Theory for Aircraft Handling Qualities Based Upon a Structural Pilot Model

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A theory for describing the manner in which aircraft dynamic characteristics determine pilot opinion ratings of aircraft handling qualities is discussed. The theory centers upon the role of pilot rate feedback in continuous tracking. A structural model of the human pilot is used to quantify the amount of rate feedback the pilot is required to use in the control of an aircraft in a specific task. Using the model, 35 vehicle configurations that have been evaluated in manned simulation are analyzed. The tasks range from simple single axis, single-loop pitch attitude tracking to precision hover and landing approach, in which control of both vehicle position and attitude are required. The manner in which control system sensitivity affects pilot opinion rating is also investigated. The rate feedback theory is supported by the results of the model-based analyses, where it is shown that the mean square value of the rate feedback signal in the model correlates with the pilot opinion ratings obtained from experiment.

Introduction

HESS and Sunyoto[1] have discussed a pilot model based technique for assessing aircraft handling qualities that was derived from a theory introduced by Smith.[2] Smith's hypothesis centered upon a physical explanation for the manner in which the human pilot generates numerical opinion ratings of the handling qualities of a vehicle, such as an aircraft. Smith held that in any closed-loop tracking task, such as aircraft pitch attitude regulation in turbulence, pitch-*rate* control is of fundamental importance, both from the standpoint of pilot/vehicle system performance, and from the standpoint of perceived vehicle handling qualities. Smith held that a physiological measure for pilot opinion rating is the rate at which nerve impulses (or an equivalent measure) arrive at the point within the central nervous system where all signals due to rate control are summed or operated upon by a decision process. In Smith's view, the relation between pilot opinion rating and the nerve impulse rate is fixed for each pilot, and is dependent upon his piloting experiences, training, and personal interpretation of the rating scale. Finally, it was Smith's contention that a model for human pilot dynamics that structurally matches the human physiology in the tracking process will lead to a natural and physical measure for pilot opinion rating. It is the purpose of the research described here to interpret and extend both Smith's theory and the research of Ref. 1 by using a model for human pilot dynamics that appears ideally suited to the study of handling qualities.

Approach

Hess and Sunyoto interpreted Smith's theory using the model of Fig. 1[3] whose *raison d'etre* was to structurally match the human physiology in the man/machine tracking problem within the limitations of a relatively simple linear representation. The model of Fig. 1 has been shown capable of capturing the salient features of human pilot dynamic characteristics for a variety of vehicles and tasks. In addition, the inner feedback loop of the model is, in essence, a rate feedback loop, in that the signal u_m is proportional to system output rate dm/dt resulting from control inputs u_δ. In Ref. 1, the root mean square (or mean square) value of u_m was shown to vary monotonically with task difficulty, at least for the limited number of single-loop configurations examined therein.

In this study, the mean square value of u_m is shown to correlate with pilot opinion ratings expressed in either the Cooper-Harper or older Cooper pilot opinion rating scales in single *and* multiloop tasks. In addition, estimation of the values of the nine model parameters is simplified since, in many cases of engineering interest, five of the parameters ($K_e, K_1, \tau_0, \zeta_n, \omega_n$) can be considered fixed at nominal values, three (k, K_2, T_1) can be determined once the order of the vehicle dynamics in the region of the crossover frequency is known, and the final one (T_2) can be determined by requiring that the pilot/vehicle dynamics conform to the crossover model of the human pilot.[4]

Handling Qualities Analyses

Figures 2 and 3 show the pilot loop closures appropriate for the tasks to be analyzed here. In the multiloop tasks, the

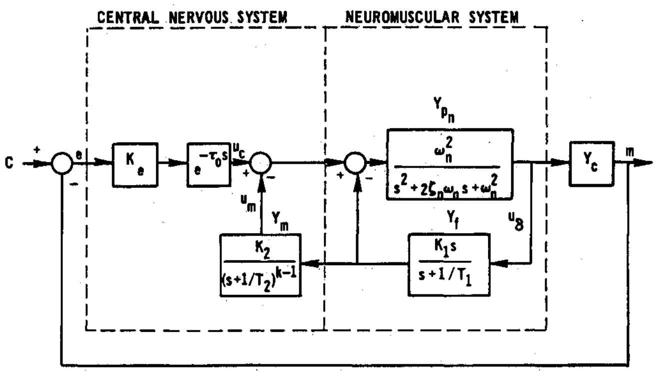

Fig. 1 A structural model of the human pilot.

