Closed-Loop Assessment of Flight Simulator Fidelity

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An analytical methodology is presented for the preliminary assessment of piloted flight simulator fidelity. The hypothesis that forms the central theme of the methodology is that many major simulator fidelity problems stem from simulator limitations that adversely affect the pilot's innermost feedback control loop, referred to here as the "primary control loop." This loop is the most critical in terms of task performance and the pilot's evaluation of vehicle handling qualities. The proposed methodology, based on a pilot/vehicle analysis of the vehicle and tasks being simulated, has the potential for serving as a tool for the rapid diagnosis of simulator fidelity problems. Selected results from experiments involving both flight test and piloted simulation of a UH-60A rotorcraft in a pair of demanding vertical and lateral hover tasks are used to exercise the methodology and indicate its potential.

Introduction

THE increased reliance on piloted flight simulation for research and training emphasizes the importance of simulation fidelity. Fidelity can be defined as "the degree to which characteristics of perceivable states induce adequate pilot psychomotor and cognitive behavior for a given task and environment."[1] Adequate pilot psychomotor and cognitive behavior implies piloting technique and performance that is equivalent to what would be obtained in flight. The problem of flight simulator fidelity can be approached by measuring piloting technique and performance in the simulator and then comparing these attributes to those measured in flight test. Pilot describing functions provide a pertinent measure of piloting technique and have been obtained in both flight[2] and simulation.[3] However, flight test data will be extremely rare in simulator research applications and probably not much more common in the training area despite the availability of the "real article" for study. This leads somewhat naturally to investigating the feasibility of using control theoretic models of the human pilot as a predictive tool in simulator fidelity studies.

Considerable progress has been made in the area of human performance modeling,[4] especially in the area of feedback control models of the human pilot.[5] It is these latter models that are of interest in this study. Although the use of feedback control models to explain fine-grained human pilot behavior in the control of dynamic systems such as aircraft is still something of an art, their utility in predicting fundamental closed-loop man/machine characteristics is well established. It is this utility that will be exploited in the research to be described.

Pilot Model

Figure 1 is a diagram of the structural pilot model to be used in this study. The model has been discussed thoroughly in the literature, e.g., Ref. 6, and will not be discussed in detail here. The model includes the effects of motion cues, and Fig. 1 shows output rate being sensed by the vestibular system then fed back to higher levels of the central nervous system where visual tracking error information is received. Output rate is assumed to be equivalent to a linear or angular acceleration in this model. The model of Fig. 1 is essentially an information processing model and does include the dynamics of the vestibular system, which is responsible for motion sensing. Extension of the structural model to include motion cues is discussed in Ref. 7. Model parameter selection is outlined in the following section.

Although the structural model of Fig. 1 is essentially a single-input, single-output model, it can be applied to multi-input, multi-output manual flight control problems through a multiloop topology such as shown in Fig. 2. Figure 2 shows a feedback structure appropriate for a rotorcraft bob-up maneuver, which will be discussed in what follows. Here, pilot dynamics are summarized in the transfer functions Yp_h and $Yp_{\dot{h}}$. The structural model includes only the pilot dynamics $Yp_{\dot{h}}$ in the innermost or "primary control loop," here concerned with vertical velocity control. This loop is defined as the one involving direct manipulative inputs to the vehicle by the pilot. In Fig. 2, these manipulative inputs occur through deflection of the rotorcraft collective control.

Modeling Methodology

Model Parameter Selection

The hypothesis that forms the central theme of this study is that many major simulator fidelity problems stem from simulator limitations that adversely affect the pilot's primary control loop. Major fidelity problems refer to those that would be manifested in significant differences in handling qualities ratings or task performance between simulation and flight test, were the latter available for comparison. The proposed modeling methodology for simulator fidelity assessment has the potential for uncovering such major fidelity problems early in the development of a simulation study. The methodology can be summarized as follows:

1) The particular vehicle and flight task to be simulated are selected.

2) Mathematical models for the vehicle are obtained for a) the flight vehicle, herein referred to as the "nominal" vehicle, and b) the simulated vehicle. This implies documenting all pertinent simulation system characteristics such as motion system dynamic response and time delays, etc.

3) A control strategy for the particular vehicle and task being simulated is developed. Successful precedents for accomplishing this step exist, e.g., Refs. 8–10. The term control strategy means a) a feedback topology indicating which sensory variables are being used by the pilot, and b) their dynamic relationship to the control variable(s) available to

