FLIGHT CONTROL DESIGN FOR ROTORCRAFT WITH VARIABLE ROTOR SPEED

A Dissertation in
Aerospace Engineering
by
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Abstract

Flight control design issues for rotorcraft with variable rotor speed are investigated, and new design methodologies are developed to deal with the challenges of variable rotor speed. The benefits of using variable rotor speed for rotorcraft are explored with a rotor speed optimization study using a modified GENHEL model of UH-60A Blackhawk. The optimization results recommend to use the optimal rotor speed in each flight condition to improve the helicopter performance. The efforts are made to accommodate the optimal rotor speed schedule into the flight control system design and also address the stability issues due to the rotor speed variation.

The rotor speed optimization results show significant performance improvements can be achieved with moderate reductions in rotor speed. The objective of the control design is to accommodate these rotor speed variations, while achieving desired flying qualities and maneuver performance. A gain scheduled model following/model inversion controller is used to control the roll, pitch, yaw, heave, and rotor speed degrees of freedom. Rotor speed is treated as a redundant control effector for the heave axis, and different control allocation schemes are investigated. The controllers are evaluated based on step responses and the ADS-33E height response requirement. Results show that dynamic variation in rotor speed can improve maximum climb rate and flying qualities for moderate to large commands in vertical speed, but that non-linear effects present significant challenges when integrating control of the aircraft and the engine. The effects of reduced rotor speeds on stability margins, torque required, and stability issues are also studied.

A power command system in the vertical axis is designed to incorporate variable rotor speed while handling torque limits and other constraints. The vertical axis controller uses a fixed nonlinear mapping to find the combination of collective pitch and rotor speed to optimize performance in level flight, climbing/descending flight, and steady turns. In this scheme, the controller is open-loop, making it an inexpensive and reliable solution. The mapping is designed to produce a desired
power level for a given pilot input. Thus the mapping can take into account the performance limits associated with the vertical axis such as power limits, torque limits, and maximum rate of descent. A model following controller is implemented for the pitch, roll, and yaw axes. The piloted simulation was performed to evaluate the controller.

The impact of variable rotor speed on closed loop stability of rotorcraft is discussed. The model following controller can provide high bandwidth control and improve performance using variable rotor speed. However, reduction of rotor speed can result in rotor body coupling and even instability. A rotor state feedback control law can be designed independently and easily integrated into the baseline model following control architecture. Simulations were performed to verify the effectiveness of RSF control to stabilize the rotorcraft dynamics or improve the command tracking performance in the presence of reduced rotor RPM.
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\( \delta_{lat} \) = Lateral cyclic pitch (inch)
\( \delta_{long} \) = Longitudinal cyclic pitch (inch)
\( \delta_{col} \) = Collective cyclic pitch (inch)
\( \delta_{ped} \) = Pedal input (inch)
\( \delta_{tht} \) = Throttle input
\( \Omega \) = Rotor speed
\( \omega, \zeta \) = Frequency and Damping ratio

Subscripts:

\( c \) = Output from command filter
\( cmd \) = Command signals
\( D \) = Pseudo control
\( cmd \) = Corresponding to roll, pitch, and yaw axis
\( trim \) = Trimmed value
Acknowledgments

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Chapter 1

Introduction

This dissertation investigated the flight control design issues for rotorcraft that make use of variable rotor speed. Control design methodologies were developed to take advantage of the rotor RPM degree of freedom to improve performance and to maintain desired handling qualities and maneuverability. This manuscript has been divided into several chapters. The first chapter reviewed the history of using variable rotor speed. In addition, previous researches on relevant technologies were discussed and the objectives of this dissertation were presented. The second chapter reported a parametric study of rotor speed optimization, which was implemented to define the optimal rotor speed schedule for the controller design. The third chapter focused on the control system design for the example rotorcraft, in which the variable rotor speed concept was actively applied in most flight conditions. From the technical perspective, Chapter 3 reported the modification of Model Following Control (MFC), a widely used control structure, which could accommodate the optimal rotor speed schedule. Chapter 4 proposed a power command system design for variable rotor speed’s application in the vertical axis. Chapter 5 investigated Rotor State Feedback (RSF) control for the potential air resonance problem at the reduced rotor speed. The last chapter summarized the contributions of this dissertation and recommended the future research works.
1.1 A History of Rotorcraft with Variable Rotor Speed

The vast majority of modern rotorcraft have been designed to operate with a constant rotor speed. One of the main reasons is to avoid the potential vibration or resonance associated with the rotor. All the structural components have their own natural frequencies. The initial design should prevent these frequencies from approaching the rotor speed and its higher harmonics. Otherwise they may produce annoying or even dangerous vibrations.

The idea of using variable rotor speeds on rotorcraft may sound ambitious and challenging. First, it will be a real challenge for dynamics engineers to choose a scope of reliable rotor speeds if the rotor speed is allowed to vary within even a limited range during the flight. Second, the implementation of rotor speed variation on rotorcraft is complicated. Unlike the fixed-wing aircraft, rotorcraft rely on the propulsion and the rotor system to provide lift and forward thrust as well as control moments. Therefore the rotorcraft’s drive system must be very reliable and efficient. Moreover, the variation in rotor speed by adjusting engine’s output speed can not be large, or it will propose a big challenge to the engine speed control design. New concepts in the design of the continuous variable speed transmission (CVT) are still not able to meet all requirements on efficiency, maximum continuous torque, and range of speed variation. Currently, there is no CVT design suitable for the practical application.

But using the variable rotor speed has tremendous potential to improve rotorcraft’s performance. The idea is to vary rotor speed according to different flight conditions in order to have a greater portion of the rotor blades operating at more optimal angle of attack resulting in higher blade section lift-to-drag ratios and maximize overall efficiency. Additionally, it is beneficial to adjust rotor speed in some flight conditions to overcome the problems associated with the advancing blade stall and the retreating blade stall. Over the years, the idea of using large rotor speed variation is especially of interest to engineers working on the design of long endurance, high speed, or heavy lift rotorcraft. Many researchers working on conventional rotorcraft also considered the possibilities of enhancing performance and maneuverability by using moderate rotor speed variation. The following dis-
discussion has offered a brief review of the history of the development of the variable rotor speed concept.

As early as 1953, a two-speed helicopter transmission [1] was installed on an Air Force H-5H helicopter and successfully flight tested (Figure 1.1). The original objective was to test a higher rotor speed to reduce the effects associated with retreating blade stall when the forward speed is increased. With the nominal engine speed kept unchanged, the transmission under test using high and low rotor speed gears provided the high rotor speed of 223 RPM and the low rotor speed of 173 RPM, which are higher and lower than the designed standard rotor speed of 194 RPM, respectively. The flight test results from this research, compared with the results using the normal transmission, gave the firsthand experience of using variable rotor speeds on rotorcraft. The flight test showed that the two-speed transmission had great advantages in enhancing the rotorcraft performance at high-altitude condition. The author also pointed out that a high collective pitch settings were required in the low rotor speed gear.

The idea of reduction in rotor speed to reduce power in high speed flight has also been proposed for high speed compound and coaxial configurations. During the flight testing of the Lockheed XH-51 compound helicopter (Figure 1.2), the rotor speed was gradually reduced to delay the effects of the high advancing blade tip speed on power required, vibration, structural loads, and general handling characteristics during the high speed flight [2]. In the flight test, the maximum true airspeed of 262.7 knots can be reached with the rotor operating at 95.5% of the normal rotor speed. But the pilot also reported that there was a feeling of reduced stability at the lower RPM settings. The flight test results also indicated that
further expansion of the rotor speed and airspeed envelope was limited by two factors. The first one was an increase in vibration levels when operating at high to intermediate rotor speed settings. This problem was associated with operating at advancing tip Mach numbers in excess of 0.91. The second factor was a rotor plane oscillation which occurred at high forward flight speeds using low to intermediate rotor speed settings.

The XH-59A, as shown in Figure 1.3, was an experimental co-axial helicopter, which was developed as part of the Advancing Blade Concept (ABC) program. The rotor was designed to operate as low as 70% of the standard rotor speed in high speed cruise flight. Slowing rotor in such design is normally meant to reduce the advancing tip Mach number in high speed flight, and therefore reduce the power required and increase the maximum speed. The dual speed control levers are provided to manually adjust power turbine/rotor speed. Therefore varying rotor speed can be used to optimize the vehicle performance or to reduce structural resonances.

More recently Karem [3] has proposed the Optimum Speed Rotor (OSR) concept, which uses large variations in rotor speed to reduce power required. This OSR concept was applied on the A160 Hummingbird unmanned helicopter (Figure 1.4) in order to improve the range and endurance. The rotor speed was designed to be

![Figure 1.2. XH-51A from www.aviastar.org](image-url)
adjusted according to the different airspeeds during the flight. The unique OSR technology enables the Hummingbird to achieve an “optimal” overall efficiency at different altitudes and cruise speeds, to reduce power required, and then save the fuel consumption.

In summary, the application of variable rotor speed for rotorcraft has existed for a long time but was limited by the practical factors such as dynamics problems and drive system implementation. Most experimental rotorcraft using this concept in early days were primarily designed to reduce rotor speed at high speed forward flight to prevent advancing side blade stall. The recent OSR concept aimed at adjusting the rotor speed over a wide range for different cruise speeds in order to achieve a higher efficiency.
1.2 Previous Research

The following section will review previous research topics that are directly relevant to this dissertation.

- Rotor speed optimization  — The study to determine which rotor speed is favorable in a specific flight condition.

- Rotor speed control  — The method to make the rotor speed follow the rotor speed command in flight.

- Flight control with variable rotor speed for rotorcraft  — The study to make use of variable rotor speed in the flight control system design the study on the effect of variable rotor speed on flight control performance or stability issues.

- Rotor state feedback  — The study of using rotor state information in feedback control design for rotorcraft.

1.2.1 Rotor Speed Optimization

The study of the rotor speed optimization is a prerequisite for using variable rotor speed. The methods and procedures used in previous researches were different in order to meet the various objectives in different projects related to variable rotor speed.

For the design of the XH-51, the primary aim was to achieve a higher forward flight speed. The helicopter flight speed is normally restricted by the advancing blade tip speed, which can’t be too close to Mach 1. In that study, the maximum Mach number for tip speed was set at 0.91. The flight test was carried out to reach a trade-off in the rotor speed and the flight speed for an acceptable performance. The similar idea was applied to the design of XH-59A and the variable rotor speed concept was implemented for the same purpose. In the flight test, different rotor speeds were tried to determine the proper RPM values for various flight conditions. In both projects reviewed above, the rotor speed variation was utilized to reduce the advancing blade’s tip speed at high speed forward flight.
Another attempt to design a variable rotor speed transmission (VRST) [4] has been made to reduce the noise level. Because reducing tip speed is considered an effective way to reduce the noise, the standard to determine how much variation in rotor speed directly depends on the rotor noise level. When this project started, to improve fuel economy was not a primary object. But it could be another benefit besides the reduction of the noise level.

Prouty[5] suggested a method to define the best rotor speed in different situations. When the helicopter is in hover, the Figure of Merit (FM) is chosen as the “index of goodness” for helicopter performance evaluation. Therefore the best rotor speed in this flight condition is chosen to maximize FM. When the helicopter is in loiter, the important factor is chosen as the Specific Endurance (S.E.), which is defined as hours of flight per pound of fuel. For cruise flight, the pertinent standard is chosen as the Specific Range (S.R.), which is defined as nautical miles per pound of fuel. And it is also discussed to improve the maximum speed using the variable rotor speed. This study was based on simple analysis without performing complex computing. However the author provided valuable information, which showed that the rotor speed optimization should be based on specific flight missions and performance indexes.

Karem’s OSR concept [3] aimed at maintaining the lifting airfoil operating at levels of maximum lift-to-drag ratio so as to improve the helicopter performance and efficiency. The rotor speed was proposed to be scheduled manually by the pilot or automatically by the computer after selecting a flight performance parameter to optimize. The examples of rotor speed schedule that were developed for level flight are based on the parameter of the power required. The author also showed an alternative embodiment of using just two or more rotor speed settings to achieve a sufficiently large gain in performance. Not surprisingly, the gain is not as great as the benefits by using the continually variable rotor speed theoretically.

Steiner [6] conducted a study to thoroughly examine the main rotor power reductions using variable rotor speed. The result was based on the numerical simulation of UH-60 Black Hawk model when the rotor speed variation was within ±15% over the nominal rotor speed. The author determined the optimal rotor speed by minimizing the power required and the rotor speed schedule has considered the airspeed, gross weight, and altitude.
In summary, the key component in rotor speed optimization is to define the flight performance parameter to optimize based on the design requirement.

1.2.2 Rotor Speed Control

The application of variable rotor speed on rotorcraft requires the practical and feasible solutions to implement the rotor speed variation. Ideally, the rotor speed can be changed continuously and efficiently over a wide speed range with the presence of a reasonable load. From the earliest two-speed rotorcraft transmission [1] to latest ongoing development of the continuous variable speed transmission, the researchers on novel transmission designs have proposed several possible solutions to efficient implementation of the variable rotor speed on rotorcraft. One of the advantages of this method was that the engine power turbine speed can be kept within a narrow speed so that the engine still performs at its best efficiency.

In 1994, a research on variable rotor speed transmission (VRST) [4] had been started. This new transmission was designed to be able to change the rotor speed from 80% to 100% continuously. In 2007, a sequential shifting control algorithm [7] for twin-engine rotorcraft was proposed to enable the rotor speed to vary over a wide range while the engines remained within their prescribed speed bands. In this study, the continuous torque is provided to the rotor system during the rotor speed variation through the shifting usage of two engines. Saribay et al. [8, 9] have been working on the Pericyclic Continuously Variable Speed Transmissions (P-CVT) design. The authors showed the conceptual designs on a 600 HP Turbine Engine with 40,000 RPM output shaft speed, to achieve the desired variable rotor speeds from 140 RPM to 300 RPM.

