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An Improved Approach to Predicting Pilot Rating Behavior

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An analytical method to predict pilot ratings is proposed and examined. The method is based upon the assumptions that the control task determines the crossover frequency at which the pilot should concentrate his control efforts, and that the degree of closed-loop stability and the corresponding pilot compensation required to attain the stability determine the pilot ratings. As an end result, a simple evaluation chart for single-input and single-output controlled elements is presented assuming that a rough estimate of the crossover frequency is given. The chart is in good accord with the actual pilot ratings. Considerations are also given on the merits and demerits of applying the method to researches of aircraft handling qualities.

Nomenclature

BW	= bandwidth, rad/s
$\left\{\dfrac{d\lvert Y_c\rvert}{d(\log\omega)}\right\}_{\omega=\omega_c}$	= amplitude-ratio slope of Y_c at ω_c, dB/decade
$\left\{\dfrac{d\lvert Y_p\rvert}{d(\log\omega)}\right\}_{\omega=\omega_c}$	= amplitude-ratio slope of Y_p at ω_c, dB/decade
$\left\{\dfrac{d\angle Y_pY_c}{d(\log\omega)}\right\}_{\omega=\omega_c}$	= phase slope of Y_pY_c at ω_c, rad/decade
GM	= gain margin, dB
j	= imaginary unit, $\sqrt{-1}$
K_p	= pilot gain
PR	= pilot rating
s	= Laplace transformation variable
T_I	= pilot's lag time constant, s
T_L	= pilot's lead time constant, s
T_L'	= pilot's second-order lead coefficient, s^2
$Y_c(s)$	= transfer function of a controlled element
$\angle Y_c(j\omega)$	= phase of Y_c, rad
$Y_p(s)$	= transfer function of a pilot model
$\angle Y_p(j\omega)$	= phase of Y_p, rad
α	= T_L'/T_L^2
ζ	= damping ratio of a second-order controlled element
τ	= pilot's reaction time delay, s
ΦM	= phase margin, rad
ϕ	= $\angle Y_p(j\omega_c)+\tau\omega_c$, rad
ω	= frequency, rad/s
ω_c	= crossover frequency, rad/s
ω_n	= undamped natural frequency of a second-order controlled element, rad/s

Introduction

RECENT development of automatic flight control systems has exerted a great influence on handling quality requirements of manned aircraft. Motions of the aircraft with these flight control systems no longer show a distinct short-period response. This implies that in determining handling quality requirements, it is not sufficient to employ the short-period natural frequency and/or damping as handling quality parameters. Urged by this trend, various revisions of handling quality requirements have been proposed.[1-3] It is noticeable that most of the revisions utilize the pilot-in-the-loop analysis which takes account of the pilot's control behavior based on the knowledge about manual control obtained over the past two decades.

The pilot-in-the-loop analysis uses the magnitude of the pilot-adopted phase lead as the key index of the pilot compensation. By making use of this analysis, a revision[1] to MIL-F-8785B was proposed. Reference 1 defines the slope and the phase of the open-loop transfer function, which includes the pilot reaction time delay, at the predetermined closed-loop bandwidth (BW) as the measures of evaluating pilot ratings of the aircraft pitch response. Using the definition, the proposal in Ref. 1 puts its base on the fact that the increase of the slope suppresses the closed-loop resonance, and the phase has effects on the pilot's phase compensation. This method has the following problems: 1) there is no direct relationship between these handling quality parameters, the slope and the phase of the open-loop transfer function at BW, and the pilot model; 2) careful attention is necessary to read the amplitude ratio and the phase characteristics from the open-loop transfer function frequency diagram. If one uses a different frequency at which these parameters are read, the result also becomes different. A more recent work[2] employs the amplitude-ratio slope and the phase of the open-loop transfer function at the crossover frequency as the parameters of the longitudinal short-period handling qualities together with two additional parameters. Moreover, unique formulas to specify the crossover frequency are recommended in this proposal. However, the proposal is also based upon empirical relationships between these handling quality parameters and the pilot control techniques.

The objectives of this paper are to propose an improved method of predicting pilot ratings and to examine it using past data. The improved method makes full use of the pilot models and their limitations in application, and is aimed at directly correlating the basic handling quality parameters, the amplitude-ratio slope, and the phase of the open-loop transfer function at the crossover frequency, with the pilot behavior. Throughout the following sections, we treat a single-loop manual control system, with emphasis placed on the application of the improved method to the short-period handling quality requirements for advanced aircraft design.

