45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
2 - 5 August 2009, Denver, Colorado

AIAA 2009-4808

Multivariable PI Control for Tip-Jet Reaction Drive Systems

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Recently there has been a push for a vertical takeoff and landing rotorcraft that can approach 450 knots, with specific interest in a tip-jet reaction drive system to provide both the lift to the rotor and thrust for forward flight or yaw control. In this paper, the feasibility of using a distributed multivariable PI controller to control both the rotor and engines on the tip-jet reaction drive system is studied. To accurately develop control laws for the system, the dynamics present on the system need to be understood. For this study, a dynamic model of the tip-jet reaction drive system is built and the sensitivity of the dynamics to the dimensions of the system is analyzed. One specific transient of interest for the tip-jet reaction drive system is rotor load control. As the rotor load demand on the tip-jet reaction drive system changes, at a given constant rotor speed, the load on the rotor can be manipulated by changing either the mass flow or the velocity through the tip-jet exhaust nozzle. The velocity can be changed by adjusting the tip-jet fuel flow and exhaust nozzle area. Mass flow can primarily be adjusted by changing the operating points of the two engines supplying air to the tip-jet nozzles. The two rotor load control schemes that are analyzed are rotor load change with and without changing engine demand settings. Either scheme is shown to be feasible, offering different benefits depending on the metrics of most importance such as response time, fuel consumption, or noise.

Nomenclature

A = control volume cross sectional area

A_{hx} = heat transfer surface area

c_p = thermal mass specific heat

d/dt = time derivative

force = momentum applied to control volume

h = control volume enthalpy

h_c = heat transfer convection coefficient

i = indicies

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J = shaft moment of intertia

L = open loop transfer function

L_e = control volume length

m = mass of thermal mass

N = shaft speed

P = control volume pressure

ρ = control volume density

power = power applied to control volume

S = sensitivity transfer function

T = complementary transfer function

T_{gas} = gas path temperature

T_{metal} = thermal mass metal temperature

Torque = torque applied to rotor shaft

V = volume of control volume

W = control volume mass flow

I. Introduction

RECENTLY there has been a push for a vertical takeoff and landing (VTOL) rotorcraft that can approach 450 knots. In the early 1990s, NASA funded an industry wide study to analyze different concepts to meet this need[1]. Out of this research, the rotor/wing concept was identified as a potential attractive option. To further explore the feasibility of the rotor/wing concept, Boeing developed a test vehicle of the Canard Rotor Wing (CRW) variant of the rotor/wing concept named the Dragonfly[2].

The Dragonfly is a CRW with a single turbofan engine driving a reaction drive rotor. This aircraft operates in three different modes: VTOL, intermediate-speed, and high-speed operation. For VTOL operation, the concept vehicle uses warm exhaust gas ducted through the rotor to provide the necessary torque to generate rotor rotation for both lift and forward thrust. As the speed of the vehicle increases and transitions into intermediate-speed operation, the rotor is slowly offloaded and engine exhaust is used to provide forward thrust. At high-speed operation, the rotor is locked and acts as a fixed wing, while the engine exhaust continues to provide forward thrust. Two test aircrafts of this concept were built, and both crashed during the testing phase. These crashes were later determined to have been due to control issues[3].

Another reaction drive system similar to the warm cycle reaction driven system of the Dragonfly is the cold cycle tip-jet reaction drive system[4]. In contrast to the Dragonfly, engine air is extracted from the bypass of two turbofan engines into a common plenum and then combusted at the rotor tips. These systems, however, do have their similarities, among which are the three modes of operation. The notable difference in the cold cycle tip-jet reaction drive system is in its operation during these three modes. In hover and VTOL operation, the cold, fan-compressed, bypass air is ducted through the rotor, thus generating the necessary lift and forward thrust, while the engine core flow is diverted to provide yaw control. During low-speed flight mode, the rotor is no longer powered, but rather is in autorotation. As the aircraft transitions from low-speed to high-speed flight mode, the lifting is initially done primarily by the rotor, but is increasingly offloaded to the wing as the tip-jet reaction drive powered vehicle gains speed. In both low and high-speed flight mode, the engines are the sole providers of forward thrust. Although the study in the subsequent sections can be applied to either concept, the motivation for the study will be centered on the cold cycle tip-jet reaction drive and further references to tip-jet reaction drive will imply the cold cycle reaction drive system concept.

