Cross Coupling in Pilot-Vehicle Systems

R. A. Hess* and D. C. Watson†
University of California, Davis, California

Multiloop pilot-vehicle analysis is applied to the problem of determining crossfeed techniques that may be employed by pilots in minimizing the effects of vehicle cross coupling. Herein, cross coupling refers to unwanted vehicle motion, which occurs in one control axis or loop as the result of pilot control actuation in another control axis or loop. The minimization or elimination of such cross coupling can significantly affect the "workload" associated with tasks such as nap-of-the-Earth helicopter flight. In contrast, situations arise in which pilots may use vehicle cross coupling to improve performance by coordinating two control actuations in the control of a single response variable. A crossfeed model is developed based upon simple control system design principles and configured in a manner amenable to pursuit or precognitive pilot control activity. A handling-qualities theory developed to analyze single-loop tasks is applied to the multiloop problem. The crossfeed model is applied to five different vehicles/configurations ranging from helicopters to fighter aircraft. Results indicate that relatively simple crossfeed commands can significantly reduce cross coupling and, in some cases, improve handling qualities as predicted by the single-loop theory.

I. Introduction

THE term "cross coupling" can refer to a variety of different phenomena in dynamic systems. As used in this research, the term can best be understood by referring to Fig. 1, which is a simplified block diagram representation of an aircraft under manual control. In the feedback system shown, two control variables δ_1 and δ_2 are available to the pilot to control vehicle output quantities x and y, respectively. Cross coupling refers to the production of y output by δ_1 actuation or x output by δ_2 actuation. In either case, the outputs can be considered unwanted since they are essentially system disturbances, i.e., uncommanded vehicle outputs. A pertinent example in helicopter flight control would be the roll attitude perturbations produced in some vehicles as a result of longitudinal cyclic actuation to control pitch attitude.

In certain instances, the existence of cross coupling can be used to the pilot's advantage. For example, in Fig. 1 the pilot might use both controls δ_1 and δ_2 in a particular maneuver to control a single vehicle output, say x, with better performance (e.g., higher bandwidth) than that obtainable using δ_1 alone. With a few exceptions,[1,2] there has not been a great deal of research undertaken to model the activity of human pilots using control "crossfeed" techniques to reduce or eliminate cross-coupling effects. However, the advent of aircraft with the requirement of nearly independent control of as many as six degrees of freedom[3] will demand knowledge of the human's capabilities in this area. In addition, the successful completion of certain tasks such as nap-of-the-Earth helicopter flight depends upon precise control of vehicles with strong cross-coupling tendencies.[2,4] The ability of the human pilot to minimize cross coupling in such tasks obviously influences vehicle effectiveness, and the "workload" required to accomplish this can certainly affect the pilot's perception of vehicle handling qualities.

Figure 2 shows a pair of hypothesized control crossfeed structures, which minimize the y output disturbance due to the δ_1 activity as discussed in Fig. 1. The dashed element shows a direct crossfeed from δ_1 to δ_2 through appropriate compensation G'_{cf}. An alternate possibility is shown by the solid element. Here, an appropriate y'_c is created by the compensation G_{cf} acting upon x_c. Both of these crossfeeds can, in theory at least, eliminate the cross coupling in question. Actually, a number of crossfeed possibilities exist, each utilizing a variable from the upper feedback loop to provide an input to the lower loop. There is no a-priori reason to view any one as superior to the others at this juncture.

II. Multiloop Pilot-Vehicle Analysis

The technique for generating multiloop models of the human pilot used here has as its basis a well-established technique for multiloop control system analysis and design.[5] Successful applications of the technique to multiloop pilot modeling are quite common.[6,7] The approach relies simply on nested single-point feedback loops in which loop bandwidths decrease as one proceeds from the innermost to outermost loop. Consider Fig. 3, which shows a hypothesized multiloop pilot model for longitudinal control of a fighter aircraft in landing approach. The loop structure represents a "backside" control technique in which throttle controls altitude and elevator controls airspeed through pitch attitude. Figure 3 also indicates hypothesized bandwidths (or open-loop crossover frequencies) for each closure. The bandwidth separation shown between closures for any control point is consonant with good design practice. The relative and absolute magnitudes of the bandwidths are assumed to be task-dependent.[7]

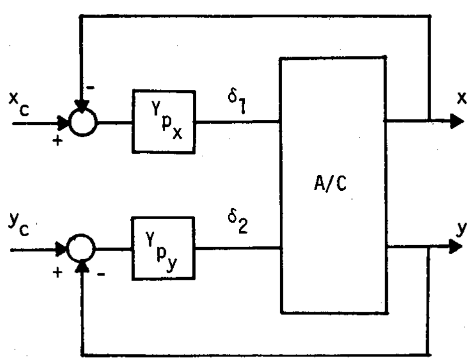

Fig. 1 Simplified pilot-vehicle system.

Received June 18, 1985; revision received March 26, 1986.

*Professor, Division of Aeronautical Science and Engineering, Department of Mechanical Engineering. Member AIAA.