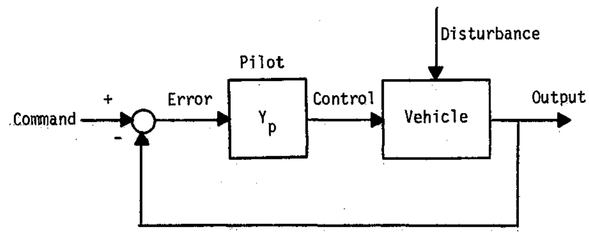

Fig. 2 A single-loop tracking task.

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structural model is employed only in the inner loop closure. This closure will be referred to as the "primary" closure herein, i.e., the one involving human interaction with a control manipulator. The required pilot compensation in the outer loop is obtained in the form of a proportional-integral-derivation (PID) controller, where the PID parameters are selected to give K/s-like open-loop characteristics around the outer-loop crossover frequency with the inner loop closed. Corroborative measurements have been reported that support such outer-loop compensation on the part of the pilot.[5]

The selection of crossover frequencies in the modeling approach for both the single- and multiloop tasks studied here deserves some comment. Inner- and outer-loop crossover frequencies are obviously important variables in any manual control task. These parameters essentially determine closed-loop system bandwidth, and consequently, system performance. A priori selection of crossover frequency in this study is simply an efficient and expedient means of transforming task performance requirements (as interpreted by the analyst) into a variable that is compatible with the structural model formulation with the goal of *assessing vehicle handling qualities*. For the pitch attitude command-following and regulation that defined the single-loop tasks studied here, a crossover frequency of 4.0 rad/s was selected. For the multiloop precision hover and landing approach tasks, the inner-loop crossover frequency was reduced to 0.3 rad/s and the outer-loop crossover frequency was selected as one-fourth the inner loop value. The 3 and 4 rad/s values are representative of the largest crossover frequencies attainable with closed-loop stability for all the configurations studied. Choosing the outer-loop crossover frequency as one-fourth the inner-loop value is a conservative specification derived from classical control system design principles.

The steps involved in setting up the structural model for a handling qualities evaluation using Smith's theory can now be outlined.

1) The task is analyzed and appropriate pilot loop closures are selected, e.g., Figs. 2 and 3.

2) The vehicle transfer function for the primary control loop is obtained.

3) An inner-loop crossover frequency is selected.

4) Given the primary loop vehicle transfer function and the specified crossover frequency, the paramter 'k' in the structural model of Fig. 1 is selected. The value of 'k' will depend upon whether gain ($k = 1$), lead ($k = 2$), or lag ($k = 0$) compensation is required, as dictated by the crossover model of the human pilot.

5) The remaining structural model parameters, save T_2, are selected from Table 1.

6) The parameter T_2 is chosen to ensure K/s-like pilot/vehicle characteristics around the inner-loop crossover frequency.

7) For reasons to be outlined in what follows, it is desirable to remove control system sensitivity issues from the handling qualities evaluation. To do this, the analyst adjusts the primary loop control sensitivity via the relation

$$K_s = \frac{1}{|Y_p(j\omega)_{\omega=\omega_c}|} \cdot \frac{1}{|Y_c(j\omega)_{\omega=\omega_c}|} \tag{1}$$

This equation ensures that the desired crossover frequency will be obtained, given the model parameter values of Table 1.

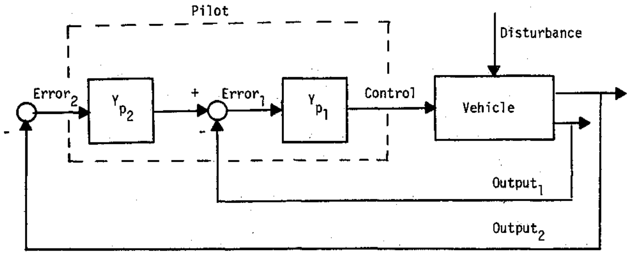
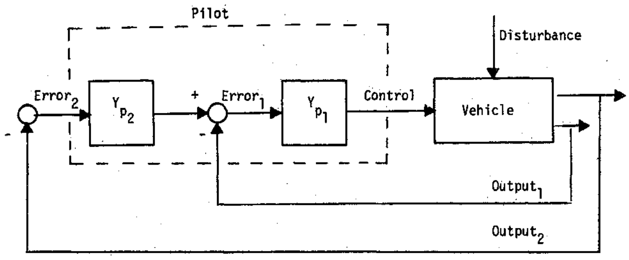


Fig. 3 A multiloop tracking task.



