Influence of Roll Command Augmentation Systems on Flying Qualities of Fighter Aircraft

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Roll command augmentation systems (CAS), in which commanded roll rate is directly proportional to stick input, provide high roll authority and precise control over the entire flight regime. However, operational experience with high-gain CAS has revealed problems with their use. Oversensitivity to small control inputs, "roll ratcheting," and pilot-induced oscillation (PIO) are commonly encountered in the early stages of development. Recent flight test and operational experiences with high-authority CAS of fighter aircraft are reviewed. Possible sources of the problems encountered are suggested, and guidelines are proposed for improving the flying qualities of aircraft equipped with roll CAS.

Nomenclature

a_y = lateral acceleration
F_{as} = aileron stick force
K_e = control system error gain
$L'_{F_{as}}$ = aileron stick effectiveness
p = roll rate
$\dot{p}$ = roll acceleration
s = Laplace operator, $\sigma \pm j\omega$
T_F = stick prefilter time constant
T_R = roll mode time constant
T_s = spiral mode time constant
δ_a = aileron deflection
τ_e = equivalent time delay
ϕ = roll attitude
ϕ_I = change in roll attitude in 1 s
ω_ϕ / ω_d = ratio of roll numerator and dutch roll mode natural frequencies

Introduction

THE importance of stability augmentation to the success of modern airplanes—especially high-performance, highly maneuverable fighter-type (Class IV[1]) airplanes—cannot be understated. Stability augmentation systems (SAS) have been an integral part of aircraft flight control systems since the first SAS flew on the Northrop Flying Wing in 1948.[2] Command augmentation systems (CAS)‡ are more recent, but they too are becoming essential components for modern fighters.

The elements of a command augmentation system (CAS) are shown in Fig. 1. A roll rate CAS utilizes an effective feedforward so that pilot control inputs are compared directly to actual roll response. Such CAS, as they are used today, can be limited in authority with parallel direct links (e.g., the F-4, F-14, F-15, F-18, and B-1), or full authority with high command gains (e.g., the F-16). The latter are the more interesting from a handling qualities standpoint.

Flight test and operational experience with Class IV airplanes with high-authority roll CAS have been very promising: responses to command inputs are sharp and rapid; precision controllability is excellent; hands-off operation is improved. However, distinct problems have sometimes arisen as well. These have been identified variously as oversensitivity to small control inputs; overcontrol with large inputs; pilot-induced oscillations; and the phenomenon known as "roll ratcheting." The causes of and cures for these shortcomings will be discussed.

This paper will focus primarily on experiences with roll CAS during high-speed maneuvering flight (Category A Flight Phases[1]). The bulk of published literature describing experience with CAS-equipped aircraft is concerned with this area. While the conclusions drawn herein might not be specifically applicable to other aircraft types or missions, the general effects of roll CAS on flying qualities are probably similar. This will become clearer as more work is done in the field.

Gradient Shaping

Experience with roll rate CAS has shown that a key element for acceptable handling qualities is the gradient between commanded roll rate and stick force, p_c/F_{as} (see Fig. 1). High-gain, high-authority systems have had problems with extreme sensitivity for small inputs and inadequate roll performance with large inputs. The cure has been to decrease p_c/F_{as} for small inputs via a nonlinear stick shaping network, while allowing a high gradient for larger inputs. Experience with the limited number of CAS discussed in this paper will show that command networks that fall within a small range of p_c/F_{as} will have acceptable response properties, as long as certain other requirements, to be discussed shortly, are satisfied. The successful p_c/F_{as} curves reviewed herein fall within the parabolic region of Fig. 2. This figure also reflects the range of actual maximum roll rates achieved for these command networks and typical pilot comments associated with p_c/F_{as} outside the hatched region. In general, the commanded roll rates were obtained for small inputs (on the order of half stick or less), but larger force inputs generally did not produce the commanded rates. This is simply a result of the fact that aircraft roll performance for large-amplitude rolls is less than ideal due to inertia, aerodynamic loads, and so on.

In almost all high-performance augmented airplanes some amount of yaw damping is provided. This has the effect of enhancing roll performance by minimizing undesirable yawing motions. While yaw dampers are important to the aircraft to be discussed here, their effects on handling qualities and performance will be considered to be separate from the roll CAS under consideration.

