rotor. The engine controllers are incremental Proportional-Integral type, typical of those used on jet engines. They were tuned for fast response, and incorporate limits based on the fuel metering valve swing, turbine metal temperature, and lean blowout. In an actual implementation, the power turbine control inputs will be tailored to achieve the desired rotor trajectory; in this effort, the aim is to demonstrate how rapidly a rotor speed change can occur given the realistic limits and response times of the propulsion system as a whole. The following section shows the results of power turbine control inputs that have been tuned by a trial-and-error process to achieve rapid, high magnitude changes in rotor speed.

Examples

Four examples are presented in this section, each of which goes through a rotor speed excursion of about 30 percent. The first is a speed ramp up from the second-highest speed range to the highest; the second is the reverse, a ramp down from the highest speed range to the second highest. In these two examples, the controller *T4.5* limit (a structural limit based on metal temperature) is removed, to demonstrate how the algorithm works under close to ideal conditions; the fuel metering valve upper limit is still in place. The third and fourth examples repeat the first and second except that the controller *T4.5* limit is active. The results presented here are all hand-tuned and make no claim to optimality in terms of command tracking or speed of transition given the selected configuration. The gear shifting occurs at the time the corresponding power turbine disengages. The four examples highlight how the rotor speed undergoes changes as a result of changes in the gearbox speed N_{GB} (*Np* times the multi-speed gear ratio).

In the first case (fig. 5), the rotor speed ramps up from range 2 to range 1. At 1.3 sec, the fuel flow of engine #2 drops to its lower limit in order to induce a disengagement of that engine, which happens shortly thereafter. When N_{GB} is sufficiently low, the gear shifting takes place, which is marked by the sudden change in N_{GB}. Shortly thereafter, the engine re-engages with the rotor. In the transition of engine #1, its fuel flow is dropped to its lower limit at 2.1 sec, but the engine remains coupled for nearly 0.4 sec. This is due in part to the fact that the gas generator must spin down a larger amount in order to decrease airflow through the power turbine and the shaft torque it delivers. The transition is smooth; however rotor acceleration is limited by the *Wf* metering valve limit during the part of the transient where engine #2 is working alone in the upper speed range.

In the second case (fig. 6), again the transition is fairly smooth. The total time to drop speed is dependent on the rotor slowing down, since it is essentially autorotating the whole time. Here engine #1 holds the rotor while fuel flow to engine #2 drops to the lean blowout limit (the minimum fuel flow that maintains combustion) allowing the power turbine to disengage and the gearbox to shift. The disengagement of engine #2 is delayed by about 0.3 sec as a result of the gas generator speed decay; for this reason, fuel to engine #1 is increased in order to maintain rotor speed somewhat constant during this time interval. A change in slope during the middle part of the transient occurs after engine #2 has re-engaged (14.7 sec), and engine #1 is waiting to disengage. This is imposed in order to prevent the *Np* of engine #1 from dropping too far below its speed band.

