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Handling Qualities Criteria for Roll Control of Highly Augmented Aircraft

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Abrupt response to a pilot's control activities is often revealed during in-flight tests of modern highly augmented aircraft, but no existing handling qualities criteria can adequately predict this phenomenon. The causes of abrupt response, analyzing the roles of different aircraft characteristics, are discussed. A theoretical approach to the analysis of this phenomenon is developed, and a criterion is proposed for predicting abrupt response in roll. It is shown that estimations according to the criterion are in good agreement with the experimental data available.

I. Introduction

IT IS extremely difficult to develop handling qualities (HQ) criteria that can be applicable to aircraft of any complexity. Flying qualities of aircraft from previous generations were selected to provide, first of all, minimum required aircraft stability; thus, HQ criteria were developed to solve this particular problem.

Modern highly augmented aircraft are designed to eliminate the dependence of aircraft flying qualities on changes in the location of the center of mass, dispersion of the aerodynamic characteristics, and aircraft flight modes. This tendency leads to great feedback coefficients in control systems and, thus, to more rapid aircraft response. Designing aircraft with higher weight efficiency leads to greater structural elasticity, which, in turn, intensifies aircraft response to the high-frequency component in pilot control activities. For these reasons flight tests often reveal a certain abruptness of aircraft response to pilot activities. This fact proves the conclusion that the existing HQ criteria cannot predict aircraft abrupt response (AR) during aircraft design.

The existing theory is not sufficient to develop such a criterion. It used to be a common notion that the closer aircraft dynamics are to the integral, the better are aircraft handling qualities (see, e.g., Ref. 1). In the 1960s–1980s it was shown by a number of authors[2–6] that in real flight conditions a vehicle with dynamics close to K/s (roll mode time constant $\tau_R \to 0$) becomes almost uncontrollable due to its abrupt reaction to pilot stick activities, as the data in Fig. 1 show.[5]

The majority of research in the field of aircraft AR in roll was devoted to studying high-frequency oscillations (roll ratchet).[7–10] However, ratchet is, in fact, only the extreme manifestation of the aircraft AR phenomenon. If we decrease τ_R and/or increase aircraft gain K, AR of the aircraft first arises in the form of too-quick response or jerks, but ratchet occurs only in the case of further decreasing τ_R and/or increasing K. No manifestations of the AR phenomenon are considered permissible in real aircraft. Suffice it to say that there is no production airplane prone to AR. The phenomenon itself has been dealt with only in test flights and is necessarily eliminated even at the expense of other design/HQ requirements. In the light of these facts, the problem of ratchet seems to be rather theoretical; the methods to prevent AR and to determine the characteristics causing it are more important for practice.

One of very few publications dealing with a criterion to predict aircraft AR in roll is Ref. 11. However, the paper deals with roll accelerations, ignoring lateral accelerations which are, in fact, the main cause of AR.[2–4,6–9] As a result, the criterion in Ref. 11 does not take into account the roles of pilot location and structural elasticity in the aircraft AR; thus, the criterion is applicable to the rigid-body aircraft where the pilot is placed off the roll rotation axis no more than 1 m above it, as in NT-33A, for example.

At TsAGI, a theoretical approach to AR analysis has been recently developed, which can be applied to various aircraft and control axes. On the basis of this approach a criterion to predict AR has been created. The basic principles of the approach were described in Refs. 12 and 13. This paper aims to substantiate and further develop the approach and criterion.

II. Setting the Experiments

Our theoretical approach is based on a simplified model of the AR phenomenon and on empirical data generalization. For such an approach to be reliable it has to adequately cover different experimental data. As far as AR data are concerned, they are insufficient to cover all the parameters that may cause this phenomenon. The authors could not find, in particular, any published data on the effect of pilot location on AR, although this affects AR greatly. Suffice it to say that the only possible way to prove the determinant role of lateral accelerations (not roll accelerations) in AR is experimental study of the effect of pilot location. Thus, in the first series of our experiments, we aimed at obtaining experimental data on the effect of the pilot location on AR in roll.