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‡In the past, CAS has also been referred to as *control,* rather than *command,* augmentation system. These terms are identical.

Roll Responses for Conventional Aircraft

It is interesting to consider the reasons for the parabolic command gradient shaping shown in Fig. 2. Fighter aircraft with conventional, fully powered hydraulic servos but without CAS (for instance, 1950's generation fighters) generally have linear stick-to-surface linkages, i.e., δ_a response to F_{as} is linear (above breakout). This is sketched in Fig. 3a. However, wind tunnel and flight tests of these aircraft show that aileron effectiveness is nonlinear with deflection; large deflections produce an incrementally larger rolling moment than do small deflections. This can be viewed as a nonlinear deflection/response characteristic, sketched in Fig. 3b. The result of these force/deflection and deflection/response characteristics is a parabolic force/response curve, shown in Fig. 3c. As an example, Fig. 4 shows the $p_{\max}/F_{as}$ curves for three aircraft, taken from flight or wind tunnel/flight test results. Two of the three lie within the p_c/F_{as} gradient range identified in Fig. 2 as acceptable for CAS. Parabolic p_c/F_{as} networks, therefore, artificially supply to the pilot what aircraft without CAS have naturally.

Roll CAS Gradients

Evolution of the CAS shaping network for a recent airplane, shown in Fig. 5, is a valuable lesson. Simulations prior to first flight produced a very steep p_c/F_{as} gradient with maximum stick forces of 4 lb (curve 1). In-flight simulation in a variable stability NT-33 ed in a decrease in the initial gradient by a factor of two (curve 2). A divergent lateral pilot-induced oscillation (PIO) encountered on the prototype was directly traceable to excessive stick sensitivity around zero. The stick sensitivity was reduced further (curve 3) and the PIO tendency disappeared. Curve 4, considered to be acceptable, is yet another reduction in the gradient. Thus, the gradient originally designed as a result of ground-based simulations (curve 1) was more than four times too high for Category A flight. This airplane also had an unusual sidearm controller, the characteristics of which may have had some influence on the choice of p_c/F_{as} shaping. However, the final curve is so similar to those of centerstick airplanes that differences in the type of controller were probably not a major factor.

Roll Ratcheting

As mentioned earlier, concerns from the piloting point of view for roll CAS have been described variously as oversensitivity to small inputs, overcontrol or sluggishness for large inputs, and "roll ratcheting." All of these can create PIOs, and, as we shall see, ratcheting is the hardest to identify, isolate, and correc, jk e other problems can be solved by relatively simple means (i.e., sensitivity is alleviated with low p_c/F_{as} gradients for small F_{as} inputs, and sluggishness is corrected by high p_c/F_{as} for large inputs—thus, the parabolic shaping shown in Fig. 2).

An example of roll ratcheting is shown in Fig. 6. The ratchet was encountered during a series of bank-to-bank maneuvers. The oscillations exhibit limit cycles at a frequency of about 18 rad/s. The roll CAS for this aircraft (referred to hereafter as aircraft A) is presented in Fig. 7; ratcheting was experienced with p_c/F_{as} curve 1 in Fig. 7. The fact that roll ratcheting occurred for this case is evidence that stick shaping

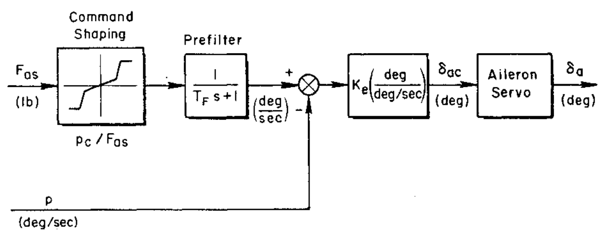

Fig. 1 Block diagram representation of full-authority roll rate command augmentation systems.

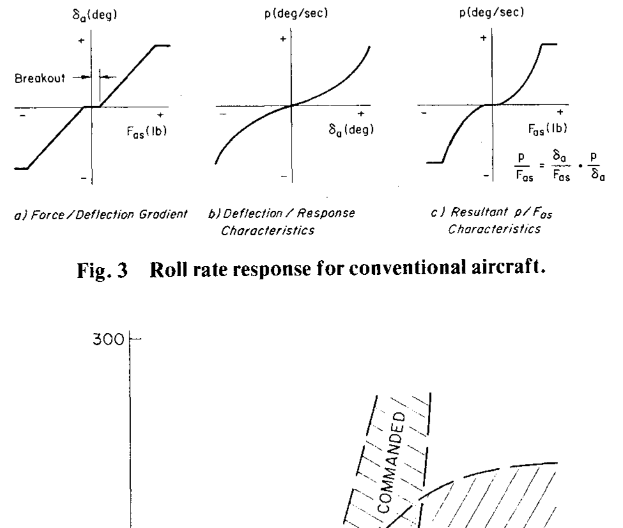

Fig. 3 Roll rate response for conventional aircraft.

