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Full Envelope Flight Control System Design Using Qualitative Feedback Theory

Odell R. Reynolds,* M. Pachter† and C. H. Houpis†
U.S. Air Force Institute of Technology, Wright–Patterson Air Force Base, Ohio 45433-7655

A controlled plant's characteristics can vary widely throughout its operational envelope. This is a major problem in nominal plant-based control system design. Hence, gain scheduling is often used for full envelope design. In this paper, it is proposed to address the plant's variability using robust control design concepts, minimizing the need for gain scheduling. In particular, the frequency-domain-based quantitative feedback theory multiple input multiple output robust controls design method is employed for the synthesis of a full envelope flight control system for an F-16 aircraft derivative. Qualitative feedback theory addresses structured uncertainty that is caused by full envelope operation. Thus, qualitative feedback theory robust control is particularly suited for full envelope controller design. Compensators and prefilters for the aircraft's pitch and lateral/directional channels are designed to meet level 1 flying qualities specifications, and these designs are validated using simulations.

Nomenclature

p = roll rate
q = pitch rate
r = yaw rate
T_R = roll mode time constant
T_S = spiral mode time constant
u = air speed
α = angle of attack
β = sideslip angle
δ_a = aileron deflection
δ_{dt} = differential tail deflection
δ_e = elevator deflection
δ_f = flaperon deflection
δ_r = rudder deflection
$\delta_{\rm rud}$ = pilot lateral input
$\delta_{\rm stk}$ = pilot longitudinal input
ζ_d = Dutch roll mode damping
θ = pitch angle
τ_{ep} = roll rate time delay
ϕ = bank angle
ω_d = Dutch roll mode natural frequency

I. Introduction

IN the quest for air superiority, aircraft designers have expanded the operational envelopes of modern fighter aircraft. An expanded operational envelope yields significant plant variability that can be treated as structured plant uncertainty in control system design. The requirement of uniformly good control performance in the complete operational envelope, therefore, mandates compensator or controller designs that can accommodate a high degree of plant variability. The conventional approach to flight control system (FCS) design entails gain scheduling, where the controller's parameters are adapted to the plant that models the aircraft's dynamics at the current operating point (flight condition) in the flight envelope.

In robust control work, it is desired that a single fixed compensator and prefilter be designed that can handle a high degree of plant variability about a nominal known plant. The objective of this paper is to investigate the feasibility of a full envelope flight control system design using fixed robust compensation to yield uniformly acceptable flying qualities, obviating the need for gain scheduling. The quantitative feedback theory (QFT) robust control design technique[1,2] is employed to design a FCS for the full subsonic envelope of a F-16 derivative. QFT addresses structured uncertainty in a straightforward and graphical manner, making it very amenable to full envelope flight control design. A complete description of this work is contained in Ref. 3, a summary is contained in Ref. 4, and related flight control work using the linear quadratic regulator controls design technique is reported on in Ref. 5.

The paper is organized as follows. The next section discusses modeling issues. The section after that discusses the control specifications that this design is attempting to meet and their connection to flying qualities requirements. QFT is briefly outlined in Sec. IV. Then Sec. V elaborates on the longitudinal flight control system design process, and in Sec. VI, the lateral directional flight control system is discussed. Section VII discusses the results of the design, and the conclusions are contained in the last section.

II. Modeling

The equations of motion of an aircraft in flight are nonlinear. Therefore, to design a FCS using conventional linear compensator design methods, one must develop a set of linearized models that describe the aircraft's dynamics about a set of equilibrium points (flight conditions). The nonlinear simulation/rapid-prototyping facility (SRF)[6] is used to extract these linearized models for an F-16 aircraft derivative. The SRF input settings for the design undertaken in this paper are confined to trimmed, straight, and level flight, with wings empty, landing gear up, and wingtip air intercept missile (AIM-9L) stores. The SRF accepts a given flight condition and outputs A and B matrices for use in the linear, time-invariant equations of motion $\dot{x} = Ax + Bu$, $x(0) = 0$ where the state vector $x = [\theta \ u \ \alpha \ q \ \phi \ \beta \ p \ r]^T$ and the input $u = [\delta_e \ \delta_{dt} \ \delta_f \ \delta_a \ \delta_r]^T$. The coupling terms between the longitudinal and lateral/directional variables in the system matrices output by the SRF are always zero. This enables the FCS design to be decomposed into separate longitudinal and lateral/directional designs, but the plant models representing flight conditions close to stall at the extreme left edge of the envelope are less valid and are not considered in this work. Shown in Fig. 1 are the 40 representative flight conditions that are chosen around the subsonic flight envelope. Finally, fourth-order actuator models are used in this work.

III. Specifications

Military standards[7] are used to define the level 1 flying qualities specifications. The specifications are given in both a time- and a frequency-domain format. The longitudinal channel time-domain specifications are based on the pitch rate response to a step input command calculated from the two-degree-of-freedom model that

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*First Lieutenant, U.S. Air Force, Department of Electrical and Computer Engineering, 2950 P Street.

†Professor, Department of Electrical and Computer Engineering, 2950 P Street.