For safe and stable operation of the tip-jet reaction drive, the control system must be able to provide the necessary thrust or lift required depending on the mode of operation all the while accounting for the interactions between the engines and the rotor. It is also evident that depending on the mode of operation, the interactions between the engines and rotor (the subsystems) may change. In hover mode, when the bypass air of the engines is ducted into the rotor, the system is highly interactive. However, in flight mode, the interaction between the engines and the rotor is minimal. In addition to safety and stability, optimization of both the aircraft and propulsion system must also be taken into account. Typically, the most optimal performance setting is minimal fuel burn; however, there may be certain situations, such as a damaged aircraft, where minimum fuel burn might not be the optimal setting. One last criterion for safe control of the system is to update the control at a rate that is consistent with the fastest significant dynamics of the system. For the tip-jet reaction drive system the dynamics are relatively fast and require a fairly fast control update rate (~20ms). This leads to the problem statement of this paper: Develop control laws to ensure safe and stable operation for the tip-jet reaction drive system.

The first step in developing the control laws for the tip-jet reaction drive system is to define the system that is to be controlled. The tip-jet reaction drive system has two engines feeding a common plenum. A simplified schematic of this system with only one engine is shown in Fig. 1[5]. In hover mode, the cold fan compressed bypass air is captured in a plenum and directed towards the rotor hub. In flight mode, the bypass valve to the rotor is closed, and the cold bypass air is mixed with hot turbine exit air and exits the system through the exhaust. There are louvers at the exhaust of the engines which divert the hot flow to provide either forward thrust in flight mode or yaw control in hover mode.

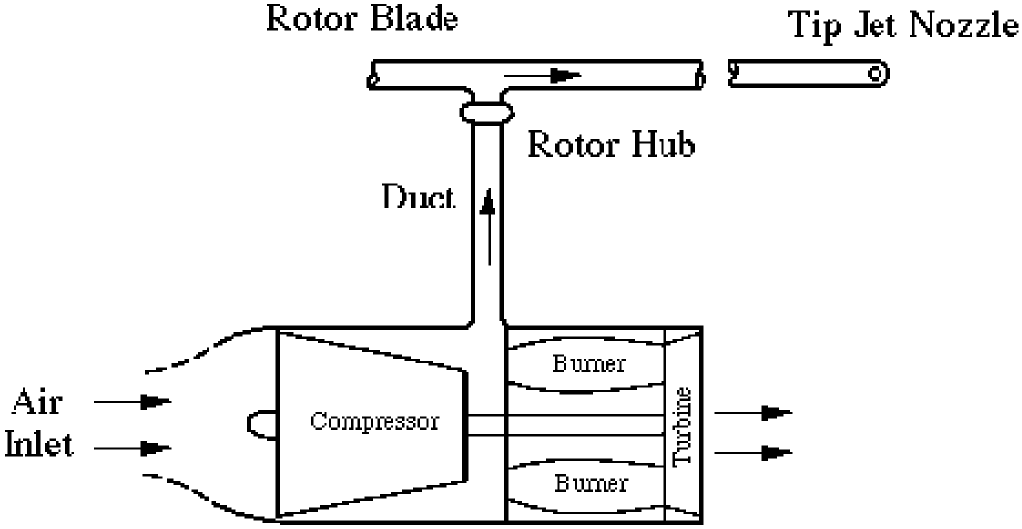

Figure 1. Cold Cycle Tip-Jet Reaction Drive System[5]

In hover mode, the cold bypass air of the two engines enters into rotor hub at section and is then routed out of each of the rotor blades to the tip-jet combustors. At the tip of each blade, fuel is mixed with the air and combusted. The hot combustion air is then accelerated through exhaust nozzles at the tip of each blade. This provides the reaction torque for the rotor, and in turn the necessary lift and thrust required for the rotor system.

Due to varying degradation, the presence of faults, and manufacturing variation, the performance of the two engines may not be identical and the corresponding effects of these differences need to be quantified. Therefore the system model must include both engines and the tip-jet driven rotor as illustrated in Figure 2.