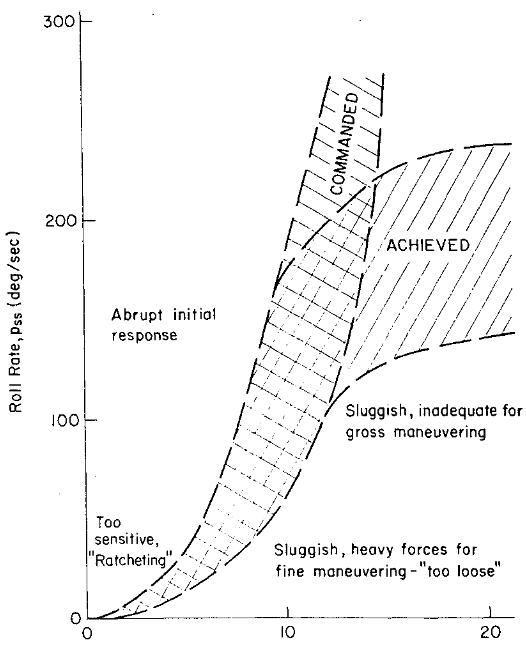

Fig. 2 Range of acceptable nonlinear roll command shaping networks based on flight tests (Class IV aircraft, Flight Phase Category A, right roll).

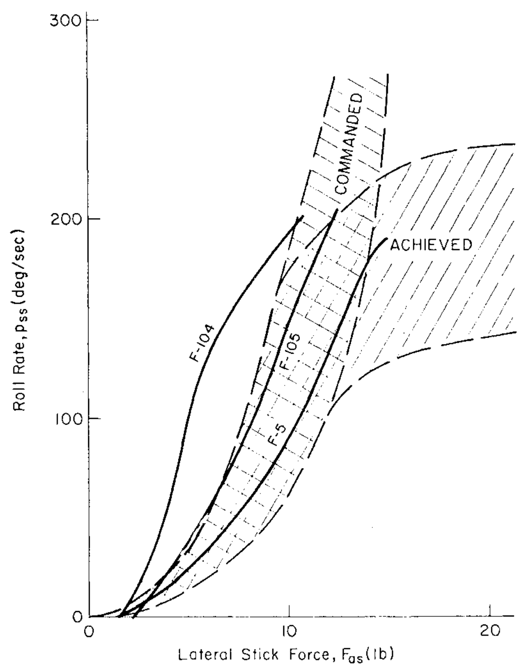

Fig. 4 Comparison of $p_{\max}/F_{as}$ for several conventional Class IV aircraft with CAS curves of Fig. 2.

alone is not a cure for this problem. The reason is that the stick sensitivity is reduced only around zero, allowing ratcheting to occur when the lateral stick is nonzero, such as in Fig. 6. Figure 7 and Table 1 document several of the CAS networks flown on aircraft A in developing an optimum CAS. This is an excellent review of all the elements of a CAS, since several gradients, prefilter lags, and error gains were evaluated.

The CAS which produced the Fig. 6 ratcheting had a prefilter lag at 10 rad/s and an error gain $K_e = 1.0$ (Table 1). As Table 1 reflects, CAS 2 involved only a reduction by one-half in K_e and eliminated the roll sensitivity. However, with the sensitivity reduced, the pilots were then aware that the steady-state roll response was much too low. With $K_e = 1.0$ and the prefilter lag reduced from 10 to 3 rad/s (CAS 3), the roll sensitivity was reduced, although not enough. It was clear from CASs 1-3 that a) the roll response for large inputs was too low; b) a reduction in the prefilter lag helped reduce sharp inputs; c) a reduction in the error gain eliminated ratcheting. Therefore, CAS 4 was evaluated. This involved a new p_c/F_{as} gradient (Fig. 7), including a 0.75 lb breakout, and lower T_F and K_e (Table 1). It also produced a mild PIO tendency during air-to-air tracking, probably due to the breakout. Finally, a slightly more sensitive gradient with no breakout (curve 5) was found to be best for all-around response.