Method of Evaluating Manual Control Systems

In this paper we consider that for an assigned control task the evaluation of the system by a pilot is defined by the system performance and the amount of the pilot workload required to attain the performance. We assume here that the difficulty of the control task is represented by the crossover frequency ω_c, which is determined by external factors such as the features of the external disturbance and the flight phase. If

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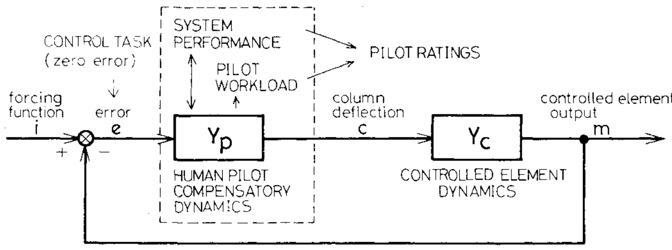

Fig. 1 Single-loop manual control system and the evaluation procedure by a pilot.

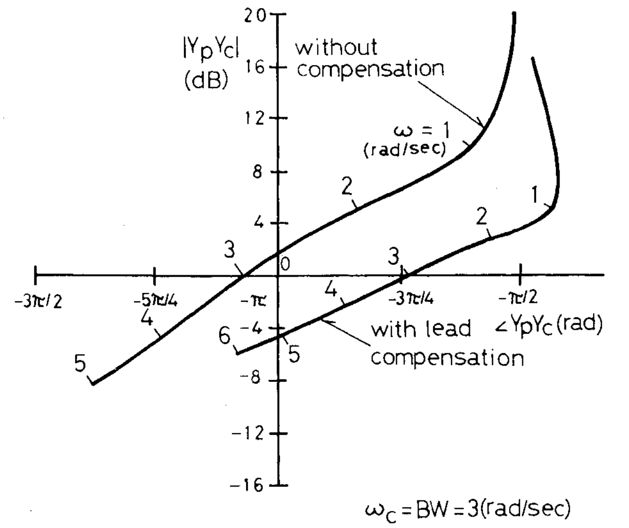

Fig. 2 Example of amplitude-ratio phase plots, from Ref. 3.

the task is a severe one, the control loop should be tightly closed to give a larger ω_c. Taking into consideration that manual control systems often have insufficient stability margins because of the pilot's inherent reaction time delay, we also assume that the system performance is mainly determined by the closed-loop stability. Under these assumptions, the pilot tries to keep the required ω_c by adjusting his compensatory dynamics.

Consider a single-loop manual control system as shown in Fig. 1. The pilot workload shown in the figure may be divided into mental and physical workloads. The mental workload corresponds to the pilot compensatory characteristics, which means that the pilot adjusts his lead-lag compensation according to the controlled-element dynamics in order to accomplish the control task. On the other hand, the physical workload, which may be affected by the external disturbance intensity, corresponds to the amount of physical work done by the pilot, i.e., the magnitude of control column deflection, physiological response such as oxygen consumption, and so on. Modern aircraft, however, are equipped with a power-boosted control device, thereby making it possible to adjust the control column gain at the designer's option. Considering this trend, we may remove from this analysis the problem of dealing with the control column gain. Therefore, we hereafter choose the mental workload, or in other words, pilot lead-lag compensation, as the index of the pilot workload.

To define the closed-loop stability in terms of the pilot compensation, we then consider the amplitude-ratio slope plots of the open-loop transfer function $Y_p Y_c(s)$ in Fig. 1. As typical examples of $Y_p Y_c$ plots, Fig. 2 is reproduced from Ref. 3. In the figure, the plots are arranged so that BW coincides with ω_c. It may be seen that each plot, in the neighborhood of ω_c, can be represented by an essentially straight line. In addition, the slope of each plot is relatively gentle. This implies that for these plots the phase-crossover frequency, at which the gain margin (GM) is read, is closer to the origin of the figure than the gain-crossover frequency, ω_c, at which the phase margin (ΦM) is read. Note also that the frequency at which the closed-loop frequency response shows its peak is very close to the phase-crossover frequency. Thus, it may be said that the degree of the closed-loop stability of these cases can be more directly estimated by using the gain margin rather than the phase margin. As these characteristics can be seen in most manual control systems, we employ the following approximation: In the neighborhood of ω_c, the gain margin (GM) of the system which we treat as the index of stability, is approximately related to the slope of the plot and ΦM as

$$\mathrm{GM} = \{\mathrm{d}\,|Y_p Y_c|/\mathrm{d}\angle Y_p Y_c\}_{\omega=\omega_c} \cdot \Phi\mathrm{M} \quad (1)$$

where ΦM is defined as

$$\Phi\mathrm{M} = \angle Y_c(j\omega_c) + \angle Y_p(j\omega_c) + \pi \quad (2)$$