In the course of the second series of experiments we determined the thresholds of pilot sensitivity to lateral specific forces acting against the background of roll accelerations because, in reality, lateral specific forces act simultaneously with angular accelerations. To understand the nature of the AR phenomenon, we must understand the effect of roll accelerations on the perception of the lateral specific forces they create. Data are available in the literature on the thresholds of sensitivity to lateral specific forces, but only for the cases when other motion system degrees of freedom were switched off.[14]

The experiments were conducted on TsAGI's flight simulator FS-102 with a six-degrees-of-freedom motion system of synergistic type (Fig. 2). The system consists of six actuators with hydrostatic bearings. The actuator's stroke is 1.8 m. The simulator is equipped with a computer-generated visual system with an optical collimator. The visual system time delay is 0.04 s.

In the course of the first series of the experiments the following piloting tasks were modeled: roll stabilization under turbulence, roll tracking, bank-angle capture, and free evaluation. The pilot used a central stick with force/displacement gradient in roll of 2.83 lb/in. and breakout force 1.1 lb.

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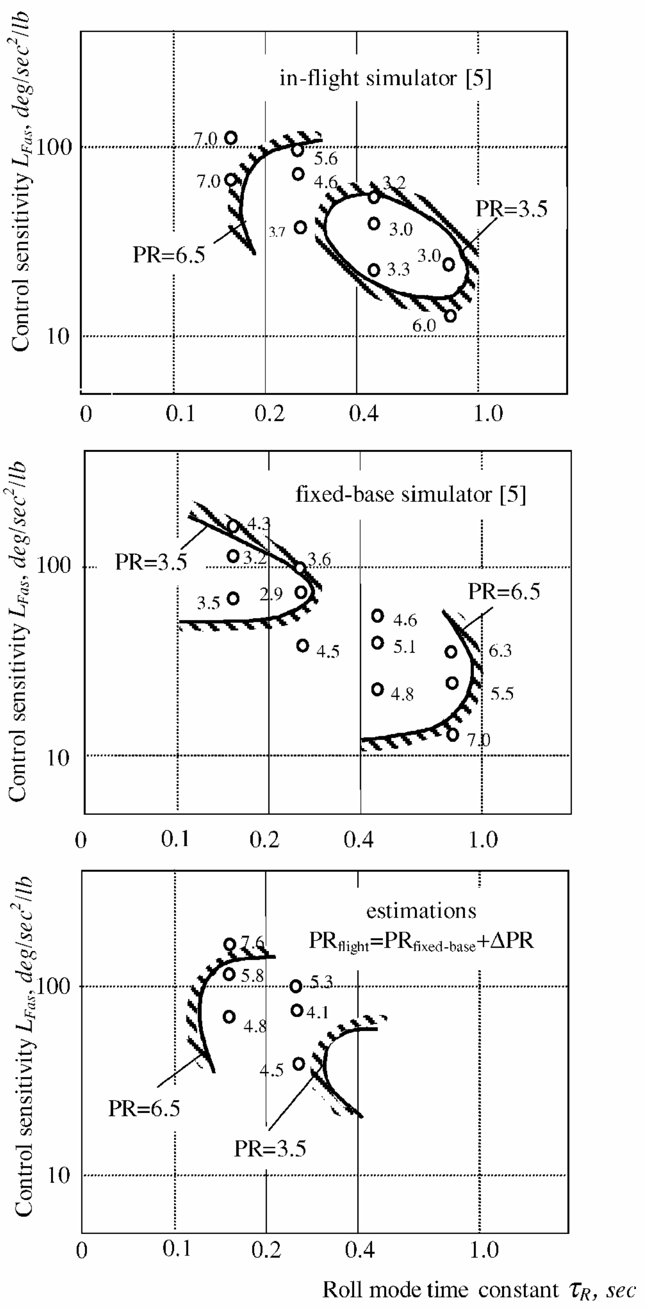

Fig. 1 In-flight and fixed-base data,[5] and estimations according to TsAGI's criterion.

Aircraft roll motion was described by the following transfer function:

$$Y_{p/\delta_{as}}(s) = K/(\tau_R s + 1)$$

where p is the roll rate, δ_{as} is the roll-stick deflection, K is the roll-control sensitivity (aircraft gain), and τ_R is the roll mode time constant. The aircraft math model computation time was 0.01 s.

This simplified model allows us to reproduce the main dynamic features of the pilot–aircraft system in roll, as well as lateral specific forces due to roll accelerations, which is the crucial factor as far as AR of rigid aircraft is concerned. It should be mentioned that, in a real airplane, lateral accelerations also arise due to uncoordinated roll motion and yaw accelerations. However, these types of lateral specific forces are low frequency; thus, first, they are practically impossible to reproduce in on-ground simulators and, second, they are not perceived by the pilot as jerky. That is why we have ignored these types of accelerations.