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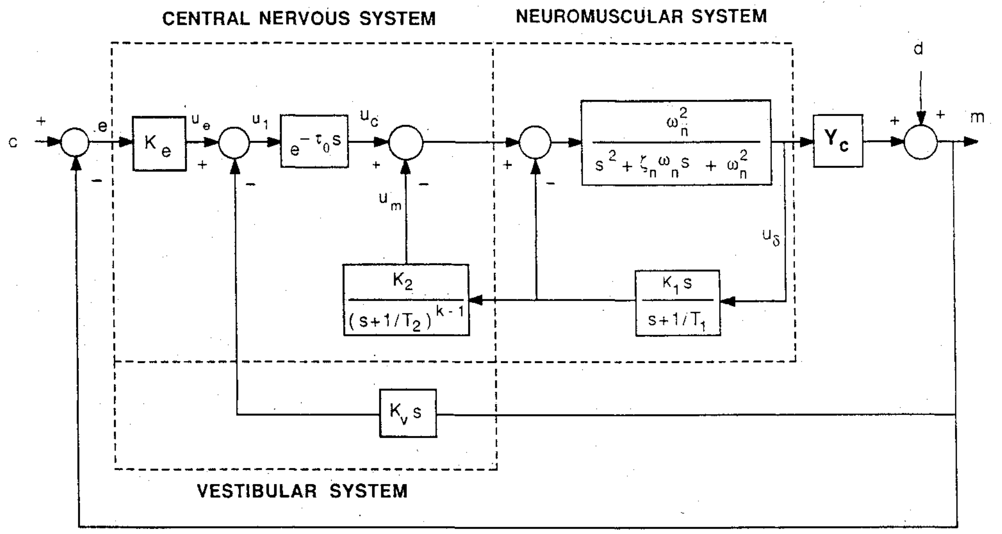

Fig. 1 Structural model of the human pilot including motion cues.

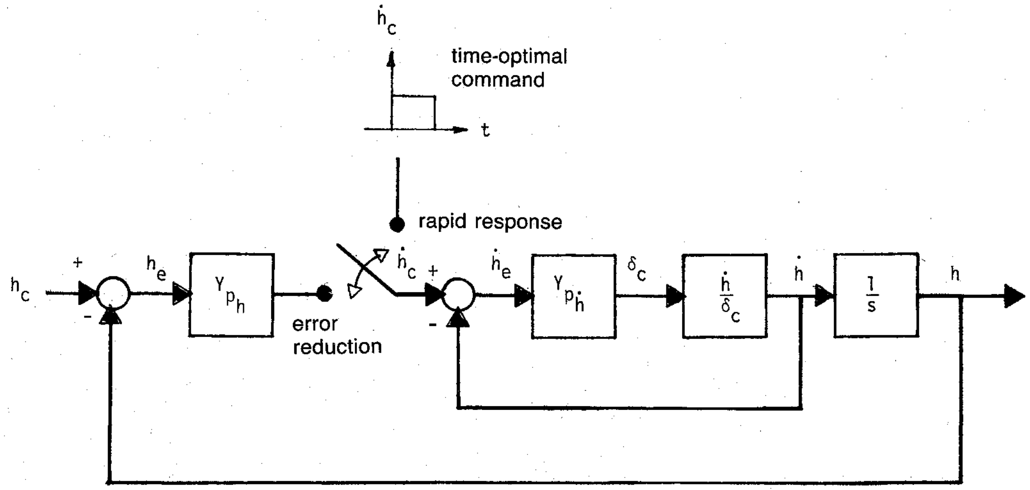

Fig. 2 Hypothesized pilot control strategy for bob-up maneuver.

the pilot, i.e., the pilot transfer functions. This includes establishing crossover frequencies. In addition, in the case of discrete maneuvering tasks, determining control strategy means including the possibility of time-optimal pilot control behavior.

4) The structural model is used to predict pilot dynamics for the primary control loop(s) for the nominal and simulated vehicles. Model parameter selection can be summarized as follows:

a) With the exception of the motion feedback gain K_v, structural model parameters are selected from Table 1 based on the order of the primary control loop, controlled element dynamics in the estimated region of frequency crossover. This order determines the k value in the first column of Table 1, i.e., zero order means $k = 0$, first order means $k = 1$, etc.

b) The control sensitivity for the primary loop controlled element is selected so that a crossover frequency is achieved with phase margin (PM) and gain margin (GM) of

$$\text{PM} = 45\ \text{deg} \quad \text{and} \quad \text{GM} > 4\ \text{dB} \tag{1a}$$

or

$$\text{GM} = 4\ \text{dB} \quad \text{and} \quad \text{PM} > 45\ \text{deg} \tag{1b}$$

These values represent adequate stability margins for the primary manual control loops. Requiring the same level of relative stability for both nominal and simulated vehicles reduces the sensitivity of the modeling procedure to the particular values given in Eqs. (1). Selection of control sensitivity by the analyst removes this parameter as a variable in simulation fidelity assessment and, if desired, allows the analyst to use the handling qualities prediction scheme presented in Ref. 8 as part of the fidelity assessment methodology. The handling qualities prediction scheme was not used in this study, however. At this stage, the pilot model described by u_δ/u_e in Fig. 1 should follow the dictates of the crossover model of the human pilot,[5] i.e., $u_\delta/e = \omega_c\{\exp(-\tau_e s)\}/s$.

c) If the crossover frequency obtained from step 2 results in a different k value than that chosen in step 1, repeat steps 1 and 2.

d) Choose the motion cue gain K_v so that the lowest damping ratio of any oscillatory roots in the transfer function, m/u_e, of Fig. 1 is $\zeta = 0.15$. This value represents a trade-off between stability and the high-frequency phase-lag reduction, which is the *raison d'être* of motion feedback.[7] As was the case with the gain and phase margins of Eqs. (1), requiring the same level of relative stability (or minimum damping ratio) for both nominal and simulated vehicles reduces the sensitivity of the modeling procedure to the particular value chosen.

e) Determine the crossover frequency again with the motion loop closed and including any visual time delays that might occur in the simulation. Adjust the gain K_e to obtain a crossover frequency that meets the criteria of Eqs. (1).