Another example of roll ratcheting is given in Fig. 8a. The pilot was attempting a steady roll with less than full control input. The ratcheting is seen to be a lightly damped oscillation at a frequency of about 12 rad/s. As the second roll on Fig. 8 shows, the pilot was later able to perform a roll without encountering ratcheting. Additionally, full-authority rolls did not produce ratcheting. This has bearing on the possible causes of these oscillations, since full-authority rolls would allow the pilot to apply more than the maximum force required (see Fig. 2), and effectively stiffen his hand and arm in response to lateral accelerations. This will be discussed in more detail shortly.

The final example of roll ratcheting we will examine occurred during flight evaluations on the USAF/Calspan variable stability NT-33. An investigation of lateral flying qualities of highly augmented fighter aircraft[3] (dubbed LATHOS for Lateral High-Order Systems) represents an excellent data base for detailed discussion on many of the handling quality concerns for modern aircraft.

While the LATHOS tests were not intended to investigate the handling qualities of command augmentation systems per se, mechanization of the lateral control effectiveness was such that it may be considered a CAS. That is, the NT-33 variable stability system was devised to command a certain ratio of steady-state roll rate to stick force (p_{ss}/F_{as})—a pseudo-CAS network. Additionally, the roll rate response was devised with a neutral spiral ($T_s \doteq \infty$) and $\omega_\phi/\omega_d \doteq 1$. Thus the lateral response was effectively first order in combination with a variable prefilter and a time delay to account for actuator lags, that is,

$$\frac{p}{F_{as}} \doteq \frac{T_F L'_{F_{as}} e^{-0.028s}}{(s+1/T_R)(s+1/T_F)}$$

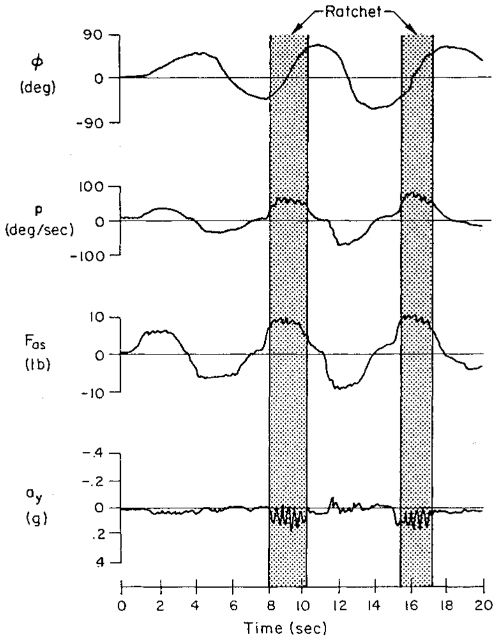

Fig. 6 Roll ratchet during banking maneuvers (aircraft A, CAS 1) $h = 20{,}000$ ft, $M = 0.75$.

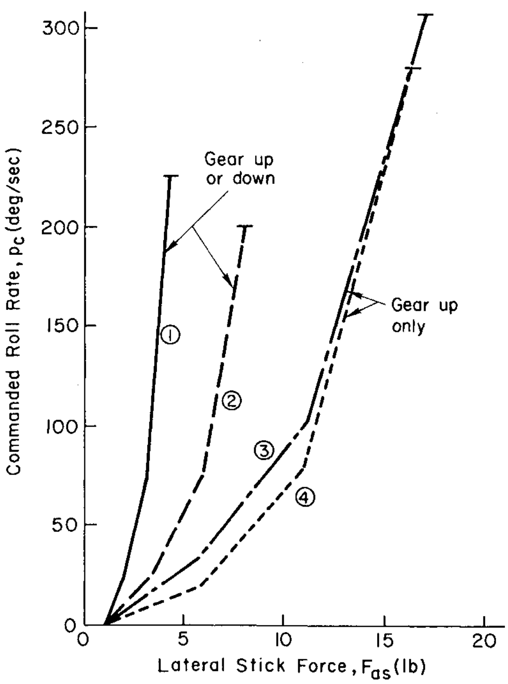

Fig. 5 Evolution of a CAS shaping network.