Fig. 2 TsAGI's 6-DOF Flight Simulator (FS-102).

Forcing function in stabilization and tracking tasks was modeled as a sum of sines:

$$F(t) = \sum_{i=1}^{15} A_i \sin(i\omega_0 t)$$

where $\omega_0 = 0.25\ \mathrm{s}^{-1}$.

The amplitude of each harmonics, A_i, corresponds to the following expression:

$$A_i(\omega_i) = \frac{k \cdot \omega_{\mathrm{br}}^2}{\left|(j\omega_i)^2 + 2(j\omega_i)\omega_{\mathrm{br}} + \omega_{\mathrm{br}}^2\right|}$$

The spectrum band ω_{br} was varied from 0.5 to 2 rad/s; the gain k was varied to keep within ± 5 deg of cockpit bank angle.

In the experiments only two degrees of freedom were used: roll and sway. Roll accelerations were reproduced by the following high-pass filter:

$$Y_{\mathrm{hp}}(s) = \frac{s^2}{s^2 + 2\zeta\omega_{\mathrm{hp}} s + \omega_{\mathrm{hp}}^2}$$

where $\omega_{\mathrm{hp}} = 1$ rad/s, and $\zeta = 0.7$.

Generally, the pilot's positions relative to the rotation axes in an aircraft (h) are different than in a flight simulator (h_{sim}). Thus, to adequately reproduce lateral accelerations $n_y = (h/g)\dot{p}$, the simulator cockpit was displaced in sway according to the following expression:

$$S_{\mathrm{sim}} = (h - h_{\mathrm{sim}})\phi_{\mathrm{sim}}$$

where ϕ_{sim} is the simulator bank angle.

In the experiments the values of h, τ_R, and K were varied. In this series of experiments one test pilot and two operators participated. (Operators had considerable experience in flying flight simulators.) Handling qualities were assessed on the Cooper–Harper scale.[15]

While determining pilot acceleration threshold values, lateral specific forces and roll rate were sinusoidally reproduced. Roll-rate amplitude was from 0 to 4 deg/s, lateral specific forces frequency was 0.5 Hz, and roll-motion frequency was 0.3 Hz. This roll-motion frequency value is typical of roll piloting; on the other hand, it allows us to reproduce roll motion for the aforementioned roll-rate amplitudes without creating too-noticeable false accelerations due to cockpit tilting. The chosen value of lateral specific forces frequency is within the frequency band of lateral accelerations in AR and, at the same time, is well reproduced in on-ground simulators.

Two operators participated in this series of experiments.

III. Theoretical Approach to Abrupt Response Estimation

A. Abrupt Response Causes

In Fig. 1, the data obtained in real flight for short roll-mode time constant values $\tau_R < 0.4$ s correspond to aircraft AR; fixed-base simulation results suggest that τ_R should be as small as possible for best HQ. This means that the role of motion cues in AR phenomena is essential. Our experiments have shown that AR can be reproduced in a flight simulator only when lateral specific forces are reproduced.[7,13] Thus, lateral accelerations play the determinant role in aircraft AR.

The lateral accelerations arising in AR are high frequency. High-frequency lateral accelerations cause involuntary body displacements because high-frequency disturbances make proper positioning of the body very difficult to maintain. Their effect is not only unpleasant, but can interfere with visual cues perception and the accuracy of control activities. High-frequency specific forces cause involuntary stick deflections, which can lead to aircraft high-frequency auto-oscillations.

Figure 3 presents integral distribution functions of roll rate and roll acceleration:

$$I(\omega) = \int_0^{\infty} S(\omega)\, d\omega$$

where $S(\omega)$ is the spectrum density of roll rate or roll acceleration.

These functions were obtained in the moving-base simulations of tracking task for different values of roll-mode time constant. From Fig. 3 it follows that the main frequency band of roll rate is within the range 0–0.5 Hz. This frequency band coincides with the frequencies of pilot control activities. That is why roll rates cannot cause a negative pilot opinion of aircraft handling qualities. Unlike roll rates, the frequencies of roll accelerations and, thus, lateral specific forces are beyond the pilot control frequency band. Therefore, the considerable high-frequency lateral specific forces are the cause of negative pilot opinion.