Table 1 Nominal parameter values for structural model

k	K_e	K_1	K_2	T_1, s	T_2, s	τ_o, s	ζ_n	ω_n, rad/s
0	1.0	1.0	2.0	5.0	[a]	0.15	0.707	10.0
1	1.0	1.0	2.0	5.0	[b]	0.15	0.707	10.0
2	1.0	1.0	10.0	2.5	[a]	0.15	0.707	10.0

[a]Selected to achieve K/s-like crossover characteristics.
[b]Parameter not applicable.

Fidelity Assessment

Simulator fidelity for the primary control loop is reflected in the similarity of the predicted pilot/vehicle dynamics for the nominal and simulated vehicles; i.e., 1) the similarity of predicted pilot transfer functions around the crossover frequency for the nominal vehicle, and 2) the similarity of the primary closed-loop transfer functions. This last requirement serves as a means of guaranteeing comparable performance between nominal and simulated vehicles.

Item 1 has a certain face validity based on the definition of simulator fidelity offered in the Introduction, i.e., the reproduction of the same piloting techniques in the simulator as would occur in flight. In terms of pilot models, piloting technique is reflected in the form of the pilot transfer functions. Similar or even identical piloting techniques may still not guarantee fidelity if the resulting pilot/vehicle performance between simulator and flight are dissimilar. Thus, item 2 requires similarity between closed-loop transfer functions for the primary loop. Interpretation of what constitutes similar transfer functions in both of these cases obviously can involve engineering judgment.

Similarity of pilot transfer functions for the nominal and simulated vehicle around the crossover frequency determined in step 4e for the nominal vehicle can best be determined by comparison of the Bode plots for u_δ/u_e in Fig. 1. Gain K_e is bypassed because control sensitivity is determined by the analyst in step 4b. Basically what is required is nearly identical magnitude and phase characteristics in u_δ/u_e over a limited frequency range commensurate with the applicability of the crossover model. Here this range will be chosen as approximately one half decade (approximately a factor of 3.0) above and below the crossover frequency for the nominal vehicle.

Similarity of the primary closed-loop transfer function is most easily quantified in terms of bandwidth. Defining closed-loop bandwidth as the frequency at which the phase lag first reaches -90 deg, the approach here will be to require that the bandwidths of the primary closed-loop transfer functions should not differ by more than one-fourth of a decade, or a factor of approximately 1.5. It should be apparent that this 1.5 factor is approximate and is intended to serve simply as a general guideline in the methodology.

The question might arise at this juncture as to why a pilot/vehicle analysis is required in this somewhat limited appraisal of simulator fidelity. Would not a simple comparison of models of the nominal and simulated vehicles, including simulator limitations, suffice as well? The problem with this approach is that differences between nominal and simulated vehicle models will always exist, even in simulated tasks where no fidelity problems are apparent. A good example of this is in the area of simulator motion cuing. The physical limitations of piloted ground-based (as opposed to in-flight) simulators means that in nearly all simulations motion washout circuits must always be included in the simulator motion drive. Obviously, in these cases, large differences exist between nominal and simulated vehicle dynamics, and these differences occur at frequencies near the crossover frequency of the associated primary control loop. It is not the differences themselves, but their effect on piloting technique and pilot/vehicle performance that determines fidelity in such cases. It is the desire to predict such differences that motivates the approach offered here.

Simulation/Flight Test Experiments

The research summarized in Refs. 11 and 12 offers an excellent source of experimental results for the exercise of the methodology proposed here. The work of Refs. 11 and 12 involved a quantitative comparison between piloting technique observed in the NASA Ames Research Center moving-base Vertical Motion Simulator and that observed in flight test for the same tasks being performed by the same pilots in the "same" nominal and simulated vehicle: the UH-60A Black Hawk rotorcraft. Simulation tests preceded the flight tests from one to two months. Simulator characteristics such as motion system dynamics and effective time delays were documented and a number of low-speed tasks or maneuvers were examined. These included the bob-up, hover-turn, dash/quickstop, sidestep, dolphin, and slalom maneuvers. The bob-up and sidestep maneuvers were selected for application of the methodology proposed herein.

The bob-up maneuver is a classic rotorcraft nap-of-the-Earth maneuver and is used for scouting, target designation, or antitank missile launching. In the studies of Refs. 11 and 12, the pilots were instructed to vertically translate from a low-altitude (bob-up) hover to an altitude that allowed the visual acquisition of a specific outside visual target and then to stabilize for 20 s. The bob-up altitude was typically around 50 ft.

The sidestep maneuver provided an evaluation task similar in complexity and combat realism to the bob-up maneuver, but exercising pilot skill in the lateral and roll axes as opposed to the vertical axis. The pilots were requested to translate laterally to the left or right from a low-altitude hover, acquire a target, and stabilize for 20 s. The lateral translation was approximately 40 ft.