It should be noted here that the abovementioned GM and ΦM can be defined even when the controlled element has unstable poles. For the unstable case, there exists a permissible range of gain change for the system to remain stable, and there are two phase-crossover frequencies. A similar relationship as Eq. (1) holds if we choose a larger one as the critical phase-crossover frequency. Now, in order to clearly show the pilot compensation necessary for the closed-loop stability, we rewrite Eq. (1) by using Eq. (2) as

$$\{\mathrm{d}\,|Y_c|/\mathrm{d}(\log\omega)\}_{\omega=\omega_c} = \frac{\mathrm{GM}\{\mathrm{d}\angle Y_p Y_c/\mathrm{d}(\log\omega)\}_{\omega=\omega_c}}{\angle Y_c(j\omega_c) + \angle Y_p(j\omega_c) + \pi} - \{\mathrm{d}\,|Y_p|/\mathrm{d}(\log\omega)\}_{\omega=\omega_c} \quad (3)$$

In Eq. (3), the pilot compensation is expressed by $\{\mathrm{d}\,|Y_p|/\mathrm{d}(\log\omega)\}_{\omega=\omega_c}$, $\angle Y_p(j\omega_c)$ and $\{\mathrm{d}\angle Y_p Y_c/\mathrm{d}(\log\omega)\}_{\omega=\omega_c}$. Among these, the first two have direct connection with the pilot compensation. On the other hand, it is difficult to find a simple relationship between $\{\mathrm{d}\angle Y_p Y_c/\mathrm{d}(\log\omega)\}_{\omega=\omega_c}$ and the pilot compensation, since the pilot dynamics contain the reaction time delay which manifests itself only in the phase characteristics. For simplicity of the analysis, $\{\mathrm{d}\angle Y_p Y_c/\mathrm{d}(\log\omega)\}_{\omega=\omega_c}$ is tentatively assumed constant hereafter. Let us then consider the relationship between $\{\mathrm{d}\,|Y_p|/\mathrm{d}(\log\omega)\}_{\omega=\omega_c}$ and $\angle Y_p(j\omega_c)$. It is quite interesting to find that simple pilot models can be used in the neighborhood of the crossover frequency irrespective of control situations. Figure 3 shows the cases where the pilot compensation can be modeled as follows: When the pilot employs the first-order lead compensation, it

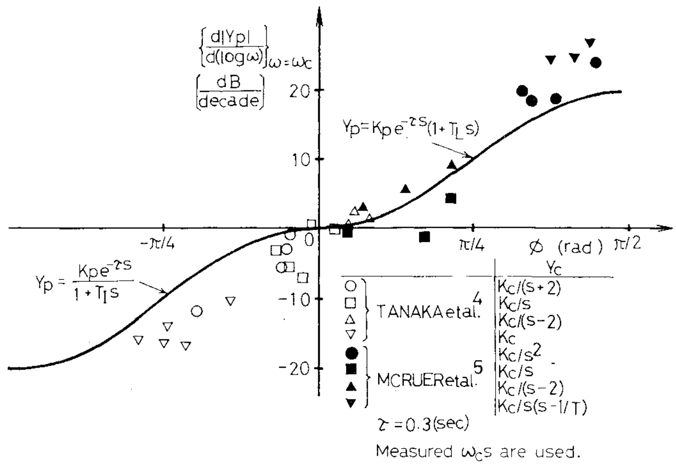

Fig. 3 Comparison between pilot models and experimental results (Refs. 4 and 5).