†Graduate Student, Division of Aeronautical Science and Engineering, Department of Mechanical Engineering. Student Member AIAA.

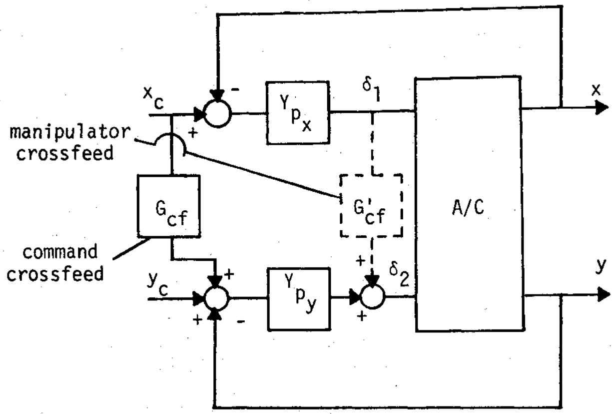

Fig. 2 Pilot-vehicle system involving crossfeed.

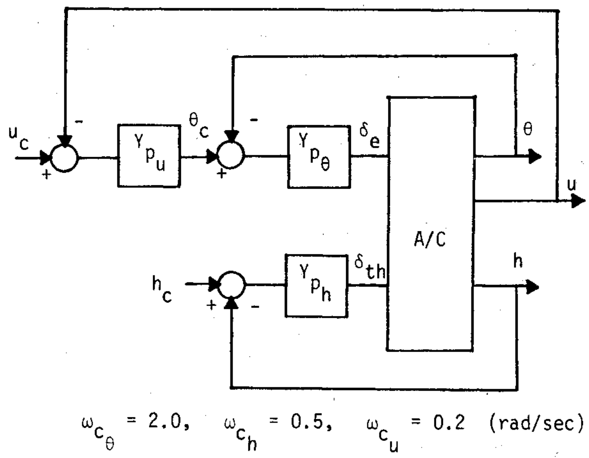

Fig. 3 Hypothesized multiloop pilot model.

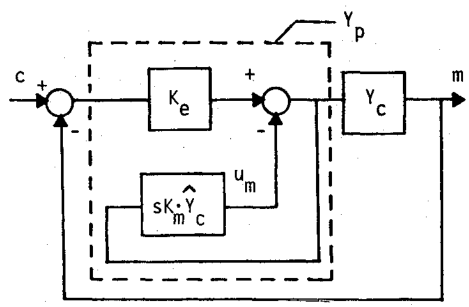

Fig. 4 Structural model of the human pilot.

The selection of appropriate pilot dynamics for the blocks Y_{p_θ}, Y_{p_h}, and Y_{p_u} is based upon repetitive application of the crossover model of the human pilot.[6] While the multiloop design technique may require iterations due to the initial selection of an inappropriate loop structure, experience soon teaches the analyst to quickly formulate an acceptable multiloop model of the pilot. For the sake of simplicity, pilot time delays are ignored in the analyses to follow. Adequate phase margins have been provided in the pilot-vehicle analyses so that the effects of the neglected delays will be minimized.

III. Crossfeed Model

Consider Fig. 2 with only the solid-line crossfeed element, i.e., crossfeeding of commands. Using the multiloop analysis techniques from Ref. 5, the transfer function y/x_c can be found as follows:

$$\frac{y}{x_c}=\frac{Y_{p_x}N^y_{\delta_1}+Y_{p_y}G_{cf}(N^y_{\delta_2}+Y_{p_x}N^{x\,y}_{\delta_1\delta_2})}{\Delta+Y_{p_x}N^x_{\delta_1}+Y_{p_y}N^y_{\delta_2}+Y_{p_x}Y_{p_y}N^{y\,x}_{\delta_2\delta_1}} \tag{1}$$

Here the terms $N^y_{\delta_1}$ and $N^{x\,y}_{\delta_1\delta_2}$, etc., represent "coupling numerators" of the first and second types, respectively. Now setting y/x_c equal to zero (implying that the crossfeed G_{cf} has eliminated the cross coupling), one can solve for the necessary crossfeed characteristics as

$$G_{cf}=\frac{-Y_{p_x}N^y_{\delta_1}}{Y_{p_y}(N^y_{\delta_2}+Y_{p_x}N^{x\,y}_{\delta_1\delta_2})} \tag{2}$$

Equation (2) can be put into a simpler form by considering Fig. 2 with $G_{cf}=0$ and using the multiloop analysis technique to calculate y/x_c and y/y_c as

$$\frac{y}{x_c}=\frac{Y_{p_x}N^y_{\delta_1}}{\Delta''},\qquad \frac{y}{y_c}=\frac{Y_{p_y}N^y_{\delta_2}+Y_{p_x}N^{x\,y}_{\delta_1\delta_2}}{\Delta''} \tag{3}$$

where Δ'' is the denominator of Eq. (1). Thus, the required crossfeed becomes simply

$$G_{cf}=-(y/x_c)/(y/y_c) \tag{4}$$

where the closed-loop transfer functions on the right-hand side have been calculated from Fig. 1. Although more complicated than Eq. (4), Eq. (2) clearly shows the influence of basic vehicle characteristics (through the coupling numerator terms) and the pilot dynamic characteristics (Y_{p_θ}, etc.) on the required crossfeed transfer function.