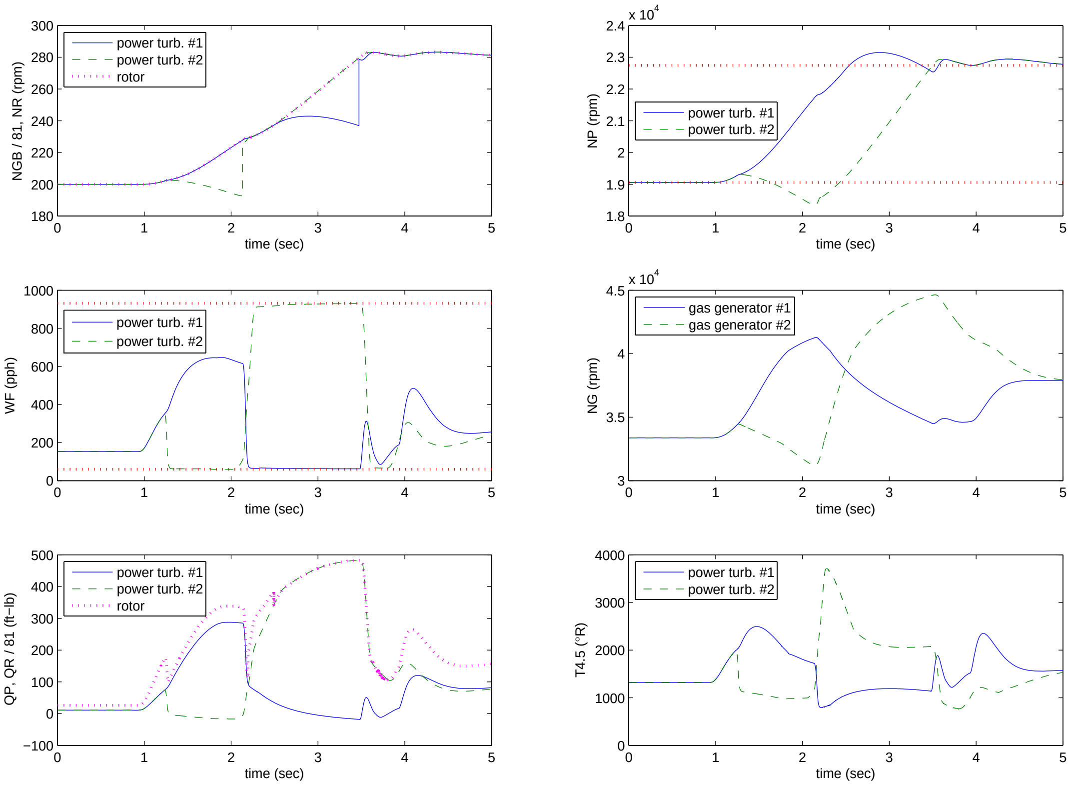

Figure 5.—Example 1: Rotor speed ramp up to highest speed range, *T4.5* limit is not active. Dotted lines on the *Np* and *Wf* plots indicate limits.