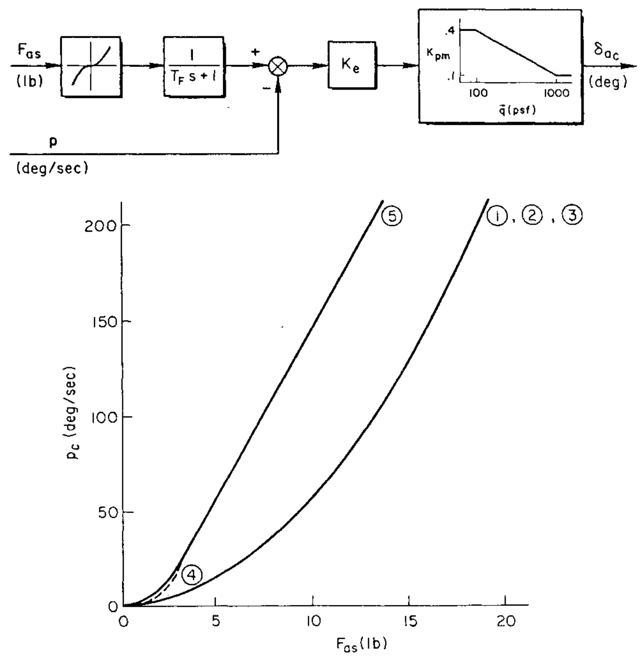

Fig. 7 Evolution of roll CAS network for aircraft A. See Table 1 for values of T_F, K_e.

Table 1 Descriptions of CAS networks for aircraft A

CAS[a]	Error gain, K_e^a, deg/deg/s	Prefilter lag, $1/T_F^a$, rad/s	Typical pilot comments
1	1.0	10	Much too sensitive to sharp inputs ($PR=7$); ratcheting (see Fig. 6)
2	0.5	10	Eliminated high sensitivity; steady-state response too low
3	1.0	3	Filter reduced sharp inputs, although not enough ($PR=7$)
4	0.375	3	Lateral PIO tendency in fine tracking (includes 0.75 lb breakout)
5	0.375	3	Best all-around response

[a] See Fig. 7.

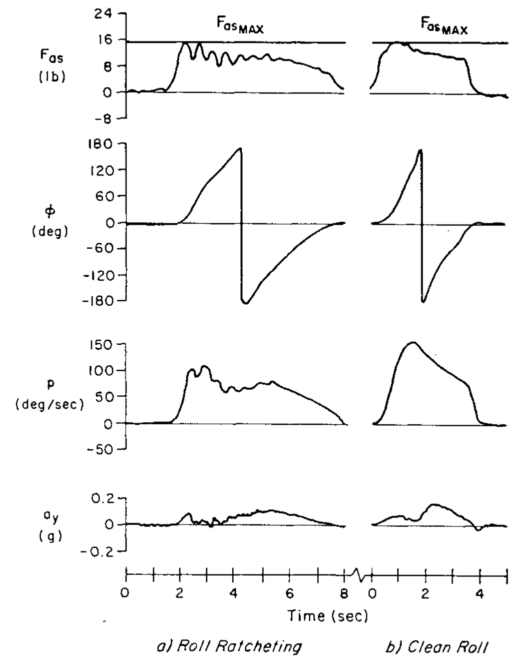

Fig. 8 Steady rolls. The roll in b was performed 32 s after a and was satisfactory, $h=10{,}000$ ft, $M=0.80$.

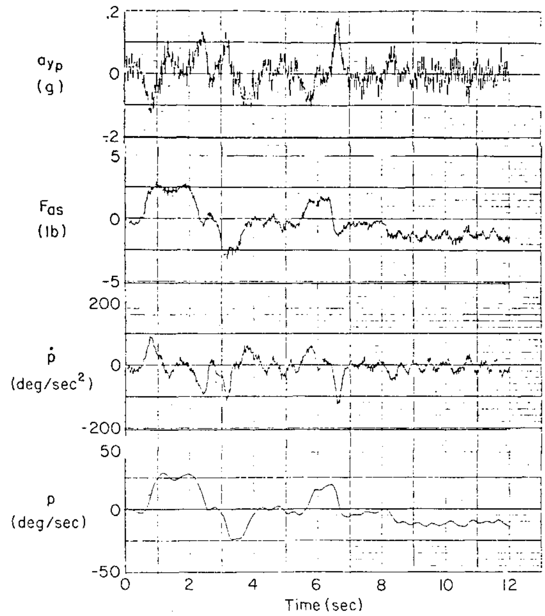

Fig. 9 Roll ratcheting experienced on LATHOS,[3] configuration 5-2.