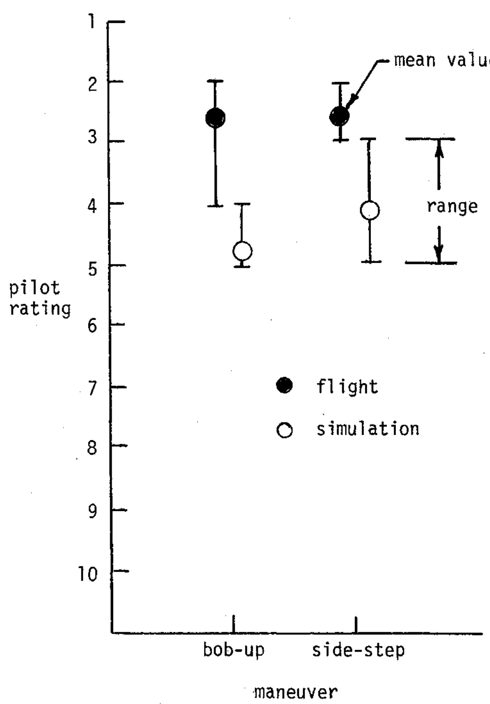

Fig. 3 Pilot ratings for flight test and simulation.

Figure 3 summarizes the mean handling qualities ratings averaged across the five evaluation pilots for the bob-up and sidestep maneuvers in flight (nominal vehicle) and simulator (simulated vehicle). The vertical bars indicate the range of ratings. As the figure indicates, there is no overlap in the handling qualities ratings (HQR), indicating that significant simulator fidelity problems were in evidence. Indeed, the difference in the mean ratings for the bob-up maneuver was the largest for any of the six maneuvers studied, whereas that for the sidestep was the third largest, behind the dolphin. All differences in mean ratings were found to be statistically significant at the 90% level by Behrens' test.[11,12] Detailed pilot comments also accompanied the HQRs summarized in Fig. 3 and further supported the existence of fidelity problems in the simulation. Thus, the bob-up and sidestep maneuvers offer excellent test cases for the proposed methodology. It should be added that differences in HQRs between nominal and simulated vehicles are sufficient but not necessary conditions for the existence of fidelity problems.

In addition to the simulation fidelity problems implied by the differences in HQRs, all the pilots in the simulation of the side-step maneuver experienced roll attitude, pilot-induced oscillations (PIOs) to some degree before and after the maneuver. The ubiquity of these PIOs in simulation and the fact that none occurred in the flight tests offers objective proof of the existence of fidelity problems in this task.

Methodology Applied

Bob-up Maneuver

Following the steps outlined in the section on modeling methodology, the vehicle and flight task have been chosen, and the pertinent mathematical models are available for nominal and simulated vehicle from the research summarized in Refs. 11 and 12, including simulator characteristics. Figure 2 shows the authors' selection for the control strategy for the bob-up maneuver. Following the lead of Refs. 11 and 12, the control strategy has been broken up into "rapid response" and "error-reduction" phases. In both phases, the primary control loop is the one controlling vertical velocity through the collective control. Note that, in the rapid-response phase, no feedback of position error is assumed to occur and the vertical velocity command $\dot h c$ is assumed to be generated as a time-optimal command by the pilot. The nature of this time-optimal command will not be discussed here. At the conclusion of the time-optimal inputs, small position errors are corrected in the error-reduction phase. Here, of course, position error information is used. In both phases, the primary control loop is the one controlling altitude rate through the collective control. The rapid-response phase will be addressed first.

Rapid-Response Phase

This phase is described by Fig. 2 with the switch in the "up" position. The vertical velocity to collective input transfer functions for the rapid-response phase for nominal and simulated vehicles were obtained by the authors using the frequency response data collected in the research reported in Refs. 11 and 12. These transfer functions are the following:
Nominal vehicle

$$\frac{\dot h}{\delta_c} = \frac{1.92(0.153s+1)e^{-0.121s}}{(3.68s+1)}\ (\text{ft/s})/\% \tag{2}$$

Simulated vehicle

$$\frac{\dot h}{\delta_c} = \frac{1.69(0.125s+1)e^{-0.195s}}{(2.65s+1)}\ (\text{ft/s})/\% \tag{3}$$

In addition, the simulator washout characteristics, again obtained from frequency response measurements conducted as part of the research reported in Refs. 11 and 12, can be given as

$$\frac{\dot h_{wo}}{\dot h} = \frac{1.79se^{-0.0428s}}{(2.04s+1)} \tag{4}$$

In the structural model, the washout dynamics were included in the block with $K_v s$ in Fig. 1. Finally, a time delay of 0.14 s was encountered in the simulation, as was associated with the visual scene generation. This was included in the analysis and will be referred to as a visual time delay in what follows. The motion washout and visual time delay were the only simulator limitations that were included in this analysis. It was assumed that the simulated visual scene was capable of providing the vertical velocity cues required by the $\dot h$ feedback loop in Fig. 2.

