RECENT TILT ROTOR FLIGHT CONTROL LAW INNOVATIONS

Dwayne F. Kimball
Senior Engineer, V-22 Handling Qualities
Bell Helicopter Textron Inc., Fort Worth, Texas

Abstract

This paper describes three distinct control law functions recently developed in conjunction with full-scale development of the Bell-Boeing V-22 "Osprey" tilt rotor. Two of these are designed to improve the speed response of the aircraft. The first quickens thrust response to power lever inputs by varying proprotor RPM through a governor feedforward circuit. The second gives the power lever direct control of an aerodynamic brake formed by the aircraft's flaperon control surfaces. The third control law function, a model follower concept for mast torque control, protects against drive system overtorque and reduces thrust axis workload in all flight modes. The paper discusses the handling qualities of the aircraft that prompted the development of these functions, and the improvements resulting from each as determined by analysis and flight simulation.

Notation

K	Control system gain
HQR	Handling qualities rating
I_p	Proprotor and drive system inertia
n_x	Acceleration along (horizontal) flight path, g's
Mn	Mach number
Q	Mast torque
Q_c	Commanded torque, from torque command/limiting system
Q_{θ_C}	Rotor aerodynamic derivative: torque with collective pitch
Q_{Ω}	Rotor aerodynamic derivative: torque with angular speed
RPM	Proprotor revolutions per minute
s	Laplace operator
T	Proprotor thrust
T_{θ_c}	Rotor aerodynamic derivative: thrust with collective pitch
T_{Ω}	Rotor aerodynamic derivative: thrust with angular speed
u_G	Gust velocity along (horizontal) flight path
δ_f	Flaperon deflection angle: positive, trailing edge down
ε	Error between commanded mast torque and measured mast torque
ζ	Damping ratio
η_T	Transmission efficiency
θ_{TH}	Engine throttle command
θ_c	Collective blade pitch
σ	Standard deviation
τ	Time constant, seconds
ϕ	Phase lag
Ω	Proprotor angular speed
ω_G	Gust frequency
$\omega_{n_{G\text{-}P}}$	Natural frequency of governed-proprotor system

Introduction

The development of the tilt rotor from the Bell XV-3 (first flight in 1955) and the Bell XV-15 (first flight in 1977) to the Bell-Boeing V-22 "Osprey" (first flight scheduled for 1988) has been characterized by an increasing level of technological sophistication to match increasingly demanding design requirements. This progression is particularly notable in the areas of flight controls and flying qualities.

The hydraulically boosted, unaugmented, mechanical flight control system of the XV-3 produced a level of flying qualities that was adequate for demonstration of the tilt rotor's feasibility (Ref. 1). The far more advanced XV-15 profited from lessons learned in the XV-3, from flight simulator evaluations, and from advances in flight control technology. The Level 1 handling qualities achieved with a mechanical-hydraulic, artificially augmented flight control system allowed the XV-15 to fulfill its research role in the areas of tilt rotor technology and mission suitability (Ref. 2 & 3).

The V-22 is the first non-experimental application of the tilt rotor concept. Although it generally follows the configuration established and proven by the XV-15, it also incorporates newer technology in key areas in order to meet stringent design requirements for operational capability, reliability, maintainability, and longevity. For example, it has a digital fly-by-wire flight control system (Ref. 4) for high reliability and the attainment of required Level 1 handling qualities as defined by MIL-F-8785C and MIL-F-83300.

An extensive flight simulation program conducted during the V-22 preliminary design phase demonstrated Level 1 handling qualities in a wide range of mission-oriented tasks (Ref. 5 & 6), and highlighted some handling qualities that warranted improvement. Two of these are of particular interest here: precision speed control in airplane mode, and mast torque management in all flight modes. These were areas of less-than-optimum handling qualities for the XV-15 as well, but in that aircraft were not serious concerns, given its experimental mission. The more rigorous operational requirements imposed on the V-22, including frequent formation flight, air-to-air refueling, and VTOL operations and conversions at high gross weights, mandated improvement. This was achieved by the development of the three control law functions described below. The flexibility of the digital fly-by-wire control system encouraged this development by making the incorporation of the control law functions into the aircraft a practical proposition.

Governor Feedforward

The first control law function, governor feedforward, was developed to quicken thrust response in the V-22. This improves precision speed control qualities, which previous testing had shown to be deficient.

Background

Flight tests of the XV-15 presented the first opportunity to evaluate tilt rotor handling qualities in precision formation flight (Fig. 1). Pilots with experience in numerous aircraft types have observed that the XV-15's response to the power lever compares unfavorably with the responses of typical turboprop airplanes of similar size and performance. Long-term acceleration and deceleration responses of the two types are similar, but short-term power lever response in the tilt rotor is relatively sluggish. Because of this, acquiring and maintaining the proper longitudinal separation in formation flight imposes a high workload on the pilot. The discernible lag between power lever control inputs and the resulting change in airspeed made the pilot use considerable power lever control input shaping in order to make precise speed corrections. This is an annoyance rather than a serious concern for the XV-15, because its experimental role does not call for frequent formation flying.

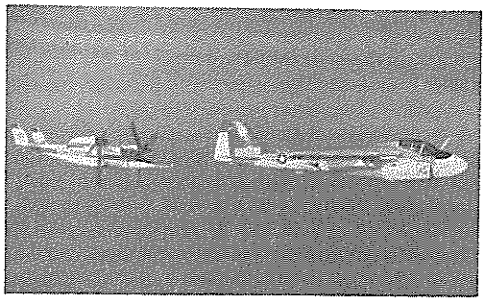

Fig. 1. XV-15 in formation flight

First assessments of V-22 handling qualities in precision formation flight occurred in ground-based flight simulation during preliminary design. Simulated flight in BHTI's fixed-base simulator and at NASA's large-motion VMS brought out the same complaints about speed control that had been voiced for the XV-15: it was difficult to control flight speed precisely because of the lag in response to the power lever. The aircraft received satisfactory ratings for control about the pitch, roll, and yaw axes in formation flight, but an unsatisfactory rating for control along the thrust axis because of high pilot workload. Because the missions of the V-22 require air-to-air refueling and formation flying, this rating was unacceptable. These circumstances led to an investigation of the mechanism of thrust response in the XV-15 and V-22, which have similar thrust/power management systems.

Thrust Response of the Tilt Rotor

Fig. 2 diagrams a simple linear model of the V-22's airplane-mode thrust power/management system coupled to the propulsion system (engines and rotors). The method of control is the same as it is in the XV-15: the power lever commands the engine throttles, and an RPM governor controls the collective blade pitch. In VTOL mode, the power lever is geared to the collective blade pitch; during conversion to airplane mode this gearing phases out as the nacelle tilts forward. When the nacelle is in airplane mode, the power lever does not have a direct effect on blade pitch. This is because in airplane mode Q_{θ_c}, the aerodynamic derivative of torque with respect to collective blade pitch, is very sensitive and velocity dependent (Table 1). The power lever cannot have direct command of blade pitch unless the circuit has a velocity-dependent gain. This is impractical because of the danger of sensor failure and its serious consequences, and therefore blade pitch is controlled through the governor alone in airplane mode.

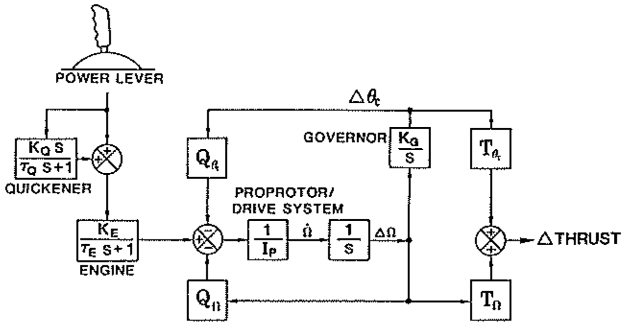

Fig. 2. The tiltrotor thrust mechanism, airplane mode

Table 1. V-22 rotor torque sensitivity to collective pitch.