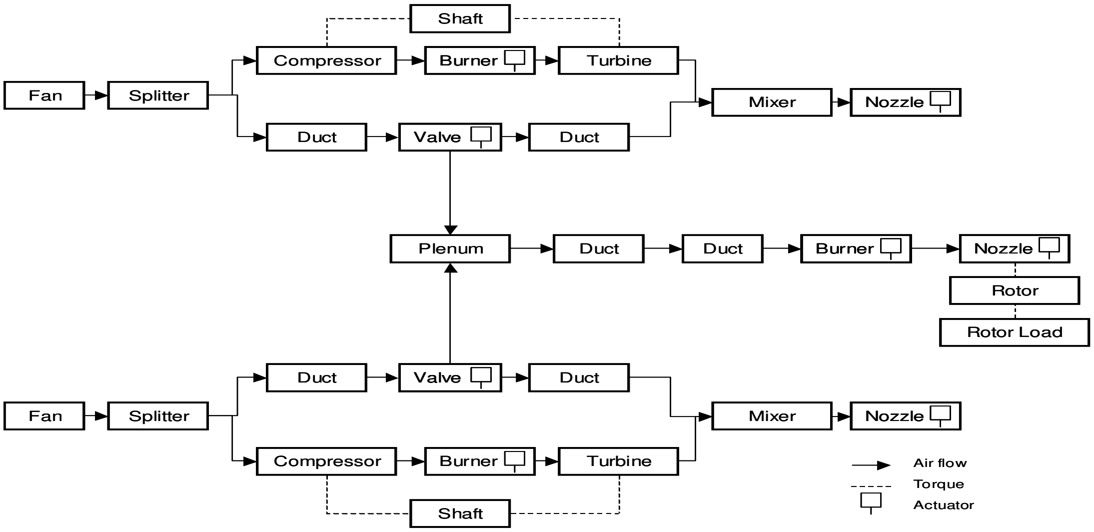

Figure 2. Tip-jet Reaction Drive System Schematic

If there were no interactions between all the inputs and outputs, each controller could be a simple single-in, single-out (SISO) controller. However, it is clear that the system is highly coupled with potentially strong interactions and cross coupling between the inputs and outputs. The fact that the Dragonfly crashed due to unaccounted for cross coupling proves that this is not a trivial issue[3]. Therefore it is imperative that the control system developed for the tip-jet reaction drive system accounts for and decouples all of the interactions.

II. Multivariable Control Methods

Control systems developed to capture and decouple the system interactions are commonly referred to as multiple-in, multiple-out (MIMO) or multivariable controllers. In addition to the interactions, Maciejowski and Dadd defined some preliminary criteria for the design of a multivariable control system[6,7] outlined next. The control system must be able to accommodate the system dynamics across the flight envelope, for varying throttle settings, and for different modes of operation. Additionally, any new controller designed should be able to provide a response comparable with or better than any existing controllers. The control system must be able reject disturbances that have dynamics which are as fast as other control dynamics. As mentioned above the control system must ensure that all system structural and physical limits along with all actuator physical and rate limits must be avoided. And lastly, the control system should be robust enough to handle other variability such as: manufacturing, component degradation, and component asymmetry. A successful multivariable control will meet all these design criteria are met.

Over the last 30 years, many different multivariable control methodologies have been developed to handle the aforementioned design criteria. The Edmunds algorithm developed in the late 1970's has provided the foundation for non-model based multivariable engine control[8]. This methodology derives a set of PI control gains based upon a target response of the system. Polley provided an extension to this methodology to ensure similar system response over the flight envelope[9]. Other methods such as H-infinity and Linear Quadratic Regulator (LQR) ensure a more robust control in the presence of disturbances at the expense of less simple control[10]. In the following analysis, the feasibility of using simple PI controls sized using the Edmunds algorithm on the tip-jet reaction drive system will be explored.

III. System Modeling and Dynamics

The first task in defining the control gains will be to develop an accurate system model representative of the tip-jet reaction drive system that captures the both the steady state performance and the dynamics of the system. Tai explored the steady state design and sizing of different reaction drive systems[11]. Kong, Park, and Kang studied the transient performance of the canard rotor wing (CRW) system modeling both the rotor and mass conservation dynamics[12].

In systems similar to the tip-jet reaction drive system; there are five general types of dynamics present during a transient: rotor, heat soak, gas path, sensor, and actuator. The rotor dynamics, equation 1, are often the slowest and most dominant of the dynamics and must be included in any system transient simulation. The gas path dynamics (often called volume dynamics), which are quantified by the unsteady mass, momentum, and energy conservation in equations 3-5, are generally the fastest.