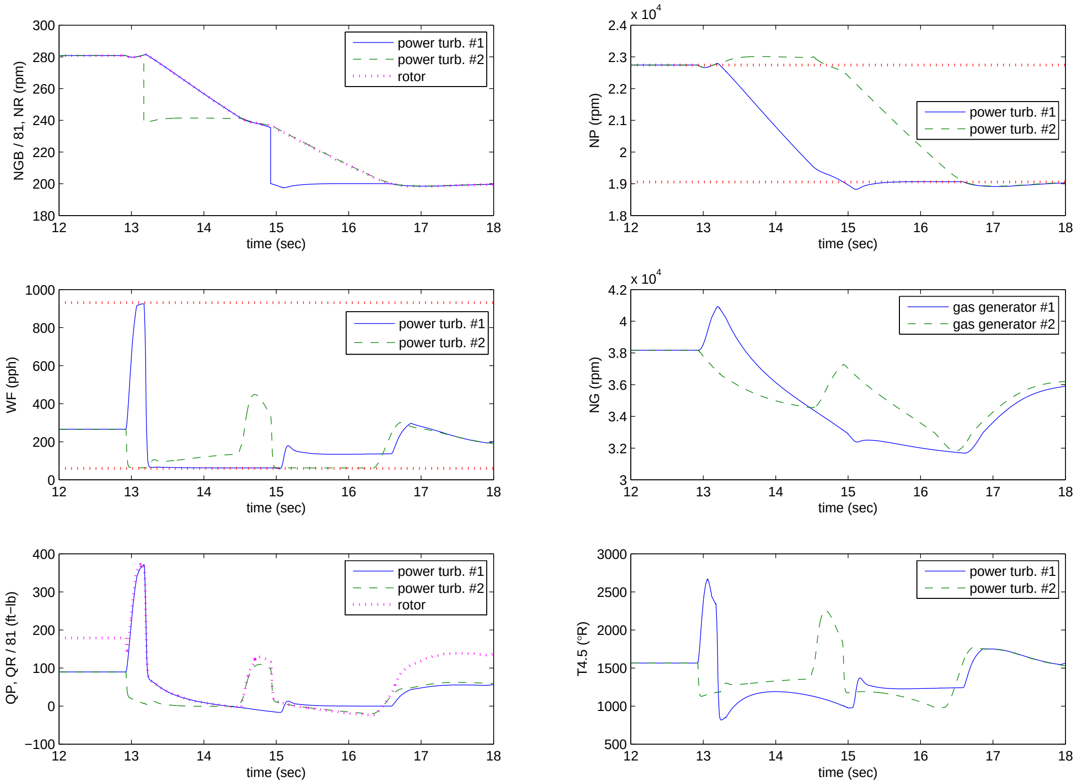

Figure 6.—Example 2: Rotor speed ramp down from the highest range, *T4.5* limit is not active. Dotted lines on the *Np* and *Wf* plots indicate limits.

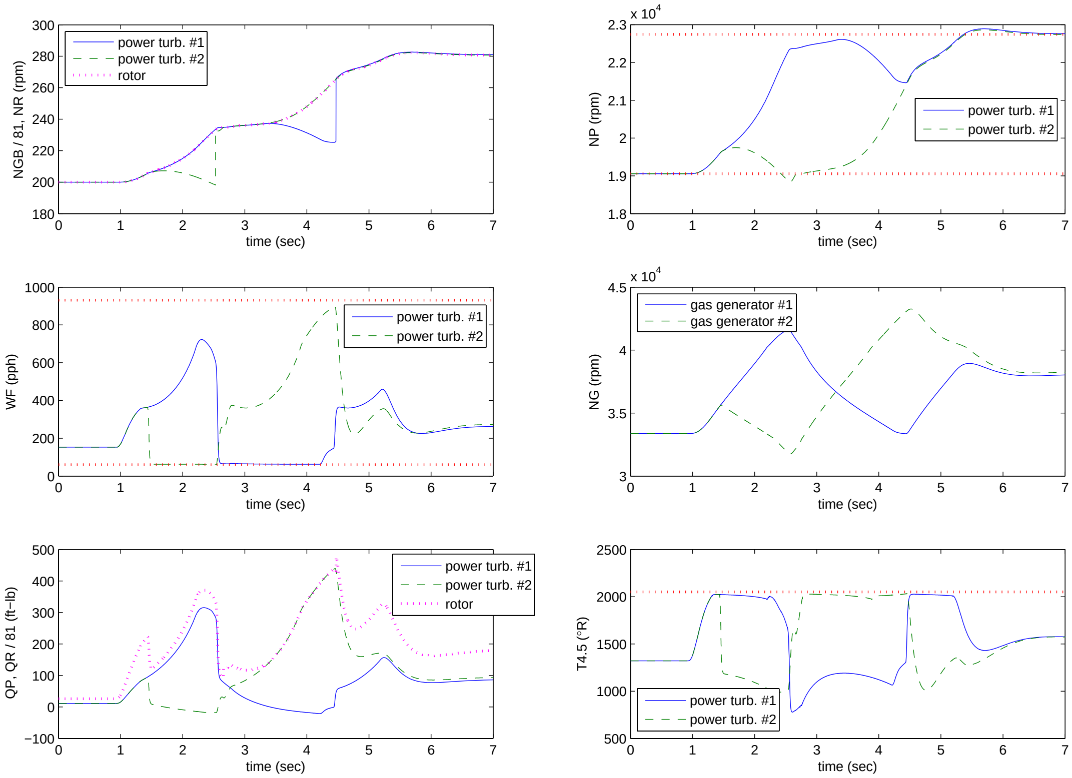

Figure 7.—Example 3: Rotor speed ramp up to highest speed range, *T4.5* limit is active. Dotted lines on the *Np*, *Wf*, and *T4.5* plots indicate limits.