This question arises: how do aircraft characteristics affect its abrupt response?

It is seen from Fig. 3 that as the roll-mode time constant value decreases, the intensity of high-frequency angular accelerations increases dramatically. Thus, the negative effect of high-frequency lateral specific forces increases if the aircraft response time shortens. When the roll-mode time constant decreases, the aircraft starts to respond to the high-frequency component in pilot stick activities. Figure 4 presents the magnitudes of aircraft roll acceleration transfer function. It is seen that at high frequencies the aircraft response

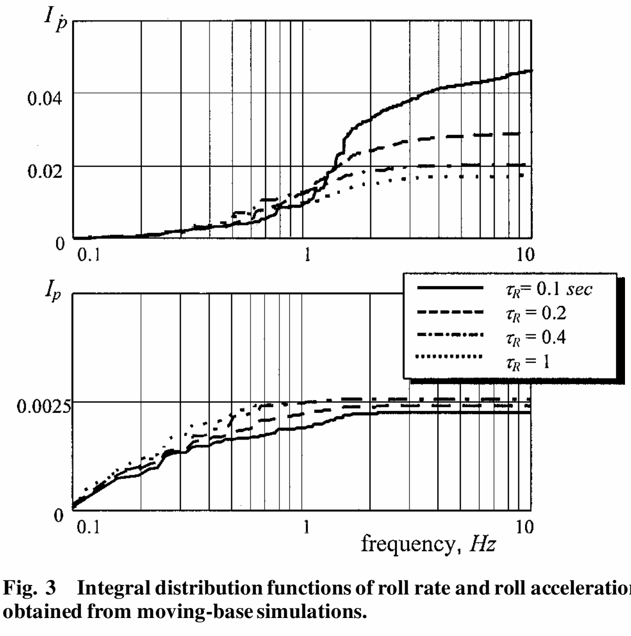

Fig. 3 Integral distribution functions of roll rate and roll acceleration obtained from moving-base simulations.

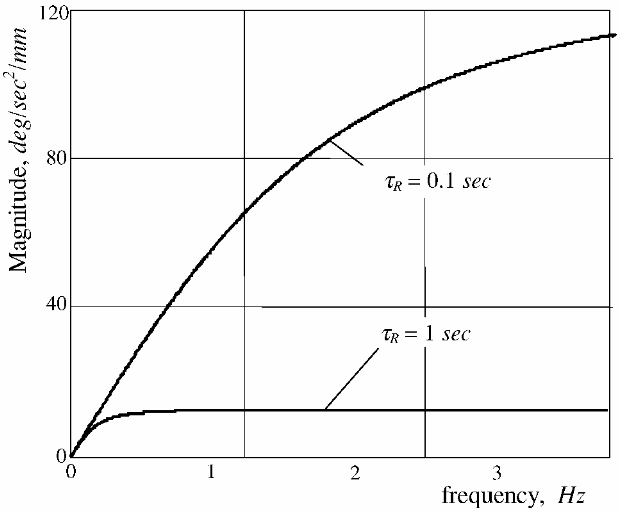

Fig. 4 Roll acceleration frequency response (*K* = const).

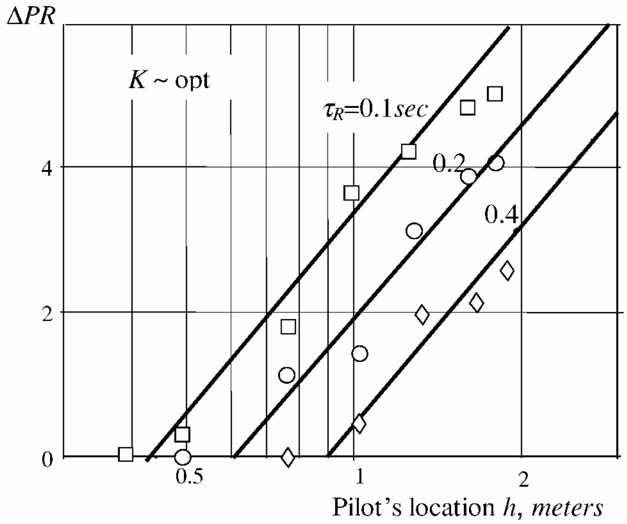

Fig. 5 Pilot rating degradation as a function of pilot location for different roll-mode time constant values.

intensity for $\tau_R = 0.1$ s is 10 times greater than that for $\tau_R = 1$ s. That is why, at short τ_R, an aircraft responds to the high-frequency (noise) component in pilot activities. As a result, high-frequency lateral specific forces arise, which cause negative pilot opinion of aircraft handling qualities.