Rotor Dynamics:

$$\frac{dN_i}{dt} = \frac{\sum Torque}{J_i} \tag{1}$$

Heat Soak Dynamics:

$$\frac{dT_{metal_i}}{dt} = \frac{h_c A_{hx}(T_{gas} - T_{metal_i})}{m_i c_{p\,i}} \tag{2}$$

Gas Path (Volume) Dynamics:

Mass Conservation

$$\frac{d\rho_i}{dt} = \frac{\sum W}{V_i} \tag{3}$$

Momentum Conservation

$$\frac{dW_i}{dt} = \frac{force + \sum PA}{Le_i} \tag{4}$$

Energy Conservation

$$\frac{dP_i}{dt} = \frac{power + \sum Wh}{V_i} \tag{5}$$

Prior transient studies of a reaction drive system only included rotor dynamics and mass conservation (along with no control)[9]. Lower frequency engine models (~50Hz), such as Numerical Propulsion System Simulation (NPSS), only include rotor and heat soak dynamics[13]. Higher frequency (dynamic) models (~2500 Hz) require all the dynamics shown in equations 1-5 plus the sensor and actuator dynamics. This is especially necessary during the simulation of high frequency events such as an engine stall, inlet temperature spikes, afterburner light off, or component failures[14.] Even if the aforementioned events were not present, the presence of relatively large ducts alone may require the incorporation of the gas path dynamics in the tip-jet reaction drive system model. Additionally, the sensor and actuator dynamics can be simulated using first order lags[15]. The resulting high accuracy dynamic model can then be used to define the minimum realization linear model used to define the PI control gains.

A feasible way to incorporate the high frequency gas path dynamics is by using the one dimensional lumped control volume approach similar to methods developed in the mid 1980's [16,17]. In this approach, each component such as the fan, compressor, burner, or duct may have a control volume associated with it as shown in Fig. 5. The calculated terms such as pressure drop/gain, heat transfer, or energy loss/gain in each component are input as force or power terms in each control volume. Referencing the tip-jet reaction drive schematic in Figure 2, each element shown would have an associated control volume.

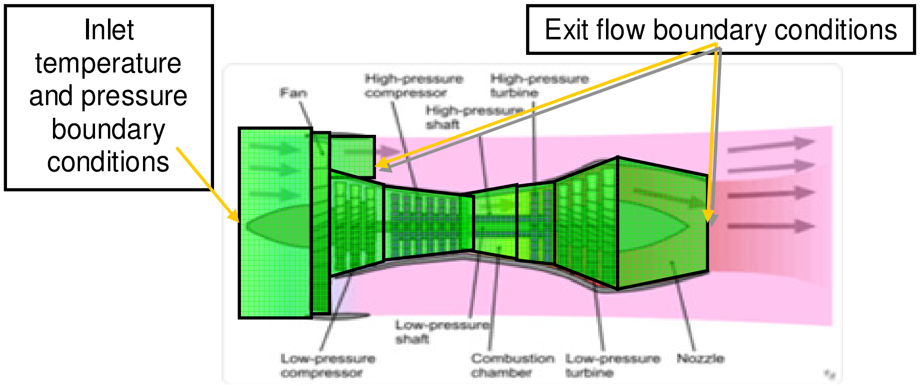

Figure 3. An Engine with Volume Dynamics

Given a typical control sampling rate of 20ms, the frequency range of interest is less than 314 rad/s. To accurately model the effect of the dynamics, a factor of approximately five or 10 is applied to the frequency rate of interest to determine which dynamics need to be analyzed and incorporated. For a sampling rate of 20 ms, dynamics greater than approximately 30 rad/s can be neglected. Using moments of inertia and thermal masses of a typical engine[18] or rotorcraft[19] and simple first order sensor and actuator models[15], the eigenvalues associated with the rotor, heat soak, sensor, and actuator dynamics are shown in Table 1. Using the eigenvectors, the rotor and heat soak dynamics are most closely associated with the smallest eigenvalues and in turn are the most dominant dynamic.

Table 1. Tip-Jet Eigenvalues and Associated Dynamics

Eigenvalues	Associated State
-50	RPM sensor
-33.3333	Pressure sensor
-26.9363	Tip Burner
-26.001	Fuel Actuator
-18.0018	Exhaust Area Actuator
-6.7835	Engine Burner
-6.5698	Engine Burner
-3.0649+0.4018i	LP and HP Rotor Shaft
-3.0649-0.4018i	LP and HP Rotor Shaft
-3.0767	LP and HP Rotor Shaft
-2.4253	LP and HP Rotor Shaft
-0.4773	Tip Rotor Shaft

The dimensions of the control volumes of the engine portion of the tip-jet reaction drive system are defined by using order of magnitude estimates of the dimensions of a 3,000 lbs thrust class turbofan engine. Since the engines have a high bypass ratio, the bypass ducts will have similar cross-sectional areas to that of the fan inlet. In order to fully understand the effect of the duct volumes on the response of the system different, duct volume dimensions estimates were studied. The different columns of Table 2 show how the top sixteen dominant eigenvalues change as the duct dimension is changed. The duct dimension in the first column is 10 times the size of a volume for an engine component. The next two columns represent increases in duct dimension of 20 to 100 times the size of volume for an engine component. When the duct dimension is only 10 times the size of an engine component volume, none of the additional eigenvalues associated with the gas path dynamics approach 30 rad/s and can therefore be neglected. However, as the dimension increases, the number of eigenvalues less than 30 rad/s significantly increases, such that when the dimension is 100 times larger the additional eigenvalues approach the same order as the shaft and heat soak dynamics and need to be included in the model.