A160 Hummingbird UAV was firstly powered by the automotive engines and then upgraded to the turboshift A160 Turbine (A160T). The A160T is equipped with a two-speed transmission gearbox, which provides two speed settings of 200 RPM and 400 RPM. It is believed that the rotor speeds between these two settings can be achieved by changing engine’s power turbine speed.

Before the continuously variable speed transmission is designed and tested successfully, the practical method to change rotor speed can be achieved through variation of engine’s power turbine speed. This method was employed on XH-51
and XH-59A introduced above and also provided an alternate for pilots of some conventional helicopters to manually adjust rotor speed. It is notable that if the engine’s output power is kept unchanged, the reduction in power turbine speed will increase the output torque since the torque and power relation is simply described as equation \( Q = P/\Omega \). This may be challenging for a big rotor speed reduction because the large torque limit will result in a much heavier transmission design.

1.2.3 Flight Control with Variable Rotor Speed

The concept of variable rotor speed has also been applied to controller design to enhance helicopters’ maneuverability or to act as a redundant controller.

Schaefer and Lutze [10] outlined the concept of continuous variable rotor speed control, in which the rotor speed is a function of airspeed, commanded load factor, and control displacements and rates. The results showed a promising improvement of maneuverability with the rotor speed varying from 90% to 120% for ground attack and air combat missions.

Similarly, Iwata and Rock [11] explored the benefits of using variable rotor speed in integrated helicopter and engine control with a continuously variable rotor speed command strategy. In the framework of integrated flight/propulsion control, the optimal rotor speed command aimed at improving the maneuverability and agility.

Enns and Sicite [12] proposed a robust reconfigurable flight control method for the failure of a main rotor actuator. The rotor speed was utilized to change the main rotor’s thrust in order to perform a closed-loop vertical velocity control.

Previous studies of involving rotor speed into the control system design showed the considerable promise to improve the maneuvering performance. However these researches treated the rotor speed as an ideal control effector and didn’t consider that the real rotor speed might not follow the command well. The application of variable rotor speed in maneuvering flight still requires further evaluation in the high-fidelity simulation model including the drive system and rotor system dynamics. In addition, to actively apply variable rotor speed in level flight is a practical idea for improving the helicopter’s fuel economy. An integrated flight/propulsion control system accommodating the variable rotor speed control is necessary for this purpose. A more complicated problem may arise from the fact that the trimmed
control settings could change from the original design points at standard rotor speed and this may lead to the inadequate control power in maneuvering flight and the degraded handling qualities.

Furthermore, Chen [13] pointed out that the flight dynamics under a large variation in rotor speed need to be well understood. He indicated that stability margins and the magnitude of basic stability and control derivatives could change dramatically with large variations in rotor speed. Because the helicopter was design and optimized at the standard rotor speed, it was very likely that the stability and control properties would become worse with the presence of a large deviation from the designed rotor speed. The author suggested that the control design for such a system would require extra care. Chen also revealed that the use of rotor state feedback (RSF) could greatly enhance the achievable bandwidth. This research was based on the model for a hover helicopter with a dropped rotor speed. Further study in using RSF in the high speed forward flight can be performed.

### 1.2.4 Rotor State Feedback

The RSF control has attracted special attention in this research because it can directly control the rotor state, which may become critical with the presence of rotor speed variation, especially for a large reduction of rotor speed. The frequency and the damping of the progressive and regressive flap/lag modes are expected to decrease at the reduced rotor speed, which will increase the likelihood of the occurrence of the rotor-body coupling. The flapping angles will become larger at the lower rotor speed due to the lower centrifugal stiffness. The direct consequence of this problem is that it will increase the probability of the blade hitting travel limits.

Takahashi [14] performed a detailed simulation study and compared the results of the control law design with and without rotor state feedback for a hovering helicopter. The RSF controller showed a better roll response using rotor state information. Howitt [15, 16] set up an experimental platform with rotor state measurement and confirmed the benefits of using RSF in flight control. The author also pointed out that the measurement system could provide sufficient accuracy for the design requirement.
Horn [17] designed a RSF controller based on the GENHEL model of UH-60A to achieve a high bandwidth control and structural load limiting in hovering and low-speed flight conditions. This research showed the fact that the rotor flap/lag modes move towards the imaginary axis as the baseline controller’s roll rate feedback gain increases, resulting in the reduced rotor modes’ damping and frequency. It is the same phenomena that is expected to happen for the reduced rotor speed. Thus the RSF method is especially meaningful here. Further study needs to be extended to the control system design for variable rotor speed as well as for the high speed flight conditions.

1.3 Research Objectives

The objective of this research is to develop effective control system design methods for rotorcraft with variable rotor speed. The features of this design, which differ from the previous research, include:

- The study is based on a high fidelity simulation model for an example helicopter of the conventional configuration with main rotor and tail rotor. With a modification on the rotor speed control module, this model can allow the rotor speed varying continuously in a prescribed range. The drive system dynamics is included in this model to account for its effect on helicopter performance and response.

- Rotor speed optimization is focused on comprehensive methods to define a rotor speed schedule across the envelope, instead of how much benefit can be achieved from the variable rotor speed. Then the optimization method could readily apply to a wide range of helicopters.

- The flight control system is designed to actively control rotor speed for a range of dynamic flight conditions. The rotor speed will be varied dynamically for maneuvering flight, and follow an optimal schedule for quasi-static trim flights.

- The proposed RSF control is applied for different rotor speeds and flight speeds.
The following technical approach is proposed to achieve the objectives:

- The simulation tool, GENHEL-PSU, is modified for this research. The rotor speed variation will be implemented by changing engine’s power turbine speed. Therefore the key modification is focused on the engine and fuel control system. The proposed rotor speed range is between 80% and 120%. As discussed previously, the output torque will increase by 25% with the rotational speed is reduced by 20%, and this may be not a challenge for transmission design.

- Rotor speed optimization study is performed with the simulation tools. This task aims at providing an optimal rotor speed schedule for control design. The power required was proposed to be the key flight performance parameter to be optimized. This part is also serving to explore the constraints related to using variable rotor speed and propose the necessity of using rotor speed variation in control system.

- Integrated flight/propulsion control system design is one of the emphases in this project. The control system should be able to realize the rotor speed control, accommodate the rotor speed optimization results, and make use of the rotor speed as an additional control effector actively. The simulation results will show the benefits of using variable rotor speed in handling qualities. Further study will discuss the effects of variable rotor speed on closed loop stability and cross coupling.

- A power command system design for the vertical axis is performed to accommodate the optimal rotor speed schedule. An updated method of rotor speed optimization involving the torque required and the control margin will be developed. The collective pitch will be reduced during the acceleration of the rotor speed for the torque limiting purpose. The nonlinear simulation will show the benefits of this design and the controller will be tested in the real-time piloted simulator.

- Rotor state feedback control is chosen to improve the baseline MFC controller performance. The analysis of the effects of the reduced rotor speed on rotor
flap/lag modes will reveal the problem. The RSF controller is designed to be easily integrated into the baseline MFC control structure and proves the expected benefits in the linear model simulation. It is also implemented in the nonlinear simulation and the simulation results will confirm that the regressive lag mode plays the key role in the observed rotor-body coupling at the reduced rotor speed.

- Finally the conclusion summarizes the contributions of this dissertation. Some ideas for the future study will be proposed.
Rotor Speed Optimization Study

Many of the important design issues for rotorcraft are related to the term performance, including the estimation of the installed engine power required for a given flight condition, the determination of the maximum level flight speed, the evaluation of the ceiling, and the estimation of the helicopter endurance [18]. When evaluating the performance of rotorcraft with variable rotor speed, a basic task is to determine the rotor speed at which the rotorcraft performance is “optimal” or clearly better than that of rotorcraft with the constant standard rotor speed. Helicopter performance is not defined by a single numerical parameter, but power required is a good one on which to focus the design optimization as it is directly related to the fuel consumption, the endurance, and the range. The objective of using variable rotor speed is to improve the rotor aerodynamic efficiency and therefore reduce the power required.

In practical design of rotorcraft with variable rotor speed, numerical simulation should be used in preliminary design to determine rotor speeds at which the minimum power required can be achieved. Flight tests should be employed to verify or correct the simulation results. For the example rotorcraft UH-60A, the comprehensive parametric study of the effect of rotor speeds is performed to investigate the performance benefits of using variable rotor speed. A similar study was being conducted independently and the results were shown in [6]. The comparison between the two studies’ results is discussed. An optimal trim schedule for rotor speed is defined and the flight controller is designed to accommodate this schedule.

In this chapter, the process of the optimal rotor speed scheduling based on
numerical simulation results are introduced and the example results for hover, level flight, climb, and descending are shown. A discussion for the optimal rotor speed schedule is performed for the issues related to overall efficiency, torque required, and control margins.

2.1 Optimal Rotor Speed Schedule

The optimal rotor speed is defined here as the rotor speed to minimize the power required at a given flight condition, which is determined by the gross weight, altitude, the total airspeed, and the flight path angle, etc. The optimal rotor speed schedule for the example rotorcraft in this dissertation was based on numerical simulation study results. The basic process was to calculate the trim results at a flight condition for different rotor speeds and then find the rotor speed for the minimum power required. Strictly, the result from this method is not guaranteed to be the theoretic optimal value because the numerical simulation can only include a finite number of trim conditions. In practice, the trim results could be assumed as a continuous function of the rotor speed. Therefore if the step size in the rotor speed is small enough, the resulting optimal rotor speed from the parametric study can be close enough to the theoretic value and also accurate enough for engineering applications.

2.1.1 Level Flight

Level flight performance was examined to find the optimal rotor speed from hover to 160 knots, with the rotor speed allowed to vary from 70% to 120%. The lowest rotor speed in operation would be 80%, though a larger range was involved here to check the lowest rotor speed boundary. Here the 100% rotor speed means the standard rotor speed used in the example rotorcraft UH60A, which is 27 rad/sec or about 258 RPM. A large range of altitudes and gross weights were also evaluated to explore the connections between the optimal rotor speed and the other operating conditions. Therefore, the optimal rotor speed schedule in the level flight is assumed to be a function of the airspeed, the gross weight, and the altitude.

Figure 2.1 shows an example of power required contours for different airspeeds
Figure 2.1. Power Required Contours for UH-60 Gross Weight=18500 lbs, Sea level Standard

and rotor speeds at a specific altitude (sea level) and gross weight (18,500 lbs). For each airspeed, the optimal rotor speed is defined by varying the rotor speed to minimize the power required. The red dotted line represents the optimal rotor speeds for minimum power required at different airspeeds for level flight. They are substantially lower than the standard rotor speed (100%) throughout the airspeed range. As discussed above, this result is not the real optimal value in theory, but it can be accurate enough for engineering applications. The power savings are significant for most airspeed and can be up to 25% at 70 knots. It should also be noted that along the lower boundary in the contour plots as shown in Figure 2.1 the rotor blades are operating relatively close to their stall angle of attack, and the collective or tail rotor actuators are operating near their physical travel limits. There is no trim reached to operate at the rotor speed below the lower boundary.

This boundary could be moved by changing the flight conditions. For examples, Figure 2.2 shows the power required contours for the gross weight of 14,000 lbs and the lower boundary is expanded. The smaller gross weight can make the helicopter reach trim with the lower collective setting or with the lower rotor speed. Conversely, the larger gross weight can move the boundary up, as shown in Figure 2.3. For each of the three gross weights, the optimal rotor speed line is close to the lower boundary.
Figure 2.2. Power Required Contours for UH-60 Gross Weight=14000 lbs, Sea level Standard

Figure 2.3. Power Required Contours for UH-60 Gross Weight=30000 lbs, Sea level Standard

Figure 2.4 shows that the rotor speed for minimum torque required is much higher than the standard rotor speed at hover and low speeds, and is lower than standard rotor speed at higher speed forward flight. In this figure, the torque is expressed as a percentage of the nominal transmission torque limit of the UH-60A, which is set to be 57,032 ft-lb [19]. Note that torque and power required are
related by equation $Q = P/\Omega$, where $Q$ is torque, $P$ is power, and $\Omega$ is rotor speed. Reducing rotor speed appears to reduce the profile power required to keep the rotor running and then the total power required would be reduced. But reduction in rotational speed can actually increase the torque required on the drive system components. Therefore the resulted torque might be either higher or lower than the standard torque (the torque required for nominal 100% rotor speed at the same flight condition). The net result is that reduction in rotor speed can provide significant performance benefits, but it might also require the rotorcraft to operate near a number of different constraints including the torque, the collective travel, the pedal travel, and the rotor blade stall. These issues will be further discussed later and here we still treat the power required as the primary factor in optimization study to determine the optimal rotor speed.