The pilot model crossfeeds used in this study will be assumed to originate at the outer-loop command in the loop causing the cross coupling and to terminate in the disturbed loop. Now two additional constraints are made at this juncture. The first requires that the bandwidth of the loop into which the crossfeed is entering be greater than or equal to that associated with the outer loop from which the crossfeed is originating. The second constraint requires that the crossfeed signal y_c' should act as a command to the innermost of the disturbed loops. Here "innermost" refers to the loop containing the pilot's control variable. This constraint allows the pilot to treat the crossfeed as a pursuit task.

A question can arise as to whether the pilot will actually be able to generate the equalization implied by the transfer function G_{cf}. This is not a minor point since the manual control literature clearly indicates that the human has limitations in this area and there is no guarantee that crossfeed transfer functions such as G_{cf} will be amenable to representation by, say, a simple gain or first-order lag. An alternate interpretation is possible here, however. Namely, one can view the crossfeed activity in the time domain, i.e., by examining the signal y_c' itself. This is especially attractive since the outer-loop command from which the signal y_c' is generated is always likely to be very simple in form, i.e., a step command, or an approximation thereof. Heffley[9] has shown, for example, that many realistic discrete flight maneuvers can be modeled by the multiloop pilot-vehicle approach discussed in Sec. II by allowing the outer-loop command(s) to be generated by a "sample-and-hold" operation on the actual continuous "task" command(s). The sampling interval of the sample-and-hold operation is inversely proportional to the outer-loop crossover frequency or bandwidth. Heffley's results suggest that, regardless of the time-dependence of the actual task command, the outer-loop command which the pilot utilizes is actually a series of step commands of varying sign and magnitude that arise from the natural scanning and sampling operation the human is known to employ in controlling a multivariable system.[10]

IV. Handling-Qualities Analysis

Reference 11 discusses a theory for handling qualities that has as its basis a structural model of the human pilot presented in Ref. 12. A simplified version of the structural model for compensatory control of a single variable is shown in Fig. 4. The model employs an inner proprioceptive feedback loop, which contains an explicit internal model of the controlled element dynamics. Reference 4 indicates that the rms value of the signal u_m in the model varies monotonically with task difficulty as perceived by the pilot. Now, one can consider that the pilot dynamics in each of the innermost loops of the pilot-vehicle systems to be discussed consist of a structural model such as the one shown in Fig. 4. Furthermore, the nature of the pilot compensation (e.g., gain, lead, or lag) predicted by the multiloop analysis provides enough information to make a relative comparison of the rms values of the u_m signals that would exist in the structural models configured to exhibit the same dynamics (gain, lead, or lag). This means that an analytical assessment of the effects of crossfeed on handling qualities can be made as discussed below.

BO-105C Helicopter

The BO-105C is a twin-turbine, lightweight utility helicopter with a single main rotor system consisting of a four-bladed, soft-in-plane, hingeless design. The flight condition of interest here is sea-level flight at 60 knots. The cross coupling to be examined is the altitude disturbance, which occurs when a longitudinal acceleration is initiated by longitudinal cylic control. Figure 5 shows the hypothesized pilot loop closures appropriate for an aircraft in backside operation. The assumed crossover frequencies in each compensatory closure are indicated in the figure, as is the appropriate crossfeed strategy as discussed in the Introduction. The relatively large crossover frequency for the altitude loop was selected on the basis of the rapid response characteristics of the hingeless rotor system. The aerodynamic data which allowed the multiloop pilot-vehicle analysis was taken from Ref. 12. The simplified compensatory pilot dynamics which resulted from the analysis are given below. In what follows, K1→K19 represent constant gain values.

$$Y_{p_\theta} \simeq \mathrm{K1}(0.5s+1), \qquad Y_{p_u} \simeq \mathrm{K2}$$

$$Y_{p_h} \simeq \mathrm{K3}(1.4s+1) \tag{5}$$

The predicted crossfeed transfer function can be adequately represented by the lower-order representation

$$G_{\mathrm{cf}} = \frac{\mathrm{K4}(66.7s+1)}{(5.13s^2+4.87s+1)} \tag{6}$$

It should be emphasized, of course, that the transfer-function simplification is not really necessary in the analysis. It was done here as an analytical convenience. Indeed, the lack of complete elimination of cross coupling in the examples is attributable to the simplifications made in the predicted crossfeed transfer functions. Note that, although the block diagram of Fig. 5 differs from that discussed in Sec. IV (Fig. 2), the same technique can be applied to finding the necessary crossfeed, i.e.,

$$G_{\mathrm{cf}} = -(h/u_c)/(u/u_c) \tag{7}$$

where the transfer functions u/u_c and h/h_c are calculated with all the compensatory loops closed, using the equalization given in Eq. (5). Figure 6 shows the altitude disturbance to an airspeed command of 20 ft/s with and without crossfeed. In all cases in these examples, the outer-loop "commands" were generated as step inputs passed through a second-order filter with unity damping ratio and a break frequency four times that of the bandwidth of the loop they were comanding. This smoothed input was felt to be realistic in that it did not result in discontinuous or extremely abrupt signals in the simulations. Figure 6 indicates that a very significant improvement in performance is possible with crossfeed. Also shown in the figure is the time history of the crossfeed command h_c'.