Control	=	longitudinal cyclic
Y_{P1}	=	structural model of Fig. 1
Y_{P2}	=	$K_y(T_L s + 1)$
Output_1	=	pitch attitude, θ
Output_2	=	longitudinal vehicle position, x
Vehicle	=	hovering helicopter
Disturbance	=	longitudinal gust velocity, u_g

Fig. 4 Longitudinal precision hover task of Ref. 6.

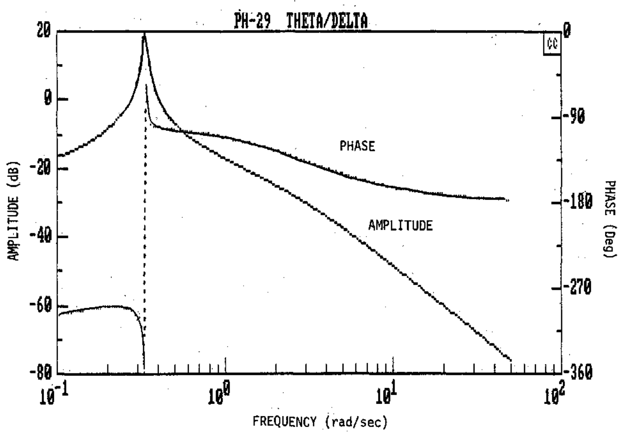


Fig. 5 Pitch attitude to longitudinal cyclic transfer function for configuration PH-29 from Ref. 6.

Table 1 Nominal parameter values for structural model

k	K_e	K_1	K_2	T_1, s	T_2, s	τ_0, 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.

8) If the task is multiloop in nature, the pilot compensation in the outer control loop(s) is selected as follows:

a) The appropriate outer-loop vehicle transfer function(s) are obtained.

b) Starting from the primary loop and working out, the crossover frequencies are reduced by a factor of four for each outer loop encountered.

c) Pilot compensation in the outer loops is kept very simple and limited to PID dynamics appropriate for creating K/s-like crossover characteristics for each outer, open-loop transfer function, with all inner loops closed.

9) The pilot/vehicle system is simulated using the disturbance and/or command signals employed in the experimental data base for which pilot opinion ratings have been obtained. The mean square value of the signal u_m is obtained. Although not included here, remnant injection can be a part of the modeling process.

Example

An example of applying steps (1–9) for a particular aircraft configuration and task will now be presented. The experimental data base is that of Ref. 6, that describes the results of a manned, fixed-base simulation of a precision helicopter hover task. The nine steps outlined in the previous section can be summarized for the analysis of configuration PH-29 from Ref. 6 as follows:

1) Figure 4 shows the pilot loop closures for the longitudinal hover task. The primary loop involves pitch attitude command-following and regulation, with an outer vehicle position loop closed around the attitude loop.

2) Figure 5 shows the Bode plot of the vehicle transfer function for the configuration under study.

3) A primary loop crossover frequency of 3.0 rad/s is selected.

4) Pilot lead compensation is required in order to obtain crossover model characteristics in the region of crossover. The lead time constant is 1/3 s and 'k' = 2.

5) Table 1 gives the structural model parameters, save T_2, associated with 'k' = 2.

6) T_2 is chosen as 0.3285 s, which places a zero in the structural model transfer function at $s = -1/T_2$ and cancels a pole in the aircraft hovering cubic characteristic polynomial. This leads to the desired broad K/s-like region in the open-loop Bode plot, as indicated in Fig. 6.

7) The primary loop control sensitivity is chosen via Eq. (1) as $K_e = 123.42$.