Figures 2.5 and 2.6 show the schedule of optimal rotor speed settings to minimize power required as a function of airspeed, gross weight, and altitude. The results show that the optimal rotor speed is quite sensitive to the specific operating conditions of the rotorcraft, so that a comprehensive schedule involving airspeed, gross weight, and ambient conditions is required to ensure the desired performance improvements achieved for all operating conditions. This would present a challenge to the flight control design, since controllers must operate for a wide range of rotor

Figure 2.4. Torque Required Contours for UH-60 Gross Weight=18500 lbs, Sea level Standard
2.1.2 Climb and Descent Flight

Further optimization studies were conducted for climbing and descending flight conditions. In this analysis, the operating condition is restricted to a single gross weight of 18,500 lbs and a single ambient condition at sea level standard. As shown
in the previous analysis, the optimal rotor speed for trim may require the aircraft to operate near constraints. It is clear that increase in the rotor speed is required to get desired performance in climbing flight. This pattern is illustrated in Figure 2.7, which shows the maximum rate of climb at different total airspeeds and rotor speeds. As the rotor speed increases from 80% to 120%, the maximum achievable climbing rate is raised across the full speed range. It also showed the fact that the maximum climbing rate is relatively low when the rotor speed is set for the optimal value for level flight. This indicates that for a level flight operating at the optimal rotor speed, the rotor speed must be increased to achieve a higher climbing rate. The simple conclusion from this figure is that to improve the maximum climbing rate at the specific airspeed, the rotor speed must be increased. Figure 2.8 shows the optimal rotor speed for different airspeeds and rates of climb. Thus, given a specified gross weight and altitude, a 2-D look up table can be used to determine the optimal rotor speed for the current airspeed and the commanded vertical speed. These optimization results will be used in the integrated flight/propulsion control system design in Chapter 3.
Figure 2.8. Optimal RPM Scheduling in Climbing Flight, Sea Level, Gross Weight=18,500 lbs

2.2 Discussion

Section 2.1 showed that the optimal rotor speed is normally lower than the standard 100% rotor speed in level flight for the specific rotorcraft used in this analysis, UH-60A Black Hawk. This section discusses some issues at the reduced rotor speed about aerodynamic efficiency, the torque required, and the control margins.

2.2.1 Aerodynamic Efficiency

The reason behind the performance improvement is that the rotor speed is optimized to allow a typical blade section to operate at an angle of attack and Mach number, which results in a higher average lift-to-drag ratio. Figure 2.9 to Figure 2.11 show the distributions of angles of attack, Mach numbers, and the lift-to-drag ratios over the rotor disk at 80 knots level flight, sea level, and the gross weight of 18,500 lbs. The optimal rotor speed in this situation is about 84% of standard rotor speed. In order to maintain the same lift, the angles of attack over the rotor disk are on average larger than the standard case, as shown in Figure 2.9. In Figure 2.10, the advancing blade’s tip speed at the optimal rotor speed is obviously lower than that at the standard rotor speed. Figure 2.11 shows the distributions of the airfoil lift-to-drag ratio over the rotor disk and that the efficiency at the optimal rotor speed is higher. Although the 84% RPM results in lower power for
level flight, it might not be practical on a regular helicopter since the rotor may stall or reach torque limits for relatively small amplitude maneuvers. However, if the rotor speed is varied dynamically, where the rotor speed is reduced in trim but increased during maneuvers, the variable RPM helicopter might achieve significant fuel savings over the course of the mission.

More results for hover and 40 knots level flight are shown in Figures 2.12 to 2.17. As expected, the overall efficiency using the optimal rotor speed is higher.

2.2.2 Torque Required

Figure 2.18 shows the difference in power required between the optimal rotor speed and the standard 100% rotor speed. This indicates that up to 15% energy can be saved with the optimal rotor speed schedule if the rotor speed variation is feasible. This would pay off directly in terms of the fuel consumption, the range, or the endurance. However, the results in Figure 2.19 showed that if the optimal rotor speed is selected to minimize power required, the torque required will actually increase relative to the nominal rotor speed for most flight conditions. Especially at hover and low speeds, the increase of torque required can be up to 14%. The results illustrate the design trade-off in selection of rotor speed in terms of power and torque required. Normally, the torque is not of direct concern to aircraft performance (in terms of range and endurance). But it needs to be considered as it relates to structural constraints on the aircraft. The torque transmitted through the main gearbox is limited due to stresses on gear teeth and drive shafts. This torque limit should not be designed too high, otherwise the transmission design will become a real challenge and the transmission’s weight will increase significantly. The aircraft can fly safely as long as the torque is below this limit. But if the aircraft is operating very close to the limit in trim, the rotorcraft will have very little margin for maneuvering. The torque required should be considered in the further study on the optimal rotor speed schedule.

Figures 2.18 and 2.19 also show that it is good to use variable rotor speed concept for the airspeed above 40 knots because the power required will be reduced significantly at the optimal rotor speed while the torque required is not increased much compared with nominal rotor speed. This conclusion is in consistent with
Figure 2.9. Angle of Attack Distribution for Level Flight 80 knots

Figure 2.10. Mach Number Distribution for Level Flight 80 knots

Figure 2.11. Airfoil L/D Distribution for Level Flight 80 knots
Figure 2.12. Angle of Attack Distribution for Level Flight 40 knots

Figure 2.13. Mach Number Distribution for Level Flight 40 knots

Figure 2.14. Airfoil L/D Distribution for Level Flight 40 knots
Figure 2.15. Angle of Attack Distribution for Hover

Figure 2.16. Mach Number Distribution for Hover

Figure 2.17. Airfoil L/D Distribution for Hover
the findings in [6].

Figure 2.18. Power Required Difference between Optimal and Standard RPM, Sea Level, Gross weight=18,500 lbs

Figure 2.19. Torque Required Difference between Optimal and Standard RPM, Sea Level, Gross weight=18,500 lbs
2.2.3 Control Margins

The control margin is another issue to be considered. As shown in Figure 2.20, both the collective control margin and the pedal control margin are smaller at the optimal rotor speed. This is especially true in the conditions of hover and the low speed forward flight. For collective control, the smaller control margin indicates a lower maximum climbing rate. There is almost no pedal control margin left at hover with the optimal rotor speed and this is a more serious problem because the pilot may lose the heading control any time. The low control margin at reduced rotor speed indicated the necessity to fix this problem in the flight control system design.

![Figures showing control margin difference between optimal and standard RPM](image)

**Figure 2.20.** Control Margin Difference between Optimal and Standard RPM, Sea Level, Gross weight=18,500 lbs
Chapter 3

Integrated Flight/Propulsion Control Design

3.1 Overview

This chapter focuses on the development of an integrated flight/propulsion control design for rotorcraft with variable rotor speed. The flight dynamics model, control system design, and the simulation are based on the modified GENHEL-PSU described in Appendix A. The control system design should define a controller architecture including flight control and rotor speed control, accommodate the optimal rotor speed schedule developed in Chapter 2, and show the performance improvement over the same rotorcraft with the fixed standard rotor speed. In a steady level flight, more specifically, the integrated flight/propulsion control system will govern the rotor speed at its optimal rotor speed, which is determined by the optimal rotor speed schedule according to the current altitude, gross weight, and airspeed information. The attitudes should be held constant as the trimmed condition, or within an acceptable variation range from the trimmed value in presence of some disturbance. Once the pilot gives the command to perform some maneuvering such as climbing, descending, or banked turn, the control system will adjust the rotor speed to its future optimal rotor speed based on the commanded input (i.e. the next steady state). During the transient process, the flight control system will command not only the conventional rotorcraft controls, including the
lateral cyclic pitch, the longitudinal cyclic pitch, the collective pitch, and the yaw control input, but also the new rotor speed control.

A model following and model inversion control architecture as described in reference [20] has been employed as the baseline control system design. The details of the controller design are introduced in section 3.2. Here it is necessary to address the difference between the designs on the conventional rotorcraft with fixed rotor speed and the one with variable rotor speed. As shown in Figure 3.1, the design of the automatic flight control system (AFCS) can be independent of the propulsion control system. This is how propulsion control is implemented on the current UH-60A Black Hawk described in Appendix A. The reference rotor speed is set to be a constant value, the nominal 100% rotor speed. The feed-forward of the collective pitch input into the engine Hydro-Mechanical Unit (HMU) will compensate the demand for torque due to collective pitch change. In this case, the propulsion control was designed to minimize the variation of rotor speed due to the fluctuation of the torque required. In Chapter 1, the method of changing rotor speed through the variation of the engine power turbine speed has been proposed for this research. For such a purpose, the original propulsion control system has been modified as described in Appendix A. A new rotor speed controller is required to track the variable command of the reference rotor speed. The presence of more complicated
coupling between load torque and rotor speed requires the design of an integrated flight/propulsion control system, as shown in Figure 3.2, for the example rotorcraft.

In the following sections, the issues about the control system design will be discussed in details. The control law will be developed, analyzed, and first evaluated using the linearized model. Then, the particular problem related to using variable rotor speed in the vertical axis will be investigated. The controller with gain scheduling against the different operating points will be implemented with the nonlinear system GENHEL-PSU. The simulation results will demonstrate the benefits of using the variable rotor speed.

### 3.2 Control System Design

#### 3.2.1 Model Following and Model Inversion Control

The baseline controller design is based on the model following and model inversion control architecture [20], as shown in Figure 3.3. The objective is for the aircraft to respond to the pilot command as a simple first or second order linear system. Each pilot control input is designated to command a specific state variable (e.g. attitude, angular rate, or translational rate). The state command is passed through a command filter that represents ideal dynamic response characteristics. The command filter produces the desired state and state derivative response. The
The state tracking error is passed through a classical proportional-integrated-derivative (PID) compensator, which is added to the desired response of the state derivative to get a pseudo-control. The pseudo-control is passed through an inverse model of the aircraft dynamics to get the control input, as shown in Equation 3.1. If the inverse model is exact, a perfect inversion will make the series combination of the aircraft and inverse model behave as a simple integrator. The error dynamics due to external disturbances will be governed by the PID compensator as shown in Equations 3.2 and 3.3. A typical choice for the compensator is that the error dynamics match the ideal response model (this is the approach used in this analysis) so that the response to disturbances is similar to response to pilot commands.

The tracking error should decay to zero and the control input should achieve the desired response.

\[ u = B_C^{-1}(v - A_Cx) \]  
\[ e = x_c - x \]  
\[ \dot{e} + K_p e + K_I \int e \, dt = 0 \]

In the normal implementation, the linear dynamics are approximated so \( B_C \) is a square matrix. But in some cases the dynamics could be approximated that the number of inputs is larger than the number of states, which results in a non-square \( B_C \).

To discuss this control structure in further, as shown in Figure 3.4, the command filter is implemented as a second order one. Normally the command input
is in the unit of angle, such as the roll attitude command, then the second order command filter gives the three reference commands including the reference angle $\theta_c$, the reference angular rate $\dot{\theta}_c$, and the reference angular acceleration $\ddot{\theta}_c$. The error dynamics are same as Equation 3.3 for the error chosen as $e = \theta - \theta_c$. Because the command input $\theta_{cmd}$ and the controlled variable $\theta$ are both in the unite of angle, this structure is implemented to realize Attitude Command Attitude Hold (ACAH) type response. Comparably, the structure shown in Figure 3.3 is normally used for Rate Command Attitude Hold (RCAH) type response.

One may notice that there could be steady state error for the structure in Figure 3.4. The steady state error can be removed by adding an integrator in error dynamics, as shown in Figure 3.5, then the characteristic equation can be described in Equation 3.4. It is a third order equation and has three poles, which can be selected as a pair of complex poles with natural frequency $\omega_e$ and damping ratio $\xi_e$ and a negative real pole $s = -p$ based on the design requirements. The parameters for such a selection are given by Equation 3.7.
\[ \dot{e} + K_p \dot{e} + K_I e + K_S \int e \cdot dt = 0 \] (3.4)

\[ K_P = 2\omega_e \xi_e + p \] (3.5)

\[ K_I = 2\omega_e \xi_e p + \omega_e^2 \] (3.6)

\[ K_S = \omega_e^2 p \] (3.7)

3.2.2 Rotor Speed Control

Rotor speed control on the UH-60A is achieved using the engine’s Electrical Control Unit (ECU) and Hydro-Mechanical Unit (HMU). Because the original rotor speed control aimed at keeping the rotor speed constant, some actions have been taken to make the rotor speed follow a rapid changing command. The modifications on these modules are described in Appendix A. The ECU is replaced with a model following control law as shown in Figure 3.6. The engine dynamics can be reduced to a simplified first order linear model including the collective pitch load demand, as shown in Equation 3.8.

\[ \dot{\Omega} = Q_1 \Omega + Q_{\delta th l} \delta th l + Q_{\delta col} \delta col \] (3.8)

The inversion can be achieved as:
In practice, the first order command filter includes a nonlinear saturation to limit rotor speed rate. The advantages include that the commanded rotor speed changes smoothly, the gas generator stays within acceleration and deceleration limits, and the rotor speed change does not require excessive torque. In this research, this rotor speed acceleration limit was set to be $2 \text{ rad/sec}^2$ (about 7.4 %/sec) or smaller. The model inversion generates the ECU contribution to the engine throttle input, $\delta_{\text{tht}}$ (this is the variable represented by the mnemonic $SPDG$ in the GENHEL T700 engine model). A proportion-integral compensator is used to ensure zero steady-state error.

\[ \delta_{\text{tht}} = Q_{\text{tht}}^{-1} \left( \dot{\Omega}_{\text{pseudo}} - Q_{\Omega} \dot{\Omega} - Q_{\delta_{\text{col}}} \delta_{\text{col}} \right) \]  

(3.9)

3.2.3 Controller Parameters

The integrated flight/propulsion control system design based on the model following and model inversion control architecture is proposed for the example rotorcraft UH-60A with variable rotor speed capability, as shown in Figure 3.7.

The input includes commands of the roll attitude, the pitch attitude, the yaw rate, and the vertical speed. The command filters for each input represent the ideal models based on desired response requirements. The parameters of the command
filter (e.g. time constant for a first order filter, or natural frequency and damping ratio for a second order filter) are selected to meet desired handling qualities specifications. In this study, the parameters were selected to meet Level 1 specifications as designated by ADS-33E for small amplitude response (bandwidth) in roll, pitch, and yaw. The vertical axis time constant was selected to meet ADS-33E height response specifications on effective time constant and phase delay. The natural frequency and damping ratios for the roll and pitch command filters are set to 2.5 rad/sec and 0.8. The time constant for the yaw axis is set to 0.4 sec, and the time constant for the vertical axis command filter is 2.5 sec.

