Excessive Roll Damping Can Cause Roll Ratchet

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HUMAN-operator-describing function data from laboratory experiments involving fixed-base compensatory tracking were used by previous researchers to develop the "crossover" model; i.e., the pilot develops compensation such that $Y_p Y_c = K/s$ in the region of crossover. This model has been interpreted by designers to imply that the ideal controlled element is $Y_c = K/s$. However, NT-33A in-flight experiments[2-4] show degradation in pilot rating with increased roll damping when the controlled element transfer function approaches K/s,

$$\frac{\phi(s)}{\phi_\epsilon(s)} = \frac{K}{s(s+\lambda_R)} \rightarrow \frac{K}{s}$$

when $\lambda_R \rightarrow \infty$.

Pilot comments[2-4] contain references to excessive roll and lateral accelerations experienced in achieving the desired roll rate. These accelerations can be avoided if the pilot uses slower applications of control input but this requires conscious effort. There are times when he reacts instinctively and suddenly and, in these situations, a pilot/airplane closed-loop "oscillation" takes place in roll. The "oscillation" is relatively high frequency, 11-17 rad/s, and is described as roll "ratchet." The time history in Fig. 1 illustrates a pilot/airplane closed-loop oscillation that occurred during evaluation of configuration 6-3 in Ref. 4, which was described as roll ratchet. The time history in Fig. 2 illustrates a roll ratchet incident experienced during the YF-16 flight test program described in Ref. 5.

Since the pilot/airplane system exhibits a lightly damped oscillation during roll ratchet, it should be possible to model the closed-loop dynamics and to calculate parameter values that would result in zero damped complex roots at the frequency observed in the flight records.

Consider first the case where the airplane transfer function is K_c/s and the pilot transfer function K_p. Then $Y_p Y_c = K/s$ and the closed-loop dynamics are determined by the value of the loop gain K. This system cannot be driven unstable by increases in loop gain. Consider next the effect of adding time delay to the control loop. The time delay causes increasing phase shift with increased frequency and the closed-loop system will exhibit instability at high loop gain. Figure 3 summarizes the block diagrams and equations for three different forms of the pilot model, i.e., $K_p e^{-\tau s}$, $K_p s e^{-\tau s}$, and $K_p s^2 e^{-\tau s}$, and form of the airplane transfer function K_c/s. These simplified cases represent pilot loop closures based on angular position, rate, and acceleration. All three of these models will exhibit closed-loop instability at the gains and frequencies indicated on Fig. 3. The values of time delay required to cause closed-loop oscillations in the frequency range, 12-17.4 rad/s, observed in the roll ratchet illustrated in Fig. 2 for configuration 6-3 are also noted in Fig. 3. Nichols diagrams for the cases illustrated in Fig. 3 are drawn in Fig. 4 for the values of time delay that will cause the closed-loop system to go unstable at $\omega = 15.7$ rad/s in each case,

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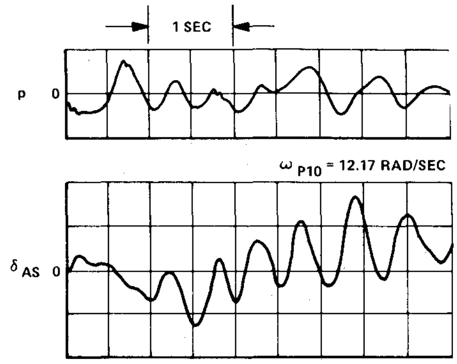

Fig. 1 T-33 high-frequency roll ratchet.

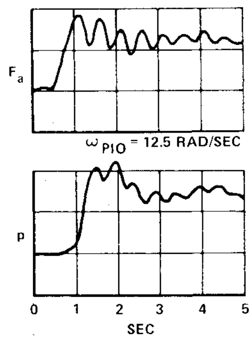

Fig. 2 YF-16 roll ratchet incident.

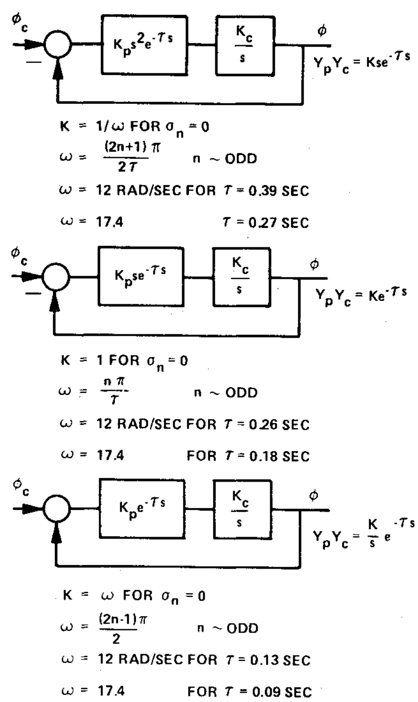

Fig. 3 Block diagrams for control of ϕ, $\dot\phi$, *and* $\ddot\phi$ with time delay in the loop.

$$Y_p Y_c = \frac{15.7e^{-0.1s}}{s};= 1.0e^{-0.2s};= \frac{se^{-0.3s}}{15.7}$$

The pilot comments[2] for airplanes with high roll damping indicate that the pilots try to use slower stick inputs to avoid abrupt responses. There are times, however, when they react instinctively and suddenly and are likely to become involved in a pilot/airplane closed-loop roll oscillation until they can modify their behavior, i.e., open the loop, reduce gain, develop lag equalization, etc.