Lateral specific forces intensity depends on pilot location relative to the rotational axis. Thus, aircraft response abruptness also depends on pilot location. This is shown in Fig. 5, where pilot ratings as a function of the pilot's location for different values of roll-mode time constant are presented.

Figure 6 shows magnitudes of lateral acceleration frequency responses for one Russian airliner.[7] It is seen that elastic-body frequency response has a resonant peak within 2–3 Hz. This frequency corresponds to the frequencies of the noise component in pilot stick activities; thus, certain structural elasticity characteristics can provoke AR.

B. Pilot Ratings Worsening as a Function of Lateral Specific Forces

Because lateral specific forces are perceived by a pilot against the background of angular motion, we need to know how this roll motion affects lateral specific forces perception.

Figure 7 shows lateral specific forces sensitivity thresholds as a function of roll-rate amplitude. It is seen that sensitivity thresholds increase approximately in proportion to roll-rate amplitude. We can conclude that the degree of lateral specific forces negative effect is

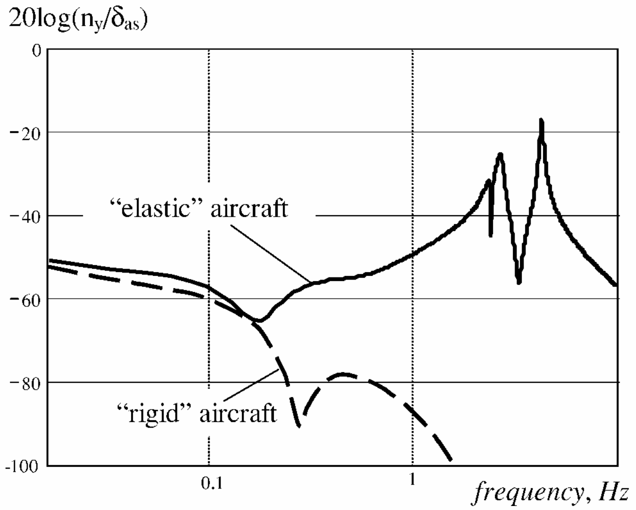

Fig. 6 Lateral acceleration frequency responses of rigid-body and elastic-body airplane.

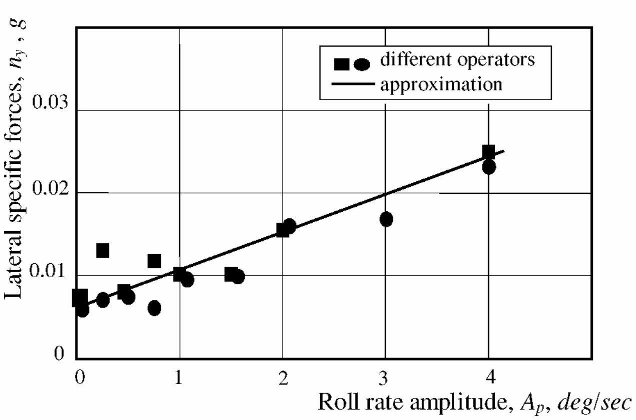

Fig. 7 Lateral acceleration sensitivity thresholds as a function of roll-rate amplitude.

determined by the ratio (λ) of the level of high-frequency lateral specific forces to the level of roll rate:

$$\Delta PR = \Delta PR(\lambda)$$

Let us assume that the levels of high-frequency lateral specific forces and roll rate are their rms values. Then we have the following:

$$\lambda = (\sigma_{n_y})/\sigma_p \tag{1}$$

Pilot rating increment as a function of parameter λ is described by the following expression (Fig. 8):

$$\Delta PR(\lambda) = \begin{cases} 0 & \lambda < 0.2 \\ 9\log\lambda + 6.3 & \lambda \geq 0.2 \end{cases} \tag{2}$$

If $\lambda < 0.2$, the lateral specific forces are not felt by a pilot (are below the sensitivity threshold) and, thus, do not negatively affect pilot opinion. As parameter λ exceeds 0.2, pilot ratings worsen according to the logarithmic law.