* Sea-level density altitude

Mode	Airspeed (knots)	Q_{θ_c} (% torque/degree)
VTOL	0	10.0
	80	8.1
Airplane	140	26
	345	111

The V-22 has a "throttle quickener" (described below) added to the power lever command circuit to the engine. With the exception of this quickener, the model shown in Fig. 2 also represents the mechanism of airplane-mode thrust control in the XV-15 and in propeller-driven fixed-wing airplanes with variable blade pitch and RPM governing (all turboprop airplanes). The thrust response characteristics of this system are dictated by two major considerations: the engine response and the governed-proprotor dynamics.

Engine response. The response of the engine to the power lever is approximated by a first-order lag, as in Fig. 2. The addition of a quickener (a high-pass filter) in the throttle command path partially compensates for this engine lag. The effect of the quickener is to improve the frequency response of the engine, within limits. The main improvement is in gain; phasing of power output to power lever input is relatively unchanged by reasonable applications of throttle quickening. The bandwidth of the engine is thus approximately $1/\tau_E$ in any case.

Governed-proprotor dynamics. The characteristic equation of the governed proprotor is a second-order system whose natural freqency may be expressed as

$$\omega_{n_{G\text{-}P}} = \frac{Q_\Omega}{2\zeta I_p}$$

The effect of the large proprotors is to drive down the ratio Q_Ω/I_p, so that the natural frequency of the tilt-rotor's governed proprotor is significantly lower than that of a turboprop airplane's governed-propeller system.

Table 2 compares the response characteristics of the engine, governed proprotor, and total thrust of the XV-15 and V-22 tilt rotors with the estimated characteristics of a light turboprop twin. The bandwidth in this context is that frequency at which the phase of the output, engine power or thrust, lags the power lever by 45 degrees.

Table 2. Propulsion system frequency response characteristics.

- Tilt rotors are in airplane mode
- Sea level density altitude
- 200 kts

Aircraft	Engine bandwidth (rad/sec)	Governed-proprotor natural frequency (rad/sec)	Thrust response to power lever, bandwidth (rad/sec)
XV-15	2.5	4.0	2.0
V-22 (with quickener)	3.5	3.2	2.1
Light Turboprop	3.3	8.4	2.9

For the turboprop, the relatively high natural frequency of its governed-propeller system means that thrust response bandwidth virtually attains the engine response bandwidth. For the tilt rotor aircraft, the relatively low natural frequencies of their governed-proprotor systems limit thrust response bandwidth to values appreciably below those of the engines.

Efforts to improve the thrust response bandwidth in the V-22 resulted in the development of the governor feedforward circuit, an additional control path for the thrust/power management system that alters the initial dynamics of the aircraft's thrust response.

System Description

Fig. 3 shows the governor feedforward circuit added to the basic thrust/power management system. In airplane-mode flight, governor feedforward establishes an indirect connection between the power lever and collective blade pitch via the collective governor. The use of the governor as the link between the power lever and the collective eliminates the need for velocity-dependent collective gearing.

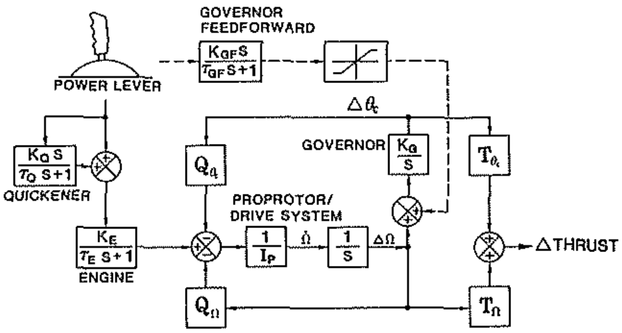

Fig. 3. The governor feedforward circuit

In function, the governor feedforward commands an RPM transient at the governor in response to power lever inputs. The RPM transient is obtained through variation of blade pitch, which in turn varies thrust. Positive power lever inputs command an RPM droop (increased blade pitch); negative power lever inputs command an RPM overspeed (decreased blade pitch). In physical terms, the circuit commands a transient transfer of kinetic energy from the rotating proprotor/drive system to the translating aircraft mass. The efficiency of this energy transfer is equal to the propulsive efficiency of the proprotors. The inertia of the proprotors becomes an asset with this control strategy, because the control system can make substantial variations in the kinetic energy of the proprotor and its drive system through perturbations of reasonable magnitude to the proprotor RPM. In the V-22, the commanded RPM excursions are limited to ±15 RPM (±4.5 % of cruise RPM). Tests have shown that this level of authority produces the necessary improvement in thrust response.

Analysis and Optimization

Fig. 4 shows the effect of the governor feedforward circuit on thrust and RPM response to a step input. These results are for the linear model of Fig. 3, with data for the V-22 at a sea-level trim airspeed of 200 knots. The input is one inch in magnitude, and thrust is shown normalized to its steady-state value, which is the same for all three systems shown. The throttle quickener is responsible for the thrust overshoot in the baseline V-22 response. Results for two values of the governor feedforward time constant, τ_{GF}, are presented. The value for K_{GF} in each case was chosen to yield equal peak RPM excursions. As the figure shows, decreasing τ_{GF} tends to produce a more abrupt thrust peak of shorter duration, due to a decreasing amount of time for the energy interchange between the proprotor/drive system and the aircraft. Because of the appreciable proprotor inertia, the results are achieved with maximum proprotor speed excursions of only ten RPM, or three percent of the V-22 proprotor speed in cruise. This sensitivity, ten RPM per one-inch step input, has been used with good success in the flight simulation evaluations of the system.

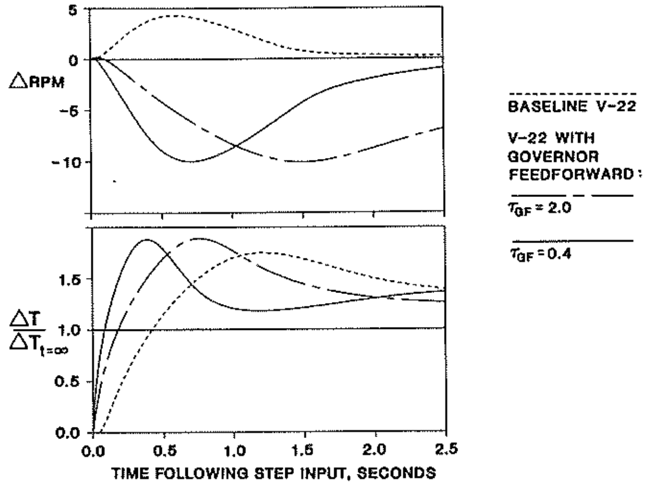

Fig. 4. Thrust and RPM response to a power lever step input

Fig. 5 shows the improvement in the frequency response of thrust to power lever displacement. The estimated response of a light turboprop airplane is also shown for comparison. Conditions are the same as for Fig. 4. The increase in phase bandwidth due to the governor feedforward circuit is impressive: bandwidth is increased from approximately 2 rad/sec for the baseline system to 7 rad/sec with governor feedforward. (Note that this is far superior even to the turboprop response.) The use of the throttle quickener in combination with the governor feedforward circuit prevents an undesirably low gain near the natural frequency of the governed-proprotor system, where rotor speed tends to be phase-shifted 180 degrees from the power lever input. Throttle quickening and governor feedforward are therefore complementary.