The reference response is compared with the actual response to generate error signals. Error dynamics could be either a proportional-derivative (PD) compensator for Attitude Command Attitude Hold (ACAH) response in roll and pitch, or a proportional-integral (PI) compensator for Rate Command Attitude Hold (RCAH) response in yaw and for Rate Command Height Hold (RCHH) response in the vertical axis. Sahani and Horn [21] suggested selecting the error dynamics to be on the same order as the command filter dynamics in order to avoid very large feedback gains. In this work, the natural frequency and damping ratio of the error dynamics are set to be 2.5 rad/sec and 0.8 for roll, 2.5 rad/sec and 0.8 for pitch, 2.5 rad/sec and 0.8 for yaw, and 0.5 rad/sec and 0.8 for vertical axis, and 5 rad/sec and 0.8 for rotor speed control.

After command filters and error dynamics modules, the psuedo-control signals are angular accelerations $\ddot{\phi}_D$, $\ddot{\theta}_D$, $\dot{r}_D$, and vertical acceleration $\dot{V}_Z D$. The inverse model requires the pseudo angular accelerations expressed in the body axis. Equations 3.10~ 3.12 [21] will perform the conversion.

$$\dot{\phi}_D = \ddot{\phi}_D - (\ddot{\theta}_D s\phi s\theta + \dot{r}_D s\phi + \dot{\psi}\dot{c}\phi s\theta + \dot{\psi}\dot{s}\phi s\phi c\theta)/(c\phi c\theta) \quad (3.10)$$

$$\dot{\theta}_D = (\ddot{\theta}_D + \dot{r}_D s\phi + \dot{\psi}\dot{c}\phi)/(c\phi) \quad (3.11)$$

$$\dot{w}_D = \dot{V}_Z D + u\dot{\theta} c\theta / c\phi c\theta \quad (3.12)$$
Here \( \cos \theta = \cos \theta, \sin \theta = \sin \theta, \cos \phi = \cos \phi, \sin \phi = \sin \phi \).

The inverse model is in the form of Equation 3.13.

\[
\begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r} \\
\dot{w}
\end{bmatrix} = [A]_{4 \times 4} \begin{bmatrix} p \\ q \\ r \\ w \end{bmatrix} + [B]_{4 \times 5} \begin{bmatrix} \delta_{\text{lat}} \\ \delta_{\text{lon}} \\ \delta_{\text{col}} \\ \delta_{\text{ped}} \\ \Omega_{\text{cmd}} \end{bmatrix}
\] (3.13)

For the conventional rotorcraft with a constant rotor speed, the model inversion method can give a unique solution to Equation 3.13. Given the states’ derivative on the left side of Equation 3.13 replaced with the pseudo-control, the rotorcraft states feedback signals \( p, q, r, \) and \( w \), and the rotor speed command simply set as zero \( \Omega_{\text{cmd}} = 0 \), the control inputs can be solved by Equation 3.14.

\[
\begin{bmatrix}
\delta_{\text{lat}} \\
\delta_{\text{lon}} \\
\delta_{\text{col}} \\
\delta_{\text{ped}}
\end{bmatrix} = [B(1 : 4, 1 : 4)]_{4 \times 4}^{-1} \begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r} \\
\dot{w}
\end{bmatrix} - [A]_{4 \times 4} \begin{bmatrix} p \\ q \\ r \\ w \end{bmatrix} - \begin{bmatrix} \delta_{\text{lat}} \\ \delta_{\text{lon}} \\ \delta_{\text{col}} \\ \delta_{\text{ped}} \end{bmatrix}
\] (3.14)

Here \([B(1 : 4, 1 : 4)]_{4 \times 4}\) is the matrix which includes the first four columns of \([B]\) matrix, and normally it is invertible. But for rotorcraft with variable rotor speed, the rotor speed control is involved and there are more inputs than state variables. \([B]\) matrix is not square and usually is full row rank. Obviously, the solution is not unique. The next section will discuss how to choose a proper solution for this situation.

### 3.2.4 Control Allocation

If the control inputs’ constraints are considered, choosing the solution for Equation 3.13 is the so-called control allocation problem [22]. In general, control allocation is to solve the solution for an equation \( Bu = m_d \), where \( B \) is a \( m \times n \) matrix and \( m < n \). Control input vector \( u \) is belonging to an \( n \)-dimensional space \( u \in \mathbb{R}^n \) and the controls are constrained to limits such as \( u_{i,\text{min}} \leq u_i \leq u_{i,\text{max}} \). In aircraft dynamics, the \( B \) matrix is the control effectiveness matrix normally with respect to
the moments. Also, it is assumed that every \( m \times m \) partition of \( B \) is nonsingular. If the control constrains and the \( B \) matrix are given, \( m_d \), which belongs to an \( m \)-dimensional space \( m_d \in R^m \), should be restricted in a subspace of \( R^m \) that is called attainable moment subset.

Previous work have intensively studied the control allocation problem. Many solution methods have been developed for different design requirements and additional constraints, which include the control power, the computing efficiency, and the control priority. In this research, the rotor speed control, primarily used as a redundant control effector in the vertical axis, is a different type of control input compared with the other four controls. This case is accordance with the daisy chaining method.

The daisy chaining method proposed to use a specified set of controls only if the rest of the controls fail to achieve the desired moment. Usually the controls are divided into two groups: primary controls \( u_1 \) and redundant controls \( u_2 \), as defined in Equation 3.15.

\[
Bu = \begin{bmatrix} B_1 & B_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{3.15}
\]

Normally \( B_1 \) is a \( m \times m \) square and invertible matrix. The number of primary controls is equal to \( m \), or denoted by \( u_1 \in R^m \). This is true for most aircraft designs because normally there is one primary control designed for each axis. Take the conventional helicopter as an example, the collective pitch is primarily responsible for the vertical axis and the pedal input is in charge of the yaw axis. The idea of daisy chaining method is to use only the primary controls before they are saturated.

In Equation 3.14, the primary controls are the lateral cyclic pitch, the longitudinal cyclic pitch, the collective pitch, and the yaw control input. The rotor speed command is the redundant input mainly used in the vertical axis. Here \( m = 4 \) and \( n = 5 \). The problem can be formed as Equations 3.16 to 3.18.
\[ m_d = \left( \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \\ \dot{w} \end{bmatrix}_D - [A]_{4\times4} \begin{bmatrix} p \\ q \\ r \\ w \end{bmatrix} \right) \]  
\hspace{1cm} (3.16)

\[ B_1 = \begin{bmatrix} b_{lat} & b_{lon} & b_{col} & b_{ped} \end{bmatrix} \]
and
\[ B_2 = \Omega \]
\hspace{1cm} (3.17)

\[ u_1 = \begin{bmatrix} \delta_{lat} & \delta_{lon} & \delta_{col} & \delta_{ped} \end{bmatrix}^T \]
and
\[ u_2 = \Omega_{cmd} \]
\hspace{1cm} (3.18)

Based on the idea of classifying the controls into two groups, there are two methods proposed:

- **Method 1:** To increase rotor speed only if the collective input has reached its travel limit. The procedure is described as followed:
  
  1. Set \( u_2 = 0 \) and solve \( u_1 \) as Equation 3.14.
  2. Check if the collective pitch input \( \delta_{col} \) reach its limit. If no, then a solution is found; If yes, go to next step.
  3. Set \( \delta_{col} = \delta_{col,limit} \) and the other four inputs are given by Equation 3.19

\[ \begin{bmatrix} \delta_{lat} \\ \delta_{lon} \\ \delta_{ped} \\ \Omega_{cmd} \end{bmatrix} = \begin{bmatrix} b_{lat} & b_{lon} & b_{ped} & \Omega \end{bmatrix}^{-1} (m_d - b_{col} \cdot \delta_{col,limit}) \]  
\hspace{1cm} (3.19)

- **Method 2:** The rotor speed command is first assigned based on the rotor speed optimization results. The procedure is described as followed:
1. Set \( u_2 = \Omega_{\text{optimum}} \), which is based on the interpolation results against the commanded flight condition.

2. Solve the other four inputs as Equation 3.20.

\[
\begin{bmatrix}
\delta_{\text{lat}} \\
\delta_{\text{lon}} \\
\delta_{\text{col}} \\
\delta_{\text{ped}}
\end{bmatrix} = 
\begin{bmatrix}
b_{\text{lat}} & b_{\text{lon}} & b_{\text{col}} & b_{\text{ped}}
\end{bmatrix}^{-1} (m_d - b_\Omega \cdot \Omega_{\text{optimum}})
\] (3.20)

Figure 3.8 shows the simulation results with the linearized model. Both methods work well to make use of the rotor speed as a redundant control effector in the vertical axis. In practice, the second method is preferred. One reason is that this method accommodates the optimal rotor speed schedule, therefore the rotor speed will be on its optimal value in the next flight condition. Another reason is that the rotor speed is not a real actuator. There can be significant phase delays and tracking errors between actual rotor speed and the command rotor speed, especially if the collective pitch is approaching its maximum value and the torque required is large. Thus a fixed rotor speed command is more appropriate in practice. Notice that in the first method, the rotor speed can not follow the command well during the transient time and this will result in slightly degrade in the vertical response. Similarly in the second method, the collective pitch still hits the limit and doesn’t
provide the commanded thrust for the maneuvering. To evaluate the simulation results, the handling quality will be introduced later in this chapter.

3.2.5 Turn Coordination

A turn coordination algorithm for model following controller has been proposed in [21]. In hover and at low speeds (below 30 knots), the heading change is achieved simply from the yaw axis input. At high speeds (above 60 knots), the yaw axis input is computed from a lateral acceleration command (which is zero for a coordinated turn) as shown in Equation 3.21 and the heading control is made via the roll attitude command. Between 30 knots and 60 knots, a linear interpolation of the two commands is applied for a smooth transition.

\[ r_{cmd} = \frac{K(a_{gcmd} - a_y) + wp + g \sin \phi \cos \theta}{u} \] (3.21)

To achieve a banked-turn above 30 knots, it requires a roll attitude change with the above algorithm. In such situation, the rotor thrust must be increased to keep the altitude (or prevent loss of height). As a redundant control effector to produce thrust, the rotor speed can be increased accordingly. But the optimal rotor speed schedule in a banked turn is different from the previous cases. There is no vertical speed command and the banked turn is supposed to be held at constant altitude. Because of the large roll angle command, the rotor thrust vector is tilted. To keep the altitude, the collective pitch is required to increase to balance the weight. This situation can be treated similar to a level flight with an increase in gross weight. The optimal rotor speed schedule can be interpolated against the 'effective gross weight', which is defined as \( W_{eff} = \frac{W}{\cos \phi} \).

3.3 Nonlinear Simulation

The model following and model inversion controller designed in the previous section is implemented in the nonlinear model of UH-60A Black Hawk, GENHEL-PSU. The modification on the engine system was introduced in Appendix A and the new rotor speed controller was introduced in last section. The existing stability augmentation systems (SAS) of UH-60A were turned off and the model following
and model inversion controller was simulated.

The inverse model parameters are scheduled with the total airspeed and the rotor speed. The fundamental guideline for gain scheduling is that the scheduling variables should vary slowly [23]. In this application, the rotor speed is a “fast variable” compared to the total airspeed. A low pass filter is employed to produce a slow varying scheduling parameter for the rotor speed. Look-up tables are also used for the optimal rotor speed schedule, as introduced in rotor speed optimization study. The gain scheduling parameters and the optimal rotor speed scheduling strategy are summarized in a data file, which are loaded into memory in execution.

### 3.3.1 Vertical Axis Evaluation

The focus in this chapter is to use the rotor speed as a redundant control effector in the vertical axis. This should be especially useful in the case that the collective control margin is not enough to perform a commanded climbing maneuver.

It was found that the vertical axis control was most challenging for lower speed, when the collective control margin is low. Thus the simulation in this section is performed at 40 knots. The simulation results for different commands are shown in Figure 3.9 to Figure 3.14.

For the simulation with a selection of 40 knots airspeed, the results are evaluated using the height response requirement for hover and low speed in the ADS-33E specifications for handling qualities of military rotorcraft [24]. The specification dictates Level 1 and Level 2 boundaries on the equivalent phase delay and first order time constant for the vertical speed response to vertical axis control inputs. A first order approximation of the vertical response transfer function is derived using least squares fitting to a simulated step response. The equivalent phase delay parameter must be less than 0.2 seconds for Level 1 and less than 0.3 seconds for Level 2. The time constant must be less than 5 seconds for Level 1. The performances of the controllers for various commands are illustrated in Figure 3.15.

Figure 3.9 verifies that the model following and model inversion controller works well on the nonlinear model with the moderate vertical speed command. The aircraft is initially trimmed at the level flight condition with the forward speed of 40 knots and the optimal rotor speed for this condition is 80%. With a vertical
speed command of 15 ft/sec, the collective pitch control margin is enough to follow the command. Even without the rotor speed variation, the collective pitch can produce a satisfying response, which meets ADS-33E Level 1 requirement.

For the large vertical speed command, the response is sluggish without rotor speed variation. Figure 3.10 shows that the aircraft is trimmed at the same flight condition as the last simulation. With a large vertical speed command 35 ft/sec and the fixed 80% rotor speed, the collective pitch hits the 100% travel limit and cannot follow the reference response. In steady state, the maximum climbing rate is about 28 ft/sec, which is much below the command value. In addition, the response is well outside ADS-33E level 1 and level 2 boundaries, as shown in Figure 3.15.