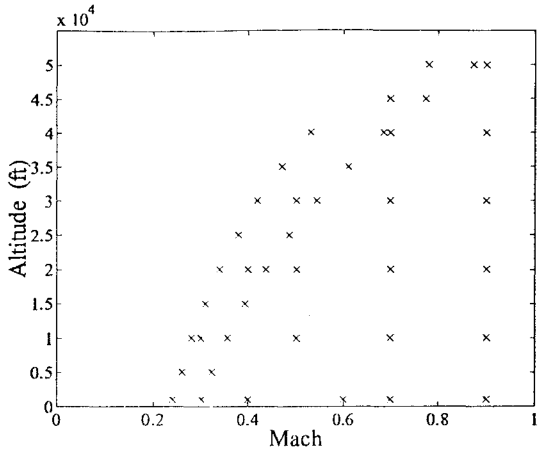

Fig. 1 Control system design envelope.

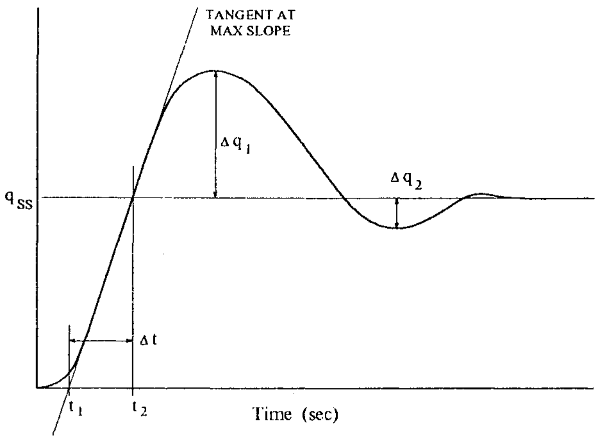

Fig. 2 Second-order q response to a step.

is determined by constraining the speed ($\dot{u} = 0$). Mathematically, this is accomplished by taking the short period approximation of the fourth-order aircraft model. The time-domain specifications are based on two straight lines drawn on the q response (Fig. 2). To meet level 1 flying qualities, the equivalent time delay t_1 must be less than 0.12 s, the transient peak ratio ($\Delta q_2/\Delta q_1$) less than 0.30, and the effective rise time ($\Delta t = t_2 - t_1$) between $9/V_T$ and $500/V_T$ s, where V_T is the true airspeed (feet per second).

For the lateral/directional channel, the flying qualities specifications are based on simultaneously matching the Bode plots of the final system to those of the equivalent fourth-order transfer functions given by

$$\frac{\phi(s)}{\delta_{\text{stk}}(s)} = \frac{K_\phi\left(s^2 + 2\zeta_\phi\omega_\phi s + \omega_\phi^2\right)\exp(-\tau_{ep}s)}{(s + 1/T_R)(s + 1/T_S)\left(s^2 + 2\zeta_d\omega_d s + \omega_d^2\right)} \tag{1}$$

$$\frac{\beta(s)}{\delta_{\text{rud}}(s)} = \frac{\left(A_3s^3 + A_2s^2 + A_1s + A_0\right)\exp(-\tau_{e\beta}s)}{(s + 1/T_R)(s + 1/T_S)\left(s^2 + 2\zeta_d\omega_d s + \omega_d^2\right)} \tag{2}$$

To meet level 1 flying qualities, the roll mode time constant must be less than 1.0 s, the Dutch roll mode damping greater than 0.40, the Dutch roll mode natural frequency greater than 1 rad/s, the roll rate time delay less than 0.1 s, and the time to double of the spiral mode $[-\ln(2)(T_S)]$ greater than 12 s. Disturbance rejection specifications in the lateral/directional channel are based either on control surface usage or are variable throughout the flight envelope. This variation prevents the use of disturbance bounds in the QFT design in either channel.

In addition, the open-loop phase margin angle of both the longitudinal and lateral/directional designs must be greater than 30 deg, and the open-loop gain margin must be greater than 6 dB (Ref. 5). To determine phase and gain margins, the open-loop transmissions from the stick inputs to the required outputs in each loop are examined. Finally, the phase margin frequency (cutoff frequency) should be less than 30 rad/s to prevent deleterious interaction with the bending modes of the aircraft.

The cross-coupling disturbance bounds are not given in a quantitative fashion for all of the plants. One requirement is that a sustained 10-deg sideslip will use less than 75% of the available roll axis power (aileron). There is also a complicated specification for the amount of sideslip angle allowed for a particular roll angle. If one simplifies the requirements in a conservative fashion over the majority of the flight envelope, a roll command of 1 deg should result in less than 0.022 deg of sideslip angle, but at low speeds the sideslip angle is allowed to increase to 0.067 deg. The maximum sideslip angle allowed in any roll maneuver is 6 deg. These disturbance requirements are not implemented in the design process but are examined afterwards to ensure specification compliance.

In this case, a robust set of specifications is not available because the flying qualities are flight condition dependent throughout the flight envelope. The lack of uniform performance bounds over the entire flight envelope illustrates a shortcoming of the current robust control paradigms.

IV. QFT Overview

QFT is a robust control design technique that uses feedback of measurable plant outputs to elicit an acceptable response from a system in the face of quantified, structured plant modeling uncertainty and disturbance signals (as caused by full envelope operation). It is an engineering robust control system design technique developed by Horowitz in the early 1970s, and modifications and improvements continue to be made today.[1,8]

QFT uses unity feedback, a cascade compensator, and a prefilter to reduce the variation of the plant output due to plant parameter variations and disturbances. QFT naturally takes into account quantitative information on the plant's variability, the robust performance requirements, and the disturbance amplitude and attenuation requirements.[2] The cascade compensator is designed to ensure that the robustness and disturbance rejection requirements can be met, and the prefilter is then used to tailor the response to meet the control specification requirements.