Table 2. Shaft, Heat Soak, Gas Path Eigenvalues with Duct Dimension Relative to Engine Dimension

10x	20x	100x
-119.00	-56.50	-18.00
-119.00	-56.50	-15.20
-101.00	-50.00	-15.20
-101.00	-46.20	-12.40
-50.00	-46.20	-12.40
-33.30	-33.30	-10.70
-26.90	-26.90	-10.70
-26.00	-26.00	-8.73
-18.00	-18.00	-8.73
-7.38	-7.38	-7.41
-7.35	-7.36	-7.41
-3.18	-3.18	-3.19
-3.08	-3.08	-3.09
-1.52	-1.52	-1.52
-1.50	-1.50	-1.50
-0.49	-0.49	-0.49

Low frequency models that neglect gas path dynamics, such as NPSS, would be suitable for simulating the tip-jet reaction drive system when the duct dimensions were similar to the 10x column. However, as the dimensions approach the 100x column, the gas path dynamics would need to be integrated into the system model. For the purposes of this study, the dimensions defined in the 10x column will be used for the subsequent runs. But all the analysis below would be the same no matter which dimension was chosen since the system model has the gas path analysis integrated.

IV. Results

For clarity, the following results are broken up into three sections. The first section describes the selection process used to define the input/output variables used in the control. The second section analyzes the results of the sizing of the PI controller. And the last section discusses the results two different schemes for controlling a rotor load demand change.

A. Control Selection and Steady State Performance

The next step in developing control laws is to define which target variables are to be controlled, i.e., the purpose of the controller. In general, the fuel metering valves are used to control thrust or lift while the exhaust valves are used to ensure that operability or performance limits are not exceeded. However since thrust or stall margin cannot be measured, certain measurements that correlate well with them are substitued. For thrust, typically the low pressure (LP) or high pressure (HP) shaft speed correlate well. To control the stall margin or the operating line of the system, either exhaust pressure ratio (EPR) or core exhaust pressure ratio (CEPR) are used. Additionally, there are a couple more general metrics used to select which variables are to be controlled: 1.) minimal interactions between inputs and outputs and 2.) minimal variance of unmeasured parameters of interest over the functional life of the system.

The relative gain array is a very simple and useful measure to capture the interactions between different potential input/output combinations[20]. Table 3 below shows the relative gain array for the tip-jet all the potential input/output combinations for the tip-jet reaction drive system. A value of 1 in the table represents a significant relationship between input and output and the converse holds true for a value of zero. To minimize interactions, the choice of the final input/output combination should be as diagonally dominant as possible (i.e., the input/output value should be as close to 1 as possible). From Table 3, the six most attractive outputs to be controlled are HP shaft speed, CEPR, tip-jet shaft speed, and EPR tip-jet.

Table 3: Relative Gain Array of Tip-Jet Reaction Drive System

Relative Gain Array	Right Fuel Flow	Left Fuel Flow	Right Exhaust Area	Left Exhaust Area	Tip-Jet Fuel Flow	Tip-Jet Exhaust Area
LP Shaft Right	**0.356**	0.000	**0.204**	0.000	0.011	0.070
LP Shaft Left	0.000	**0.355**	0.000	**0.205**	0.011	0.070
HP Shaft Right	**0.292**	0.000	0.027	0.000	0.006	0.019
HP Shaft Left	0.000	**0.292**	0.000	0.027	0.006	0.019
EPR Right	**0.250**	0.000	**0.260**	0.000	-0.017	0.062
EPR Left	0.000	**0.251**	0.000	**0.259**	-0.017	0.061
CEPR Right	0.040	0.000	**0.480**	0.000	-0.034	0.081
CEPR Left	0.001	0.040	0.000	**0.480**	-0.034	0.081
Tip Jet Shaft	0.001	0.001	-0.001	-0.002	**1.373**	**-0.372**
EPR Tip	0.016	0.015	0.007	0.007	**-0.106**	**0.321**
Duct Pressure Right	0.044	0.002	0.025	-0.001	**-0.100**	**0.293**
Duct Pressure Left	0.002	0.043	-0.001	0.025	**-0.100**	**0.293**