Figure 3.11 shows the simulation result with the application of the second control allocation method. Unlike the linear system simulation, this non-linear model includes a much more realistic engine model and the torque constraints are revealed. Using the proposed control allocation method, it is more challenging to have the rotor speed follow the command, especially if the collective input is high and the torque load is large. In many cases the torque available is not enough
Figure 3.10. GENHEL-PSU Simulation V=40 Knots, No RPM Variation, Vertical Speed Command=35 ft/sec

Figure 3.11. GENHEL-PSU Simulation V=40 Knots, with RPM Variation, No Vertical Acceleration Limit, Vertical Speed Command=35 ft/sec
to accelerate the rotor. Figure 3.11 shows that the rotor speed command is not followed well and the response is not satisfying.

A solution for the torque constraint is to limit the commanded vertical acceleration. A nonlinear saturation is placed in the command filter to restrict the command vertical acceleration within some range. Figure 3.12 shows the steady state vertical speed can reach the command of 35 ft/sec and the response at least meets ADS-33E Level 2 requirements. Although the response appears to show reasonable first order characteristics, the equivalent phase delay derived using the methods outlined in ADS-33E is large, as shown in Figure 3.15. However, the response is clearly superior to the case without rotor speed variation.

Figures 3.13 and 3.14 show similar step responses to a moderate vertical speed command 25 ft/sec. These results are also included in the ADS-33E evaluation results in Figure 3.15. The response with rotor speed variation is clearly superior and meets the Level 1 specification.

Figure 3.12. GENHEL-PSU Simulation V=40 Knots, with RPM Variation, Vertical Acceleration Limited, Vertical Speed Command=35 ft/sec
Figure 3.13. GENHEL-PSU Simulation V=40 Knots, No RPM Variation, Vertical Speed Command=25 ft/sec

Figure 3.14. GENHEL-PSU Simulation V=40 Knots, with RPM Variation, Vertical Speed Command=25 ft/sec
3.3.2 Turn Coordination

The turn coordination algorithm introduced in the previous section is also evaluated in GENHEL-PSU simulation. Figure 3.16 shows a coordinated turn response to the roll angle command at 80 knots with the fixed standard 100% rotor speed. With a step roll angle command of 25 degrees, the aircraft performs a steady turn at about 6 deg/sec. After about 30 seconds, a turning maneuver of approximately 180 degrees will be fulfilled. During the steady turn, the lateral acceleration is kept as nearly zero. This proves that the algorithm described in Equation 3.21 works well.

Figure 3.17 shows the simulation results at the same flight condition as Figure 3.16, except that this time the rotorcraft is running at the optimal rotor speed 84%. Though an expected value of yaw rate response is achieved and the 180 degrees turn is fulfilled too, the lateral acceleration is not kept as zero and it is not even small during most of the turn. This unwanted oscillation in lateral acceleration can be eliminated using the variable rotor speed control.

The optimal rotor speed schedule in a banked turn was described in previous section. Figures 3.18 and 3.19 show the simulation results. Similar to the previous
flight condition, the simulation is started with a trimmed level flight of 80 knots and the rotor speed is on its optimal value of 84%. Given the roll angle command of 25 degrees, the control algorithm not only gives the corresponding conventional inputs but also commands the rotor speed to its next optimal value 89%. The unwanted oscillation clearly diminished and the lateral acceleration is kept small during the steady turn.

Another simulation for 120 knots also proves that the variable rotor speed control can improve the coordinated turn performance. As shown in Figure 3.20, the rotorcraft is trimmed at 120 knots level flight and the optimal rotor speed is 90%. Without the rotor speed variation, the lateral acceleration appears a large oscillation throughout the turn. Figures 3.21 and 3.22 show that the response is much better if the rotor speed is increased to 93%.

**Figure 3.16.** Coordinated Turn at 80 Knots, 100% RPM
Figure 3.17. Coordinated Turn at 80 Knots, 84% RPM

Figure 3.18. Coordinated Turn at 80 Knots with Variable Rotor Speed
Figure 3.19. Coordinated Turn at 80 Knots with Variable Rotor Speed

Figure 3.20. Coordinated Turn at 120 Knots, 90% RPM
Figure 3.21. Coordinated Turn at 120 Knots with Variable Rotor Speed

Figure 3.22. Coordinated Turn at 120 Knots with Variable Rotor Speed
3.4 Problems Related to Reduced Rotor Speed

Figure 3.23 shows the variation in the rotor mode eigenvalues as rotor speed is reduced from 100% to 80% when the aircraft is operating at 80 knots. Both the damping and natural frequency of all rotor modes are reduced, and the lag mode eigenvalues are approaching the imaginary axis. This behavior is observed throughout the flight envelope, and would indicate that care must be taken when implementing closed loop control at low rotor speed. As the frequency of the rotor lag modes is reduced, there is increased likelihood that rotor-body coupling will occur. Since the damping of these modes is also decreased, stability margins must be thoroughly evaluated to ensure closed loop instability is avoided.

The rotor-body coupling will be increased at reduced rotor speed. This also can be partially demonstrated using the equations of the static flapping due to pitch and roll velocities given in [25]. Figures 3.24 and 3.25 show that the magnitude of flapping is increased with the rotor speed reduced in the steady flight.

In the following sections, several problems related to variable rotor speed, especially the reduced rotor speed, in the integrated flight/propulsion control system will be revealed.
Figure 3.24. Flapping due to Roll Rate in steady flight, V=80 knots

Figure 3.25. Flapping due to Pitch Rate in steady flight, V=80 knots

3.4.1 High Bandwidth Design

The high order linearized models of the unaugmented aircraft are used in analysis here and the first step is to verify that they are reasonable. CIFER is a well-established software tool for identifying high order linear models of rotorcraft based on frequency response [26]. To ensure that our perturbation based linear models were reasonable, we simulated the response of the aircraft to frequency sweeps and extracted frequency response characteristics for various input and output pairs using CIFER. Sample results are shown in Figures 3.26 and 3.27, which show the
Figure 3.26. Bare Airframe Frequency Response, Roll Rate due to Lateral Input, 140 knots, 100% RPM

Figure 3.27. Bare Airframe Frequency Response, Roll Rate due to Lateral Input, 140 knots, 90% RPM
roll rate frequency responses due to lateral input at 140 knots with 100% and 90% rotor speed respectively. The identification result with a coherence value of 0.6 or above is viewed as valid. The results compare the response of the perturbation based linear model to that identified by CIFER and show the good agreement in the frequency range of 0.5 to 40 rad/sec.

While generating the gain scheduling files in Matlab environment, stability margins were checked for each axis at each operating point. For the most part the stability margins were quite good for the target bandwidths designed for each axis for the range of rotor speed used in the optimal schedule. However, it was found that for slight increases in the roll axis bandwidth stability margin issues could arise at the low range of rotor speed.

Examples in Figure 3.28 show open loop Bode diagrams for the roll axis model following controller with various design natural frequencies for the command filter. The baseline natural frequency for the command filter was set to 2.5 rad/sec. This should meet the ADS-33E Level 1 requirement for roll axis bandwidth of 2.5 rad/sec. Results for higher design bandwidths are also shown in the diagram and the gain curve shifts upward. For the 100% rotor speed case there are no major stability issues. The gain and phase margins are well above 8 dB and 60
degrees even for a design bandwidth of 4 rad/sec. In the 90% rotor speed case some stability issues begin to emerge when we attempt to achieve high bandwidth control. When a design bandwidth of 3.5 rad/sec or 4 rad/sec is used, a gain crossover is produced at the lag progressing mode frequency (approximately 35 rad/sec in the 90% rotor speed case). While the phase margin is still around 60 degrees in these cases, a gain crossover at this high frequency is problematic since it results in a very low time delay margin. The time delay margin is the phase margin divided by the gain crossover frequency (in consistent units). In the case of a 4.0 rad/sec design bandwidth, the resulting time delay margin is only 29 milliseconds. This is not enough for most digital flight control systems. A gain crossover at that high frequency would likely result in closed loop instability.

3.4.2 Roll-Pitch Cross Coupling

Roll-Pitch cross coupling is a normal phenomena for rotorcraft and it can be inspected using a decoupled flight controller. The inverse model used in model inversion was given by Equation 3.13 and it included the cross coupling effects between roll and pitch in $A$ matrix. A decoupled controller can use a simpler inverse model as Equation 3.22:

$$
\dot{p} = L_p p + L_{\delta_{tot}} \delta_{lat}
$$

$$
\begin{bmatrix}
\dot{q} \\
\dot{w}
\end{bmatrix} =
\begin{bmatrix}
M_q & M_w \\
Z_q & Z_w
\end{bmatrix}
\begin{bmatrix}
q \\
w
\end{bmatrix}
+ 
\begin{bmatrix}
M_{\delta_{lom}} & M_{\delta_{col}} & M_{\Omega} \\
Z_{\delta_{lom}} & Z_{\delta_{col}} & Z_{\Omega}
\end{bmatrix}
\begin{bmatrix}
\delta_{lom} \\
\delta_{col} \\
\Omega_{cmd}
\end{bmatrix}
$$

$$
\dot{r} = N_r r + N_{\delta_{ped}} \delta_{ped}
$$

(3.22)

Because such an inverse model does not account for the cross coupling between pitch and roll axes, the response can show the effect of the reduced rotor speed.

Figure 3.29 shows the cross coupling effect in the three axis attitudes response to a pitch doublet input for the rotorcraft operating with 100% rotor speed at 40
knots. The coupling between roll and pitch is noticeable but not severe. Figure 3.30 shows the case for 80% rotor speed and the cross coupling is clearly increased. This result proves that the effect of the cross coupling between roll and pitch grows with the rotor speed reduced.

This kind of coupling can be solved with the coupled controller as given by Equation 3.13. The coupled inverse model accounts for the cross coupling effect and the simulation results prove that either at standard 100% or reduced 80% rotor speed, the cross coupling between roll and pitch is not noticeable, as shown in Figures 3.31 and 3.32.

3.4.3 Rotor-Body Coupling

Another kind of coupling, rotor-body coupling, is not the same type of coupling as the roll-pitch cross coupling. Figures 3.33 and 3.34 show the responses to roll doublet input for rotorcraft operating at 140 knots with 100% and 90% rotor speed, respectively. Compared with the response for 100% rotor speed, the one for 80% rotor speed shows an unwanted high frequency oscillation, which is normally the prelude to one or more of the rotor modes becoming unstable. Rotor state feedback [17] is a potential solution to the problems of rotor-body coupling and closed loop instability.
Figure 3.29. Decoupled Controller, Response to Pitch Doublet Input, 40 Knots, 100% RPM

Figure 3.30. Decoupled Controller, Response to Pitch Doublet Input, 40 Knots, 80% RPM
Figure 3.31. Coupled Controller, Response to Pitch Doublet Input, 40 Knots, 100% RPM

Figure 3.32. Coupled Controller, Response to Pitch Doublet Input, 40 Knots, 80% RPM
Figure 3.33. Coupled Controller, Response to Roll Doublet Input, 140 Knots, 100% RPM

Figure 3.34. Coupled Controller, Response to Roll Doublet Input, 140 Knots, 90% RPM
In previous chapter, the integrated flight/propulsion control system using a model following/model inversion control architecture was designed, implemented, and evaluated. The variable rotor speed control was applied as a control effector for the vertical axis to improve the maximum climb rate and flying qualities. For the rotorcraft with variable rotor speed in a trimmed level flight, its optimal rotor speed can be determined by the operation conditions of the airspeed, the altitude, and the gross weight. Given a collective pitch input, which represents a vertical speed command, the optimal rotor speed for climbing or descending flight can be scheduled against the commanded vertical speed value and the present level flight airspeed, as shown in Figure 2.8. In this case, the vertical axis control system is called a vertical speed command system. In practice, the vertical axis also can be designed as a power command system, where the collective input commands a desired power output. The primary vertical axis controller could be designed as an open loop system, thus improving reliability and reducing complexity. Such a design can also potentially have the advantage in envelope protection.

This chapter is focused on the power command system design for the vertical axis. The topics include the optimal rotor speed schedule for the power command, the power command system design for the collective axis, nonlinear simulation, and the piloted simulation on the realtime simulator.
4.1 Power Command Schedule

In this chapter, one important task is to perform the optimal rotor speed scheduling for this new concept, such that the optimal rotor speed should be scheduled with the power command, instead of the vertical speed command. The power command schedule is different from last chapter’s vertical speed command schedule in the key scheduling variable. Given a specific level flight condition, it is based on the power command or the commanded power required to specify the optimal rotor speed and the future vertical speed (keeping the same horizontal air speed). This will bring another challenge because the future flight condition (especially in descending flight) may not be determined only by the power command. In other words, there is possibility that two or more flight conditions may require the same amount of power, as shown in Figure 4.1.

In the trimmed vertical flight, the amounts of power required for 80 ft/sec descending and 20 ft/sec descending are almost same. Thus the vertical speed is not a single value function of the power required value. From GENHEL simulation results, this mostly happens at low speed descending flight in a region of vortex ring state (VRS). But because GENHEL doesn’t include a VRS model, the simulation results in and near vortex ring state actually are probably not accurate, and thus the results for the high rate of decent cases are questionable. In any case it is not desirable to descend at high rates of descent where the power increases with increasing descent rate. This is called settling with power and is generally consid-
ered an unsafe flight regime. Therefore, the new optimal rotor speed schedule for power command should include a lower power command boundary to avoid this region for safety.

Another problem is about the control margin and torque required issues discussed in Chapter 2. The power command is limited by the engines’ maximum power output, while the torque required should be secured lower than the torque limits of the transmission and drive system. In addition, there should be some control margin left for any flight condition. Unfortunately the analysis in Chapter 2 already showed that the yaw control margin is very low at hover and low speeds using the optimal rotor speed schedule, which was based only on minimizing the power required. Here a modified rotor speed optimization method is applied for these issues.