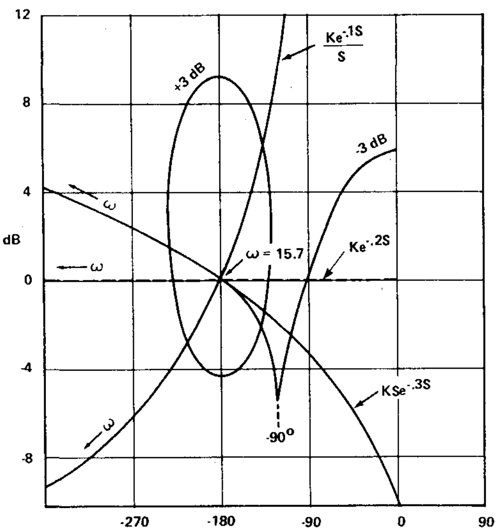

Fig. 4 Nichols diagrams.

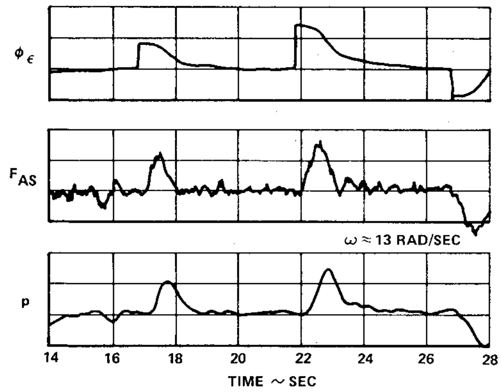

Fig. 5 Bank angle tracking roll ratchet (from Ref. 3).

To model this situation, consider that the full adapted pilot uses lag equalization to obtain satisfactory bandwidth to control bank angle and to avoid abrupt responses and high angular accelerations. Then assume that, as the result of an abrupt change in the target motion, the pilot becomes involved in responding directly to the roll angular acceleration. The model would change from

$$Y_p Y_c = \frac{Ke^{-\tau_p S}}{s(s+\lambda_p)}$$

to

$$Y_p Y_c = \ddot{K} s e^{-\tau_p S}$$

The Nichols diagram for this latter dynamic system is illustrated in Fig. 5 which was drawn for $\tau_p = 0.3$ s and exhibits instability at $\omega = 15.7$ rad/s for a loop gain $\ddot{K} = 1/\omega = 1/15.7$. When the perception modality is switched from visual observation of bank angle error to perception of angular acceleration by means of vestibular system, neck muscle spindle sensing, and body pressure sensing, it is not obvious how the pilot's gain would be modified but experimental evidence suggests that a high enough gain would be adapted to cause closed-loop resonance.

The time history illustrated in Fig. 5 was taken during a bank angle tracking task performed during the in-flight evaluations reported in Ref. 3. The task was displayed to the pilot by means of a head-up display so that records of the error displayed, the pilot's stick force response, and the resulting roll rate are available. A number of observations can be made after study of the closed-loop responses in Fig. 5:

1) The pilot exhibits a 0.25-0.30 s time delay in applying stick force following a step change in the bank angle command.

2) The stick force and roll rate time histories exhibit roll ratchet at $\omega = 13$ rad/s.

3) The roll ratchet oscillation appears in both of the two recorded responses to step bank angle commands. The magnitude is larger in the second response.

4) The second response exhibits a longer tail in reducing the bank angle error to zero. This observation is consistent with the angular acceleration model, i.e., the closed-loop system exhibits a root that is approaching zero at the origin. The closed-loop system will exhibit droop.

5) In responding to the step bank angle command, it can be observed that the pilot abruptly applies about 3.5-4 "lines" of stick force independent of the magnitude of the bank angle step command. He then modifies the stick force approximately 0.25-0.3 s after start of the initial force application. The second force application is of higher amplitude in the second record than it is in the first record. The bank angle command was larger in the second record. Note also that the second force application in each record occurs when the p response starts to move, i.e., when the angular acceleration is applied but before there is a noticeable change in the bank angle or reduction in the ϕ_E trace from the step-command initial value.

These observations tend to confirm that the pilot may be operating on angular acceleration information (or lateral linear acceleration at his head) in performing the bank angle tracking task. The observed time delays would cause closed-loop instability at the observed oscillation frequency if the pilot were closing the loop on acceleration feedback.

Conclusions

1) The roll angular acceleration and the lateral linear accelerations at the pilot station are important considerations in flying qualities.

2) The angular and linear accelerations can become objectionably high when the roll damping is very high ($\tau_R = 0.15$ s) and the height above the X stability axis is large.

3) Roll ratchet may be explained by a model that assumes the pilot is closing the aileron loop on angular acceleration response cues.

4) The ideal roll transfer function is $\phi/F_{AS} = K/s(s+\lambda)$, not K/s. This is because the angular acceleration response to pilot input becomes too large as $\lambda \to \infty$. The response becomes too abrupt and the pilot/airplane closed-loop system is destabilized by the pilot's time delay.

References

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