Equation (2) is based on our experimental data, as shown later in this section.

C. Calculating Parameter λ

The value of parameter λ is determined according to the diagram in Fig. 9 for a number of reasons.

Generally, spectrum of characteristics of pilot activities depend not only on the aircraft characteristics, but also on the piloting conditions: piloting task, urgency for high performance, and turbulence. To estimate whether aircraft is prone to AR, it is natural to consider

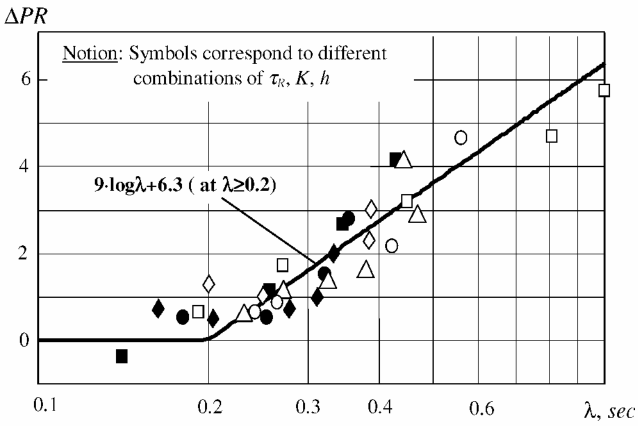

Fig. 8 Pilot rating degradation as a function of parameter λ.

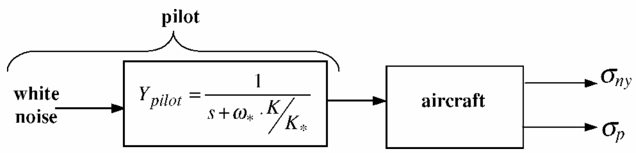

Fig. 9 Diagram of parameter λ calculation.

those piloting conditions in which a pilot is more susceptible to the influence of lateral accelerations.

Our experiments have shown that AR is especially pronounced when no turbulence occurs and the pilot is not occupied by a piloting task, but manipulates the stick at will to evaluate HQ in an open loop. (The pilot does not close the loop.) That is why the diagram to calculate parameter λ is the model of aircraft control in an open loop.

The amplitudes of the low-frequency component of the pilot activity, which is created deliberately, in the first approximation are inversely proportional to aircraft gain. The amplitudes of the high-frequency (noise) component in pilot activity are inversely proportional to the frequency and depend only slightly on aircraft gain. This type of pilot activity can be presented as white noise passing through the following filter (Fig. 9):

$$Y_{\text{pilot}} = 1/[s + \omega_*(K/K_*)] \tag{3}$$

where K is aircraft gain in the stick-deflection-to-roll-rate transfer function, $K_* = 0.32\ \text{rad} \cdot \text{s}^{-1} \cdot \text{in.}^{-1}$ is a certain constant that may be interpreted as the characteristic gain, and $\omega_* = 1$ rad/s. Parameter ω_* was introduced in expression (3) in order for the dimensional representation of the components in the denominator of the expression to be the same.

It should be borne in mind that model (3) differs from the well-known pilot models for a closed loop and is applicable only to predict aircraft AR.

D. Defining Function $\Delta PR(\lambda)$ and Determining the Value of K_*

First, we determined the difference between moving-base and fixed-base pilot ratings for all the combinations of τ_R, K, and h considered in the experiments. (The difference is due to HQ worsening caused by AR). Then, ΔPR were presented as functions of the values of λ obtained according to Fig. 9 for various values of K. These functions of empirical ΔPR for the calculated values λ were approximated by the following function:

$$\Delta PR(\lambda) = \begin{cases} 0 & \lambda < a \\ b\log\lambda + c & \lambda \geq a \end{cases} \tag{4}$$

The values of parameters a, b, c, and K were selected for the dispersion between the experimental data and the estimations according to function (4) to be minimal. As a result, the values $a = 0.2$, $b = 9$, and $c = 6.3$ in function (4) and the value $K_* = 0.32$ rad · s^{-1} · in.$^{-1}$ were selected.

Figure 8 shows that Eq. (2) is in adequate agreement with the experimental data.

IV. Criterion to Estimate Abrupt Response in Roll

A. Defining the Criterion

The proposed criterion is, in fact, a summary of the theoretical approach considered earlier.