In the further rotor optimization study, a large set of trim data was generated that produced a schedule of the power and torque required and the trimmed control positions as a function of the longitudinal speed $V_x$, the vertical speed $V_z$, the rotor speed $\Omega$, the gross weight $W$, and the altitude $h$. Using these results, at each flight condition ($V_x, V_z, W, h$) we can find the optimal rotor speed, $\Omega_{opt}$, that minimizes some objective function. The objective function, $J$, is defined primarily to minimize the power required, $P$, but will minimize the torque required, $Q$, if the torque required is above the transmission limit. It also includes a term to consider the yaw control margin if it is less than 20%. The objective function is defined as Equation 4.1.

$$ J = \begin{cases} 
W_P P + \max(W_{CM}(20 - \hat{\delta}_{ped}), 0), & \text{for } Q < 100\% \\
W_Q Q + \max(W_{CM}(20 - \hat{\delta}_{ped}), 0), & \text{for } Q \geq 100\% 
\end{cases} \quad (4.1) $$

Here $\hat{\delta}_{ped}$ is the yaw control margin in percentage. $W_P$, $W_Q$, and $W_{CM}$ are weighting factors. In this way, for each airspeed, altitude, and gross weight, the optimization finds a schedule of the optimal rotor speed versus vertical speed that minimizes power while ensuring there is adequate yaw control margin. The transmission torque limit is also effectively imposed in this optimization, since torque overrides the power if it is above a prescribed limit.
In forward flight, above 40 knots, we find that the power required increases monotonically from power required less than 0 at the maximum rate of descent to power required greater than the power limit at the maximum climb rate. Thus we can readily define a one-to-one mapping that determines the optimal rotor speed and collective pitch setting for the desired power level between 0 and 100% in a given flight condition:

$$\Omega_{\text{opt}} = f(V_z, V_x, W, h) \quad (4.2)$$

Here each and every power command setting, $P_{\text{cmd}}$, maps to a unique vertical speed. For airspeeds below 20 knots, there are cases where the power required increases with rate of decent. This would represent conditions where vortex ring state or settling with power is occurring, which are descending flight regimes we seek to avoid. In those cases, the minimum power command would correspond to a power required where the aircraft begins to approach a vortex ring state, i.e. the

$$[\Omega, \delta_{\text{col}}]_{\text{opt}} = f(P_{\text{cmd}}, V_x, W, h) \quad (4.3)$$
vortex ring state upper boundary, and the system would not command a power below this level (unless the aircraft is on the ground). The VRS boundary can be specified using the method describe in reference [27]. Between 20 knots and 40 knots, a smoothed boundary connects the VRS boundary and the autorotation line, all of which will define a minimum power command line throughout the horizontal speeds from hover to 160 knots. Figure 4.3 shows the example maximum and minimum power lines for the gross weight of 18,500 lbs and standard sea level condition.

Figure 4.4 shows the optimal control mapping relationships at a gross weight of 18,500 lbs and a horizontal speed of 80 knots. The power command is in percentage where 100% represents 3400 HP, which is the assumed maximum output power. The right side y-axis is the optimal rotor speed in percentage. The right side y-axis shows the corresponding collective pitch input at the trim state, which will be used in design of an open loop vertical axis controller later. The left side of the figure shows the optimal power, torque, rotor speed, collective, and yaw control margin versus vertical speed, which was then re-mapped to a power command schedule.
Figure 4.4. Optimal Rotor Speed Schedule for Power Command, V=80 knots

Figure 4.5. Optimal Rotor Speed Schedule for Power Command, Vertical Flight

shown on the right side of the figure.

Figure 4.5 shows the power command schedule for the vertical flight.
4.2 Control System Design

Figure 4.6 shows the control architecture for the power command system design. The most important difference from the control system design introduced in Figure 3.2 is the vertical axis. Because the vertical axis is designed as an open loop structure, which will change the model inversion equations discussed in Chapter 3, there is no need to include the vertical axis in the model. Then the number of states will be reduced to three, which are roll, pitch, and yaw angular rates while the number of inputs is still five, including lateral pitch, longitudinal pitch, pedal, collective pitch, and the rotor speed command, as shown in Equation 4.4.

\[
\begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix} = [A]_{3 \times 3} \begin{bmatrix}
p \\
q \\
r
\end{bmatrix} + [B]_{3 \times 5} \begin{bmatrix}
\delta_{lat} \\
\delta_{lon} \\
\delta_{ped} \\
\delta_{col} \\
\Omega_{cmd}
\end{bmatrix} \tag{4.4}
\]

Given the pseudo controls and the aircraft states, as well as the collective pitch input and the rotor speed command, which are provided by the vertical axis power command schedule result, the model inversion will generate the other three inputs, as shown in Equation 4.5.

---

Figure 4.6. Flight Control System Architecture
\[
\begin{bmatrix}
\delta_{lat} \\
\delta_{lon} \\
\delta_{ped}
\end{bmatrix}
= [B_1]^{-1}_{3 \times 3}
\begin{bmatrix}
\dot{\mathbf{p}} \\
\dot{\mathbf{q}} \\
\dot{\mathbf{r}}
\end{bmatrix}
- [A]_{3 \times 3}
\begin{bmatrix}
p \\
q \\
r
\end{bmatrix}
- [B_2]_{3 \times 2}
\begin{bmatrix}
\delta_{col} \\
\Omega_{cmd}
\end{bmatrix}
\]

(4.5)

Here the control matrix \([B]_{3 \times 5}\) is divided into two parts as \([B]_{3 \times 5} = [B_1, B_2]\).

The command in vertical axis or the collective stick is the power level and will utilize collective pitch and rotor speed together to govern the motion in vertical direction. The detent position of collective stick represents the power required for a level flight trim operating at its optimal rotor speed. The maximum collective will command the maximum power and the minimum collective means a zero power required for the autorotation. If the pilot lifts the collective stick from its detent position, an optimal rotor speed command will be given to maximize the rate of climb for the given power setting. Based on collective stick’s position, current horizontal air speed, altitude, and effective gross weight, the controller give the collective pitch input and rotor speed command through the direct mapping, described as followed:

\[
[\Omega, \delta_{col}]_{opt} = f(P_{cmd}, V_x, W_{eff}, h)
\]

(4.6)

The effective gross weight is defined as follow:

\[
W_{eff} \triangleq \frac{W}{\cos \phi_{cmd}}
\]

(4.7)

Here the denominator contains the cosine of the commanded bank angle. This was found to provide nearly optimal performance in coordinated turn maneuvers. The rotor thrust is increased to provide the required load factor, and the helicopter performance characteristics are similar to a helicopter in rectilinear flight with increased gross weight.

An important issue has been revealed and discussed in vertical axis control in Chapter 3. For a moderate collective input, there is sufficient torque available to perform the maneuver as well as to accelerate the rotor in climbing maneuvers. But if the collective input is high and the torque load is large, it is challenging to get the rotor speed to follow the command. In many cases the torque available will be not enough to meet the required torque to accelerate the rotor.
A solution is to reduce the collective input’s magnitude directly during the acceleration of the rotor, as implemented in the control law of Figure 4.7. The reduction should be proportional to the commanded rotor speed acceleration. A proposed form is given by Equation 4.8:

$$\Delta \delta_{col} = k \frac{\dot{\Omega}_{cmd}}{Q_{\delta_{col}}}$$

Here $Q_{\delta_{col}}$ is the derivative in rotor speed control model and $k$ is a tuning parameter, which will be affected by the total drive system inertia.

### 4.3 Nonlinear Simulation

The flight control system introduced in the previous section, including MFC controller, rotor speed controller, and the vertical axis controller, is implemented in the nonlinear model of UH-60A Black Hawk, GENHEL-PSU. The initial testing was performed with an outer loop controller[20], which provides translational rate command (TRC) control and allows the helicopter to maintain forward and lateral speeds without the use of qualified pilots during climb and descents. As shown in Figure 4.8, the longitudinal stick input will manage the forward speed and then generate pitch attitude command. Similarly, the lateral stick will generate roll attitude command. Such a TRC controller is implemented in this study primarily because the evaluation of the designed vertical axis controller requires a matching flight conditions in simulation and the predefined rotor speed schedule, which is achieved at the trimmed condition with the constant forward, lateral, and vertical speeds.
Another issue needs to be considered in design of a variable rotor speed helicopter is the torque limit of the transmission. If the maximum allowed output power from engines is same, it is expected that rotorcraft with variable rotor speed running at a minimum rotor speed of 80% will require a transmission with approximately 25% higher torque limit compared to the same rotorcraft using a constant 100% rotor speed. In this study the gearbox torque transmission limit is set at 69,259 ft-lb, which roughly corresponds to the maximum engine power at sea level when operating at nominal 100% RPM. However, when the rotor speed is reduced below 100%, the torque limit can be reached at lower power levels. This torque limit is included in the rotor speed optimization study to ensure the torque required is within the limit when running at the optimal rotor speed. The torque limit is also considered in the transient response in the design of the dynamic collective input reduction, as shown in Figure 4.7.

Figure 4.9 shows the vertical speed response to a command of 40 ft/sec with rotor speed held constant. The flight was trimmed for a level flight of 30 knots and the optimal rotor speed for this condition is 80% of the standard RPM. The useable collective pitch at this reduced RPM is about 23% and it is not enough to follow a high vertical speed command such as 40 ft/sec. If the rotor speed is kept
constant during the maneuvering and the collective pitch is increased to its 100% travel limit, the maximum climb rate response is about 28 ft/sec in steady state.

In the same condition but with the application of variable rotor speed, the vertical speed response can reach an expected vertical speed of 41 ft/sec, as shown in Figure 4.10. The power command input is 90%, or 3060 HP, as shown in Figure 4.11. The collective pitch input is increased by several percent and the rotor speed improved to 98%. Figure 4.11 shows that the torque load is higher than the torque limit at the beginning of the maneuver, and the rotor speed is not well controlled during that period.

In Figures 4.12 and 4.13, the simulation results show that the response using the torque limiting from the control law in Figure 4.7. Figure 4.12 shows that during the transient time, there is a dynamic reduction of collective pitch, which will relieve the torque requirement while the rotor is accelerated. Figure 4.13 shows that the torque follows a smooth first order response without large peaks. Furthermore, the rotor speed follows the command quite well. One may notice that the dynamic reduction shows a “stair” shape at the beginning. This is because the reduction is proportional to commanded rotor speed acceleration, which is limited by the upper and lower bounds.
Figure 4.10. Simulation V=30 Knots, with RPM Variation

Figure 4.11. Simulation V=30 Knots, with RPM Variation
Figure 4.12. Simulation V=30 Knots, with Torque Limiting

Figure 4.13. Simulation V=30 Knots, with Torque Limiting
4.4 Piloted Simulation

The piloted simulation was performed on the real-time simulation facility at Penn State to evaluate the designed controller. In this preliminary test, the helicopter is started in a hover at low altitude at an airport. The pilot then accelerates the helicopter forward to an airspeed of about 100 knots and climbs at maximum climb rate, which for the current controller is achieved by full up collective. The aircraft is leveled out and the pilot performed a 180 degree turn, descends and returns the aircraft to the airport. The maximum rate of climb maneuver is easy to achieve since the pilot need only pull the collective to the stop without worrying about overtorque.

A portion of the simulation results are shown in Figures 4.14 to 4.16. Figure 4.14 shows the power command schedule. The rotor speed follows the rotor speed command very well during the flight and is effectively an additional control effector. The actual power required follows the power command very accurately. Figure 4.15 shows the vertical speed, total airspeed, and torque. The results show that the torque is kept below the prescribed limit throughout the flight, even during the maximum rate of climb maneuver. Figure 4.16 shows the time history of the aircraft attitude throughout the maneuver. The controller appears to function well for the most of the flight envelope. However, some oscillation was observed in the vertical axis in hover near the ground. It is expected that one further tuning of the controller will alleviate this problem. Also, some high frequency oscillations were observed at high speeds and believed due to interaction with the lag progressive mode. This issue will be studied in Chapter 5.
Figure 4.14. Piloted Simulation Results

Figure 4.15. Piloted Simulation Results
Figure 4.16. Piloted Simulation Results
The results demonstrated in Chapter 2 recommended using the reduced rotor speed, which would lead to a much lower power required especially at forward flight. However, Chapter 3 also showed the concerns with stability issues at reduced rotor speed. The analysis on eigenvalues showed some rotor modes (e.g. the lag modes) at low rotor speed are approaching the imaginary axis, which may result in the rotor-body coupling phenomenon. In Chen’s study [13] on the rotor speed drop in hover, he pointed out that the flight dynamics under a large reduction need to be well understood. He indicated that stability margins and the magnitude of basic stability and control derivatives can change dramatically with a large reduction in rotor speed. Chen also suggested that the use of rotor state feedback (RSF) could greatly enhance the achievable bandwidth and gust rejection properties when using reduced rotor speed.

The rotor-body coupling phenomenon is a direct result of coupling of rotor modes and fuselage dynamics. It has been a big hurdle to achieve the high bandwidth control on rotocraft for a long time. With the classic method of expending bandwidth using high feedback gains, some rotor state modes may become dynamically coupled with the fuselage dynamics and result in undesirable oscillations or even instability. The rotor mode that plays the primary role in the coupling may not be same for different rotorcraft, but normally related to the lightly damped lag modes. Dryfoos et al. [28] showed that the rotor-body coupling was observed on RAH-66 Comanche prototype aircraft and believed that the Regressive Lag Mode (RLM) is the significant part. While in UH-60M flight test [29], the high
frequency oscillation observed in pitch and roll axes appeared to be related to the progressive lead-lag mode. The application of variable rotor speed may result in the same consequence, especially at the reduced rotor speed. Because the nature of the both situations is the same rotor-body coupling, the similar methods may be valid on control system design for rotorcraft with variable rotor speed.