QFT is a transparent frequency-domain design technique in that tradeoffs between compensator complexity and performance are readily visualized as structured uncertainty is addressed. Structured plant uncertainty is embodied in a set of two-dimensional magnitude-phase templates that correspond to a set of fixed frequencies. The stability bounds are calculated using these templates and the phase margin. The performance bounds are derived using the templates and upper and lower limits on the frequency-domain response. The disturbance bounds are based on the templates and an upper limit only. The loop shaping is done on the Nichols chart that naturally displays the phase and gain margins, stability bounds, performance bounds, and disturbance rejection bounds. The disturbance rejection and tracking action of the compensator is based on keeping the loop's transmissivity above the disturbance and tracking bounds on the Nichols chart. Thus, a curve fitting problem in a two-dimensional plane needs to be solved by loop shaping. During the loop shaping process, modifying the poles and zeros of the compensator produces immediately visible results, enabling the designer to choose between compensator complexity (order) and system performance.[1,9]

A limitation of QFT is that the final design only guarantees the performance of the feedback variable. If some of the specifications are based on a different variable, then one can use QFT only to design for the specifications based on the feedback variable. Additionally, both upper and lower frequency-domain limits must be present to derive the tracking bounds. If they are not, one can either artificially choose them, or design for as much robustness as possible, and then validate the results using an iterative prefilter design method.

Finally, multi-input/multi-output (MIMO) systems are decomposed into their multi-input/single-output (MISO) counterparts, where the coupling between the channels is treated in the same manner as a disturbance that needs to be rejected.[1,2] Thus, the control system is converted into a set of linear time invariant (LTI) MISO plants that are controlled using a QFT designed controller. Hence, a beneficial byproduct of MIMO QFT design is the ensuing approximate decoupling of the closed-loop robust control system—a most desirable state of affairs. Fortunately, an efficient MIMO QFT CAD package has been developed at the U.S. Air Force Institute of Technology that greatly facilitates the QFT design process.[8]

V. Longitudinal FCS

For the longitudinal channel FCS design, the flight envelope is partitioned into two regions: those flight conditions with dynamic pressure ($\bar{q}$) below 130 psf and those with $\bar{q}$ above 130 psf. In the low $\bar{q}$ region, angle of attack α is controlled, and in the high $\bar{q}$ region, normal acceleration N_z at the pilot station is controlled, making the relevant transfer function minimum phase. Furthermore, this flight envelope partitioning makes physical sense, because the aircraft is incapable of responding with high N_z at low-dynamic pressure, and the pilot is incapable of distinguishing small variations in N_z. Thus, at low-dynamic pressures, the pilot flies (commands) angle of attack, and at high-dynamic pressures, the pilot commands normal acceleration. This partition is not a limitation of the QFT design method but, rather, is in conformity with flying qualities requirements.

A. QFT Innovation

In conventional, nominal-plant-based flight controls design work, successive loop closures are routinely performed. An innovation in this work entails two successive loop closures that are robustly performed using QFT. In the first part of the longitudinal design, QFT is used to close an inner loop, with the fast variable, pitch rate, as the feedback variable, for robust stabilization. These robustly stable new closed-loop plants are used in an additional outer-loop QFT design, with normal acceleration, pitch rate, and angle of attack fed back, to robustly achieve the control performance specifications. The reduction in uncertainty afforded by the inner-loop robust QFT compensator causes a considerable reduction in outer-loop uncertainty, affording a full envelope robust compensator design to be accomplished. This approach is also physically motivated, and it is in line with standard FCS design practice. The two-loop longitudinal FCS design concept is illustrated in Fig. 3. In this figure, A/C + Act is the aircraft and actuators, Gq is the inner-loop compensator designed in this section, and Gnz and F_n would be the outer-loop compensator and prefilter designed in the next section.

The desired goal of the inner-loop compensator design is to robustly stabilize all of the plants. Integral action is added for disturbance rejection. Input disturbances are endemic in full envelope flight control due to the unavoidable change in trim elevator setting as the aircraft moves from one flight condition to the next. This change in trim setting is equivalent to a plant input disturbance. Indeed, some effort went into modeling the trim change disturbance's amplitude and frequency through an examination of the elevator trim settings around the envelope. Automatic retrimming that would be imperceptible to the pilot translates into a single 30-dB QFT disturbance rejection bound that needs to be met. The frequency for this bound is chosen as 0.16 rad/s, and is based on a heuristic estimation of the aircraft's speed of movement from flight condition to flight condition. Hence, the QFT disturbance rejection requirement is quantitatively established.

The final QFT loop shaping is shown in Fig. 4. The nominal loop transmission is shown as a solid line with relevant frequencies marked. The stability and disturbance bounds are denoted by ($\cdot$)S and ($\cdot$)D, respectively. The stability bounds are all satisfied and the disturbance bounds are satisfied below 0.16 rad/s. This implies that the low-frequency operating point transition disturbance rejection is satisfied. The designed second-order compensator is successful in reducing the height of the outer-loop templates in half and reducing their width by various amounts throughout the applicable frequency range. The inner-loop compensator is then placed in a cascade with the plant, the feedback loop is closed, and the new augmented plants, with pitch rate command as the input and normal acceleration and pitch rate as outputs, are formed for the outer-loop design.

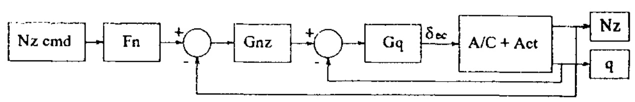

Fig. 3 Dual loop longitudinal FCS concept.