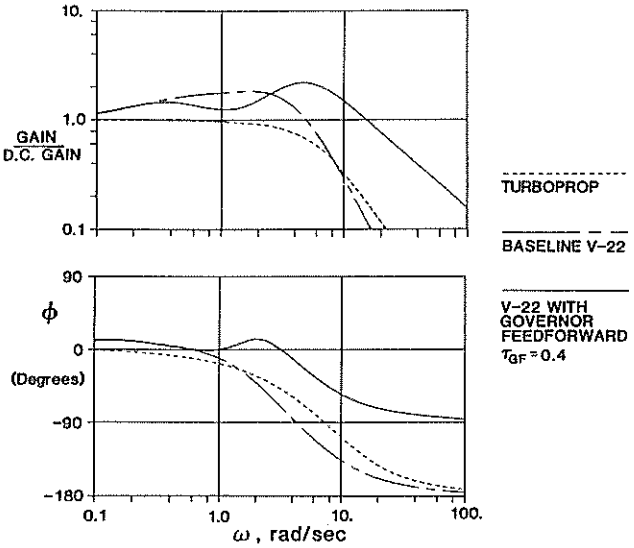

Fig. 5. Thrust response to power lever, frequency domain

Tests in the flight simulator with a pilot in the control loop led to the final selection of the system time constant. The tests evaluated time constants of 0.4 and 2.0 seconds: the former produced better performance in the simulation environment. Accordingly, all subsequent handling qualities evaluations used the 0.4-second time constant.

Handling Qualities Evaluations

The governor feedforward circuit was programmed into the V-22 flight simulation, and pilots evaluated it in simulated formation flight. The simulation of formation flight used the computer-generated visual target shown in Fig. 6 as the "lead" aircraft. The visual cues this target generated were the only positioning cues available to the pilot.

The task. The formation flight task was divided into two subtasks for this evaluation: join-up and position hold. Join-up consists of arresting the closure rate and assuming the correct position with respect to the lead aircraft. Position hold involves maintaining the correct position for a period long enough for an evaluation of handling qualities--normally 30 seconds. Pilots assigned handling quality ratings to the thrust axis for each subtask, following the guidelines established by Cooper-Harper (Ref. 7).

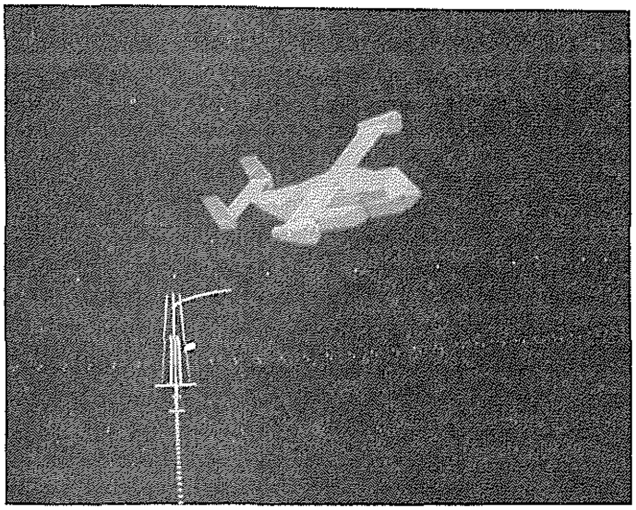

Fig. 6. Visual target for formation flight simulation

Evaluations were conducted in calm air and in moderate turbulence (four feet per second RMS). The turbulence model was based on the Dryden spectral form, with a scale length of 1,750 feet.

Evaluation results. The results are shown in Fig. 7. The data points are averaged handling quality ratings. The calm-air ratings are based on results from five test pilots. Turbulent-air ratings are averaged results from two test pilots. The governor feedforward circuit raised the pilot ratings in the thrust axis from Level 2 (unsatisfactory, with "deficiencies which warrant improvement") on the Cooper-Harper scale, to Level 1 ("satisfactory without improvement"). Pilots' comments indicated that the addition of the governor feedforward circuit eliminated the lag in response to movement of the power lever, that the improvement in control predictability allowed them to use more aggressive closure rates, and that the new circuit reduced the workload of formation flying.

Fig. 8 shows the average standard deviation of the longitudinal separation between the two aircraft in the position hold subtask (data acquired during 30 seconds of position hold). These results indicate the accuracy with which the pilots were able to maintain a constant separation from the lead aircraft in simulated formation flight. Both the baseline aircraft and the aircraft equipped with governor feedforward achieved good results in calm air. But in turbulence, which forces a more intensive involvement of the pilot in the control loop, the positive effect of govenor feedforward on precision speed control is strongly evident: it reduces the standard error in longitudinal separation by two-thirds.

Simulation fidelity. The simulator is fixed base, and initially there was concern that without acceleration cues the pilots would fail to discern the short-term improvement in thrust response produced by

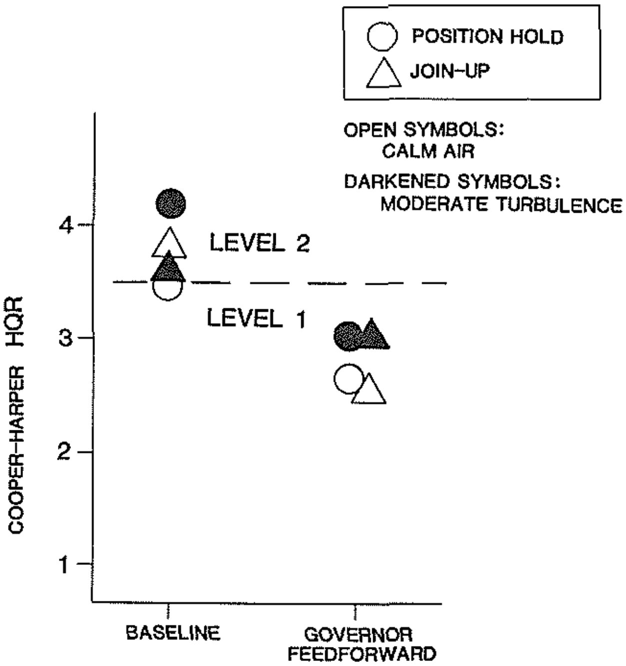

Fig. 7. Rating of thrust-axis handling qualities with governor feedforward

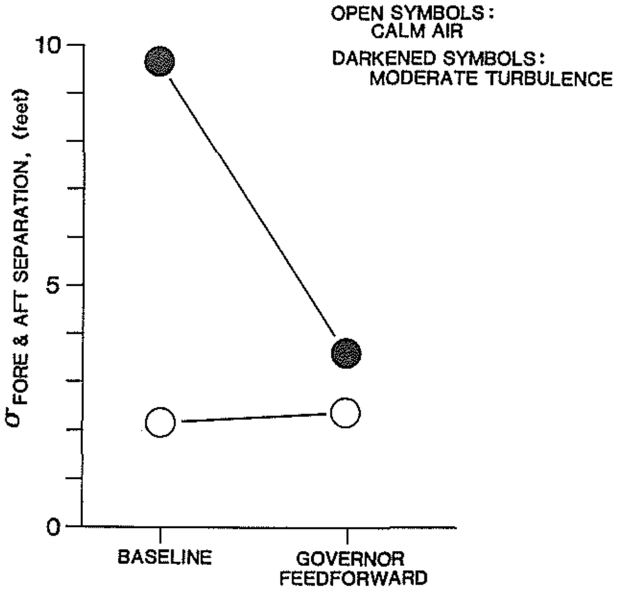

Fig. 8. Accuracy of position holding in formation flight with governor feedforward

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The analysis demonstrated and flight simulation verified that the governor feedforward circuit has a decisive effect on airplane-mode thrust response characteristics. The circuit has been incorporated into the V-22 flight control software.