The methods of control system design proposed for the rotor-body coupling problem include dynamic compensators, lead shaping in the feed ward, notch filters, and RSF control, etc. The RSF control is more appropriate for rotorcraft with the variable rotor speed because it is especially useful in limiting flapping angles, which are expected to become larger at low rotor speed than at standard rotor speed due to the lower centrifugal stiffness. In addition, the RSF control structure proposed by Horn[17] is easy to integrate with a MFC control structure. However, we need to notice the extra cost of special sensors for rotor states.

This chapter will investigate the potential of using RSF control on the example rotorcraft in chapter 3. The RSF controller described in reference [17] is proposed to be integrated with the original MFC control structure to achieve Attitude Command Attitude Hold (ACAH) response type in the pitch and roll axes. The main objective of using RSF control is to extend the achievable bandwidth and prevent the rotor-body coupling, which was observed in lateral response with the baseline MFC control. The optimal rotor speed was observed much lower than the standard rotor speed at normal level flight conditions, and then the interested flight condition for this paper will start from a trimmed level flight running at a reduced rotor speed.

In the following sections, several problems related to using variable rotor speed, especially the reduced rotor speed, in the integrated flight/propulsion control system will be discovered.

### 5.1 Flight Dynamics Model Analysis

This section is going to review the simulation model properties and show more details about the rotor modes, which are important in this chapter.

The controller design and preliminary simulation and verification are based on 28th order linear models, which are extracted from GENHEL non-linear simula-
tion model using a perturbation method, as describe in Appendix A. The design flight condition is from hover to a maximum cruise speed of 160 knots at a gross weight of 18,500 lbs at standard sea level. The standard rotor speed for UH-60A Blackhawk is 27 rad/sec and we assume a maximum variation of 20%, which means the command rotor speed ranging from 21.6 rad/sec to 32.4 rad/sec. Though the variable rotor speed command is designed to be able to operate at a higher rate than the standard rotor speed, for most flight conditions the optimal rotor speed is much lower than the standard rotor speed.

Figure 5.1(a) shows the variation in the rotor mode eigenvalues as rotor speed is reduced from 100% to 80% when the rotorcraft is operating at 80 knots. Both the damping and natural frequency of all rotor modes are reduced, and the lag mode eigenvalues are approaching the imaginary axis. Figure 5.1(b) shows that at 140 knots, some rotor modes eigenvalues will go across the imaginary axis and become unstable.

Figure 5.2 is from the reference [17] and illustrates part of the root locus by varying roll rate feedback gain for the baseline control structure. The reason of this type of rotor-body coupling is explained in Appendix ???. One may compare Figure 5.2 with Figure 5.1 and will see that the lag modes move with the similar trend. This fact indicates that the RSF control design, which was proved to be successful for rotor-body coupling problem, is promising in this study too.

The rotor-body coupling is expected to be revealed in the form of unwanted
high frequency oscillations. The oscillation frequency will be close to a rotor mode natural frequency. In order to show this phenomenon, Tables 5.1 and 5.2 summarize the rotor modes eigenvalues and their natural frequencies at the reduced rotor speeds. The optimal rotor speeds for the level flight conditions of 80 knots and 140 knots are 84% and 92% of the standard rotor speed, respectively.

Table 5.1. Summary of Modes at 80 knots and 84% RPM

<table>
<thead>
<tr>
<th>Rotor Modes</th>
<th>Eigenvalue</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive Flap</td>
<td>$-8.8248 \pm 43.1191i$</td>
<td>44.0129 rad/sec</td>
</tr>
<tr>
<td>Regressive Flap</td>
<td>$-6.0488 \pm 3.6316i$</td>
<td>7.0552 rad/sec</td>
</tr>
<tr>
<td>Progressive Lag</td>
<td>$-0.5420 \pm 32.9532i$</td>
<td>32.9577 rad/sec</td>
</tr>
<tr>
<td>Regressive Lag</td>
<td>$-1.2812 \pm 14.6746i$</td>
<td>14.7304 rad/sec</td>
</tr>
</tbody>
</table>

Table 5.2. Summary of Modes at 140 knots and 92% RPM

<table>
<thead>
<tr>
<th>Rotor Modes</th>
<th>Eigenvalue</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive Flap</td>
<td>$-9.3119 \pm 47.2927i$</td>
<td>48.2007 rad/sec</td>
</tr>
<tr>
<td>Regressive Flap</td>
<td>$-6.5310 \pm 3.2229i$</td>
<td>7.2829 rad/sec</td>
</tr>
<tr>
<td>Progressive Lag</td>
<td>$0.5076 \pm 36.2369i$</td>
<td>36.2405 rad/sec</td>
</tr>
<tr>
<td>Regressive Lag</td>
<td>$-1.0579 \pm 15.8697i$</td>
<td>15.9049 rad/sec</td>
</tr>
</tbody>
</table>
5.2 Control System Design

This section will introduce the steps in design of the RSF controller and how to integrate it into the baseline MFC control structure.

5.2.1 Baseline Controller

The baseline controller is the same as described in Chapter 3. In this chapter, the focus will be on the rotor-body coupling problem for the reduced rotor speed case, instead of the use of variable rotor speed application in the vertical axis. Therefore the rotor speed command is set as a constant as scheduled by rotor speed optimization results in this study. In following simulations, the rotor speed command can be set to zero without loss of generality. Therefore the model inversion solution will have a unique solution as Equation 5.1.

\[
\begin{bmatrix}
\delta_{lat} \\
\delta_{long} \\
\delta_{col} \\
\delta_{ped}
\end{bmatrix} = [B]^{-1} \begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r} \\
\dot{w}_D
\end{bmatrix} - [A]_{4 \times 4} \begin{bmatrix}
p \\
q \\
r \\
w
\end{bmatrix}
\] (5.1)

5.2.2 Rotor State Feedback Controller

In reference [17], an RSF controller was designed using a Linear Quadratic Regulator (LQR) approach. The rotor dynamic model is assumed to be approximately decoupled from the fuselage and engine states and reduced to a lower order state space form through an order reduction process. An 8th order rotor states model as Equation 5.2 will be used in the LQR augmented plant model design, as shown in Figure 5.3.

\[
\dot{x} = Ax + Bu
\]

\[
x = \begin{bmatrix}
\beta_{1c} \\
\beta_{1s} \\
\beta_{1c} \\
\beta_{1s} \\
\zeta_{1c} \\
\zeta_{1s} \\
\zeta_{1c} \\
\zeta_{1s}
\end{bmatrix}^T
\]
An LQR gain matrix is calculated by solving an Riccati equation to minimize the cost function:

\[
J = \int_0^\infty (z_p^T z_p + z_i^T z_i + z_a^T z_a) dt
\]

Note that Equation 5.3 requires some auxiliary variables to be included in an augmented plant model for LQR design implementation and gain calculation. Figure 5.4 shows the structure of the LQR controller and the signals flow chart. There are two inputs and the commended flapping angles are calculated from these two
commanded angular accelerations with an assumption that the roll and pitch channels are decoupled. The saturation functions are used to restrict the commanded flapping angles. These flapping limits can be selected based on design requirements such as mechanical or structural limits. Thus this approach is also effective for hub moment limiting. The eight rotor state signals would be provided by a rotor blade measurement system. The reliable rotor state measurement is a challenge, though several research rotorcraft already have prototype measuring systems installed. This study assumes a functional rotor blade measurement system and the rotor state variables are simply provided by the simulation model. The augmented plant model used in the control synthesis is replicated in the control implementation to provide auxiliary variables for the LQR controller. The output of the controller will be the lateral and longitudinal cyclic pitch inputs for the rotorcraft.

5.2.3 Controller Synthesis

The previous two sections introduced the baseline MFC controller and the RSF controller, each of which can be designed independently according to system design requirements.

Figure 5.5 shows the method to integrate the two controllers together. The MFC controller will be kept unchanged with the add-on RSF controller. Once

Figure 5.5. Schematic of Control System with RSF Controller
the RSF is required to be engaged, the pseudo controls of angular accelerations in roll and pitch will be sent to the RSF controller as the commanded angular accelerations. The RSF controller will convert them to flapping commands and then calculate the lateral and longitudinal cyclic pitch inputs based on the RSF control laws. The cyclic pitch commands are also provided to the model inversion equation 5.1 to compute the other two controls, the collective pitch and the yaw control input. An alternative method for the collective and the yaw control is to use a decoupled model of yaw and heave dynamics and then to compute them independently.

5.2.4 Linear Model Simulation

The MFC and RSF controllers introduced above are simulated with a 28th order linear model of the helicopter using Matlab/Simulink environment. The two controllers can be tested separately and then integrated at the end. For the problems formulated in first section, the linear simulation can prove the validation of the rotor state feedback control on rotorcraft with a reduced rotor speed.

First, the simulation is performed for a level flight condition of 80 knots operating at 84% RPM. Figure 5.6 shows the baseline controller’s performance for a high designed bandwidth of 4.5 rad/sec for roll axis and the notable high frequency oscillation occurs and leads to instability in the end.
With the RSF controller engaged, the response is much better, as shown in Figure 5.7. It was found that the closed loop’s damping is reduced after engaging the RSF controller. Technically this problem can be solved through adjusting error dynamics’ damping ratio. From the simulation results we can see that although there is some overshoot, the response generally tracks the command and the system is stable.

### 5.3 Nonlinear Simulation

The RSF controller was implemented in the nonlinear model GENHEL-PSU and further verified through the nonlinear simulation. The overall implementation is similar to the one in Chapter 3 except for the issue related to the derivation of rotor states in multi-blade coordinates [17]. In the actual rotorcraft the sensors may measure the flapping and lead-lag angles of individual blades, so the conversion to the multi-blade coordinates should be performed using Equations 5.4.

\[
\beta_{1c} = \frac{1}{2} \sum_{i=1}^{4} \beta_i \cos \psi_i
\]
\[ \beta_{1s} = \frac{1}{2} \sum_{i=1}^{4} \beta_i \sin \psi_i \]

\[ \dot{\beta}_{1c} = \frac{1}{2} \sum_{i=1}^{4} (\dot{\beta}_i \cos \psi_i - \Omega \beta_i \sin \psi_i) \]

\[ \dot{\beta}_{1s} = \frac{1}{2} \sum_{i=1}^{4} (\dot{\beta}_i \sin \psi_i + \Omega \beta_i \cos \psi_i) \]

\[ \zeta_{1c} = \frac{1}{2} \sum_{i=1}^{4} \zeta_i \cos \psi_i \]

\[ \zeta_{1s} = \frac{1}{2} \sum_{i=1}^{4} \zeta_i \sin \psi_i \]

\[ \dot{\zeta}_{1c} = \frac{1}{2} \sum_{i=1}^{4} (\dot{\zeta}_i \cos \psi_i - \Omega \zeta_i \sin \psi_i) \]

\[ \dot{\zeta}_{1s} = \frac{1}{2} \sum_{i=1}^{4} (\dot{\zeta}_i \sin \psi_i + \Omega \zeta_i \cos \psi_i) \] (5.4)

In the GENHEL simulation, the multi-blade coordinates will not be exactly steady in trim, but exhibit a small oscillation at a frequency of 4 cycles per revolution. Here we use a low pass filter to smooth the values of these rotor states, though an extra phase lag is introduced due to this filter.

A roll doublet input of 15 degrees was applied in the non-linear simulation to test the controller design. Firstly the simulation results are shown in Figure 5.8 for 80 knots level flight with the baseline MFC controller and a high design bandwidth of the roll channel for 4.5 rad/sec and at standard 100% rotor speed. The roll response is good and the flapping angle is small in steady states.

Figure 5.9 shows the same type input on the rotorcraft running at the optimal
Figure 5.8. Baseline MFC Controller, Roll Doublet Response at 100% RPM and 80 knots Level Flight, Sea Level

rotor speed, which is 84% of the standard rotor speed for 80 knots level flight. The simulation shows that the high frequency oscillation starts to appear on rotor states as well as on roll response. The oscillation frequency observed is at 4.81 Hz or 30.22 rad/sec. which is very close to As shown before, the open loop progressive lag mode’s natural frequency is 32.9577 rad/sec. The closed loop progressive lag mode is traveling towards the right half plane with the increasing feedback gain and the frequency is identified to be 32.9832 rad/sec. There is no other mode nearby that frequency. Obviously, the oscillation is due to the progressive lag mode. We can also see that the trimmed value of the coning flapping angle at the optimal rotor speed is higher than the value at the standard rotor speed due to the lower centrifugal stiffness. The lead-lag angles also show the oscillation and it is the source of the rotor-body coupling. The progressive lag mode may be already unstable but the nonlinear factors on the rotor system, such as lag dampers, prevent the lead-lag angles from diverging, which results in the limit cycle oscillation.

Figure 5.10 shows the simulation results for the RSF controller. With the same flight condition and rotor speed as Figure 5.9, RSF controller directly commands the rotor states and the significant improvement in roll response is shown. Furthermore, the flapping response during maneuvering is much smaller in RSF
control. This would be especially useful for rotorcraft running at reduced rotor speed. Because the coning angle is already very large at the reduced rotor speed, the allowable extra fluctuation in flapping would be very low and a high control input may drive the flapping angle to its mechanical limit or the “stop”. The flapping limits in RSF control imposed a constraint on commended flapping angles and can be used to prevent blades from hitting the stop directly.