The third example (fig. 7) is again the ramp up in speed, but this time with the *T4.5* limit active. Here there is about a one second dwell time in the speed range overlap band as engine #2 tries to increase the rotor speed, only to have its fuel flow retarded by the *T4.5* controller limit. This transient takes nearly twice as long to complete as the similar one with no limit. The reason is that in the current example, engine #1 takes longer to disengage since engine #2, working alone with its fuel flow restricted, cannot keep the rotor speed increasing at the rate it did in the former example. The final example (fig. 8) is nearly identical to the second example, but the *T4.5* limit restricts fuel flow at the points where each engine is attempting to "lift" the rotor off the other. It does not cause a noticeable delay in the transient.

Discussion

Based on the preliminary results presented in this paper, the feasibility of the SSC methodology is successfully demonstrated for variable rotor speed control. By performing the sequential shifting between the two highest-speed gear ratios, it was shown that the momentary decoupling/shifting caused no loss in rotor speed during the transition and only moderate deviations from a completely smooth speed ramp-up. The transition on the downward ramp produced an extremely smooth speed change; only a slight deviation from the ramp was necessary for the engine to disengage from the rotor. In all cases, the power turbine speeds remained within their prescribed speed bands with only minimal overlap (<1 percent) for smooth hand-off.

The results were obtained using a very simplified simulation, and show that relatively slow (on the order of several seconds) speed variation of nearly 30 percent is obtainable, but that compares well with the XV-15 (the experimental predecessor of the V-22 Osprey) conversion time of 12.5 sec (ref. 19). The examples used linear models, and did not account for vehicle or aerodynamic effects. Some of the concerns with vehicle integration include torque changes and yawing induced by sudden sequenced gear shifts, the impact of related tail rotor speed changes, and the effect of the large power changes on the transmission. These concerns need a more complex simulation to investigate. Multi-speed gearboxes of acceptable size and weight were assumed, and while such gearboxes might be cumbersome, placing them near the engines minimizes their bulk because they are able to operate in a high speed/low torque regime. The examples showed that even though the individual gearboxes experienced large changes in torque, they were relatively smooth, as was the total torque on the rotor. The examples addressed the impact of engine controller limits, but not the issues of stall