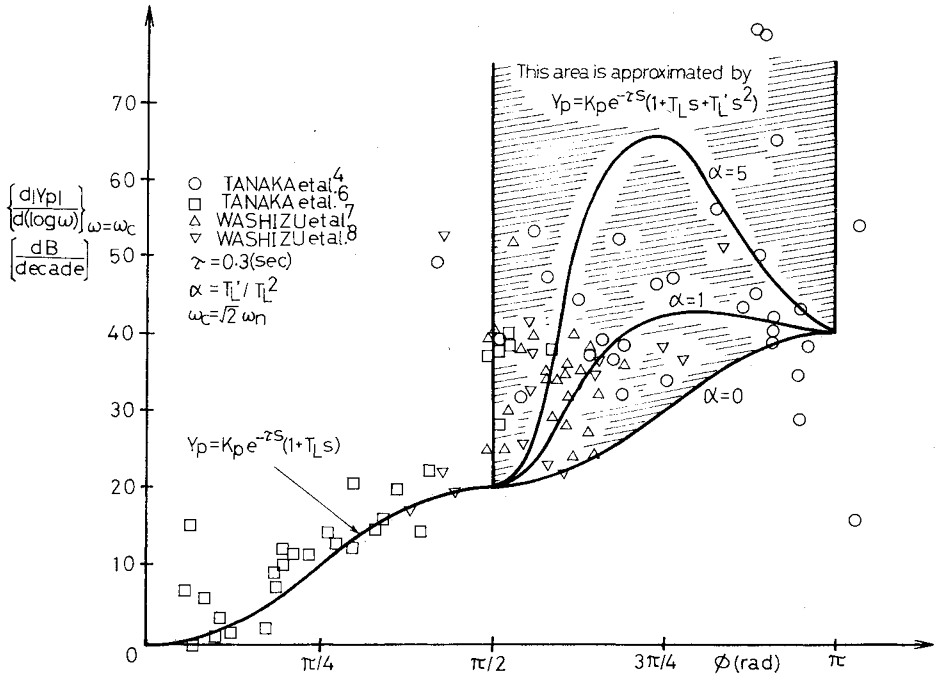

Fig. 4 Comparison between pilot models and experimental results when $Y_c = \omega_n^2/(s^2+2\zeta\omega_n s+\omega_n^2)$ (Refs. 4, 6-8).

seems appropriate to adopt the model

$$Y_p(s) = K_p e^{-\tau s}(1+T_L s) \qquad \text{for } \phi>0 \tag{4}$$

where s denotes the Laplace transformation variable, and the pilot reaction time delay, τ, contains the neuromuscular lag time constant and is fixed here at 0.3 s. By putting $s=j\omega$ in Eq. (4), ϕ is defined by

$$\phi = \angle Y_p(j\omega_c) + \tau\omega_c \tag{5}$$

Differentiating the amplitude-ratio characteristics of $Y_p(j\omega)$ with respect to $\log\omega$, we obtain the relationship between the amplitude-ratio slope and the phase as

$$\{d|Y_p|/d(\log\omega)\}_{\omega=\omega_c} = 10(1-\cos 2\phi) \tag{6}$$

When the pilot employs the first-order lag compensation, we may properly adopt the model

$$Y_p(s) = K_p e^{-\tau s}/(1+T_I s) \qquad \text{for } \phi<0 \tag{7}$$

Differentiating the amplitude-ratio characteristics of $Y_p(j\omega)$ with respect to $\log\omega$, we obtain the relationship

$$\{d|Y_p|/d(\log\omega)\}_{\omega=\omega_c} = -10(1-\cos 2\phi) \tag{8}$$

Equations (6) and (8) are the relationships between $\{d|Y_p|/d(\log\omega)\}_{\omega=\omega_c}$ and ϕ when the pilot compensation can be expressed by the aforementioned models. The solid line in Fig. 3 shows these relationships which agree with the describing function data obtained in various tracking experiments. Figure 4 shows the cases for the second-order controlled elements, where the pilot can be modeled either as Eq. (4) or as

$$Y_p(s) = K_p e^{-\tau s}(1+T_L s+T_L' s^2) \tag{9}$$

For the pilot model of Eq. (9), the relationship between the amplitude-ratio slope and the phase is obtained as

$$\{d|Y_p|/d(\log\omega)\}_{\omega=\omega_c} = 20 + 10\sqrt{1+4\alpha\tan^2\phi}\,(1+\cos 2\phi) \tag{10}$$