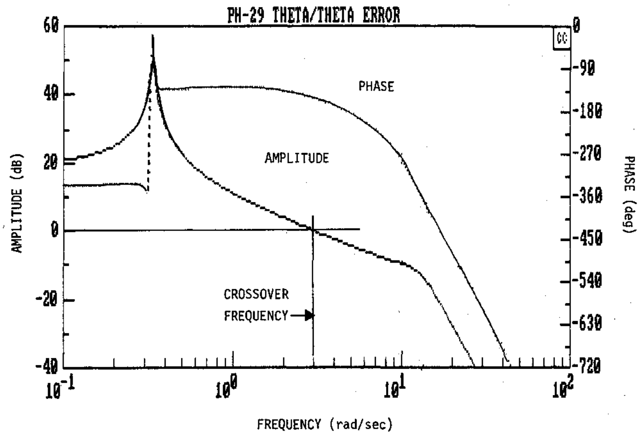


Fig. 6 Open-loop pilot/vehicle transfer function for configuration PH-29 from Ref. 6.

Table 2 Vehicle configurations analyzed

Miller and Vinje[6]	McDonnell[7]
PH-1	$1/s$ (1, 2)[a]
PH-13	$1/s(s+1)$ (1, 2)
PH-27	$1/s(s+2)$ (1, 2)
PH-28	$1/s(s+4)$ (1, 2)
PH-29	$1/s^2$ (1, 2)
PH-32	$1/s^2$ (2, 2)
PH-33	$1/s^2$ (2, 3)
PH-34	$1/(s^2+2(0.7)(16)s+16^2)$ (1, 2)
PH-37	
Arnold[8]	**Franklin[9] (after Picha[10])**
1D	2
2D	5
3A	11
4A	12
5A	15
10	22
11	24
12	28
14	29

[a](i, j) refers to pitch command characteristics.

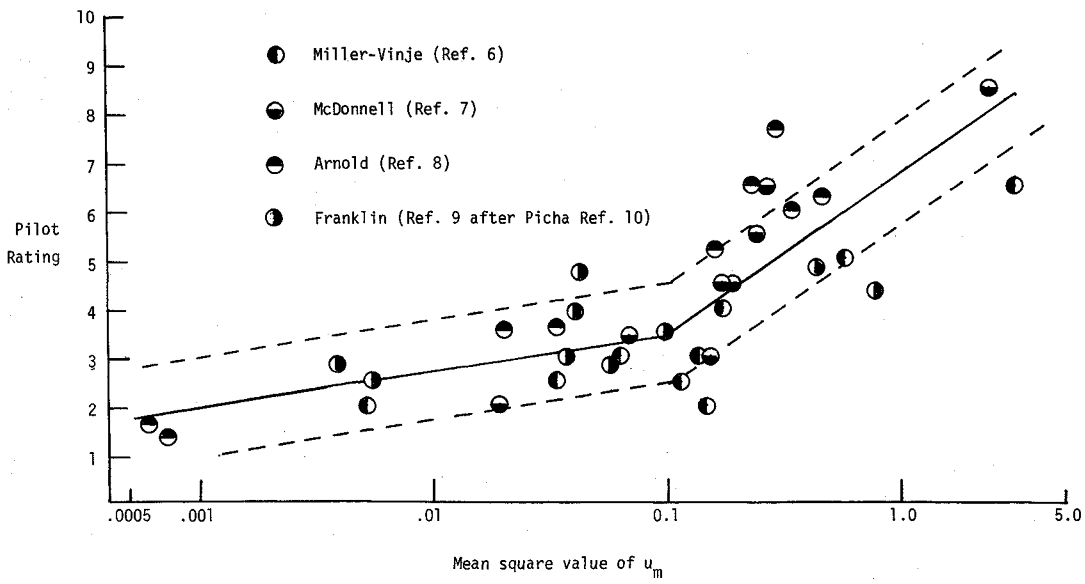


Fig. 7 Pilot opinion ratings vs mean square value of u_m.