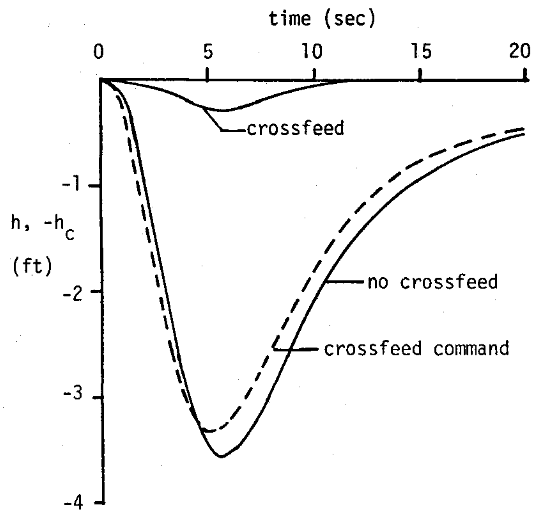

Fig. 6 Time histories for airspeed command; BO-105C.

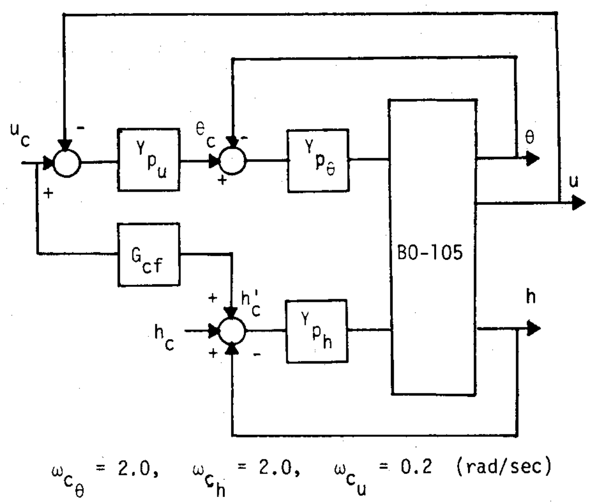

Fig. 5 Pilot loop closures for BO-105C helicopter.

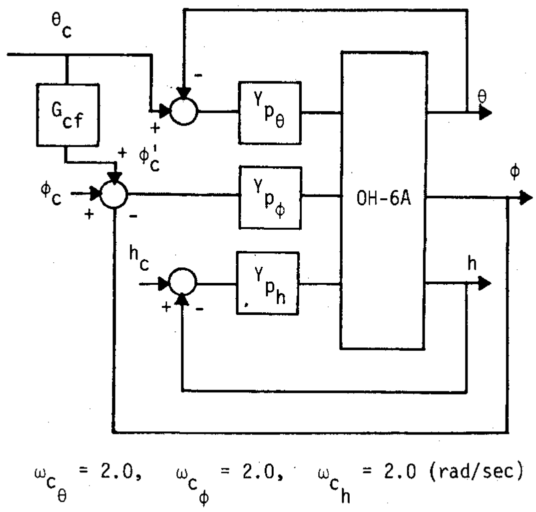

Fig. 7 Pilot loop closures for OH-6A helicopter.

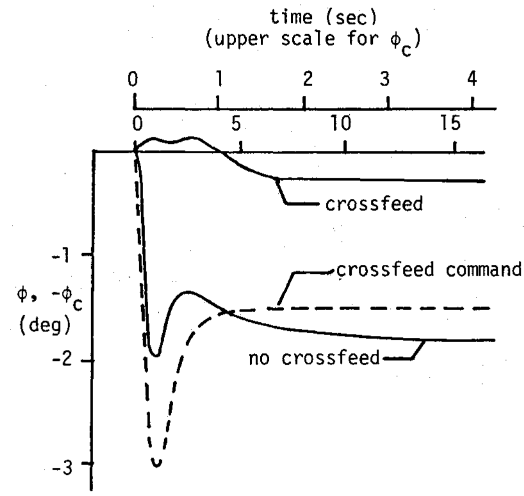

Fig. 8 Time histories for pitch attitude command; OH-6A.

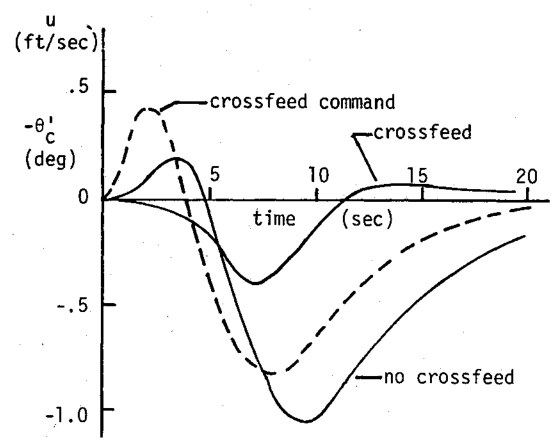

Fig. 10 Time histories for altitude command; QSRA.