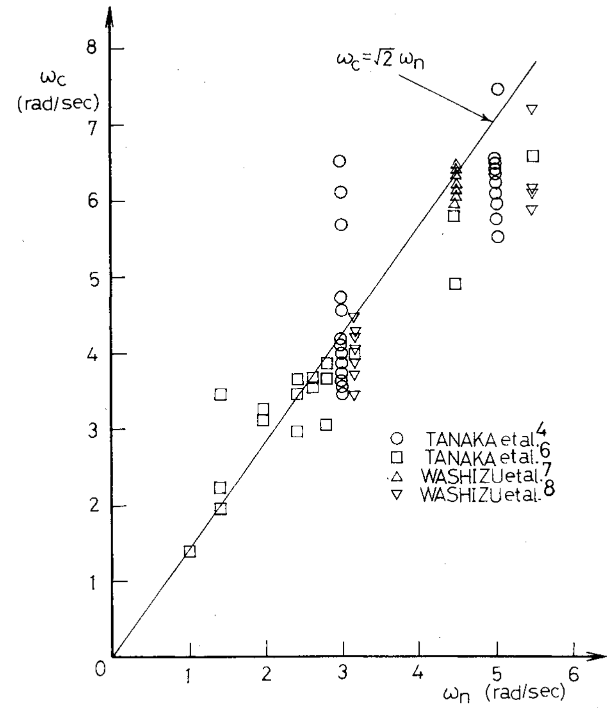

Fig. 5 Relationship between ω_c and ω_n when $Y_c = \omega_n^2/(s^2+2\zeta\omega_n s+\omega_n^2)$ (Refs. 4, 6-8).

where $\alpha = T_L'/T_L^2$ and $K_p>0$. The shaded area in Fig. 4 results by varying α. It is obvious that most of the data for ϕ greater than $\pi/2$ and less than π match with the model, Eq. (9). It should be noted that for simplicity we employ the approximation $\omega_c = \sqrt{2}\omega_n$ in Fig. 4. This is due to the fact that the most effective factor in determining the crossover frequency for the second-order controlled elements seems to be the natural frequency of the element ω_n, as shown in Fig. 5. In summary, for the cases where the pilot phase lead ϕ is negative, we may use Eq. (8). For the cases where ϕ is positive and less than $\pi/2$, we may use Eq. (6). For the cases where ϕ is greater than $\pi/2$ and less than π, we may use Eq. (10).

On the abovementioned basis, we estimate the degree of the pilot compensation as a function of $\{d|Y_p|/d(\log\omega)\}_{\omega=\omega_c}$ and $\angle Y_p(j\omega_c)$ depending upon the assumed GM. Let us

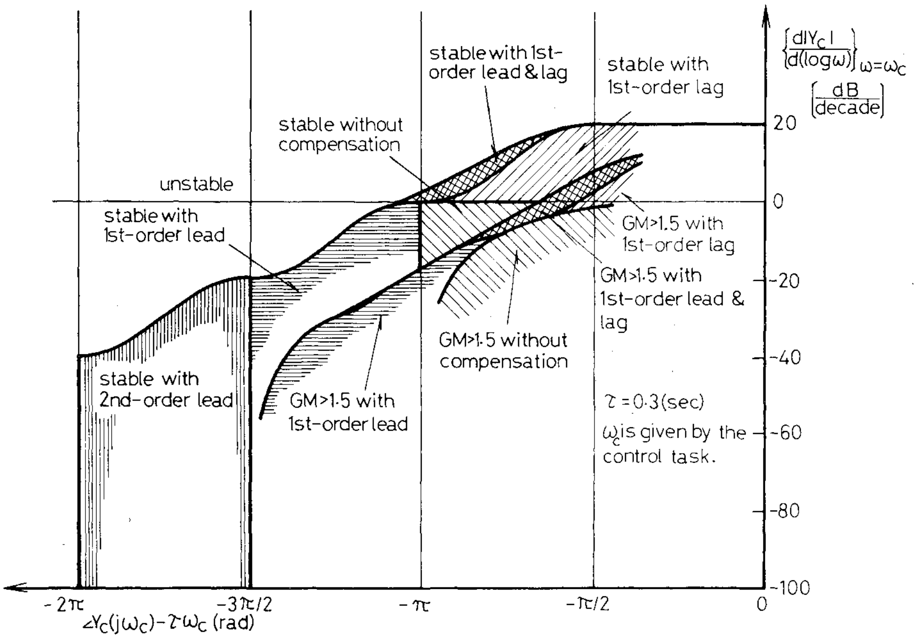

Fig. 6 Chart for evaluating manual control systems.