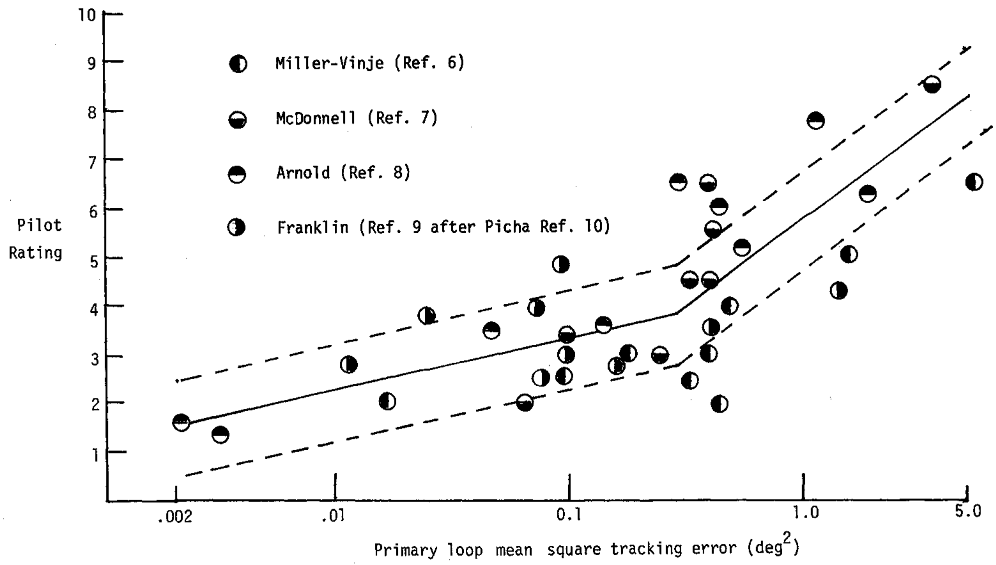


Fig. 8 Pilot opinion ratings vs model generated mean square tracking error.

8) As follows: a) The appropriate outer-loop transfer function for this task can be given as

$$\frac{x}{\theta} = -\frac{g}{s(s - X_u)} \tag{2}$$

b) The outer-loop crossover frequency is selected as 0.75 rad/s which is one-fourth of the inner-loop value.

c) The required outer-loop compensation is

$$Y_{p_2} = K_y(T_L s + 1) = -0.0071(3s + 1) \tag{3}$$

9) The pilot/vehicle system was then simulated, and a u_m mean square value of 0.17 was obtained, with structural model output m expressed in degrees of pitch attitude. The reported Cooper rating was 4.0 in Ref. 6.

Results

The procedure outlined in the previous sections was applied to 35 configurations, whose handling qualities have been evaluated in four manned simulation studies. These included: eight configurations from the single-loop laboratory pitch attitude tracking task of McDonnell,[7] nine configurations from the single-loop pitch attitude tracking task of Arnold,[8] nine configurations from the multiloop longitudinal precision hover task of Miller and Vinje,[6] and nine configurations from the multiloop glideslope tracking task of Franklin,[9] and reported by Picha.[10] In each of these simulations, configurations were chosen for analysis, with an eye toward providing as large a range of reported Cooper and Cooper-Harper ratings as possible. Thus, the author analyzed only part of the configurations in any study and was more interested in breadth than in depth in the interpretation and extension of Smith's theory. Table 2 summarizes the configurations analyzed here. The notation in Table 2 is taken from the references describing the simulations. The reader is referred to Refs. 6–10 for complete descriptions of the tasks, vehicle dynamics, and command and/or disturbance properties. Suffice to say that variations in *all* the aforementioned characteristics are included in the configurations chosen for study here.

Figure 7 shows a plot of the mean square value of u_m obtained from the modeling procedure plotted vs the reported pilot opinion ratings for the 35 configurations analyzed. The solid line in the figure represents a hand-faired fit to the results; the dashed lines represent ± 1 pilot rating. Approximately 80% of the points lie within the ± 1 rating band surrounding the hand-faired solid line. It should be noted that the Miller-Vinje data used the Cooper, rather than Cooper-Harper, pilot opinion scale; however, the ratings from this scale were assumed to be identical to those expressed on the Cooper-Harper scale for the purposes of this study. In all cases, the output of the structural model in the primary loop was expressed in degrees of vehicle pitch attitude. In the case of the McDonnell data, in which the output of the controlled element dynamics in the laboratory tracking task was described in terms of centimeters of display indicator movement at a specified display viewing distance, output in degrees of vehicle "pitch attitude" was obtained by considering that the angle in degrees subtended at the pilot's eye by pitch display indicator movement was equivalent to vehicle pitch attitude in degrees. Thus, the display was interpreted as one would a contact analog format.