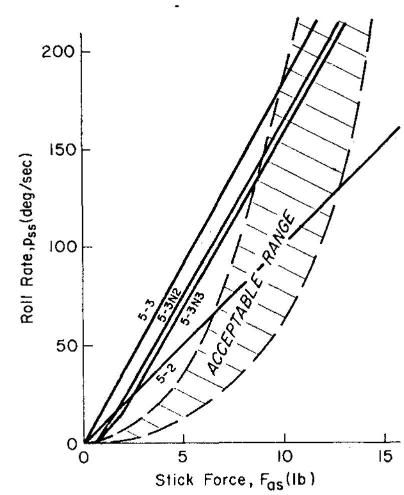

Fig. 10 Roll gradients for LATHOS[3] configurations 5-2 and 5-3 ($T_R=0.15$ s) compared with acceptable range from Fig. 2.

For the configurations with ratcheting, $T_R=0.15$ s. Figure 9 illustrates the ratcheting from a HUD tracking task. The ratcheting is best seen in the $\dot{p}$ and F_{as} traces, at a frequency of about 16 rad/s.

Figure 10 compares the p_{ss}/F_{as} gradients flown on LATHOS in Category A tasks (air-to-air tracking, HUD tracking, and aerial refueling) with the acceptable range from Fig. 2. No breakout or friction forces were mechanized. Several values of prefilter lag, T_F, were used with configurations 5-2 and 5-3. Figure 11 shows the influence of prefilter time constant on pilot ratings.

For configuration 5-2 ($p_{ss}/F_{as}=10$), the roll response for small inputs lies well above the acceptable range in Fig. 10, while the response for large inputs falls below the range of acceptable gradients. The pilot comments for configuration 5-2 are consistent with this observation. Typical comments were: "Took off pretty smartly initially, but felt heavy for final response.... Not predictable for fine tasks.... Quick, sharp, ratcheting." Pilot ratings for this case were Level 3 ($PR=7$, 7). These ratings and comments were for $T_F=0.025$ s. However, increasing T_F did little to improve the ratings (see Fig. 11) because of the inadequate response. Pilot comments reflect this: "Gross acquisition sluggish.... Sensitivity low.... Took a lot of force."

For configuration 5-3 ($p_{ss}/F_{as}=18$, Fig. 10) the final response is improved, but the small-control-input response is much too sensitive. Typical pilot comments for the 40 rad/s filter case ($T_F=0.025$, Fig. 11) were: "Gross acquisition—no problem. Fine tracking was characterized by jerkiness.... Had the perception that the stick was moving in my hand." Prefilters of 3.33-10 rad/s ($T_F=0.1$ and 0.3, Fig. 11) produced Level 1 pilot ratings. With $T_F=1.0$, however, a *PR* of 7 was given; this was "Smooth but sluggish.... Wouldn't respond to aggressive inputs."

Finally, two nonlinear gradients (5-3N2 and 5-3N3, Fig. 10) had the effect of reducing the sensitivity for small inputs while still providing good power for large inputs. For 5-3N2, a pilot rating of 4½ was given due to "Beginning of ratcheting—not strong.... Jerky even with small inputs." For 5-3N3 a *PR* of 4 was similarly given because "Initial response [was] too abrupt.... Adequate final roll rate for large inputs."

The LATHOS results are very similar to those for aircraft A (Fig. 7), that is, ratcheting was reduced by the addition of a

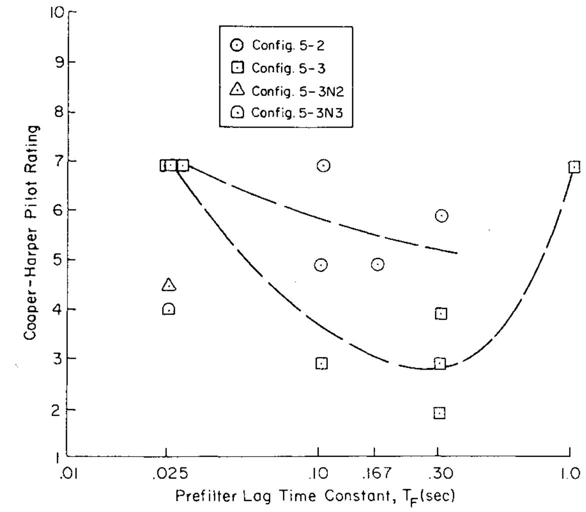

Fig. 11 Influence of prefilter lag on pilot ratings for LATHOS,[3] $T_R = 0.15$ s.