Figure 4 compares the corresponding closed-loop transfer functions $\dot h/\dot h_c$. Using the frequency at which the phase angle reaches -90 deg as a bandwidth criterion, Fig. 4 indicates that the approximate vertical velocity control bandwidths are seen to be 4.95 and 2.78 rad/s for the nominal and simulated vehicles, respectively. The bandwidths are seen to differ by a factor of 1.78, which, by the definition adopted in the section on modeling methodology, identifies the transfer functions as dissimilar. Thus, one sees that simulator fidelity problems should be assumed to exist. The first two rows of Table 2 indicate the structural pilot model parameters for the analyses. A comparison of the pilot transfer functions u_δ/u_e for nominal and simulated vehicles in a frequency range a factor of 3.0 above and below the crossover frequency of the nominal pilot/vehicle system (2.89 rad/s) revealed no significant differences.

Error-Reduction Phase

This phase is described by Fig. 2 with the switch in the "down" position. Since the outer loop of Fig. 2 is not a primary control loop, the pilot transfer function Yp_h is formulated as a proportional-integral-derivative (PID) controller using the crossover model of the human pilot. A useful rule of thumb for selecting outer-loop crossover frequency is to separate the crossover frequencies of the inner and outer loops by approximately a factor of 4.[8] Since the vertical velocity loop

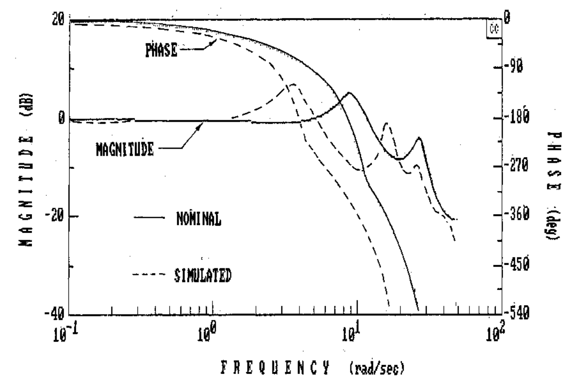

Fig. 4 $\dot h/\dot h_c$ pilot/vehicle closed-loop transfer functions.

Table 2 Parameter Values for Structural Model Simulator Fidelity Assessment[a]

Vehicle	K_e	K_v	ω_c, rad/s	Task
Nominal	1.0	0.03	2.89	Bob-up
Simulated	0.82	0.02	2.27	Bob-up
Nominal	1.0	0.15	1.78	Sidestep
Simulated	0.90	0.20	1.38	Sidestep

[a]Remaining model parameters identical to those in second row of Table 1.

for the nominal and simulated vehicles had crossover frequencies of 2.89 and 2.27 rad/s, respectively, the outer position loop in Fig. 2 should have crossover frequencies for the nominal and simulated vehicle of 0.72 and 0.57 rad/s, respectively. In this frequency range, the effective controlled elements $h/\dot{h}_c$ in Fig. 2 both have first-order characteristics, i.e., they resemble K/s dynamics. Thus, according to the crossover model of the human pilot, Yp_h should have the form $Yp_h = K_h$ for both nominal and simulated vehicles. Figure 5 shows the Bode diagrams for the transfer functions h/h_e for the nominal and simulated vehicles. The K_h values have been chosen as 0.69 and 0.61 for the nominal and simulated vehicles, respectively, to give the desired crossover frequencies of 0.72 and 0.57 rad/s.

The Bode diagrams in Fig. 5 indicate that the pilot could increase the crossover frequency of the outer loop for the nominal vehicle to approximately 1 rad/s with a phase margin of approximately 65 deg and a gain margin of over 7 dB. If the pilot were to attempt the same 1 rad/s crossover frequency in the simulator, although the phase margin would not change appreciably, the gain margin would decrease to < 4 dB. This value is less than that required in the primary control loop and would be inadequate for an outer position loop where stability margins must allow for relatively large variations in pilot gain and effective time delays.

The research of Refs. 11 and 12 reported outer-loop pilot/vehicle crossover frequencies in the error-reduction phase of the bob-up maneuver that ranged from 0.7 to 1.1 rad/s in flight and from 0.5 to 1.3 rad/s in simulation. The values at the lower extreme of these experimental frequency ranges are seen to be close to those predicted with the factor-of-four rule of thumb, whereas the values at the upper extreme are close to the 1 rad/s crossover frequency just discussed. It should be noted that the pilots consistently complained about poor heave damping in the bob-up task in the simulator.[11,12] However, the heave damping in the simulated vehicle was adequate. The analysis herein suggests that the inadequate stability margins resulting from the pilots' attempt to adopt the same outer-loop crossover frequency in the simulator as was possible in flight (where adequate stability margins did exist) may have led the pilots to suspect inadequate heave damping in the simulator.

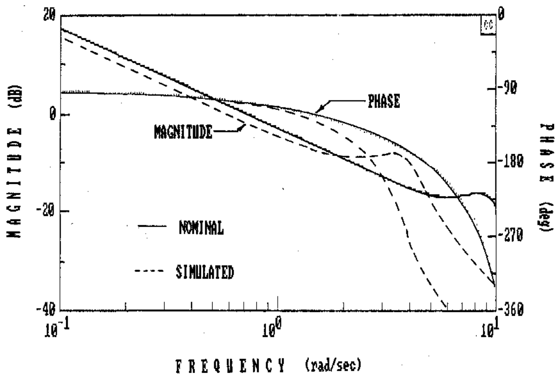

Fig. 5 h/h_e pilot/vehicle transfer functions.