Aerodynamic Braking System

The search for an effective solution to the problem of precision speed control in airplane mode simultaneously produced two different but complementary control law functions: the governor feedforward circuit and an aerodynamic braking system. The feedforward circuit addresses the problem at its source by improving thrust response to the power lever. The aerodynamic braking system, in contrast, improves the pilot's ability to decelerate the aircraft by using the power lever to trigger the transient deployment of an aerodynamic brake.

Description

The aerodynamic brake: The aerodynamic braking system creates a speed brake from the aircraft's flaperon control surfaces (Fig. 9). This approach avoids adding the weight and mechanical complexity of a separate control surface for the braking function. The V-22 flaperons normally function as flaps to augment lift and alleviate download, and as ailerons for roll control (Ref. 8). All flaperons deflect collectively to form a full-span slotted flap, and the left inboard and outboard flaperons deflect together and opposite to the right inboard and outboard flaperons to form full-span ailerons, as depicted in Fig. 10. The aerodynamic braking system adds a third flaperon function by commanding opposing deflections of the inboard and outboard segments. If the flaperon controls were mechanical, these overlapping functions would require a sophisticated mixer, but the V-22's fly-by-wire controls accommodate them easily.

The opposing inboard and outboard deflections commanded by the aerodynamic braking system are ratioed so as to maintain a constant lift curve (vs. angle of attack) during brake deployment. A crossfeed path to the elevator commands an appropriate deflection of that surface to counteract the pitching moment accompanying brake deployment. These refinements prevent the deployment of the brakes from adding to the pilot's longitudinal control workload.

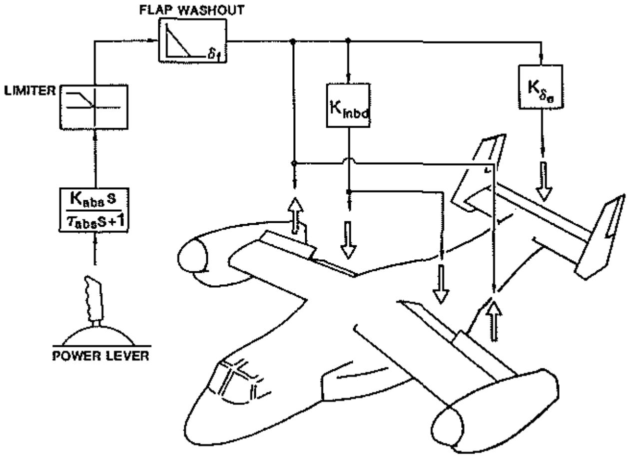


Fig. 9. The aerodynamic braking system

The maximum opposing flaperon deflection commanded by the braking function is 80% of the travel defined for the aileron function. Full simultaneous application of aileron and aerodynamic brake results in some degradation in the effectiveness of each, but, as Fig. 10 shows, considerable aileron control remains.

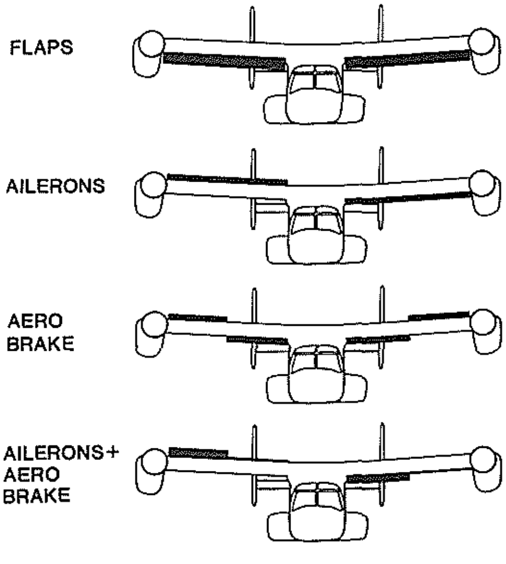
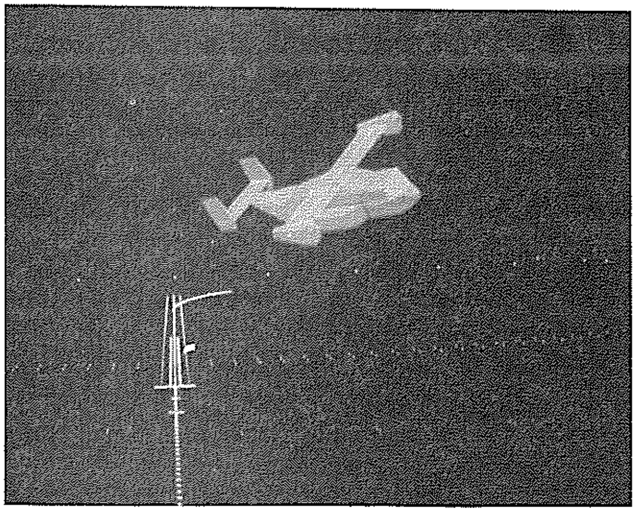


Fig. 10. Flaperon functions

The actual drag produced by the flaperon brake is equal to 60% of the drag of the airframe in its clean configuration at 200 KCAS, based on drag data from wind tunnel testing. (A flap-dependent gain limits the use of the flaperons as brakes to the flaps-up



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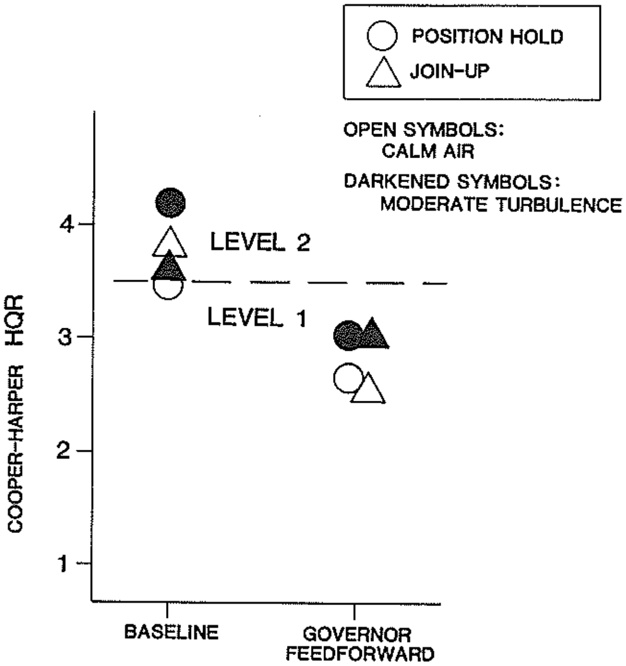

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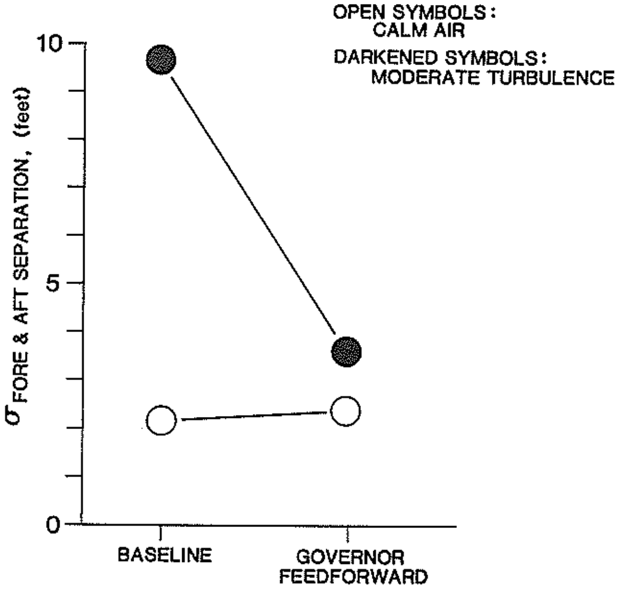