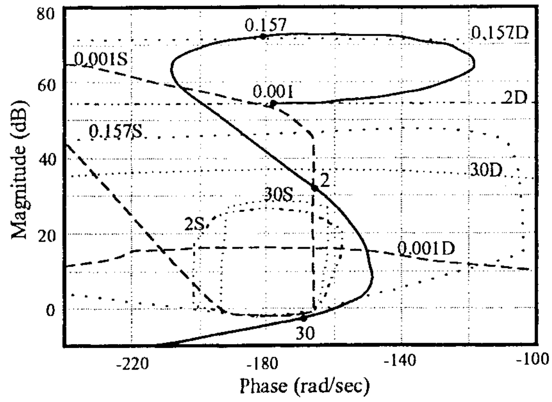

Fig. 4 Longitudinal channel inner-loop shaping.

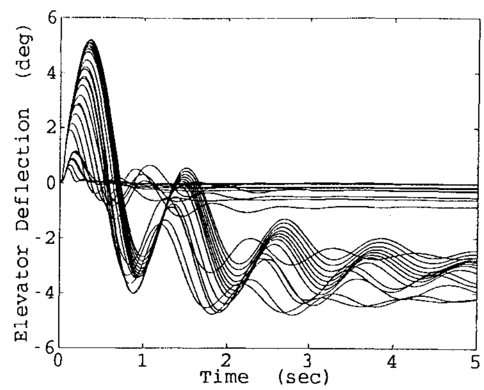

Fig. 5 Elevator response to a 1-g command.

B. Outer-Loop Design

The benefit of the inner-loop design is a reduction in the size of the templates used in the outer-loop design, enabling full envelope flight control with little gain scheduling. The relevant plants now contain the inner stabilization loop, so the outer-loop portion of the longitudinal design is undertaken, with the goal of normal acceleration command tracking.

A potential problem in this design is that the specifications are not based on the controlled variable. A solution to this problem is to add a portion of the specification state to the control variable. Hence, it is decided to mix a portion of the pitch rate into the control variable, which gives QFT some influence over that state. Additionally, handling qualities theory suggests that the pilot does not fly N_z, but rather a combination of N_z and pitch rate called C^*.

Because there are no flying qualities specifications for C^* in Ref. 7, there are no upper or lower response limits, and the QFT design must be performed using only the robust stability bounds that are set to a conservative phase margin of 35 deg to ensure that the required 30 deg is met. Because of the parameter uncertainty reduction afforded by the inner loop, a simple proportional plus integral (PI) compensator is all that is needed to meet the required stability bounds. The cutoff frequency specification is only violated for one flight condition (1000 ft, Mach 0.9) and it is still below 40 rad/s.

The compensator designed was successful in reducing the uncertainty enough that the final C^* time-domain responses all fit into a very small envelope. It was still desired, however, to obtain a good N_z response. Because there are no tracking bounds, the prefilter is interactively designed by examining the time responses. A slight oscillation in a couple of high-speed N_z responses is eliminated by scheduling the prefilter at a dynamic pressure of 400 psf. This design meets level 1 flying qualities for the pitch rate, but the N_z tracking is not perfect. This is due to the choice of a control variable, which is not purely N_z. The final N_z values, however, are close for the high-speed plants (Fig. 7), and the C^* response has perfect tracking, so the design is considered successful.

Another issue addressed in the prefilter design was the elevator time responses that contain a saturation in both rate and deflection.

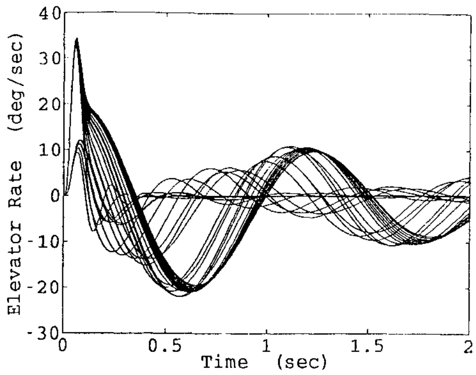

Fig. 6 Elevator rate response to a 1-*g* command.

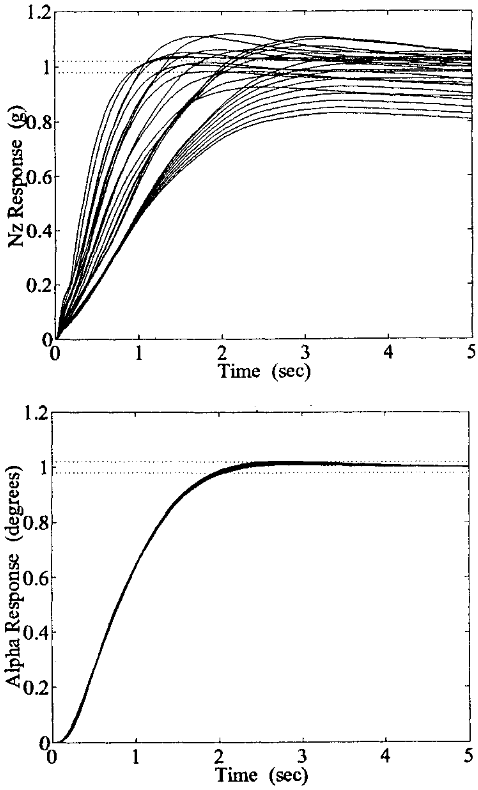

Fig. 7 Time responses for the longitudinal channel.