construct an evaluation chart which shows the relationship between the controlled-element characteristics at ω_c and the closed-loop performance determined by the pilot compensation. In the first place, we derive the conditions for the controlled element under which the closed-loop stability can be attained with a given pilot model. The closed-loop system is stable when GM>0 and ΦM>0. Combining these conditions with Eqs. (1) and (2), and referring to the fact that generally,

$$\{d\angle Y_p Y_c/d(\log\omega)\}_{\omega=\omega_c}<0$$

we obtain the conditions

$$\{d|Y_c|/d(\log\omega)\}_{\omega=\omega_c}<-\{d|Y_p|/d(\log\omega)\}_{\omega=\omega_c} \quad (11)$$

and

$$\angle Y_c(j\omega_c)-\tau\omega_c>-\pi-\phi \quad (12)$$

1) Stability conditions of the closed-loop system without any pilot compensation. When the pilot employs no compensation, that is, when $Y_p(s)=K_p e^{-\tau s}$,

$$\{d|Y_p|/d(\log\omega)\}_{\omega=\omega_c}=0 \qquad \text{and } \phi=0$$

Thus, from inequalities (11) and (12), we obtain the stability conditions:

$$\{d|Y_c|/d(\log\omega)\}_{\omega=\omega_c}<0 \quad (13)$$

and

$$\angle Y_c(j\omega_c)-\tau\omega_c>-\pi \quad (14)$$

The closed-loop system is stable in the region satisfying inequalities (13) and (14) without any pilot compensation. The region is shown in the chart of Fig. 6, where the abscissa is $\angle Y_c(j\omega_c)-\tau\omega_c$ and the ordinate is $\{d|Y_c|/d(\log\omega)\}_{\omega=\omega_c}$. Next, we explain other regions by using the same chart.

2) Stability conditions with first-order pilot lead. Employing Eq. (6), we can rearrange inequality (11) as

$$\{d|Y_c|/d(\log\omega)\}_{\omega=\omega_c}<-10(1-\cos2\phi) \quad (15)$$

The pilot can stabilize the closed-loop system in the region satisfying inequalities (12) and (15) with the first-order lead compensation. When $\phi=0$ in these conditions, the region is the same as that of the conditions obtained in *1* above. By increasing ϕ from 0 to $\pi/2$, this region gradually moves to the lower left in parallel with the curve satisfying the relation

$$\{d|Y_c|/d(\log\omega)\}_{\omega=\omega_c}=-10(1-\cos2\phi) \quad (0\le\phi\le\pi/2) \quad (16)$$

In Fig. 6 this region is denoted as the region stable with the first-order lead.

3) Stability conditions with first-order pilot lag. In the same manner as made up to this point, the region is obtained by moving the region satisfying the conditions for *1* in parallel with the curve satisfying the relation

$$\{d|Y_c|/d(\log\omega)\}_{\omega=\omega_c}=10(1-\cos2\phi) \quad (-\pi/2\le\phi<0) \quad (17)$$

4) Stability conditions with first-order pilot lead and lag. The region of this case is obtained by moving the region satisfying the conditions for *2* in parallel with Eq. (17), just as similarly as the region of the conditions for *3* is obtained from the region of the conditions for *1*.

5) Stability conditions with second-order pilot lead. Substituting Eq. (10) into inequality (11), and noting that the widest region is obtained when $\alpha=0$ in Eq. (10), the stability conditions are

$$\{d|Y_c|/d(\log\omega)\}_{\omega=\omega_c}<-10(3+\cos2\phi) \quad (18)$$

and inequality (12). This region is obtained by moving the region satisfying the conditions for *1* in parallel with the curve

$$\{d|Y_c|/d(\log\omega)\}_{\omega=\omega_c}=-10(3+\cos2\phi) \quad (\pi/2<\phi\le\pi) \quad (19)$$

Secondly, we derive the conditions under which GM is kept greater than a certain value. As an example, GM>1.5 is studied. Here, we use the past data to choose an appropriate value of $\{d\angle Y_p Y_c/d(\log\omega)\}_{\omega=\omega_c}$ as

$$\{d\angle Y_p Y_c/d(\log\omega)\}_{\omega=\omega_c}=-4$$

Using these values and Eq. (3), the conditions are

$$\{d\,|Y_c|/d(\log\omega)\}_{\omega=\omega_c} < \frac{-6}{\angle Y_c(j\omega_c)-\tau\omega_c+\phi+\pi} - \{d\,|Y_p|/d(\log\omega)\}_{\omega=\omega_c} \tag{20}$$

and inequality (12).