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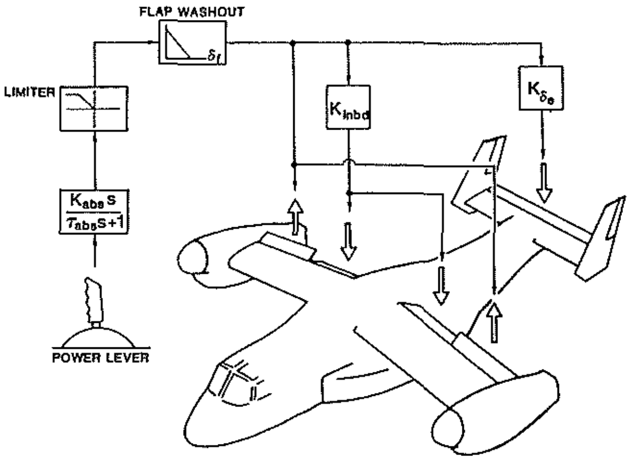

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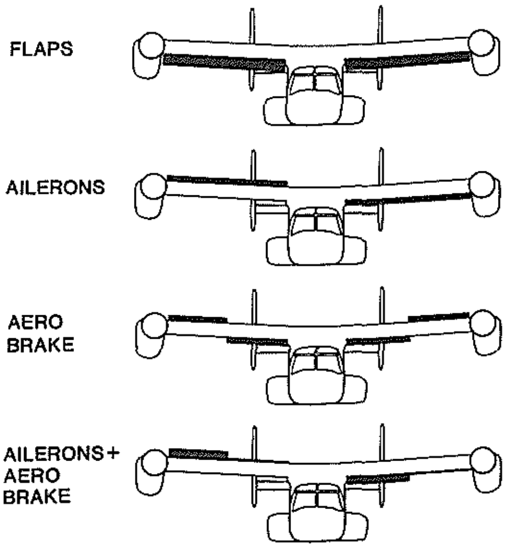

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Brake Control. The flaperons make an effective aerodynamic brake for the aircraft, and one that should function well in a precision tracking task. However, the pilot must have a means of controlling the brake that is likewise suited to precision formation flight. Usual practice in fighter aircraft is to use a separate cockpit switch for brake deployment, but this is too coarse a control for precision application, and the added primary control increases pilot workload. Instead, a circuit that deploys the brake in response to power lever displacement was developed (Fig. 9). The circuit consists of a high-pass filter in series with an asymmetric limiter. With this circuit, negative power lever inputs command a transient brake deployment that acts to decelerate the aircraft to the new, lower trim speed. The transient nature of the brake deployment keeps the brake retracted in the steady state for aerodynamic efficiency and to permit repeated brake applications. The aerodynamic brake would be used only during precision airplane-mode formation flight and air-to-air refueling.

Optimization in the flight simulator with a pilot in the loop resulted in the selection of a time constant, τ_{abs}, of two seconds, and a sensitivity such that a negative power lever step input of 0.5 inch (12.5%) deploys the brake fully. The deceleration following such a step input is shown in Fig. 11 for the V-22 in the baseline configuration, for the aircraft equipped with governor feedforward, and for the aircraft with governor feedforward and aerodynamic braking. These results are for a constant-altitude deceleration from a sea-level trim condition of 200 knots at a gross weight of 40,000 pounds. (The figure also shows the actual deflections of the flaperons during the maneuver.) The aerodynamic braking produces a pronounced increase in deceleration immediately following the power lever step, and a gradual return to the baseline deceleration level as the brake retracts. The result is a more abrupt arrestment of the closure rate when the pilot uses the system during formation flight or during air-to-air refueling.

Evaluation of Handling Qualitities

Pilots evaluated the aerodynamic braking system in Bell's fixed-base V-22 flight simulation in conjunction with their evaluations of the governor feedforward circuit already described. Because the braking system was intended to be complementary to the governor feedforward circuit, all evaluations of the aerodynamic brake were made with the governor feedforward circuit also active.

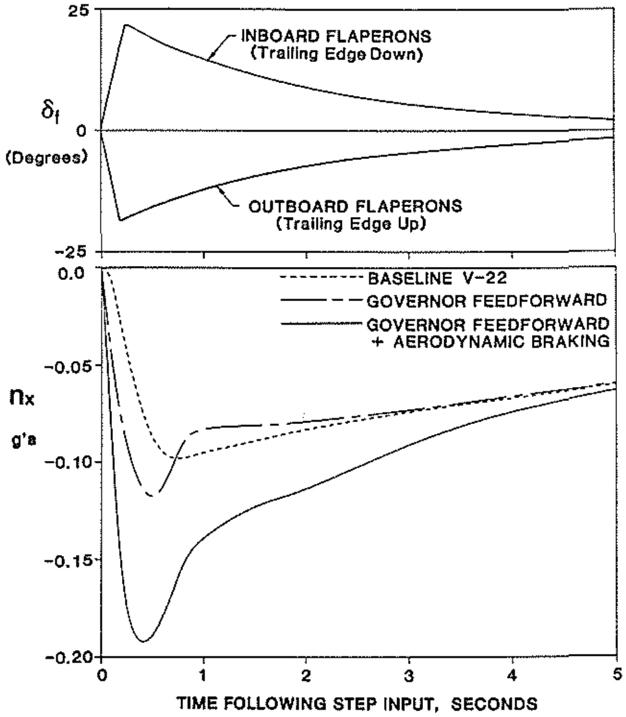

Fig. 11. Deceleration with the aerodynamic braking system

Evaluation results. The addition of aerodynamic braking to the aircraft equipped with governor feedforward made a further improvement in handling quality ratings for formation flight. Fig. 12 presents the resulting handing quality ratings, together with the results for the baseline V-22 and the V-22 with governor feedforward only. The calm-air results average the ratings of five test pilots, the turbulent-air results those of two test pilots. For both subtasks, the average HQR in calm air was 2, indicating that pilot compensation was no longer a factor in task performance. Join-ups were easier, and successful join-ups from conditions of unusually high closure rate were possible with the braking. Less control shaping was required for position acquisition, and power response in general gave the impression of being improved. Workload in the position-hold subtask was reduced.

Fig. 13 compares the accuracies with which pilots maintained longitudinal position with the three control systems tested. The addition of aerodynamic braking resulted in modest improvements (over the other two systems tested) in positioning accuracy in both calm and rough air.