Both were examined in relation to the maximum normal acceleration that can be commanded at each flight condition throughout the envelope. Prefilter time constants were chosen to minimize the possibility of rate or deflection saturations. The maximum deflection allowed is 20 deg, and the maximum rate is 60 deg/s. The final elevator deflections and rates for a 1-g N_z command are shown in Figs. 5 and 6. As can be seen, there is plenty of elevator deflection authority available for higher g maneuvers. The bottleneck is the elevator rate. Only one additional g is available at many flight conditions, but these also correspond to the low $\bar{q}$ plants. More authority is available at the high $\bar{q}$ plants, as required. One cause of the high initial elevator rates is the step command used. A pilot, however, is not capable of inputting a pure step command; there is an inherent delay. However small, this will decrease the initial rates, but the only way to be certain the control system will work is through simulations with a paper pilot in the loop.

Hence, precluding actuator saturation is of paramount importance in high gain-prone robust control of an open-loop unstable plant; as is the case in the F-16 A/C derivative in this paper. The main concern here is not just the obvious actuator saturation-induced FCS performance degradation, but rather the saturation-induced opening of the innermost feedback loop, by virtue of the actuator being strategically located at the plant's input. In this case, opening the feedback stabilization loop will cause catastrophic consequences because the open-loop plant is unstable and feedback is used for stabilization. Hence, actuator rate saturation caps the achievable robustness benefits of feedback.

Because of the small template size in the low $\bar{q}$ portion of the design, the inclusion of the specification state was not necessary. Once again, lack of tracking bounds requires designing for maximum robustness only. The result is an exceptionally small time-response envelope (Fig. 7), which easily enables iterative prefilter design to obtain level 1 flying qualities.

The final flight control system is shown in Fig. 8. The block labeled Gq is the inner loop compensator designed in the previous section. Gc is the outer compensator for the C^* variable. Ga and Fa are the outer-loop compensator and prefilter for the alpha control variable.

VI. Lateral Directional FCS

There are three control signals available for the lateral/directional FCS channel, but the standard F-16 coupling of the differential tail and aileron commands is used. This creates a 2 × 2 MIMO plant, where the primary inputs are generalized aileron and rudder deflections, and the controlled outputs are stability axis roll rate and sideslip angle. If a roll is commanded, yaw rate is required to produce a coordinated turn, whereas sideslip angle is not desired. Although yaw rate is a faster variable, sideslip angle is the controlled variable

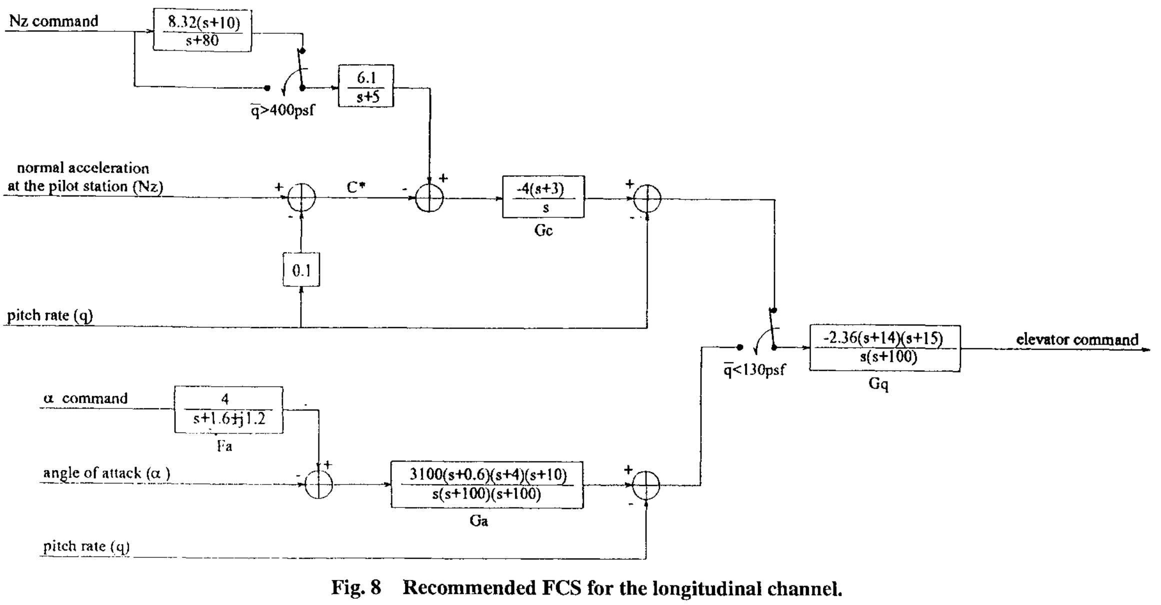

Fig. 8 Recommended FCS for the longitudinal channel.

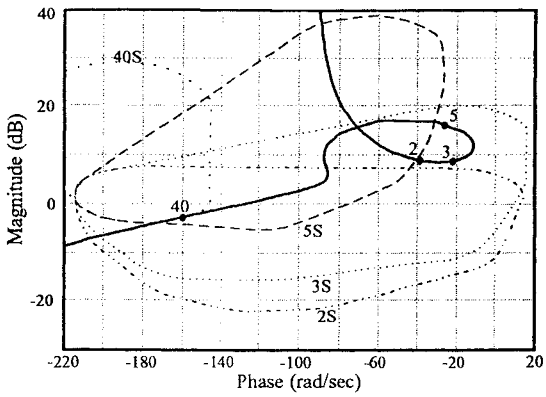

Fig. 9 Initial lateral channel (2, 2) loop shaping.