Sidestep Maneuver

Following the steps outlined in the section on modeling methodology, the vehicle and flight task have been chosen, and the pertinent mathematical models are available for nominal and simulated vehicles from the research summarized in Refs. 11 and 12. Figure 6 shows the authors' selection for control strategy for the sidestep maneuver. Again, rapid-response and error-reduction phases have been hypothesized. As in the case of the bob-up maneuver, the roll attitude command for the rapid-response phase is assumed to be generated as a time-optimal control input by the pilot. The nature of this time-optimal input will not be discussed here. At the conclusion of the time-optimal inputs, small position errors are corrected in the error-reduction phase. Here, of course, position error information is used. In both phases, the primary control loop is the one controlling roll attitude through the lateral cyclic control. The rapid-response phase will be addressed first.

Rapid-Response Phase

The roll attitude to lateral cyclic input transfer functions for the nominal and simulated vehicles were obtained by the authors using the frequency response data collected in the research reported in Refs. 11 and 12. These transfer functions are the following:

Nominal vehicle

$$\frac{\phi}{\delta_a} = \frac{0.887}{s(s^2/7.7^2 + 2(0.396)s/7.7 + 1)} \text{ deg/\%} \tag{5}$$

Simulated vehicle

$$\frac{\phi}{\delta_a} = \frac{1.284e^{-0.023s}}{s(s^2/6.76^2 + 2(0.4)s/6.76 + 1)} \text{ deg/\%} \tag{6}$$

The simulator washout characteristics obtained from frequency response measurements conducted as part of the research reported in Refs. 11 and 12 can be given as

$$\frac{\phi_{wo}}{\phi} = \frac{se^{-0.097s}}{(s+1)(s/10+1)} \tag{7}$$

Again a 0.14 s visual time delay was encountered in the simulation and was included in the ϕ feedback loop of Fig. 6.

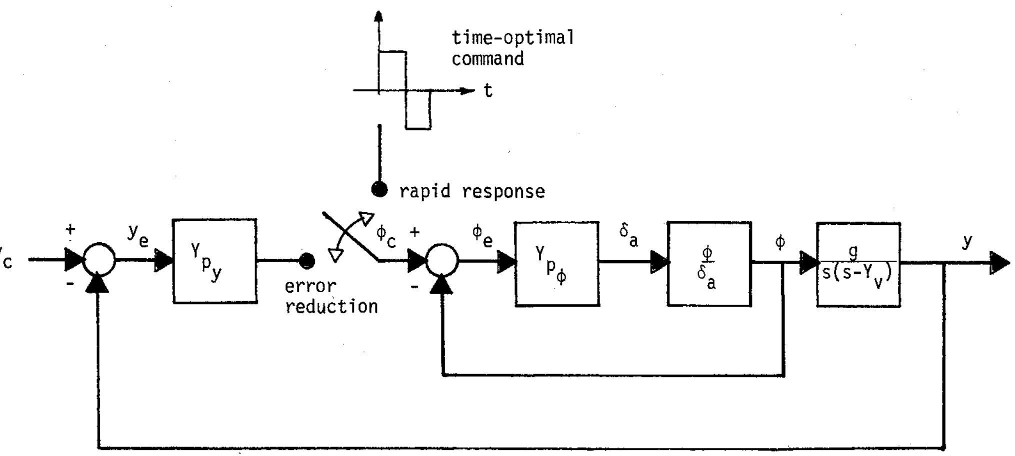

Fig. 6 Hypothesized pilot control strategy for sidestep maneuver.

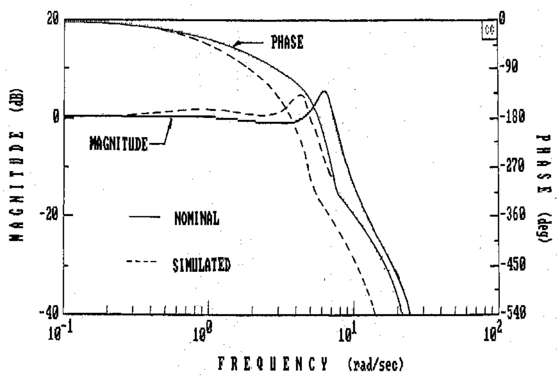

Fig. 7 ϕ/ϕ_c pilot/vehicle closed-loop transfer functions.

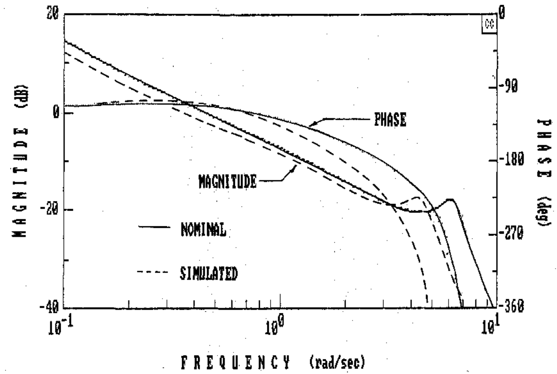

Fig. 8 y/y_e pilot/vehicle transfer functions.