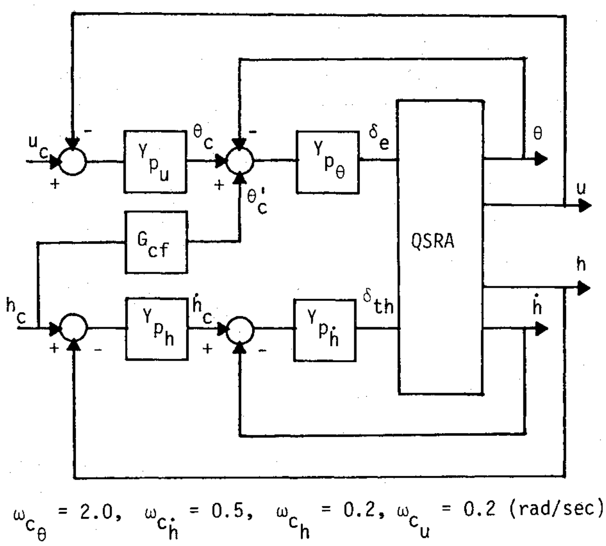

Fig. 9 Pilot loop closures for QSRA aircraft.

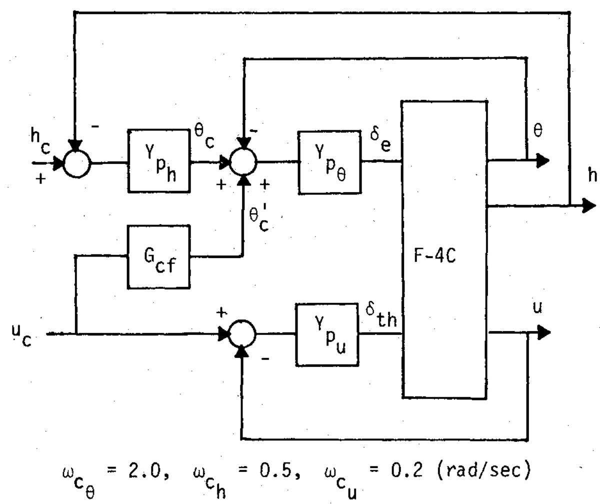

Fig. 11 Pilot loop closures for F-4C aircraft.

The ratio of the rms values of the appropriate u_m signals in a structural model representation of Y_{p_h} is

$$\frac{(\sigma_{uh})_{\mathrm{cf}}}{\sigma_{uh}} \simeq 1.0 \tag{8}$$

This indicates that little degradation in handling qualities is predicted by the technique of Ref. 11 when comparing pilot control with and without crossfeed.

OH-6A Helicopter

The OH-6A is a single-turbine, light observation helicopter with a four-bladed, fully articulated main rotor. The flight condition of interest here is sea-level flight at 60 knots. An ideal turn coordination autopilot was assumed. The cross coupling to be examined is concerned with the roll attitude disturbances which occur when pitch attitude changes are made with longitudinal cyclic control. Figure 7 shows the hypothesized pilot loop closures appropriate for an aircraft in backside operation. The crossover frequencies are also shown. The aerodynamic data for the vehicle model was taken from Ref. 13. The simplified compensatory pilot dynamics which resulted from the analysis are

$$Y_{p_\theta} \simeq \mathrm{K5}(s+1), \qquad Y_{p_\phi} \simeq \mathrm{K6} \tag{9}$$

An adequate representation of the predicted crossfeed transfer function can be given as

$$G_{\mathrm{cf}} = \frac{\mathrm{K7}(0.667s+1)}{(0.0667s+1)} \tag{10}$$

Figure 8 shows the roll attitude disturbance of a 10-deg pitch attitude command with and without crossfeed. Again, a considerable improvement in performance is evident. The time history of the crossfeed command ϕ_c' is also shown.

The ratio of the rms values of the appropriate u_m signals in structural model representations of Y_{p_ϕ} is

$$\frac{(\sigma_{u\phi})_{\mathrm{cf}}}{\sigma_{u\phi}} \simeq 2.7 \tag{11}$$

A handling-qualities decrement is predicted for roll attitude control with crossfeed, i.e., the rms value of u_m for roll attitude control with crossfeed is a factor of 2.7 larger than the value without crossfeed. This number can be placed in perspective by referring to Ref. 11, where a factor of 2.6 is concomitant with a controlled element change from $(Ke^{-0.375s})/s$ to K/s^2. Of course, the caveat here is that we are dealing with a multiaxis control task, whereas the data of Ref. 11 involves only single-axis tasks. Nonetheless, the handling-qualities result offers an interesting comparison between control techniques, and suggests that the pilot would find the crossfeed technique objectionable, despite the performance improvement.