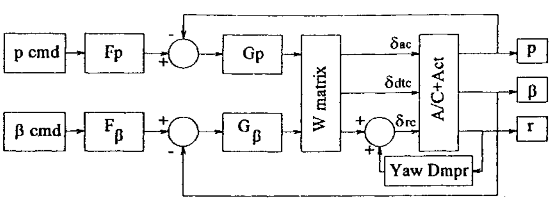

Fig. 10 Lateral directional flight control system.

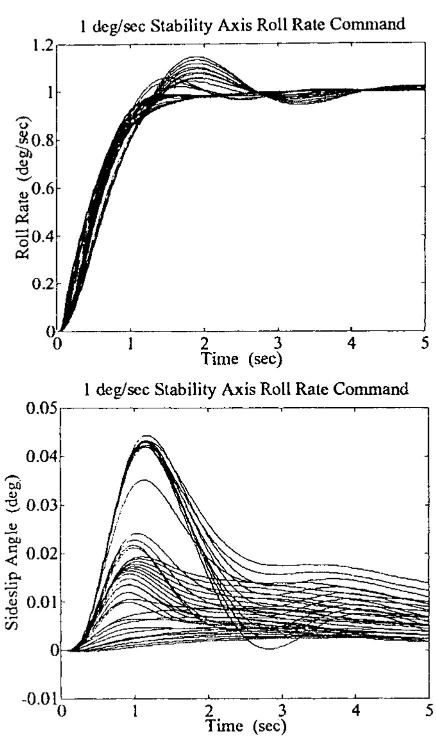

Fig. 11 Time response for (1,1) channel.

of choice because QFT is designed to work by minimizing cross coupling between the two commands as required.

Because there are no robust quantitative upper bounds in any of the channels, it is decided to design each of the channels for stability bounds only. This design method ensures the highest cross coupling rejection and robustness while still meeting the 30-deg phase margin angle and 6-dB gain margin requirements. To insure that the required 30 deg is met, slightly conservative stability bounds corresponding to 35 deg are used in each of the diagonal channels. Method 1 (Ref. 1) of the MIMO QFT design process is used because the q_{ii} (Ref. 1) were minimum phase, and method 1 keeps the system bandwidth to a minimum.

A. Design of a Robust Yaw Damper (Washout Filter)

The extremely wide templates in the (2,2) channel (sideslip command to sideslip) indicated that there could be a problem designing a robust compensator for this channel. Indeed, a third-order compensator did not provide enough lead to the system to meet the stability bounds as shown in the loop shaping of Fig. 9. Another 60 deg of lead is required to bring the nominal loop outside the 3 rad/s stability bound (3S), and adding gain to move the loop above the bounds would require violating the 30-rad/s cutoff frequency, whereas lowering the gain to move the loop below the bounds would eliminate much of the robustness. Hence, similar to the pitch channel design concept, an inner-loop yaw damper that includes a washout filter in the feedback path is designed to reduce the size of the outer-loop templates and allow a design to be accomplished. This procedure is not out of step with conventional FCS design procedures.[10]

The underdamped nature of the Dutch roll mode creates very large templates at those frequencies, preventing a successful design with all of the plants. This would normally indicate that multiple compensators need to be designed, but here QFT is once again used to design an inner-loop compensator to robustly decrease the plant variation in the outer-loop design. Because the goal of this yaw damper is to increase the damping of the Dutch roll mode, the closed-loop poles are of primary interest, whereas the zeros are of no concern because they remain unchanged for the final design. This aspect of the design allows the use of QFT, because although the damper is placed in the feedback path and not in cascade, the QFT design method is still valid because it uses the open-loop transmissions, which are the same irregardless of feedback or cascade design.

The fastest variable (yaw rate) is chosen as the feedback variable to the rudder command. Stability bounds of 60 deg are chosen to introduce as much robust damping to the system as possible. A differentiator is added to the feedback compensator because the purpose of the yaw damper is to eliminate the fast transient oscillations while allowing for acceptable slow pilot control authority.[10] In flight control parlance, a robust washout filter is designed. The yaw damper is then added to the bare aircraft model, the loop is closed, and new plants and templates are formed for the outer-loop design stage.

B. Outer Loop Design

The standard aileron-differential tail interconnect (W) is used when the outer-loop plants are constructed with the yaw damper

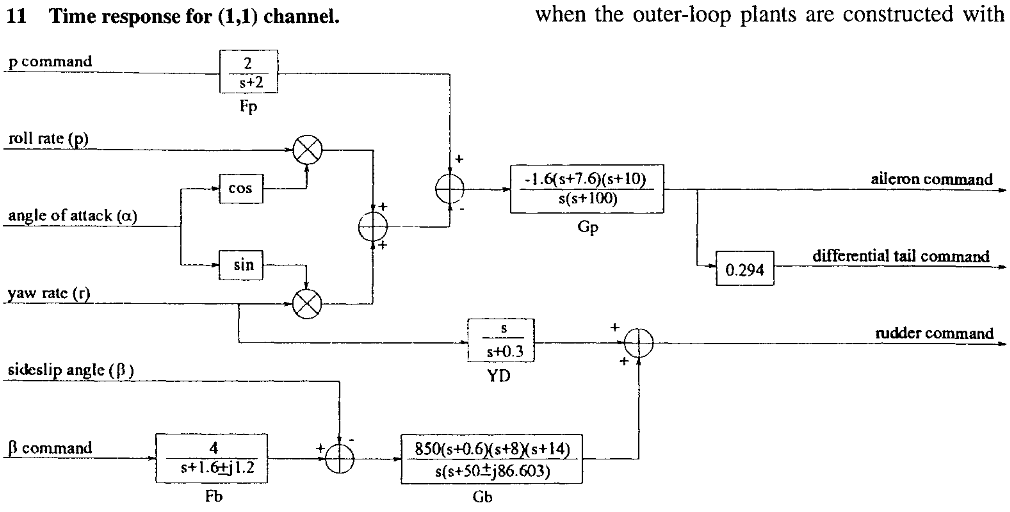

Fig. 12 Recommended FCS for the lateral channel.