The motion washout and time delay were the only simulator limitations included in the analysis.

Figure 7 compares the closed-loop transfer functions $\phi/\phi c$. Using the same bandwidth definition as for the bob-up maneuver, the approximate attitude control bandwidths are 3 and 1.92 rad/s for the nominal and simulated vehicles, respectively. The bandwidths differ by a factor of 1.56, which identifies the transfer functions as dissimilar. Continuing with the methodology of the previous section, one again sees that simulator fidelity problems should be assumed to exist. The last two rows of Table 2 indicate the structural pilot model parameters for the analyses. As in the case of the bob-up maneuver, a comparison of the pilot transfer functions u_δ/u_e of a factor of 3 above and below the 1.78 rad/s crossover frequency revealed no differences.

Error-Reduction Phase

Since, as previously defined, the outer loop in Fig. 6 is not a primary control loop, the pilot transfer function Yp_Y is formulated as a PID controller using the crossover model. The roll attitude loop for the nominal and simulated vehicles employed crossover frequencies of 1.78 and 1.38 rad/s, respectively. Thus, employing the rule of thumb for crossover separation between inner and outer loops, the outer position loop in Fig. 6 should have crossover frequencies for the nominal and simulated vehicles of 0.45 and 0.35 rad/s, respectively. Using the dynamics of the UH-60A, as before, and including the y/ϕ transfer function with $Y_v = -0.0465$ 1/s, the effective controlled elements y/ϕ_c in this frequency range in Fig. 6 both have second-order characteristics, i.e., they resemble K/s^2 dynamics. Thus, according to the crossover model of the human pilot, for both nominal and simulated vehicles, Yp_y should have the form $Yp_Y = \phi_c/y_e = K_Y[T_L s + 1]$. This means that $\phi_c = [K_Y T_L]\dot{y}_e + K_Y y_e$. The latter equation assumes that, in the simulation, appropriate visual cues are available for the pilot to obtain the feedback quantities $\dot{y}_e$ and y_e.

Figure 8 shows the Bode diagrams for the transfer functions y/y_e for the nominal and simulated vehicles when the

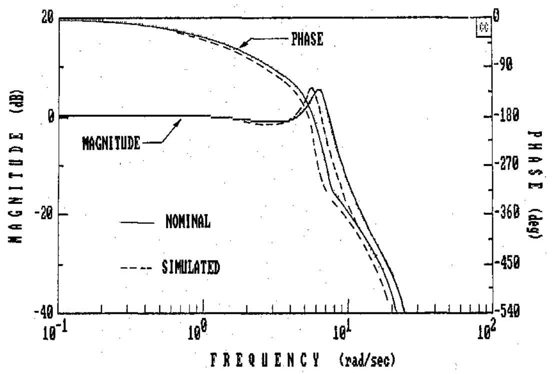

Fig. 9 ϕ/ϕ_c pilot/vehicle closed-loop transfer functions, simulation without visual time delay.

Yp_Y just given is used. In both cases, the lead time constant T_L has been chosen as 10 s. The K_Y values have been chosen as 0.00131 and 0.000935 for the nominal and simulated vehicles, respectively, to yield the aforementioned outer-loop crossover frequencies of 0.45 and 0.35 rad/s.

As in the case of the bob-up maneuver, examining the Bode diagram for the nominal system in Fig. 8 reveals that the outer-loop crossover frequency could be increased to 1 rad/s and still have an adequate phase margin of approximately 50 deg. However, if the pilot were to attempt to employ the same 1 rad/s crossover frequency in the simulator, the phase margin would be reduced to approximately 35 deg. This value is less than that required in the primary control loop and would be unacceptable for an outer position loop. Unfortunately, no crossover frequency measurements were reported in Refs. 11 and 12 for the sidestep maneuver.

All the pilots exhibited PIOs to some degree in the simulation before and after each of the sidestep maneuvers. However, none of the pilots exhibited PIOs in flight. The average frequency of the PIOs sampled in Refs. 11 and 12 was 1.44 rad/s, with maximum and minimum frequencies of 2.5 and 1.14 rad/s. Were the PIOs to be catalyzed by the pilots' attempt to achieve the same outer-loop crossover frequency in the simulator as in flight, the PIO frequency would be comparable to the frequency for the simulated outer-loop pilot/vehicle transfer function in Fig. 8 where the phase passes through −180 deg. This frequency is seen to be approximately 1.9 rad/s, which falls within the range of frequencies of the PIOs just mentioned.