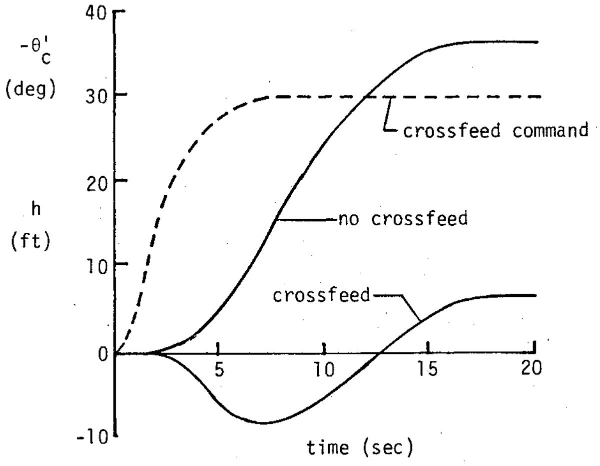

Fig. 12 Time histories for airspeed command; F-4C.

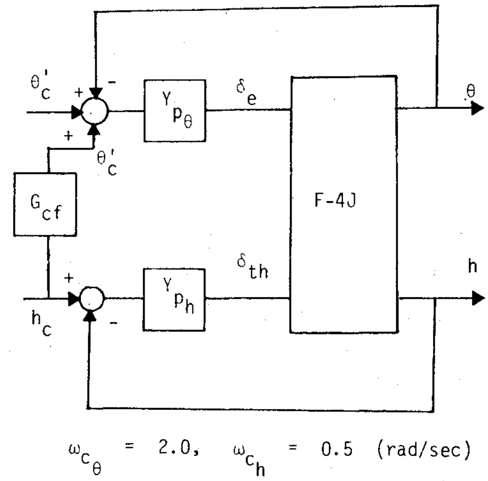

Fig. 13 Pilot loop closures for F-4J aircraft.

QSRA

The Quiet STOL Research Aircraft (QSRA) is an advanced propulsive-lift airplane employing hybrid upper-surface blowing for propulsive lift. It is powered by four turbofan engines. The model employed here was obtained from a NASA Ames flight-simulation model. For the configuration studied here, the vehicle possessed a pitch control augmentation system and a direct lift control system. The flight condition of interest is a 75-knot landing approach. The cross coupling to be examined is the airspeed disturbance that occurs when an altitude change is made using throttles only. Figure 9 shows the hypothesized pilot loop closures appropriate for an aircraft in backside operation. The crossover frequencies are also shown. An explicit vertical velocity inner loop has been employed in the modeling to support a flight-director design, which is not the subject of this research. The simplified compensatory pilot dynamics which resulted from the analysis are

$$Y_{p_\theta} \simeq K8, \qquad Y_{p_h} \simeq K9$$

$$Y_{p_{\dot h}} \simeq K10/s, \qquad Y_{p_u} \simeq K11 \tag{12}$$

An adequate representation of the predicted crossfeed transfer function can be given as

$$G_{cf} = \frac{K12s(0.37s^3 + 2.11s^2 + 2.6s - 1)}{3.37s^4 + 11s^3 + 13s^2 + 6.37s + 1} \tag{13}$$

Note the nonminimum phase dynamics. Figure 10 shows the airspeed disturbance to a 50-ft altitude command with and without crossfeed. Also shown is the crossfeed command θ_c'. Note that even without crossfeed, the airspeed disturbance is quite small. Nonetheless, the task does offer a comparison of the relative performance improvements that can be obtained with crossfeed; these improvements are considerable.

The ratio of the rms values of the appropriate u_m signals in a structural model representation of Y_{p_θ} is

$$\frac{(\sigma_{u\theta})_{cf}}{\sigma_{u\theta}} \simeq 0.42 \tag{14}$$

Note that a handling-qualities improvement is predicted for the pitch attitude control task.

F-4C Aircraft

The F-4C is a twin-engine Air Force tactical fighter. The flight condition of interest is a 230-ft/s landing approach. The cross coupling to be examined is the altitude disturbance that occurs when an airspeed change is initiated using the throttles. Figure 11 shows the hypothesized pilot loop closures appropriate for an aircraft in frontside operation (which is the proper technique for this particular F-4 variant). The assumed crossover frequencies are also shown. The aerodynamic data for the model was obtained from Ref. 14. The simple pitch attitude stability augmentation system (SAS) given in Ref. 14 was included. The simplified compensatory pilot dynamics for this task are

$$Y_{p_\theta} \simeq K13(s+1), \qquad Y_{p_h} \simeq K14, \qquad Y_{p_u} \simeq K15 \tag{15}$$

The predicted crossfeed transfer function can be adequately represented here as a simple gain, $G_{cf} = K16$. Figure 12 shows the altitude disturbance to an airspeed command of 20 ft/s with and without crossfeed. A significant improvement is evident. The crossfeed command θ_c' is also shown.

The ratio of the rms values of the appropriate u_m signals in a structural model representation of Y_{p_θ} is

$$\frac{(\sigma_{u\theta})_{cf}}{\sigma_{u\theta}} \simeq 1.2 \tag{16}$$

A slight decrement in the handling qualities associated with the attitude loop is predicted.