In Ref. 2, Smith used the Optimal Control Model of the human pilot[4] to implement his handling qualities theory by attempting to correlate multiloop rate feedback activity with the pilot opinion ratings reported in Ref. 6. Although Smith analyzed more of the Ref. 6 configurations than the author, the correlation obtained in Fig. 7 for the data of Ref. 6, using the structural model, are consistently superior to Smith's results in Ref. 2.

Figure 8 shows a plot of the mean square tracking error in the primary loop, as generated by the structural model, for the 35 configurations studied here. Trends similar to that of Fig. 7 are evident, with slightly poorer correlation between the model tracking error and the reported pilot opinion ratings. As in the case of Fig. 7, the solid line represents a hand-faired fit to the results, with the dashed lines representing ± 1 pilot rating. Comparing Figs. 7 and 8, the question naturally arises as to why the rate feedback signal u_m, rather than the tracking error e, should play the pivotal role in a theory of aircraft handling qualities. The answer to this question is surprisingly simple, almost axiomatic, but often unappreciated: whereas tracking error may be a function of vehicle handling qualities, *the converse is not true*. This is due to the fact that tracking error can exist and be defined in unambiguous fashion whether or not the pilot is actively controlling the vehicle and being exposed to its handling qualities. The same cannot be said for the signal u_m, which depends for its definition and existence upon active pilot control of the vehicle.

As an example, consider the pilot of a stable aircraft monitoring the pitch attitude indicator as his aircraft flies through atmospheric turbulence. Clearly, tracking error exists and is defined in unambiguous fashion by the continuous movement of the artificial horizon. Equally clear is the fact that this error is not defining handling qualities (other than the characteristics of unattended operation) since the pilot is not controlling the vehicle. Thus, tracking error itself cannot be considered to be the yardstick by which the pilot assesses vehicle handling qualities. Theoretically, it is an effect rather than a cause. Thus, the correlation between the model generated tracking error and recorded pilot opinion ratings evident in Fig. 8 is of little more than academic interest in a theoretical treatment of vehicle handling qualities. This argument is reinforced by the discussion in the following section involving control system sensitivity effects, wherein experiment has shown that the relationship between tracking error and handling qualities is essentially nonexistent.

Control System Sensitivity Effects

It is known that, for any particular vehicle dynamics, control manipulator, and task, there exists a control system sensitivity which the human finds optimum. Larger or smaller values result in degraded pilot opinion ratings. In addition, experimental evidence suggests that the human pilot is quite capable of maintaining nearly constant crossover frequency *and tracking performance* across a large range of control sensitivities. Reference 1 discussed the subject of control sensitivity using the structural model with K/s vehicle dynamics and using model parameter values selected to give matches to measured pilot describing functions. The treatment is extended here, using K/s^2 vehicle dynamics and employing the structural model with nominal parameter values taken from Table 1.

To model, in approximate fashion, the limitations of the human neuromotor system in providing the very precise low-amplitude control inputs required for tracking with large control sensitivities, a small "residual" broadband motor noise was injected at the model summing junction where u_m was subtracted from u_c. The variance of this noise was selected as 1% of the value of the variance of u_c when optimum sensitivities were being used. With optimum or low sensitivities, this noise has practically no effect on model behavior. At high-control sensitivities, however, the residual noise will introduce inaccuracies in the control inputs.

The K/s^2 controlled element dynamics used in Ref. 7 are selected for study. These correspond to the "K/s^2 (1, 2)" entry in Table 2. In Ref. 7, control sensitivities were investigated from $0.1K_B$ to $10K_B$, where K_B refers to the "best" or optimum sensitivity as determined by the subject. Now, assume the control sensitivity selected via Eq. (1) is optimum. If one considers lowering this sensitivity by a factor of 10 to $0.1K_B$, the model (and presumably the human) can compensate by a reciprocal increase in the gain K_e from the nominal unity to 10.0. This results in a maintenance of the 4.0 rad/s crossover frequency, no change in tracking performance from that associated with the optimum sensitivity but a large increase in the mean square value of u_m. According to Smith's theory and the results of Fig. 7, this latter increase would indicate larger (poorer) pilot opinion ratings. These results are corroborated by experiment.[7]