in place. Second-order compensators are then designed to meet the stability bounds and the 30-rad/s cutoff frequency in each channel. Figure 10 shows the final lateral/directional control concept. F_β and G_β are the prefilter and compensator for the (2, 2) channel, and Fp and Gp are the prefilter and compensator for the (1, 1) channel.

As in the longitudinal design, the lack of both robust upper and lower bounds necessitates iterative design of the prefilter. The prefilter time constants were adjusted iteratively using the Bode plot matching required by Ref. 7. The matching was very sensitive to the prefilter time constants, and slight variations in the time constants produced identical time responses but significantly different poles and zeros. This is probably because two fourth-order transfer functions need to be matched simultaneously, and many different combinations of poles and zeros can produce similar Bode plots in specified ranges. The time responses for a 1-deg/s roll rate command are shown in Fig. 11. The cross-coupling rejection can easily be seen here and is similar in the other channel.

The final flight control system is shown in Fig. 12. The (1,1) compensator and prefilter are Gp and Fp, the (2,2) compensator and prefilter are Gb and Fb, and the inner loop yaw damper is denoted YD.

VII. Results

For each of the flight conditions shown in Fig. 1, the pitch rate response of the short period approximation is obtained and evaluated as in Fig. 2 for the longitudinal channel. In the lateral/directional channel, the final system Bode plots are matched to the models given in Eqs. (1) and (2). As specified in Ref. 7, these Bode plots are matched in the 0.1–10-rad/s frequency range.

In the longitudinal channel, the equivalent time delay, effective rise time, and transient peak ratio are all within level 1 flying qualities specifications as shown in Fig. 13. The gain margin and phase margin requirements are met as well. The only difficulty is the one flight condition that did not meet the cutoff frequency requirement, but it was still below 40 rad/s, which is close to specifications. This is the same flight condition that the inner-loop compensator was unsuccessful in stabilizing. It was known early in the design process that this plant may cause difficulties, because it is isolated on a corner of the

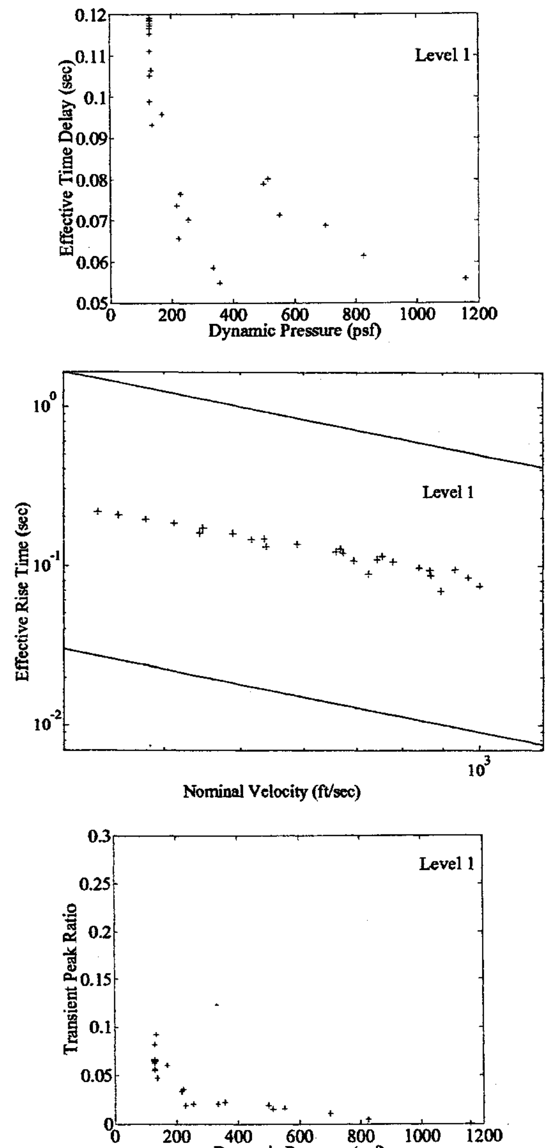

Fig. 13 Time-domain specification results for the C^* design.