F-4J Aircraft

The F-4J is a carrier-based Navy fighter aircraft similar to the F-4C discussed previously. The flight condition of interest is a 221-ft/s landing approach. Unlike the preceding examples, the pilot seeks to use cross coupling to advantage here. Figure 13 shows the hypothesized pilot loop closures appropriate for an aircraft in backside operation (which is the proper technique for this F-4 variant). The airspeed loop has been deliberately ignored here because we are attempting to model a maneuver in the carrier approach environment where the pilot is interested in making a rapid altitude change close to the carrier. Thus, by the time a significant airspeed change has occurred, the carrier landing will have been accomplished. The aerodynamic data for the model was obtained from Ref. 15. The crossfeed evident in Fig. 13 is intended to improve or quicken the vehicle's altitude response. The ability of Navy pilots to develop such a crossfeed has been identified as an indispensable condition for full realization of an aircraft's flight-path regulation potential in the carrier environment.[16] The simplified compensatory pilot dynamics for this task are

$$Y_{p_\theta} \simeq K17(s+1), \qquad Y_{p_h} \simeq K18(6.67s+1) \tag{17}$$

Referring to Fig. 13, with all loops closed (including the crossfeed), one can calculate

$$\frac{h}{h_c} = \frac{Y_{p_h}(N^h_{\delta_{th}} + Y_p N^{\theta\ h}_{\delta_e \delta_{th}}) + G_{cf} Y_{p_\theta} N^h_{\delta_e}}{\Delta + Y_{p_h} N^h_{\delta_{th}} + Y_{p_\theta} N^\theta_{\delta_e} + Y_{p_\theta} Y_{p_h} N^{\theta\ h}_{\delta_e \delta_{th}}} \tag{18}$$

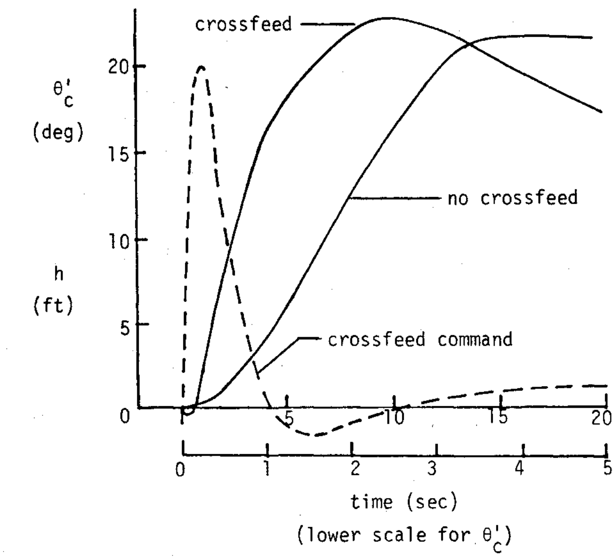

Fig. 14 Time histories for altitude command; F-4J.

This can be rewritten as

$$\frac{h}{h_c} = \frac{h}{h_c}\bigg|_{G_{cf}=0} + G_{cf}\left(\frac{h}{\theta_c}\right) \tag{19}$$

Now let

$$\frac{h}{h_c} = \left(\frac{s/\omega_{b_1}+1}{s/\omega_{b_2}+1}\right)^n \frac{h}{h_c}\bigg|_{G_{cf}=0} \tag{20}$$

where ω_{b_1} is the bandwidth of the altitude loop with $G_{cf}=0$ and ω_{b_2} the bandwidth of the altitude loop with crossfeed. Substituting Eq. (20) into Eq. (19) and letting $n=1$ for simplicity, one obtains

$$G_{cf} = \frac{h}{h_c}\left[\frac{(1/\omega_{b_1} - 1/\omega_{b_2})s}{s/\omega_{b_2}+1}\right] \bigg/ \frac{h}{\phi_c} \tag{21}$$

For the present example, $\omega_{b_1}=0.5$ rad/s and ω_{b_2} was selected as 0.8 rad/s. An adequate representation of the transfer function of Eq. (21) can be given as

$$G_{cf} = \frac{\text{K}19(11.1s^2+6.67s+1)}{3.33s^3+66.6s^2+331.3s-1} \tag{22}$$

Again, note the presence of nonminium phase dynamics. Figure 14 shows the altitude response to a 20-ft command with and without crossfeed. The improvement in performance is dramatic. Also shown is the crossfeed command θ_c'. It should be noted that although the crossfeed pitch attitude command has a maximum value of 20 deg, the resulting maximum pitch attitude is only 11 deg. The decrease in altitude evident in Fig. 14 beyond 10 s could be eliminated by including a low-frequency washout term in Eq. (22), effectively removing the nonzero steady-state pitch attitude also evident in the figure.