The use of the brake did not degrade handling qualities in the other control axes in formation flight. Tests to evaluate roll control effectiveness in high-roll-

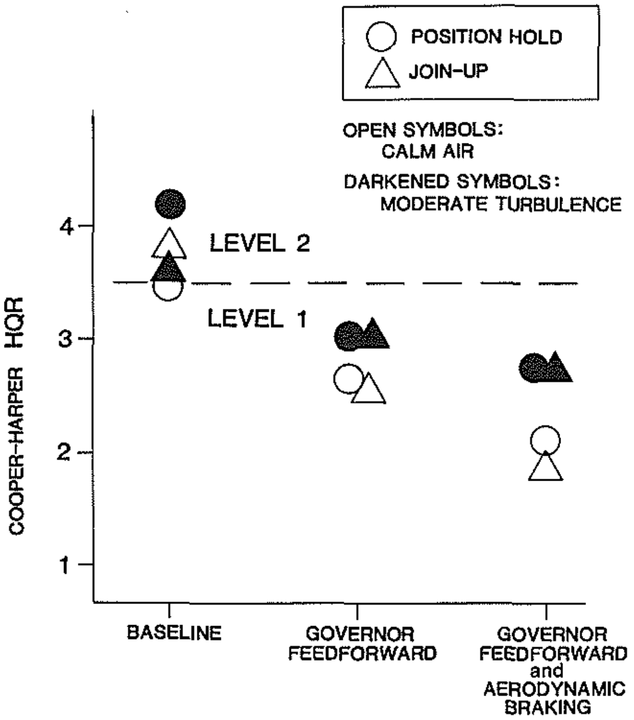

Fig. 12. Rating of thrust-axis handling qualities with aerodynamic braking

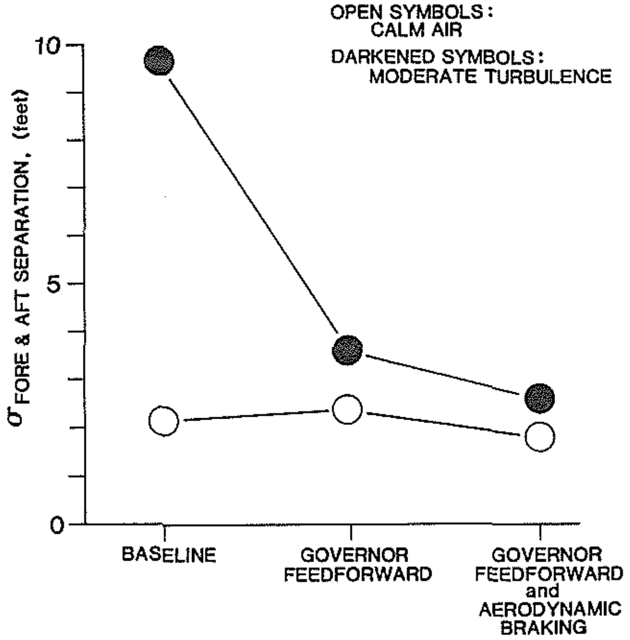

Fig. 13. Accuracy of position holding in formation flight with aerodynamic braking

rate maneuvers with the brake deployed showed roll control to be degraded (from HQR=3 with brake retracted to HQR=4 with brake deployed) but adequate in these circumstances. Because the pilot would not normally use the brake during aggressive lateral maneuvers, this degradation is considered to be tolerable.

The results of the simulation evaluation validated both the concept of the flaperon-derived aerodynamic brake and the use of the power lever to control aerodynamic braking directly.

Because of the impressive improvement the governor feedforward circuit makes in precision speed control, the aerodynamic braking system will not be added to the V-22 control system unless the operational flight test phase shows it to be required. However, its existence as a developed, proven solution to the difficult problem of precision speed control serves to further reduce V-22 program risk.

Torque Command/Limiting System

Another aspect of V-22 flying qualities that has received attention is that of in-flight torque management. Whereas certain specific tasks in the operational envelope of the aircraft call for improved precision speed control, improvements in the area of torque management benefit the entire operational envelope of the V-22. As was the case for precision speed control, the more stringent mission-oriented requirements for flying qualities imposed on the V-22 necessitated a departure from a control strategy that was adequate for the experimental XV-15. The resulting control law function, torque command/limiting, uses feedback control to make significant improvements in cockpit workload, power level control sensitivity, and drive system overtorque protection for the V-22.

Background

The XV-15 uses what may be described as a "throttle command" approach to thrust/power management. The application of throttle command to the V-22 has highlighted several limitations of this control method that combine to degrade handling qualities along the thrust axis.

The throttle command method. Fig. 14 illustrates the steady-state relationship between the power lever and rotor mast torque for the thrust/power management system of the XV-15. (Mast torque is the torque output from the transmission into the rotor, transmitted by the rotor mast). The power lever commands engine throttle setting. Engine power is a function of this commanded throttle setting, ambient conditions, and inlet ram recovery. The power output, after correction for accessory loads and transmission losses, results in a mast torque that varies inversely with the RPM. The throttle command approach to control has the merit of being straightforward to implement, and it has been used with satisfactory results in the XV-15 and fixed-wing turboprop aircraft.

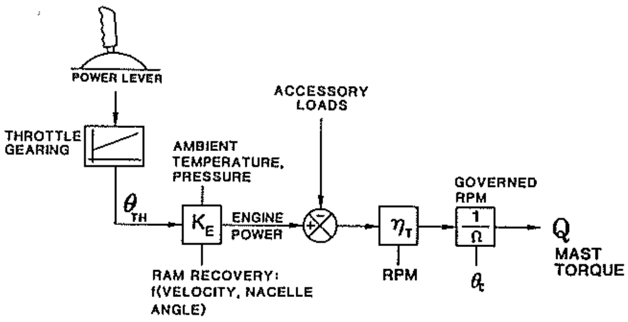

Fig 14. Steady-state relationship between mast torque and power lever in the XV-15

When circumstances are such that the mast torque limit is the upper limit on power available, this approach to torque management forces the pilot to monitor and regulate the torque level to avoid overtorques. This becomes a significant contributor to pilot workload in tasks that require intense control activity in the thrust axis and near-maximum power for flight path control. Such tasks will occur for the V-22 operating at heavy gross weights in its VTOL assault transport role.

As Fig. 15 shows, the V-22 has excess installed power in hover up to a 7500-foot density altitude, and in cruise up to a 14,000-foot density altitude. The aircraft must have this installed power margin for hot-day and high-altitude performance, and also for single-engine performance. For operation at low density altitudes, however, the combination of excess installed power and the throttle command approach to power control produces several undesirable characteristics. First, as Fig. 16 shows, this situation creates the potential for significant overtorques. Although this is not threatening from the standpoint of the transmission design limits, repeated overtorques have an appreciable effect on the MTBRs (mean time between removals) of transmissions and other drive system components. Second, the power lever control sensitivity suffers because there is less usable power lever throw under conditions of excess installed power. This effect is mitigated by the use of a nonlinear throttle gearing, which concentrates much of the upper throttle range into the final fraction of power lever throw. However,, this solution aggravates sensitivities in high-density-altitude conditions, where control must be achieved in the nonlinear range of the throttle gearing. Third, the combined effects of increasing ram recovery on engine power and reduction of proprotor RPM produce a significant and uncommanded increase in rotor torque during con-versions from VTOL-mode hover to airplane-mode cruise. This effect requires continuous control by the pilot during conversion to avoid overtorques.