The simulation for 140 knots shows the similar results as 80 knots. In Figure 5.11, rotorcraft is running at the optimal rotor speed for 140 knots level flight, which is 92% of the standard rotor speed. During the first 15 seconds the baseline MFC controller is applied and after then the RSF controller will be engaged. There is a clear oscillation in the figure before the RSF controller is engaged. The
observed oscillation frequency is about 5.42 Hz or 34.05 rad/sec, which is close to the open loop progressive lag frequency of 36.24 rad/sec. The closed loop mode is not changed much and is identified to be 36.76 rad/sec. After the RSF controller runs, the flapping angles are restricted and the oscillation at the progressive lag frequency tends to disappear. Another frequency oscillation with very small magnitude starts to show in the flapping angles and this frequency is determined about 16 Hz, which is just the 4 cycles per revolution at 92% of the standard rotor speed. Furthermore, the roll response is good and shows the expected improvement over the baseline MFC controller.
Figure 5.11. RSF Controller, Roll Doublet Response at 92% RPM and 140knots Level Flight, Sea Level
Conclusions and Future Work

6.1 Conclusions

The objective of this dissertation is to investigate the advanced flight control methodologies for application to rotorcraft with large variations in rotor speed. The design methods were implemented, tested, and evaluated using the modified GENHEL-PSU software. The modification was mainly focused on implementation of the rotor speed control system.

Based on the GENHEL-PSU, the optimal trim schedule for rotor speed has been developed in Chapter 2. The following conclusions can be drawn from the results of this parametric study:

- Trim optimization studies confirmed that significant power savings (more than 20% for best situations) can be achieved by reducing the operating rotor speed across the envelope and particularly interested when the airspeed is over 40 knots.

- The trim results also showed that if the rotor speed is set for a minimum power required, the aircraft is likely to operate much closer to constraints associated with control margins, torque limits, and rotor stall.

- The optimal rotor speed trim schedule is quite sensitive to the operating condition such as gross weight and ambient conditions. Thus, a comprehensive schedule involving those factors is desired, and the flight control design
would have to accommodate a wide range of operating points.

- Scheduling rotor speed for steady maneuvering conditions such as climbs and descents is also necessary to achieve a desired maneuver performance.

- Overall, the angle of attack for blade elements is larger while the Mach number is smaller to operate at the reduced rotor speed than the standard rotor speed. This results in an overall higher aerodynamic efficiency benefitted from the variation in rotor speed for different flight conditions.

In Chapter 3, the focus is the design of an integrated flight/propulsion control system. The baseline control architecture is a model following and model inversion controller. The gain scheduling method is adopted to account for the nonlinearities. The specific control allocation problem associated with the vertical axis and rotor speed control is introduced, and a concise and effective solution is given. The following conclusions can be drawn from this part:

- Torque constraints and other non-linear effects in the engine model are critical when designing a controller that integrates rotor speed control in the vertical axis. Initial attempts in implementing controllers in the non-linear model showed that results for small amplitude inputs are fine. But for large amplitude inputs the controller worked very poorly until constraints were accounted for in the control law.

- Following a vertical speed command, the best approach appears to be to set the rotor speed for optimal performance first, and then increase collective input to track the command model. A large increase in collective input raises the torque level and makes it difficult to accelerate the rotor.

- The vertical axis controller designed in this study has demonstrated to give reasonable performance and Level 1 response characteristics, except for large amplitude inputs at certain conditions result in Level 2 due to high apparent phase delays. This problem might be overcome by further tuning of the command filter.
• The coordinated turn algorithm involving the optimal rotor speed schedule for the effective gross weight can clearly improve the performance of steady turn.

• For this particular simulation model, reduced rotor speed reduces frequency and damping ratio of the rotor lag modes. This would indicate that stability margins should be thoroughly analyzed with a high order model of the vehicle dynamics.

• A slight increase in the design bandwidth of the flight control system could result in low stability margin issues when operating at a reduced rotor speed. This was mainly displayed in the form of a high frequency gain crossover frequency that resulted in unreasonably low time delay margins.

• Although the roll-pitch cross coupling effect is more noticeable at reduced rotor speed, it could be solved using the coupled controller.

• The rotor-body coupling cannot be completely resolved using control law developed in Chapter 3.

Chapter 4 proposed a power command system design for the collective axis, which accommodates the optimal rotor speed schedule. The following conclusions can be made:

• A power command system is designed for collective axis to accommodate the optimal rotor speed schedule. The zero power command represents the autorotation flight, and the maximum input will command the maximum climbing rate. For hover and low speed flight conditions, the vortex ring state is considered in the schedule.

• The initial nonlinear simulation with the help of an outer loop controller shows that the power command system can easily accommodate the optimal rotor speed schedule. With the torque limiting method applied on the controller, the large overshoot of the torque response vanished and the actual rotor speed could follow the command very well. In the steady state, the torque required is also ensured within a safe range due to the pre-treatment in rotor speed optimization study.
Piloted simulation evaluation using Penn State’s real-time simulation facilities shows the power command design for variable rotor speed performs well as the design expectation.

In Chapter 5 a rotor state feedback (RSF) control system was designed for the example rotorcraft with variable rotor speed to prevent the rotor-body coupling at high forward speed. The controller was designed to be integrated with the original model following control (MFC) system to provide ACAH control in pitch and roll axes without changing the original variable rotor speed application structure in the vertical axis. The design methods were first implemented and tested using the linear model extracted from GENHEL model of the UH-60A and evaluated under Matlab/Simulink environment. The implementation in non-linear simulation environment GENHEL-PSU was introduced. The simulation results confirmed the enhancement on roll response with the application of the RSF controller for some flight conditions. The following conclusions can be made:

- The design process showed how to seamlessly integrate the RSF controller to the baseline MFC control structure described in Chapter 3. Overall this approach is straightforward and most of the original work and conclusions on MFC control and RSF control are still valid.

- Both the linear and non-linear simulations showed the expected oscillation observed in roll axis response with the baseline MFC control system. The oscillation frequency was determined to be close to the rotor’s progressive lag mode frequency. The study confirmed that the progressive lag mode can play a strong role in rotor-body coupling phenomenon.

- Using RSF control can significantly improve the performance and effectively prevent the rotor-body coupling. Due to the fact that RSF controls rotor states directly, it is also helpful in restricting flapping angles at reduced rotor speeds.

In summary, the contribution of this dissertation is the framework to actively use variable rotor speed control for rotor craft. Within this framework, the optimal rotor speed study, MFC design, the power command system, and the RSF control all are focused on the special problems associated with variable rotor speed.
6.2 Future Work

The last section summarized the research work on flight control design for rotorcraft with variable rotor speed in this dissertation. The experiences and lessons learned from this research have given directions for the future research.

In the rotor speed optimization study, the following topics could be considered:

- Normally the rotorcraft operating with the optimal rotor speed is running near some constraints and control margins. This dissertation also confirmed that the large variation may result in stability problems. Therefore it is not worth to use a large variation in rotor speed to gain a small benefit. A comprehensive optimal rotor speed schedule may be determined by a cost function which includes the power required, torque required, control margins, and the amount of rotor speed variation from the standard value.

- The optimal rotor speed schedule can be simplified to operate at at finite and discrete set of RPM settings. This may reduce the challenge on the design of the continuous variable rotor speed drive system. And the performance under such a schedule should still gain benefits from the rotor speed variation.

In control system design, the following future work may be interesting:

- The thorough examination on frequency response for open-loop as well as closed-loop systems needs to be performed using CIFER, for the complete range of the operating rotor speed.

- To overcome the torque constraints problem in using rotor speed variation, two methods could be potentially applied. One idea is to implement the envelope protection system [30]. Another option is to develop a quadratic form of the torque estimation algorithm involving rotor speed variation similar to the one in [19]. Then the optimization algorithm based control allocation methods can be applied to minimize the torque required.

- The gain scheduling method solves the non-linear problems with a preprogrammed way. It is applied here due to its easy implementation, but there is no guarantee for the system performance and stability. Further research
could explore the effects of the inverse model selection, the linear model reduction, and interpolation methods on the closed-loop performance.

For RSF control, the following research work may be considered:

- The piloted simulation should be performed to evaluate the performance of the integrated RSF and MFC controller.

- The rotor state measurement system is required for rotor state feedback control.

- Because of the practical problems in rotor states measurement, it is desirable if the output feedback method can work using only part of rotor states, such as flapping angles.

- Other control methods can be investigated to replace the LQR design.
Appendix A

Simulation Platform

A modified version of the GENHEL software has been developed at Penn State University (GENHEL-PSU) for the basic research on rotorcraft flight dynamics and control. It will be employed in this research with some modifications. This part will provide the basic information about GENHEL-PSU, particularly on the features mostly important to this research. The focus is the modification on the engine and fuel control system.

A.1 Overview of GENHEL-PSU

GENHEL-PSU is based on the U.S. Army/NASA Ames GENHEL model [31] of the UH-60A Black Hawk, which is a well-established Fortran-based simulation code. GENHEL accurately represents the flight dynamics and has been verified with flight test data. GENHEL-PSU was developed as the major component of the Penn State Multi-Disciplinary Rotorcraft Simulation Facility (MDRSF) [32]. Compared with GENHEL, there are several improvements and new features made in GENHEL-PSU, some of which are related to this research and described as followed:

- There is a network interface with realtime simulation environment to transmit data from the flight dynamics model to the external flight simulation software FlightGear. As required by this interface code developed in C++, the GENHEL-PSU code is compiled and executed with Compaq Visual For-
tran 6.6 and Visual Studio 6.0, which not only provides debugging features but also allows easy compilation of mixed-language code.

- The interface with the MatLab software environment provides a straightforward interface to perform the simulation and data analysis. The Matlab script can specify the operation points and perform a bunch of trim, linearization, and numerical simulations. Therefore, all the trim results, linearized models, and the simulation time history data can be managed, analyzed, and displayed with powerful MatLab tools.

- High order linearized models can be generated using perturbation method. The 28-state vector includes 8 rigid body fuselage states (3 velocities and 3 angular rates in body axes, pitch and roll Euler angles), 12 rotor states (flapping and lagging dynamics in multi-blade coordinates), 3 inflow states (Pitt-Peters model), and 5 engine states (rotor speed, gas generator speed, turbine temperature, fuel flow, and HMU load demand spindle). The input vector consists of the lateral and longitudinal cyclic pitches, collective pitch, pedal, and the RPM governor input to the engine’s Hydro-Mechanics Unit (HMU), which is represented by SPDG in GENHEL.

- GENHEL-PSU can disable independent channels of the existing UH-60A control laws and interface with modified, user-defined flight control laws. The flight control modules are completely decoupled from the flight dynamics model. Hence the new flight control design could be implemented fast and integrated seamlessly.

- The existing models of the stability augmentation system (SAS) and flight path stabilization system (FPS) have also been modified so that both systems can be turned on or turned off individually.

A.2 Modifications on GENHEL-PSU

In this research, the GENHEL-PSU code is compiled and executed with Intel Fortran Compiler 9.1 and Microsoft Visual Studio 2005 under the Windows XP operating system. It is not difficult to migrate GENHEL-PSU, which is originally
a Compact Fortran project, to Intel Fortran project. It requires some changes in project properties and some source code improvements due to a little difference between two compilers in compiling process.

As discussed in Chapter 1, the rotor speed variation can be achieved through change in the engine’s power turbine speed. Thus it is necessary to modify the engine and fuel control system in GENHEL-PSU. On UH-60A, the rotor speed control is achieved using engine Electrical Control Unit (ECU) and Hydromechanical Control Unit (HMU) [33]. A rotor speed controller, which is based on the model following control structure introduced in Chapter 3, is developed to replace ECU. Because the collective feed forward effect has been included in inverse model of rotor speed controller, the load demand dynamics should be removed from HMU. The torque motor dynamics is also removed as shown in Figure A.1. All the modification is to command a rapid change in rotor speed.

![Figure A.1. T700 Hydromechanical Control Unit (HMU) Modification (Figure from: [33])](image)

In the gear box module, limits were removed to enable the engine’s power turbine speed to be changed with a large variation.
Notice that in engine’s trim calculation, the original trim strategy is still applied and the original GENHEL’s ECU and HMU modules are only used to achieve a trimmed state. In other tasks for this project including linearization and simulation, the modified HMU module will be selected and ECU will be disabled.
Rotor-Body Coupling due to Feedback

The rotor-body coupling can arise due to the high feedback gain. This problem can be illustrated using the root locus diagram. Consider the open loop transfer function of Equation B.1 as an example.

\[
y(s) = \frac{3}{u(s)} \cdot \frac{916}{s + 3} \cdot \frac{1}{s^2 + 8s + 916}
\]  

(B.1)

There are three poles: \( s_{1,2} = -4.0 \pm 30.0i \) and \( s_3 = -3.0 \). Obviously the open loop system is stable. Consider a simple feedback introduced and the closed loop system is such as Figure B.1.

The root locus for this system is shown in Figure B.2. With the increasing feedback gain \( K \), the closed loop poles should travel towards the open loop zeros. For the system B.1, there are three zeros, which are at infinity. The pair of complex roots will go across the imaginary axis and keep moving towards the right half plane infinity as \( K \) increases from zero to infinity. Therefore the choose of a high gain

\[\text{Figure B.1. Closed Loop System}\]
feedback may lead to an unstable closed loop system as shown above.

This is similar to the transfer function from lateral control to roll rate of the helicopter. Normally the roll mode is well damped and placed on the real axis at left half plane, which is similar to the pole $s_3 = -3.0$ in Equation B.1. The progressive lag mode includes a pair of complex poles, which are similar to the poles $s_{1,2} = -4.0 \pm 30.0i$ and they are light damped. An important fact is that there are no nearby zeros around the progressive lag mode, which is the same situation in the above example. Therefore the closed loop system may become unstable with the presence of a large feedback gain in the closed loop. In fact, even the closed loop progressive lag mode is close enough to the imaginary axis, the high frequency oscillation will start to show in the output and this will be annoying for the pilot.
Bibliography


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