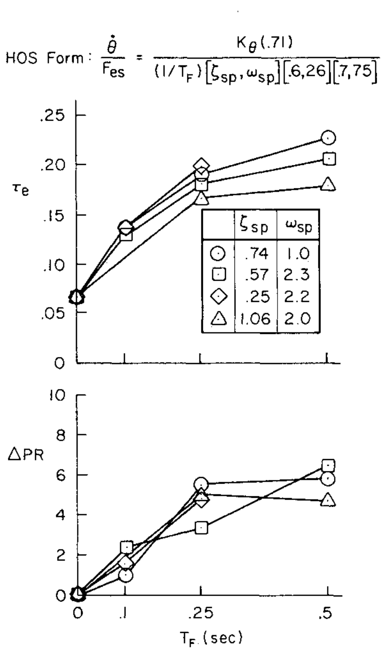

Fig. 12 Effect of prefilter on equivalent time delay and pilot ratings in longitudinal axis.[4]

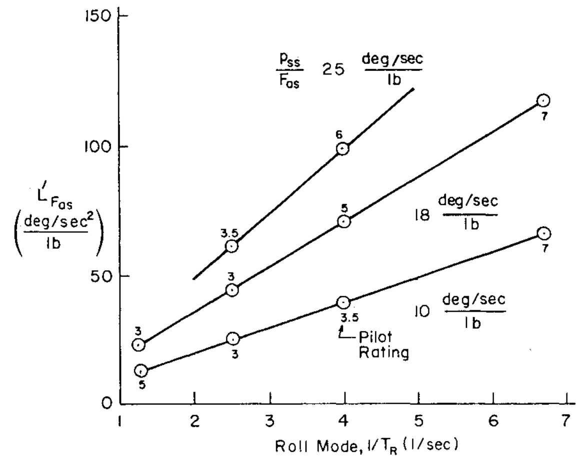

Fig. 13 Effect of roll mode—LATHOS[3] (Category A).

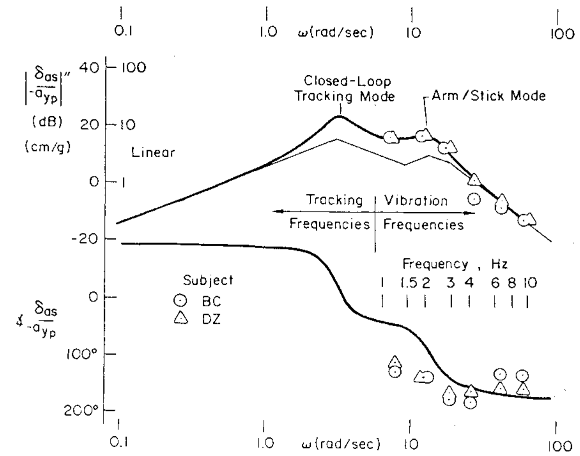

Fig. 14 Comparison of models and data for closed-loop stick deflection responses under lateral vibration.[9]

roll prefilter around 3 rad/s. However, stick prefilters are a major contributor to overall effective time delay, τ_e. For example, Fig. 12 shows that a 3 rad/s prefilter contributes about 0.1 s to the overall time delay in the longitudinal axis.[4] For sophisticated aircraft control systems, with structural filters, sensor filters, and so on, included, a prefilter as low as 3 rad/s could cause an unacceptably large delay. The prefilter should not be looked on as a final solution.

Implications for the Handling Qualities Standard

The ultimate goal of this limited review of some roll CAS is to develop tentative handling qualities requirements (or, barring that, guidelines). The pertinent paragraphs from the current military specification (MIL-F-8785C[1]) will be reviewed; much of what follows also appears in the proposed MIL Handbook,[4] written by the authors as a recommended replacement to MIL-F-8785C. The Handbook format (supplying guidance to the designer and procuring agency) is especially well-suited for instances where hard requirements cannot yet be devised. The discussions that follow will relate directly to requirements in MIL-F-8785C.