The ratio of the rms values of the appropriate u_m signals in a structural model representation of Y_{p_h} is

$$\frac{(\sigma_{uh})_{cf}}{\sigma_{uh}} \simeq 0.27 \tag{23}$$

A large improvement is predicted in the handling qualities for the altitude closure. This and the accompanying performance improvement would argue strongly for the likelihood of such a crossfeed being adopted by the pilot. It is interesting to note that, in describing the crossfeed technique analyzed here, Heffley et al.[16] state that "This pursuit crossfeed satisfies the prescribed Navy technique, but it brings about a quantum *decrease in pilot workload* (increase in excess control capacity) with a commensurate *improvement in flight-path performance.*" (Italics are those in Ref. 16.)

V. Conclusions

The preceding analysis has indicated that

1) Significant reductions in cross coupling in pilot-vehicle systems can occur with relatively simple crossfeed commands. Although, in some instances, the cross coupling in the examples was small without crossfeed activity (due to compensatory pilot model activity in the disturbed loops and/or the actions of stability augmentation systems), the relative reductions in cross coupling that accrued with crossfeed were significant.

2) The crossfeed commands derived are not only valid for a step command, per se, but for any maneuver in which the outer-loop command is generated as a series of steps consonant with a sample-and-hold strategy. Thus, it would appear that such crossfeed commands can be learned by the pilot and applied in a pursuit or even precognitive fashion.

3) The handling-qualities analysis technique utilized is, in theory at least, applicable to the multiloop tasks studied here. The technique is very simple to apply once the multiloop pilot-vehicle analysis is complete and a simulation of the pilot-vehicle system is implemented. It allows an axis-by-axis evaluation of the effects of altered pilot control strategy, such as the use of crossfeed.

4) The crossfeed modeling technique should now be applied to the analysis of performance and handling-qualities data from manned simulation (ground-based or in-flight) where the amount and nature of cross coupling have been experimental variables.

Acknowledgments

This research was supported by a postbaccalaureate grant through the Flight Dynamics and Controls Branch of NASA Ames Research Center. The assistance of Dr. Robert T. N. Chen of that branch is gratefully acknowledged.

References

[1]Hoh, R. H. and Ashkenas, I. L., "Handling Quality Criterion for Heading Control," *Journal of Aircraft*, Vol. 14, Feb. 1977, pp. 142-150.

[2]Heffley, R. K., "A Compilation and Analysis of Helicopter Handling Qualities Data, Vol. II: Data Analysis," NASA CR-3145, Aug. 1979.

[3]Hoh, R. H. et al., "Development of Handling Quality Criteria for Aircraft with Independent Control of Six Degrees of Freedom," AFWAL-TR-81-3207, April 1981.

[4]Kelley, H. L., Pegg, R. J., and Champine, R. A., "Flying Quality Factors Currently Limiting Helicopter Nap-of-the-Earth Maneuverability as Identified by Flight Investigation," NASA TN D-4931, Dec. 1968.

[5]McRuer, D. T., Graham, D., and Ashkenas, I., *Aircraft Dynamics and Automatic Control*, Princeton University Press, Princeton, NJ, 1972.

[6]McRuer, D. T. and Krendel, E. S., "Mathematical Models of Human Pilot Behavior," AGARDograph-AG-188, Jan. 1974.

[7]Hess, R. A. and Beckman, A. A., "An Engineering Approach to Determining Visual Information Requirements for Flight Control Tasks," *IEEE Transactions on Systems, Man and Cybernetics*, Vol. SMC-14, March/April 1984, pp. 286-298.

[8]Hess, R. A., "Pursuit Tracking and Highter Levels of Skill Development in the Human Pilot," *IEEE Transactions on Systems, Man and Cybernetics,* Vol. SMC-11, April 1981, pp. 262-273.

[9]Heffley, R. K., "Pilot Models for Discrete Maneuvers," AIAA Paper 82-1519-CP, Aug. 1982.

[10]Allen, R. W., Clement, W. F., and Jex, H. R., "Research on Display Scanning, Sampling, and Reconstruction Using Separate Main and Secondary Tracking Tasks," NASA CR-1569, July 1970.

[11]Hess, A. and Sunyoto, I., "Toward a Unifying Theory for Aircraft Handling Qualities," *Journal of Guidance, Control and Dynamics*, Vol. 8, July-Aug. 1985, pp. 440-446.

[12]Hess, R. A., "A Structural Model of the Adaptive Human Pilot," *Journal of Guidance and Control*, Vol. 3, Sept.-Oct. 1980, pp. 416-423.

[13]Heffley, R. K., et al., "A Compilation and Analysis of Helicopter Handling Qualities Data, Vol. 1: Data Compilation," NASA CR-3144, Aug. 1979.

[14]Heffley, R. K. and Jewell, W. F., "Aircraft Handling Qualities Data," NASA CR-2144, Dec. 1972.

[15]Craig, S. J., Ringland, R. F., and Ashkenas, I. L., "An Analysis of Navy Approach Power Compensator Problems and Requirements," Systems Technology Inc., Hawthorne, CA, TR 197-1, March 1971.

[16]Heffley, R. K., Clement, W. F., and Craig, S. J., "Training Aircraft Design Considerations Based on the Successive Organizations of Perception in Manual Control," *Proceedings of the Sixteenth Annual Conference on Manual Control*, Massachusetts Institute of Technology, 1980, pp. 119-127.