Now, if one considers raising the sensitivity by a factor of 10 to $10K_B$, the model (and presumably the human) can compensate by a reciprocal decrease in the gain K_e. However, although such a decrease maintains a constant crossover frequency, there is a significant deterioration in tracking performance brought about by the residual motor noise. Since such performance deterioration has not, in general, been noted in experiment, some other mechanism for coping with large control sensitivity must be pursued with the model. One such mechanism is an increase in the gain K_1 in the innermost feedback loop in the structural model. This decreases the amplitude ratio of the transfer function u_δ/u_c, which has the desired result of reducing the effects of the motor noise while not changing the basic compensation provided by the structural model. Although varying the gain K_2, as proposed in Ref. 1, can produce similar results, much larger changes in the

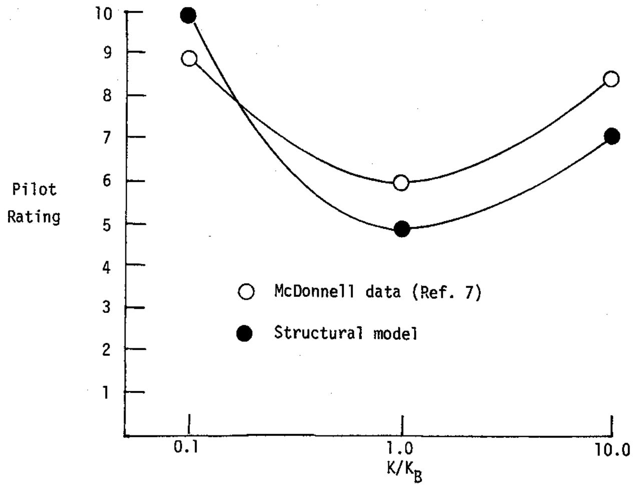


Fig. 9 Control sensitivity effects.

closed-loop neuromuscular system roots occur. In a physiological sense, increasing K_1 is equivalent to an increase in the average tension of the agonist/antagonist muscle groups driving the manipulator.

Because of the large decrease in the amplitude of the u_δ/u_c transfer function that occurs when K_1 is increased, the model gain K_e must now be *increased* to maintain the desired crossover frequency. The overall effect of these changes is the maintenance of the 4.0 rad/s crossover frequency, no deterioration in tracking performance, and, again, a large increase in the mean square value of u_m over that associated with the optimum sensitivity. This latter increase would indicate larger (poorer) pilot opinion ratings. Again, these results are corroborated by experiment.[7] It should be noted that the choice of the variance of the motor noise was arbitrary here. In reality, it would depend upon the size of the particular muscle group that uses the manipulator, the order of the controlled element dynamics around crossover, and the characteristics of the manipulator itself.

Figure 9 shows pilot opinion ratings from the McDonnell study for the K/s^2 controlled element for variations in controlled element sensitivity K over a range of 100. Also shown are results from the structural model simulations, in which the mean square value of u_m and the solid hand-faired line in Fig. 7 were used to generate pilot opinion ratings. For the high sensitivity, the model gain K_1 was increased from 1.0 to 25, which minimized the effects of motor noise on tracking performance. The gain K_e was then increased from 1.0 to 2.4 to maintain the desired crossover frequency. The model ratings *cannot* be considered "predictions" because of the arbitrary way in which the motor noise variance was assigned. For this reason, control system sensitivity effects have been eliminated from the modeling procedure via Eq. (1). Nonetheless, the structural model has provided a framework within which to interpret Smith's theory in the analysis of the effect of control system sensitivity on pilot opinion ratings.

Conclusions

1) A theory for aircraft handling qualities that postulates that rate control activity is of fundamental importance in perceived handling qualities can be interpreted in terms of a structural model of the human pilot.

2) The mean-square value of a feedback variable in the structural model, proportional to vehicle output rate due to control activity, correlates with numerical pilot opinion ratings in a series of longitudinal single- and multiloop tasks.

3) The present limitation of the modeling approach in serving as a predictive tool in handling qualities research is that the measure of rate control activity u_m is a dimensional quantity dependent on the particular units of vehicle output in the primary control loop (degrees of pitch attitude in all cases analyzed herein).

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