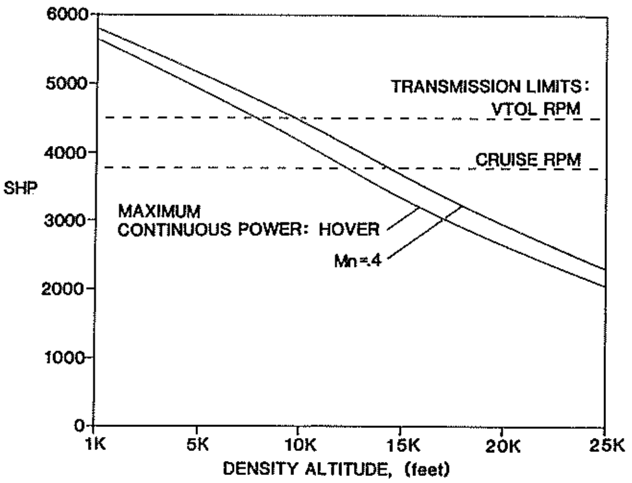

Fig. 15. V-22 installed power

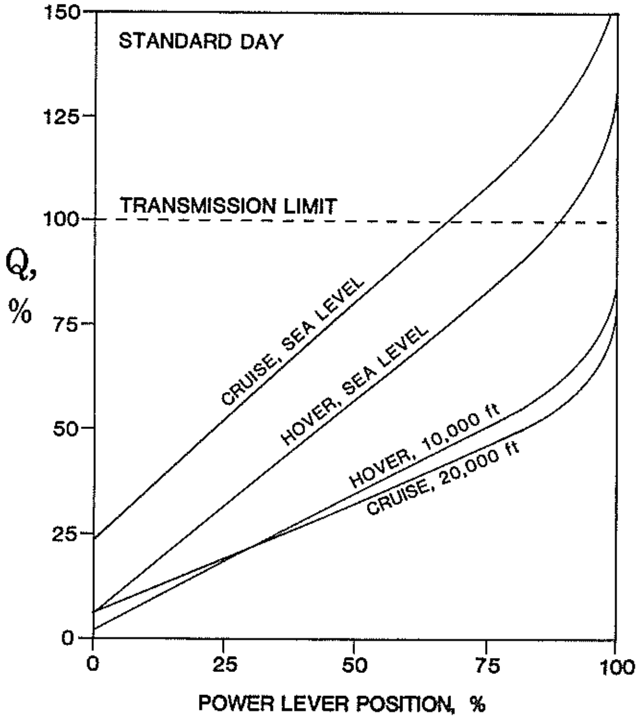

Fig. 16. Torque control with throttle command

The simplicity of the throttle command approach to torque management is thus offset by its propensity toward inadvertent overtorques, degraded sensitivity of the power lever control, and increased pilot workload.

Automatic torque limiting. A system for automatic torque limiting was investigated as a means of correcting the deficiencies of the throttle command approach to torque control. This system used feedback of measured mast torque (already available in the V-22 from flight-critical sensors) to eliminate inadvertant overtorques in the steady state. By itself, however, automatic torque limiting produced a variable control "dead-zone" at the forward end of the power lever throw, and did nothing to improve control sensitivity. This investigation led to the concept of a "torque command" system for automatic regulation of torque.

Torque command control. A model follower system for torque control was developed to give the power lever direct torque command. The result, designated the torque command/limiting system, solves all of the problems posed by the throttle command approach to torque management. It gives automatic protection against inadvertent overtorques, optimizes power lever control sensitivities at all flight conditions, and decouples torque from changes in ambients, RPM, and inlet recovery conditions at low density altitudes.

System Description

General. The torque command/limiting system is shown schematically in Fig. 17. In the digital fly-by-wire control system of the V-22, it resides entirely within the flight control software, where it operates in parallel with the power lever control path to the thrust/power management system.

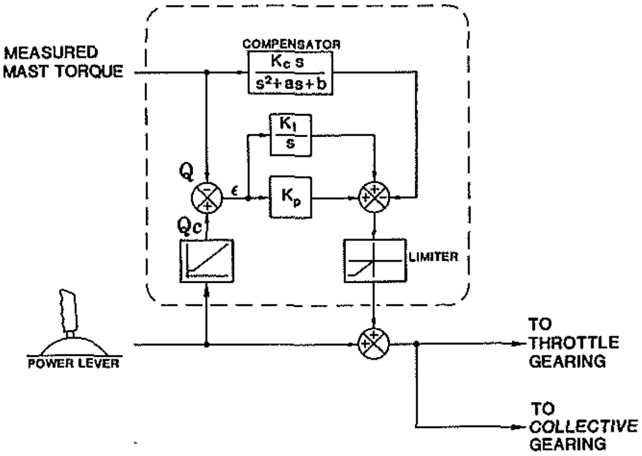

Fig. 17. The torque command/limiting system

The system generates a torque command signal, Q_c, *from the power lever position according to the* specified command model. Any error, ε, between the torque command and the measured mast torque generates a corrective signal to drive torque into agreement with the command model. The average of the left and right mast torques is used for feedback. This approach makes the system tolerant of the rotor torque "splits" *(equal and opposite torque variations) that occur* during lateral maneuvers. The combination of integral (Ki) and proportional (Kp) gains in the error processor maintains zero steady-state error and good response dynamics. The compensator (Kc) enhances the system's damping and gust-rejection characteristics.

Output limiting. The form of the system output limiter is very important for the practical application of torque command/limiting. The limiter, as shown in Fig. 17, passes only negative output signals. As a result, the torque command/limiting system is only in the loop when torque level would otherwise exceed the command model value. This is the case, for instance, in conditions of excess installed power. But at high altitudes, or in cases of single or dual engine failure, the torque command/limiting system is disengaged from the control system by the output limiter. Without this provision, operation at high altitudes or with one failed engine would result in an objectionable power lever control deadzone. In the event of a dual engine failure, the system would demand collective pitch at the expense of proprotor RPM in a vain attempt to maintain the commanded torque level. The asymmetric output limiter reliably safeguards against these possibilities.

Operation. Fig. 18 shows the torque versus power lever behavior of the V-22 with torque command/limiting. Comparision with the throttle command behavior of Fig. 16 reveals several improvements. First, the curves for low-altitude operation have collapsed into the single torque command model. The command model improves control sensitivity significantly and precludes overtorques. At the higher altitudes, the torque command/limiting system drops off line (due to the asymmetric output limiter) and thrust/power management reverts to throttle command; control sensitivity is further reduced, full power lever advance still corresponds to maximum permitted power (determined by engine limitations at altitude), and the nonlinear throttle gearing required without torque command/limiting is eliminated.

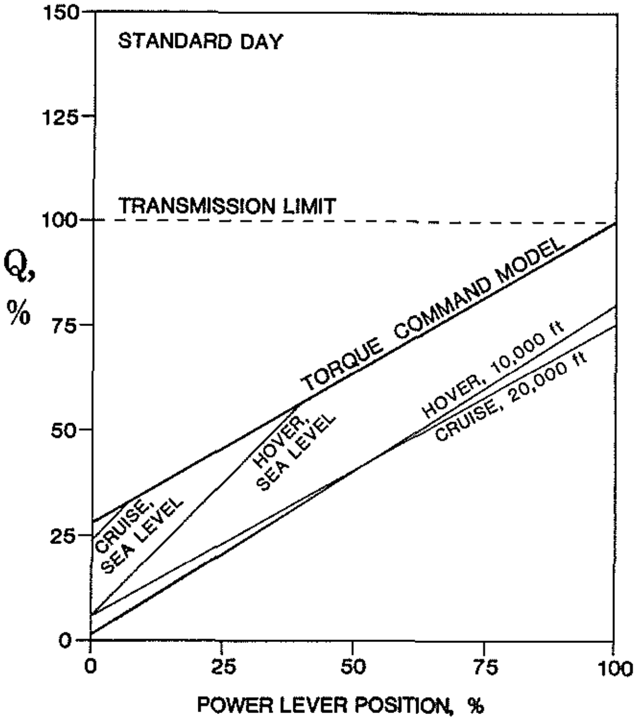

Fig. 18. Torque control with torque command/ limiting

Override provision. Inevitably, during the life of the aircraft extraordinary situations arise that require that the pilot have access to maximum installed power. At these times, survival of the aircraft and its occupants override considerations of drive system longevity. Because of this, the torque command/limiting system has an emergency override designed into it. During flight simulator evaluations, pilots used a push-button switch located on the power lever within easy reach of the left thumb to override torque command/limiting. When depressed, the switch triggered an exponential decay of the torque command/limiting system output, and full engine power was thereafter available on demand. Early evaluations have shown this approach to be satisfactory from the standpoints of human factors and control.