In accordance with the criterion, worsening roll-handling qualities due to aircraft AR are determined by ratio λ of rms of lateral specific forces at pilot location, σ_{n_y}, to rms of roll rates, σ_p.

Worsening pilot rating ΔPR as a function of parameter λ is determined by Eq. (2) or from Fig. 8.

To calculate values of σ_{n_y} and σ_p we assume that the pilot model is white noise passing through filter (3). Then the values of σ_{n_y} and σ_p can be determined by motion equations solution or from the following expressions:

$$\sigma_{n_y}^2 = \frac{1}{2\pi} \cdot \int_{-\infty}^{+\infty} |Y_{n_y}(i\omega) \cdot Y_{\text{pilot}}(i\omega)|^2 \, d\omega$$

$$\sigma_p^2 = \frac{1}{2\pi} \cdot \int_{-\infty}^{+\infty} |Y_p(i\omega) \cdot Y_{\text{pilot}}(i\omega)|^2 \, d\omega$$

where Y_{n_y} and Y_p are, respectively, lateral specific forces and roll-rate transfer functions.

In the case when "aircraft + control system (prefilter)" dynamics in roll can be described by the transfer function

$$Y_p/\delta_{\text{as}} = [K/(\tau_R s + 1)][1/(T_{\text{prefilter}} s + 1)]$$

parameter λ can be calculated as follows:

$$\lambda = \frac{h}{g}\sqrt{\frac{\omega_*(K/K_*)}{\tau_R + T_{\text{prefilter}} + \tau_R T_{\text{prefilter}}\omega_*(K/K_*)}}$$

B. Agreement with the Experimental Data

The estimations according to the proposed criterion are in good agreement with all in-flight and on-ground experimental data available for maneuverable aircraft, which can be seen, for example, in Figs. 1 and 5.

We have found no detailed data in the literature on AR of transport aircraft with a wheel, except for the data on AR obtained in the course of flight tests of a Russian airliner with a wheel.[7] The applicability of our criterion to transport aircraft has been evaluated on the basis of the data for this particular aircraft.

During the first in-flight tests of the airliner the majority of test pilots noticed that, in cruise flight, aircraft response to wheel deflections was too abrupt. The main cause of AR in this case was a certain structural elasticity of the airliner. AR was eliminated by introducing a first-order lag filter into the ailerons and interceptors control loop. It was found, by means of a trial-and-error method, that the minimum value of the filter time constant at which AR disappeared was $T_{\text{filter}} = 0.2$ s.

Figure 10 shows pilot rating increments due to AR for the airliner in question; the increment was calculated according to our method for the two filter time constant values $T_{\text{filter}} = 0$ and $T_{\text{filter}} = 0.2$ s, which were tested in flight. It is seen that AR occurs only if $T_{\text{filter}} = 0$, which agrees with in-flight results. In the course of in-flight tests no pilot ratings were given, but the majority of the test pilots noticed rather abrupt response to wheel deflections. Their comments are in adequate agreement with worsening pilot rating ($\Delta PR = 2.5$) calculated according to our method.

Large values for the filter time constant lead to a delay in the control system. That is why filter time constants are usually selected

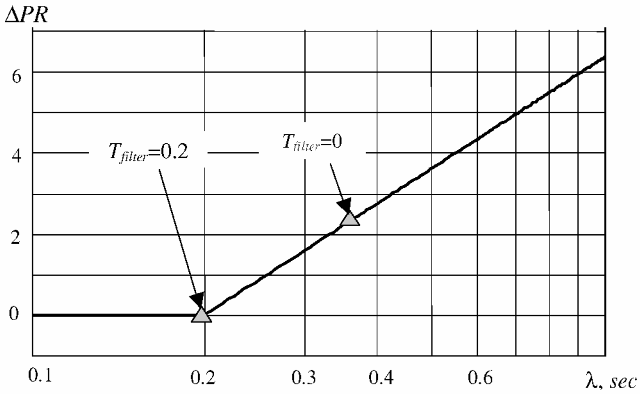

Fig. 10 Comparison of different filter cases.

to be a minimum corresponding to aircraft abrupt responding disappearance, that is, parameter λ corresponds to $\Delta PR(\lambda) = 0$. Thus, we may assume that $T_{\text{filter}} = 0.2$ s is that very minimum value of filter time constant. Figure 10 shows that this particular filter time constant value practically equals the estimated filter time constant corresponding to AR disappearance.