Before any final choices on control input/output combinations are made, the variance of unmeasured performance metrics over the life of the system need to be analyzed. Unmeasured parameters like thrust and stall margin are indirectly controlled via a correlation with a measured parameter. This correlation may change over the useable life of the system which may result in margining of both steady-state and transient performance. The input/output control pair should be chosen such that variance of unmeasured parameters is minimal over the useable life of the system. Figure 4 summarizes some of the variance of performance metrics such as engine thrust, turbine inlet temperature, and compressor stall margin over the life of the engine when EPR tip, Tip-jet speed, LP shaft speed, and CEPR are used in the control.

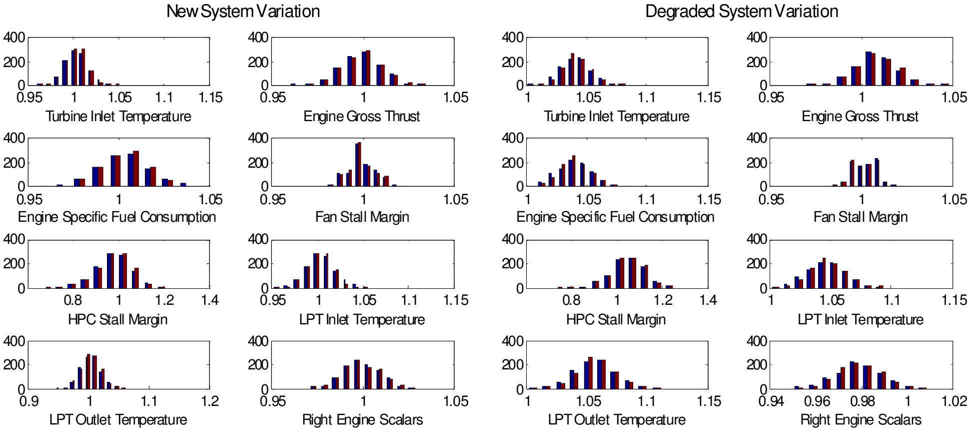

Figure 4. Cycle Variation of System Performance Metrics

In this analysis it was seen that variance in LP stall margin significantly reduced over the life of the system when HP shaft speed was used in the control as opposed to LP shaft speed. This was the overriding factor in choosing LP shaft speed over HP shaft speed. Even though the variance was minimized, turbine and tip-jet temperatures increase as the system ages. Given this fact, the steady state performance may be margined to ensure the hot gas components are not operated at conditions that would adversely affect the life of the system. However, further analysis of this fact is beyond the scope of the paper. Once the control input/output parameters are defined, the actual PI controller can be sized.

B. Control Sizing and Analysis

Since the tip-jet reaction drive system has three fairly distinct subsystems (2 engines and 1 reaction drive rotor), it could be broken down into three smaller distributed subsystem controllers. The merits of using either a centralized or distributed controller need to be discussed before sizing the gains of the PI controller. A centralized controller will account for all the interactions between inputs and outputs. In terms of performance, this would be the most optimal setup. However, additional costs may be required to account for the communications needs to overcome the large distance between control inputs and outputs, thus making a centralized controller a less attractive option. If the interactions between the subsystems are small enough, a distributed controller may provide a feasible option. An additional argument for a distributed controller is based on the operational profile of the system. If the system is operated such that the potentially large interactions are minimal, a distributed controller may be appropriate. For an initial feasibility study, the distributed PI controller for each subsystem will be studied.

Using the Edmunds algorithm, a set of PI gains will be defined for each of the distributed subsystem controller. Given the dynamics of the system defined in the previous section, the target open loop bandwidth of the engine and tip-jet subsystem controls were chosen to be 3 Hz and 0.5 Hz, respectively. Open loop transfer function (*L*), complementary transfer function (*T*), and sensitivity function (*S*) singular values are plotted against frequency in Figure 5 to ensure the control has acceptable properties[21]. The open loop response for each engine and the tip-jet rotor match the desired response until about 8 Hz and 3 Hz respectively. The closed loop response is zero at low frequencies (< 3Hz for the engines and < 1Hz for the tip-jet) which ensures good reference tracking and disturbance rejection. The sensitivity function approaches zero at higher frequencies (> 10Hz for the engines and > 1Hz for the tip-jets), ensuring good noise rejection.