6) *GM>1.5 dB without any pilot compensation.* The conditions are obtained from inequality (20) as

$$\{d\,|Y_c|/d(\log\omega)\}_{\omega=\omega_c} < \frac{-6}{\angle Y_c(j\omega_c)-\tau\omega_c+\pi} \tag{21}$$

and inequality (12).

7) *GM>1.5 dB with first-order pilot lead.* The region is obtained by moving the region satisfying the conditions for *6* in parallel with Eq. (16).

8) *GM<1.5 dB with first-order pilot lag.* The region is obtained by moving the region satisfying the conditions for *6* in parallel with Eq. (17).

9) *GM>1.5 dB with first-order pilot lead and lag.* The region is obtained by moving the region satisfying the conditions for *7* in parallel with Eq. (17).

Comparison with Actual Pilot Ratings and Discussion

A comparison of the results obtained by the proposed method with the experimental data, $\{d\,|Y_c|/d(\log\omega)\}_{\omega=\omega_c}$, $\angle Y_c(j\omega_c)$, and corresponding pilot ratings from Ref. 3, is shown in Fig. 7, where we tentatively set ω_c as equal to BW. Figure 7 indicates: 1) if the pilot can keep GM>1.5 without compensation, pilot ratings (PR) fall in the range of PR≤3.5; 2) if the pilot can keep GM>1.5 with the first-order compensation, pilot ratings fall in the range of 3.5<PR≤6.5; and 3) otherwise, 6.5<PR.

In addition, it is worth noting that the results of the comparison of this theoretical chart with the experimental pilot controllability limits well support the method. Most experimental data of the controllability limits are proved to be located near the stability boundary in Fig. 6. Also, it has been confirmed that the stability boundary with the first-order pilot lead coincides with the controllability limit for the first-order unstable controlled elements, and that the boundary with the second-order pilot lead agrees well with the limit for the second-order unstable controlled elements. This implies that near the controllability limit the pilot should employ a first-order lead compensation for first-order unstable controlled elements, and a second-order lead compensation for second-order unstable controlled elements, respectively.

Advantages of this method are summarized as: 1) simplicity of evaluation, in the sense that the method needs to evaluate only two parameters associated with the controlled element, $\{d\,|Y_c|/d(\log\omega)\}_{\omega=\omega_c}$ and $\angle Y_c(j\omega_c)$; 2) applicability to any controlled element irrespective of its stability; 3) predictability of the controllability limit of manual control systems; and 4) capability of estimating pilot dynamics simultaneously with control difficulty or pilot control efforts.

Other observations are:

1) The method proposed in this paper gives no definite ω_c, which depends on the control task. It seems desirable that ω_c be classified according to the flight phases, just as is done in Ref. 1. Nevertheless, the proposed method has another advantage: the results of the method are insensitive to the change in ω_c. Referring to Bode's theorem, $\{d\,|Y_c|/d(\log\omega)\}_{\omega=\omega_c}$ has a correlation with $\angle Y_c(j\omega_c)$ when the controlled element is of minimum phase system. For the cases where no large fluctuation of the amplitude-ratio slope is shown, the relationship is

$$\angle Y_c(j\omega_c) \simeq (\pi/40)\{d\,|Y_c|/d(\log\omega)\}_{\omega=\omega_c}$$

Thus, a change in ω_c shifts the plotted points on the chart so that they move almost in parallel and slightly laterally along the boundaries. Therefore, we can obtain the steady predictions of pilot ratings, if a rough estimate of ω_c is given. A simple estimate of ω_c gives approximately $\sqrt{2}$ times the dominant frequency of the controlled element. The severer the control task is, the larger ω_c may become appropriate.

2) In the cases where the assumptions of this method do not hold, however, the results may have large errors. Possible origins of such an error may be the assumptions that the closed-loop stability is the most effective parameter in the determination of the system performance, and that τ and $\{d\angle Y_pY_c/d(\log\omega)\}_{\omega=\omega_c}$ are considered to be constants.