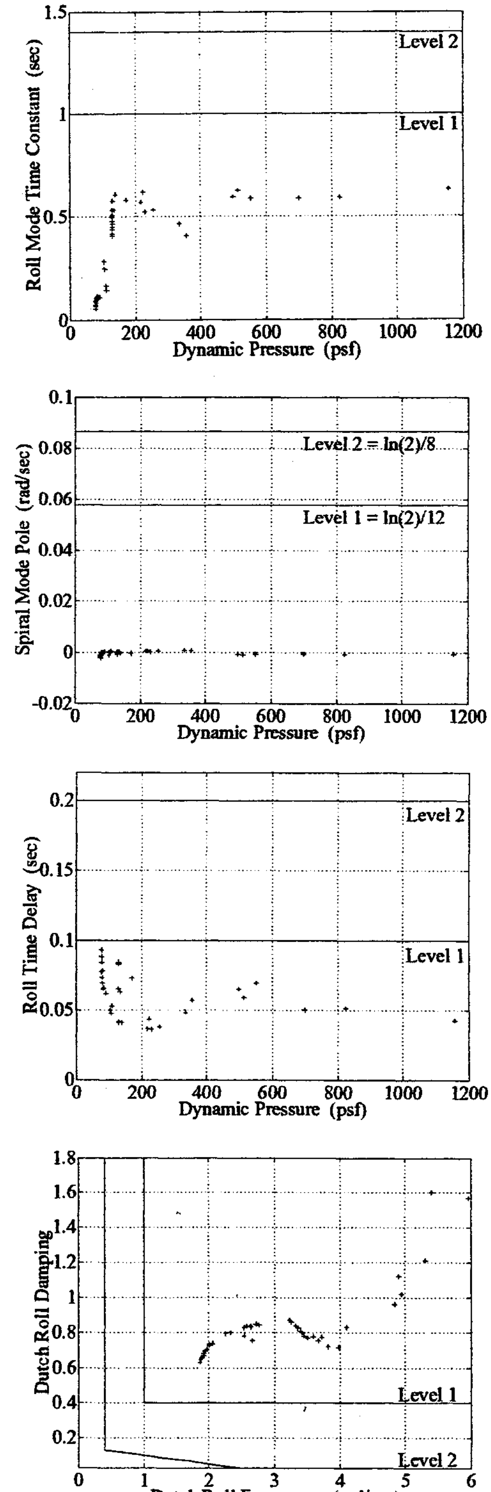

Fig. 14 Graphical interpretation of lower order Bode plot matching.

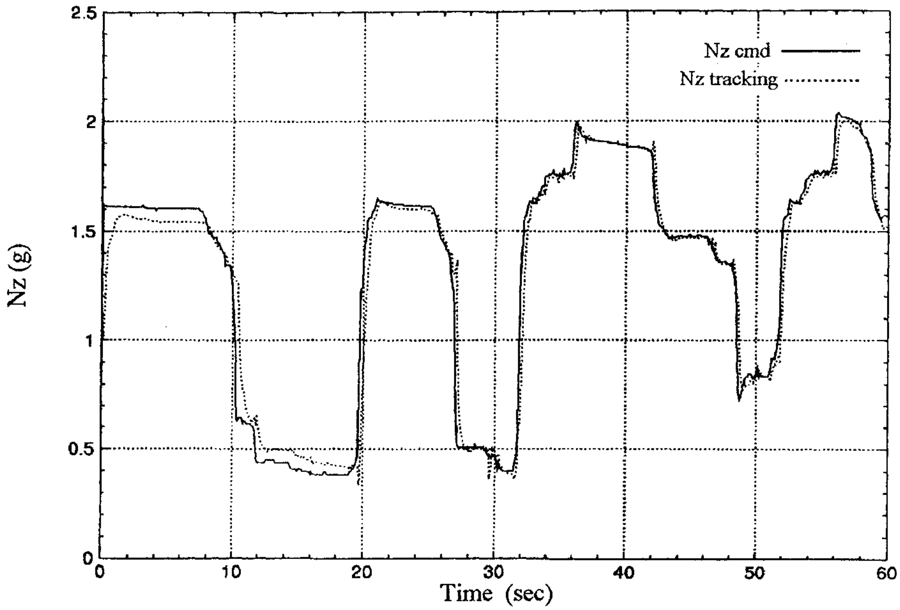

Fig. 15 Nonlinear simulation, pitch maneuver.

longitudinal templates. It is probably grouped more closely with the transonic flight conditions, which are not included in this work. The limited success of the present controller with this flight condition coupled with its position in the QFT template, indicates that perhaps gain scheduling is required in this region of the flight envelope.

For the lateral/directional channel, the equivalent time delay, roll mode time constant, and Dutch roll natural frequency and damping are all within level 1 flying qualities specifications as shown in Fig. 14. In addition, all of the spiral mode time constants were stable, meeting level 1 flying qualities requirements. The two loop shaping efforts produced loops with greater than 40-deg phase margins and 6-dB gain margins, and it is assumed that the overall 30-deg phase margin and 6-dB gain margin is met.

Finally, a full nonlinear simulation was performed with the given controller at 10,000 ft, Mach 0.9. The pitch channel results are given in Fig. 15.

VIII. Conclusions

In this paper, the process of full envelope flight control design is addressed from an engineering point of view. Robust QFT control methods that directly address parametric uncertainty or parameter variation were employed for full envelope control, minimizing the need for point designs and gain scheduling. The lack of robust specifications, coupled with the difference between the control variable and the specification variable, allowed the use of QFT to design for maximum robustness only. Iterative prefilter design was then used to obtain level 1 flying qualities. The graphical QFT templates were especially useful, however, in pointing out potential difficulties in the design process. A special effort has been made to marry the QFT design method to full envelope FCS design work, where elaborate military specifications on flying qualities need to be met. Hence, the QFT robust control design method has been employed in innovative ways but that are still in line with conventional flight control system design methods based on successive loop closures. Additionally, attention has been given to the actuator saturation problems present in robust control design. A full envelope flight control system for an F-16 derivative, with flying qualities that meet Ref. 7 standards has been designed.

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