Analysis and Optimization

The design goal was to incorporate the torque command/limiting system into the V-22 without degrading the thrust precision control characteristics, longitudinal aircraft dynamics, or gust sensitivity of the propulsion system. Initial thrust response characteristics of the basic, optimized thrust/power management system were retained by means of a second-order shaping function imposed on the torque command model. With this, command model dynamics following a power lever input may be matched to the torque response of the baseline aircraft. Thus the system has short-term dynamics that are similar to those of the baseline aircraft, yet constrains torque to the command model value in the steady state. This results in thrust response characteristics with torque command/limiting that are dynamically similar to the optimized characteristics of the baseline control system.

Linear analysis verified the stability and analyzed the dynamic response of the torque command/limiting system coupled with the airframe and with the propulsion and flight control systems of the V-22. The analysis showed the aircraft phugoid mode to be unaffected by the addition of the system. The linear analysis resulted in the addition of the compensator to the system (Fig. 17). This compensator improves the short-period damping and gust-rejection characteristics. (Gust rejection is a particular concern because the torque command/limiting system uses mast torque feedback, and mast torque in a tilt rotor is inherently sensitive to gusts due to the low proprotor disk loading in high-speed airplane-mode flight.) Fig. 19 shows the gust sensitivity finally achieved with the compensator in the circuit for airplane-mode flight at 200 knots. These results show that torque command/limiting can be used without degrading the baseline aircraft's gust sensitivity characteristics.

Programming of the system into the V-22 simulation program permitted time domain analysis in a nonlinear environment of high fidelity. Discrete time steps for control system calculations were matched to the anticipated computational frame time of the V-22 onboard flight control computers. Algorithms used in the system definition were identical to the anticipated flight control software definition. The results supported the linear analysis, and demonstrated the stability and performance of the system under simulated flight conditions.

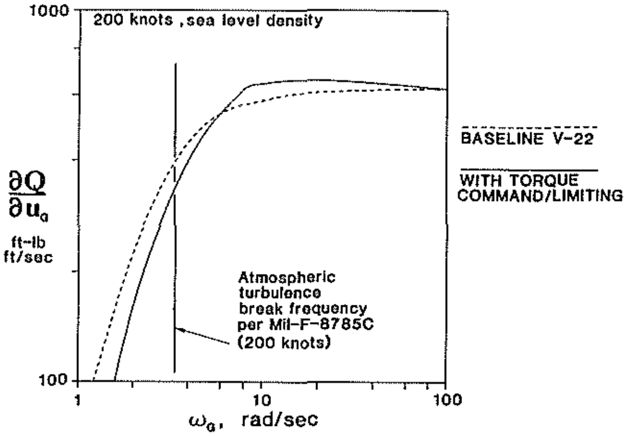

Fig. 19. Gust sensitivity in forward flight

Handling Qualities Evaluation

Piloted simulation evaluations of the V-22 with the torque command/limiting system have examined a variety of tasks. The system has demonstrated improved thrust-axis handling qualities in precision hover and reduced pilot workload in all flight modes.

Reduced pilot workload. The torque command/limiting system made significant reductions in pilot workload during simulations of low-speed maneuvering, conversions at heavy gross weights, and short (rolling) takeoffs and conversion/climbout at extreme gross weight. The automatic torque limiting feature of the system allowed the pilots to eliminate torque from their primary instrument scan. They could obtain maximum permitted power in any situation reliably by simply advancing the power lever to the control stop. This simplified their power control task, and allowed them to use a more "heads up" approach to the maneuvers.

The technique of applying full power lever (to the stop) at the onset of conversion tended to focus pilot attention on pitch attitude (longitudinal stick) to control flight path, rather than on power. This is the correct focus, since pitch rotation is necessary for transferring lift onto the wing as speed increases and nacelle angle decreases. Because they were naturally forced into the proper control action by the technique, pilots with little prior tilt rotor experience found conversions to be easier. One such pilot estimated that the system reduced cockpit workload during this task by 50%.

Handling qualities. *Precision hover is the critical* task for the evaluation of modifications to the thrust/power management system. The evaluation used a special visual environment that furnishes the visual cues a pilot must have to sense accurately the displacement of the aircraft in three-dimensional space (Fig. 20). The pilot lines up the sight on the near tower with the target on the far tower, and parallax then allows him to detect lateral and vertical drift. There is a set of targets for hover in ground effect, and one for hover out of ground effect. In this environment, the bob-up and height-arrest and hold characteristics of the V-22 with torque command/limiting were compared with the response of the baseline aircraft. Due primarily to the improved sensitivity of the power lever control, the handling quality ratings assigned to the thrust axis with the torque command/limiting system on line were one pilot-rating point better than those assigned to the baseline V-22 throttle command system. At the maximum VTOL operating weight of 47,500 pounds, this improvement shifted handling quality ratings from Level 2 (HQR=4) for the baseline aircraft to Level 1 (HQR=3) for the aircraft with the torque command/limiting system.

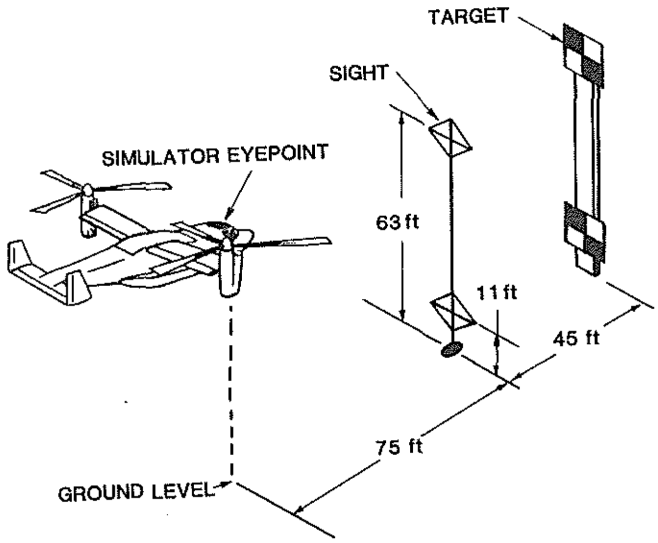

Fig. 20. Precision hover visual environment

Torque Command/Limiting and the V-22

Due to the very substantial benefits that the torque command/limiting system brings to the areas of drive system overtorque protection, pilot workload reduction, and power lever control sensitivity, the system will be incorporated into the V-22 flight control system.

Concluding Remarks

The three control law functions discussed here can improve the handling qualities of the tilt rotor aircraft. The simple governor feedforward circuit modifies the initial thrust response dynamics in airplane mode sufficiently to improve pilot ratings from Level 2 to Level 1 in the precision formation flight task. The aerodynamic braking system improves precision speed control even further when used in conjunction with the governor feedforward. The *torque comand/limiting* system reduces pilot workload and improves thrust axis handling qualities by automatically limiting torque and improving power lever sensitivity.

These control law functions exemplify the potential for innovation afforded by the digital fly-by-wire approach to flight control. Of the three, only the governor feedforward circuit is conducive to implementation into a conventional, predominantly mechanical control system such as that of the XV-15. Incorporation of the aerodynamic braking and torque command/limiting control laws into such a system would require extensive control hardware modifications, and would impose significant penalties in the areas of weight and hardware complexity. But the power and flexibility of the digital fly-by-wire flight control system are such that all three of these control circuits may be added to the V-22 without a single hardware design change: the circuits are entirely contained within the onboard flight control software. In the case of the aerodynamic braking system, the purely software nature of its implementation permits the designers to take a "wait and see" attitude toward adding it, since the time it would take to upgrade the software is a fraction of the time required to redesign control system hardware.

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