A few remarks are to be made on the correlation of the proposed method with overall handling quality requirements. The evaluation method introduced in this paper enables us to plainly predetermine the pilot rating for a single-input single-output controlled element. The actual aircraft handling

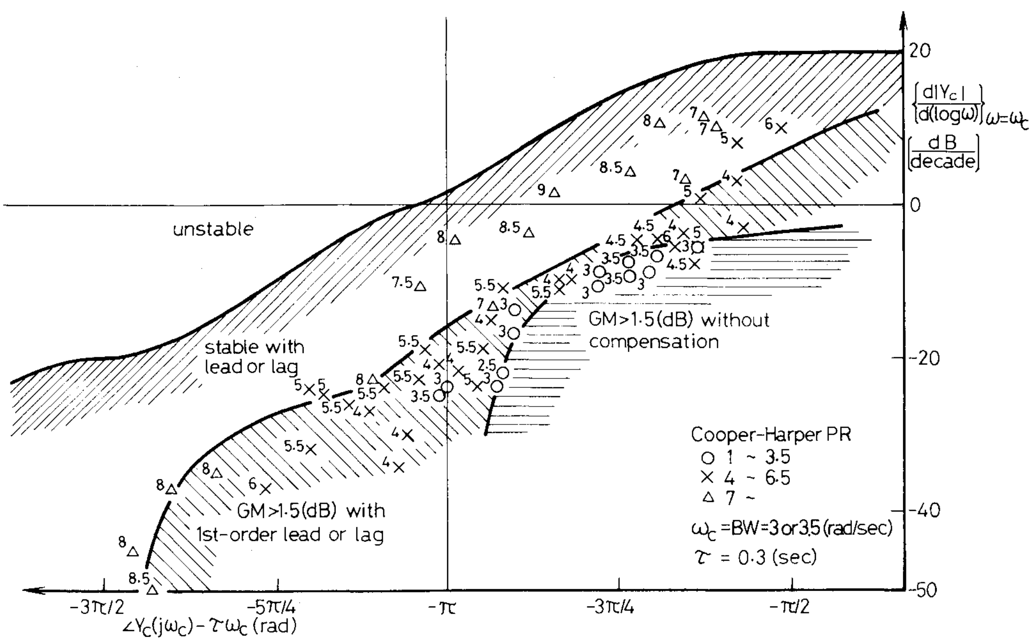

Fig. 7 Proposed evaluation method plotted against experimental results of Ref. 3.

qualities, however, cannot be specified by such a single-loop response, even though we confine ourselves to the longitudinal axis and employ the motion cue factor as is seen in Ref. 2. The handling qualities of the approach and landing phase are required to have a good outer-loop flight path or speed control response through the inner-loop pitch attitude control, especially for STOL-type aircrafts. These outer-loop response characteristics should be specified by a method similar to the one for the inner-loop pitch attitude response. If we succeed in determining a proper performance index such as the response time of the flight-path change, in place of the stability criterion used here, the pilot's evaluation of the outer-loop response may also be assessed. In the future, we may find a way to the analytical and comprehensive evaluation of the aircraft handling qualities, first by expressing the aircraft mission in more fundamental engineering terms, then by dividing the mission into smaller tasks depending upon the flight phases and control loops involved, and finally by synthesizing the rated value for each task obtained through the proposed method. To this end, it is also indispensable to obtain detailed information on human behavior in controlling multivariable systems.

Conclusion

The present paper has proposed and examined an improved method to predict pilot ratings. A simple evaluation chart for evaluating single-loop manual control systems has been presented by putting a focus on the open-loop frequency characteristics of the system and by making full use of pilot models and their limitations. This evaluation chart illustrates the approximated value of the attainable gain margin of the closed-loop system, which consists of a pilot model and the given controlled element. The parameters of the controlled element are the amplitude-ratio slope and the phase at the predetermined crossover frequency. A good agreement of the chart with actual pilot ratings indicates that this chart can be applied to predicting the pilot ratings of the aircraft pitch response assuming that a rough estimate of the crossover frequency is given. Moreover, observations on the advantages of this method suggest that the chart can be widely used as one of the basic tools for assessing the characteristics of single-loop manual control systems of various engineering fields. Further efforts to define the control tasks for each mission of the aircraft will enable us to extend the method to overall handling quality requirements for advanced aircraft design.

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