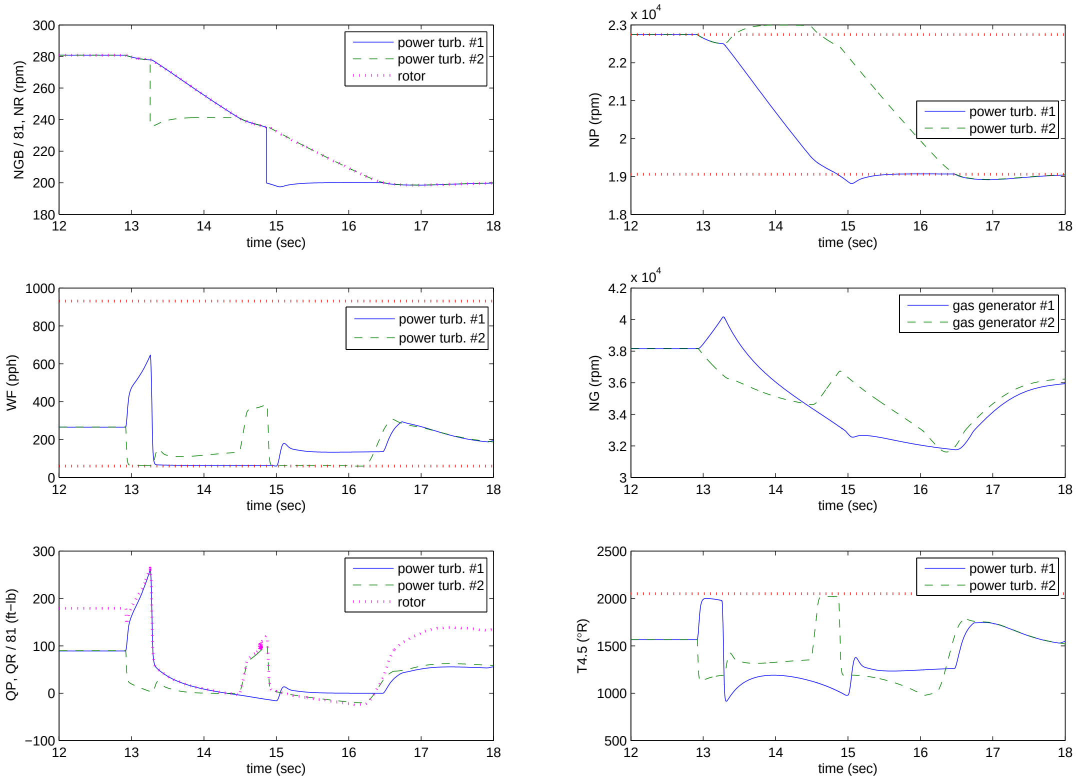

Figure 8.—Example 4: Rotor speed ramp down from highest speed range, *T4.5* limit is active. Dotted lines on the *Np*, *Wf*, and *T4.5* plots indicate limits.

margin, power, and specific fuel consumption over the 15 percent operating range. They also did not address the effect of limitations imposed by engine deterioration and ambient temperature on the approach, especially as the engines are operating near a controller limit. Potential future work that addresses some of these issues includes: incorporation of more realistic nonlinear models of all components; an optimal control law for coordinated gear shifting and speed changing subject to constraints of the speed and overlap bands, as well as controller limits and system dynamics (this might result in a control law that provides unusual trajectories such as purposely overspeeding on the upward slope to facilitate quick switching to higher gear); and automation of the complete procedure because of the complexity of the coordinated gear shifting/speed changing process.

Conclusions

A proof of concept of a sequential shifting control for continuously variable rotor speed was proposed and demonstrated. The design addressed the specific constraints of limited power turbine variability in current turboshaft engines, and continuous available power across the speed range. The benefits of such a system include noise reduction and improved agility. There were several significant simplifications made for modeling purposes, but the examples showed that the rotor speed variation was relatively smooth as was rotor torque delivered during the procedure. Additional modeling and optimization of the speed shifting procedure will give a better idea of what can be achieved, but some improvement should be expected.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

A proof of concept of a continuously variable rotor speed control methodology for rotorcraft is described. Variable rotor speed is desirable for several reasons including improved maneuverability, agility, and noise reduction. However, it has been difficult to implement because turboshaft engines are designed to operate within a narrow speed band, and a reliable drive train that can provide continuous power over a wide speed range does not exist. The new methodology proposed here is a sequential shifting control for twin-engine rotorcraft that coordinates the disengagement and engagement of the two turboshaft engines in such a way that the rotor speed may vary over a wide range, but the engines remain within their prescribed speed bands and provide continuous torque to the rotor; two multi-speed gearboxes facilitate the wide rotor speed variation. The shifting process begins when one engine slows down and disengages from the transmission by way of a standard freewheeling clutch mechanism; the other engine continues to apply torque to the rotor. Once one engine disengages, its gear shifts, the multi-speed gearbox output shaft speed resynchronizes and it re-engages. This process is then repeated with the other engine. By tailoring the sequential shifting, the rotor may perform large, rapid speed changes smoothly, as demonstrated in several examples. The emphasis of this effort is on the coordination and control aspects for proof of concept. The engines, rotor, and transmission are all simplified linear models, integrated to capture the basic dynamics of the problem.

15. SUBJECT TERMS
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