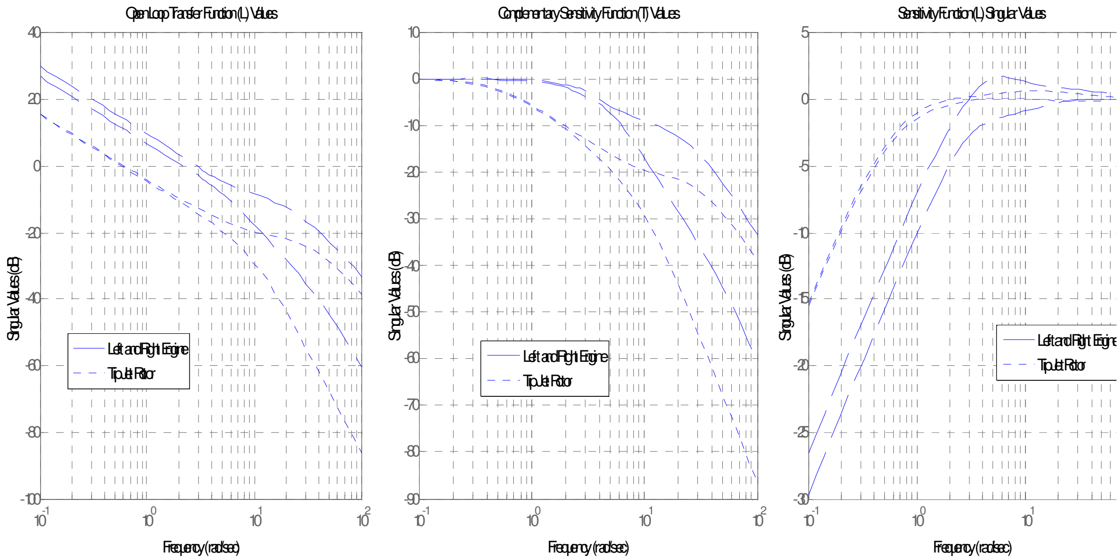

Figure 5. Singular Value Plots Versus Frequency

From analysis of these plots, the control system gains have been sized appropriately to meet desired response targets. The next step is to analyze the sized control on the actual tip-jet reaction drive system to analyze the feasibility of the PI controller. If there are significant undesired responses, the PI control may have to either be resized or a different controller may need to be analyzed.

C. Transient Simulations

As the rotor load demand on the tip-jet reaction drive system changes, at a given constant rotor speed, the load on the rotor can be manipulated by changing either the mass flow or the velocity through the tip-jet exhaust nozzle. The velocity can be changed by adjusting the tip-jet fuel flow and exhaust nozzle area. Mass flow can primarily be adjusted by changing the operating points of the two engines supplying air to the tip-jet nozzles. The two transients that will be analyzed are rotor load change with and without changing engine demand settings.

1. Rotor load change without changing engine demand settings

Figure 6 below shows the response of the tip-jet reaction drive system to rotor load change controlled by keeping engine settings constants. Given a 10% reduction in rotor demand, the tip-jet rotor takes approximately 12 seconds to settle to a new steady-state operating point. In this transient, tip-jet fuel flow and exhaust nozzle area are decreased to maintain tip-jet shaft speed and supply pressure while the interactions of the reaction drive subsystem and the engines are minimal.

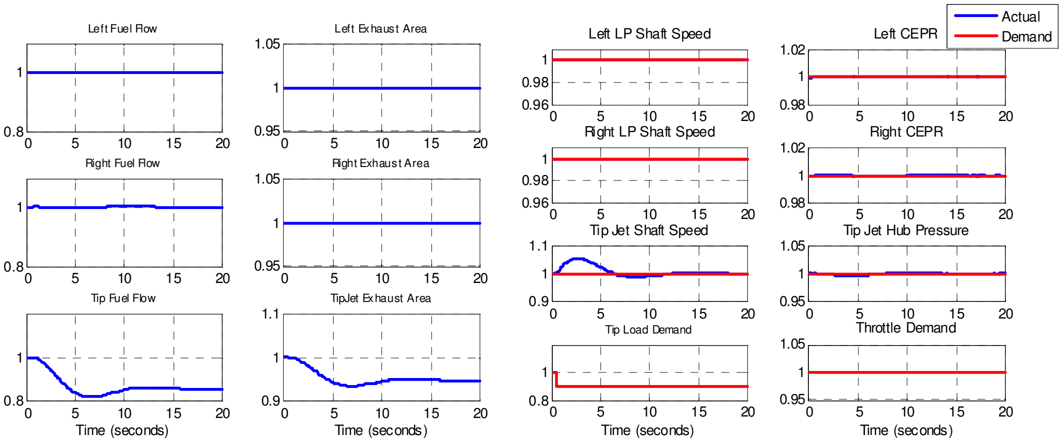

Figure 6. Rotor Load Change Response: a.) Control Inputs b.) Measured and Demanded Outputs

2. Rotor load change with changing engine demands

Figure 7 below shows the response of the tip-jet reaction drive system to rotor load change controlled by varying the engine settings. The CEPR and tip-jet pressure are scheduled to maintain the stall margin in the engines as the engine speed target is varied. The LP shaft takes about 12 seconds to settle, however the overshoot from the prior run in less noticeable. There appear to be minimal oscillations in the plots of CEPR and hub pressure.