Simulator Improvements

The methodology for the assessment of simulator fidelity that has been discussed here should also allow the analytical evaluation of the effect of changes in simulator limitations on the pilot/vehicle system. Although space does not allow a detailed discussion of this topic, a brief example is in order. Focusing on the sidestep maneuver, one can evaluate the benefits of eliminating 1) the 0.14 s visual time delay, 2) the motion washout dynamics [replacing the right side of Eq. (7) with unity], and 3) both the time delay and the washout dynamics. Eliminating motion washout dynamics is an admittedly impractical solution for improving the fidelity of a ground-based simulator; however, analyzing the effects of such a change would be pertinent if one were comparing the relative merits of ground-based vs in-flight simulation with a variable stability vehicle.

The steps in the modeling methodology for this task were repeated for each of the three system variations just mentioned. Figures 9–11 compare the closed-loop $\phi/\phi c$ transfer functions for the simulated and nominal vehicles with these changes. As the figures indicate, both changes make some improvement in the similarity of the primary closed-loop transfer functions. No differences in the pilot transfer func-

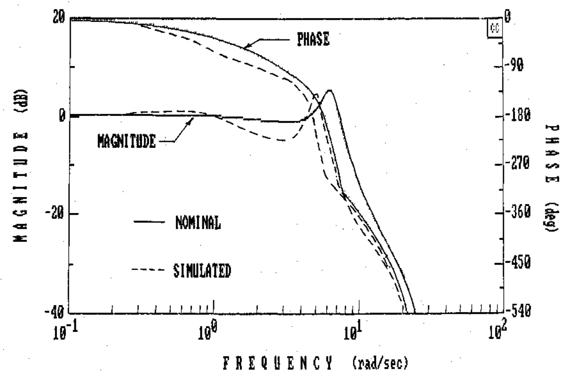

Fig. 10 **ϕ/ϕ_c pilot/vehicle closed-loop transfer functions, simulation without motion washout dynamics.**

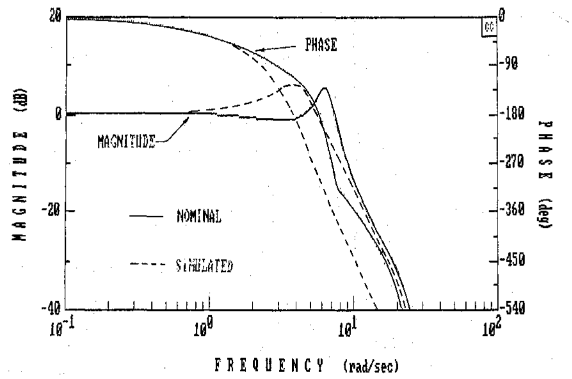

Fig. 11 **ϕ/ϕ_c pilot/vehicle closed-loop transfer functions, simulation without visual time delay and motion washout dynamics.**

tions u_δ/u_e were noted in the frequency range a factor of 3.0 above and below the crossover frequency of the nominal vehicle. Eliminating the motion constraints would, according to the bandwidth criterion adopted here, yield a simulation with pilot/vehicle transfer functions similar to those in flight. The biggest similarity is obtained when both visual time delay and motion system constraints are eliminated. These are not surprising results, but they are, nonetheless, reassuring since the methodology is sensitive to changes in simulator characteristics that bring the simulated vehicle into closer agreement with the nominal one. The remaining discrepancy between nominal and simulated vehicles in Fig. 11 is attributable to the differences in the roll attitude dynamics between nominal and simulated vehicles, i.e., Eqs. (5) and (6).

Discussion

Using the methodology proposed here, it is possible that an analysis of a simulated vehicle and task could indicate no potential fidelity problems but the simulation itself could be found to be unacceptable. This failure could have two causes. First, the fidelity problem may arise from sources outside the primary control loop. For example, the simulation of a lateral/directional flight task may provide adequate visual cues for roll attitude control, but not have sufficient field of view or texture for lateral flight path control. Second, the analyst may not have properly quantified a simulator limitation in the primary control loop. As an example, in the bob-up task that was studied here, it was assumed that adequate visual cues existed in the simulator for the pilot to sense vertical velocity $\dot{h}$ necessary for closing the primary control loop in the vertical axis. If this were not the case, the analyst would have to recognize and quantify this deficiency in terms of control theoretic variables that affect the modeling in the primary control loop. This is often not a trivial task. Of the two weaknesses just outlined, it is the second that is probably the more likely and that reduces the utility of the proposed methodology, which is concerned with the adequacy of the primary control loop alone. Work is currently underway to address this issue.

Summary

A relatively simple analytical methodology was employed for the preliminary assessment of the fidelity of the primary control loop in piloted simulations. It was hypothesized that many major fidelity problems stem from simulator limitations that adversely affect this control loop.

In analyzing a pair of piloting tasks for which flight and simulation data were available, the methodology indicated the existence of simulator fidelity problems that were experimentally verified by differences in both subjective and objective measures, i.e., pilot handling qualities ratings (with supporting comments) and pilot/vehicle performance.

The methodology permitted the analytical evaluation of three changes in simulator characteristics that brought the simulated vehicle into closer agreement with the nominal one: the elimination of a visual time delay, the elimination of motion washout dynamics, and a combination of these two changes. Each of these changes resulted in a prediction of improved simulator fidelity.

Research is continuing in the area of quantifying visual simulator limitations in a manner compatible with the control theoretic approach, which formed the basis of the methodology.

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