Thus, the materials of airliner flight tests give us reason to believe that our criterion is applicable to predict AR not only for maneuverable aircraft, but also for transport aircraft having a certain structural elasticity. However, additional experiments are needed to fully prove our preliminary conclusion.

V. Conclusions

The reason for aircraft AR with short response time is high-frequency lateral specific forces arising due to roll accelerations or certain structural elasticity characteristics. Handling qualities in AR are determined by the ratio of the lateral specific forces to the roll-rate values.

The proposed criterion can predict aircraft AR response in roll. The estimations according to this criterion agree with the experimental data available.

References

[1]McRuer, D., "Human Dynamics in Man–Machine Systems," Automatica Corp., Vol. 16, No. 3, 1980, pp. 237–253.

[2]Harper, R. P., Jr., "In-Flight Simulation of the Lateral-Directional Handling Qualities of Entry Vehicles," Calspan Corp., Rept. TE-1243-F-2, Buffalo, NY, Feb. 1961.

[3]Monagan, S. J., Smith, R.E., and Bailey, R. E., "Lateral-Directional Flying Qualities of Highly Augmented Fighter Aircraft," Calspan Corp., Rept. 6645-F-8, Buffalo, NY, Aug. 1981; also AFWAL-TR-81-3171, March 1982.

[4]Smith, R. E., "Evaluation of F-18A Approach and Landing Flying Qualities Using an In-Flight Simulator," Calspan Corp., Rept. 6241-F-1, Buffalo, NY, Feb. 1979.

[5]Wood, J. R., "Comparison of Fixed-Base and In-Flight Simulation Results for Lateral High Order Systems," *Proceedings of the AIAA Atmospheric Flight Mechanics Conference*, AIAA, New York, 1983, pp. 1–7.

[6]Chalk, C. R., "Excessive Roll Damping Can Cause Roll Ratchet," *Journal of Guidance, Control, and Dynamics*, Vol. 6, No. 3, 1983, pp. 218, 219.

[7]Rodchenko, V. V., Zaichik, L. E., Yashin, Y. P., Lyasnikov, V. V., Galyuchenko, A. M., and Rufov, I. W., "Investigation of Feel System and Control Sensitivity Characteristics Influencing PIO of Unmaneuverable Aircraft," *Investigation of Pilot Induced Oscillation Tendency and Prediction Criteria Development*, Wright Lab., WL-TR-96-3109, Wright–Patterson AFB, OH, May 1996.

[8]Höhne, G., "A Biomechanical Pilot Model for Prediction of Roll Ratcheting," *Proceedings of the AIAA Atmospheric Flight Mechanics Conference*, AIAA, Reston, VA, 1999, pp. 187–195.

[9]Koehler, R., "Unified Approach for Roll Ratcheting Analysis," *Journal of Guidance, Control, and Dynamics*, Vol. 22, No. 5, 1999, pp. 718–720.

[10]Hess, R. A., "Theory for Roll-Ratchet Phenomenon in High-Performance Aircraft," *Journal of Guidance, Control, and Dynamics*,

Vol. 21, No. 1, 1998, pp. 101–108.

[11] Innocenti, M., and Thukral, A., "Roll Performance Criteria for Highly Augmented Aircraft," *Journal of Guidance, Control and Dynamics*, Vol. 14, No. 6, 1991, pp. 1277–1286.

[12] White, A. D., and Rodchenko, V. V., "Motion Fidelity Criteria Based on Human Perception and Performance," *Proceedings of the AIAA Modeling and Simulation Technologies Conference*, AIAA, Reston, VA, 1999, pp. 485–493.

[13] Zaichik, L. E., Rodchenko, V. V., Yashin, Yu. P., and Rufov, I. V., "A Theoretical Approach to Estimation of Acceleration Effects on Piloting," *Proceedings of the AIAA Modeling and Simulation Technologies Conference*, AIAA, Reston, VA, 2000, pp. 1–8.

[14] Hosman, R. J. A. W., and van der Vaart, J. C., "Thresholds of Motion Perception Measured in a Flight Simulator," *Proceedings of the Twelfth NASA–University Annual Conference on Manual Control*, Delft Univ. of Technology, Delft, The Netherlands, 1976, pp. 956–983.

[15] Cooper, G. E., and Harper, R. P., Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.