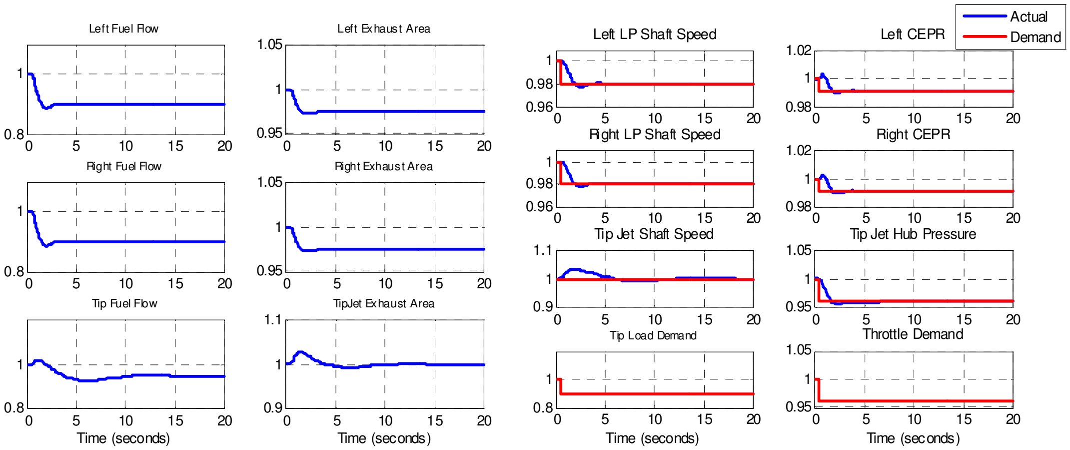

Figure 7. Rotor Load and Engine Speed Demand Change Response: a.) Control Inputs b.) Measured and Demanded Outputs

From a response time and interaction perspective, there appears to be minimal difference between the two control schemes. In addition, use of engine demands does offer the benefits of reducing the amount of tip-jet fuel flow required when increased loads are present. This may be very advantageous in reducing both the fuel consumptions and the noise of the tip-jet system. It was noted during these experiments that as the eigenvalues of tip-jet rotor shaft approached that of the engine shafts, the interactions present using the later scheme became much more noticeable resulting in a much different tip-jet rotor speed response time when compared with the former scheme.

V. Conclusion

From the analysis of the transients above a simple distributed PI control for use on the tip-jet reaction drive system is a feasible option. Two different control schemes to control rotor load demand changes were analyzed. The first controlled load by keeping engine demands constant and rejecting the load primarily with the tip-jet fuel and exhaust area actuators. This scheme rejected the load quickly with minimal interactions between the reaction drive and engine subsystems. The second scheme controlled the load with both adjusted engine demands and tip-jet fuel and exhaust area actuators. This scheme also rejected the load quickly with minimal interactions between the reaction drive and engine subsystems. Additionally, use of engine demands does offer the benefits of reducing the amount of tip-jet fuel flow required when increased loads are present. This may be very advantageous in reducing both the fuel consumptions and the noise of the tip-jet system. Either scheme is shown to be feasible, offering different benefits depending on the metrics of most importance such as response time, fuel consumption, or noise.

One limitation of the PI control is the fairly large variation of the unmeasured performance or life related variables over life of the system. Certain variables such turbine and tip-jet temperatures increase and stall margins tend to decrease. Also, the amount of thrust the engine may decrease too. Given this fact, the steady state performance may be margined to ensure the hot gas components are not operated at conditions that would adversely affect the life of the system. The transient response of the system may also be affected. This would result in potentially bigger hardware or suboptimal performance. This is one area in which model based control can offer significant benefits[22]. Potential further areas for analysis of control of a tip-jet reaction drive system would be the use of robust or model based control. Use of model based methods such as performance seeking control or model predictive control may result in a a.) more optimal steady-state performance b.) more robust/safe transient performance.

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