Roll Performance

Roll control effectiveness is specified in MIL-F-8785C (paragraph 3.3.4) in terms of time to achieve a specified bank angle change. Though we have not presented any data in this format, it has been shown elsewhere[4] that this is not a problem for CAS-equipped aircraft in general. As the comments presented in this paper suggest, when the p_c/F_{as} gradient is properly shaped (Fig. 2) and there are no other objectionable characteristics, pilots find roll performance to be quite good for the aircraft we have examined. In order to achieve adequate performance, a necessary (but not sufficient) requirement is a high p_c/F_{as} gradient for large F_{as} inputs.

Linearity

Paragraph 3.3.4.4 of MIL-F-8785C requires that "There shall be no objectionable nonlinearities in the variation of rolling response with roll control deflection or force. Sensitivity or sluggishness in response to small control deflections or force shall be avoided." Since a nonlinear p/F_{as} is desirable (see Fig. 2), the key words are "objectionable nonlinearities." A necessary but not sufficient condition for meeting this requirement is a p_c/F_{as} curve within the hatched area of Fig. 2 for small inputs.

We have already seen one exception to this, however: the LATHOS configuration 5-3 (Fig. 10), with prefilter lags of 3.33-10 rad/s, received good pilot ratings (Fig. 11). The full explanation of this result is not clear at this time except to note that the time delay from other sources in the NT-33

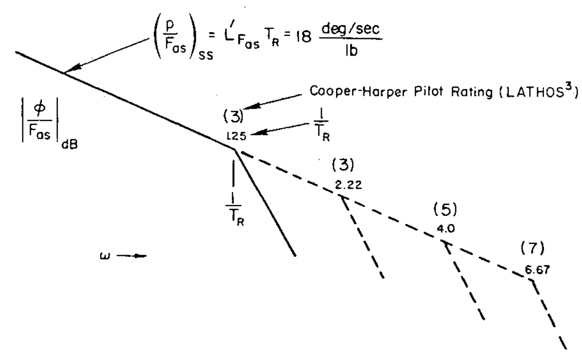

Fig. 15 Effect of $1/T_R$ on high-frequency gain.

variable stability experiment was very small; hence there was little or no penalty due to the stick filter.

Roll Mode Time Constant

The effect of roll mode time constant obtained in LATHOS is given in Fig. 13. Values of T_R within the existing MIL-F-8785C Level 1 boundary were tested. The data for $1/T_R$ greater than 1 support the current boundary ($T_R \leq 1.0$ s) up to a value of $1/T_R \doteq 3$ ($T_R \doteq 0.33$). For $1/T_R$ greater than 3, the pilot ratings show a consistent degradation—a trend that is not included in the current requirement. As discussed in the review of roll ratcheting, the pilot comments for these cases center about excessive lateral abruptness and ratcheting. These results are supported by the fact that some of the airplanes equipped with high-gain CAS that experienced roll ratcheting also have short T_R.

As shown in Figs. 6, 8, and 9, ratcheting is characterized by near-limit-cycle oscillations at frequencies between 2 and 3 cycles/s (12 and 18 rad/s), well above the frequency of pilot control in the roll axis. The apparent dominant factor in ratcheting is excessive control gain (i.e., stick sensitivity) at these high frequencies. It has been suggested[5] that the root cause of ratcheting is related to pilot closed-loop response to lateral acceleration cues: With a reasonable pilot lag, a closed-loop instability can exist when T_R is too short. Previous in-flight and rolling simulator experiments[4,6] have not revealed any strong trends to support this, but many of those tests did not include values of T_R as short, or tasks as stringent, as those flown on LATHOS. In addition, light general aviation airplanes typically have roll modes at frequencies as high as 10 rad/s (for example, the Navion at sea level and an air speed of 104 knots has $1/T_R = 8.4$ rad/s, Ref. 7) and do not experience ratcheting-type oscillations.

Another possible explanation for ratcheting is physiological in nature. That is, since the mass combination of pilot hand/arm and control stick are subjected to abrupt lateral accelerations, the effect would be that of a "bobweight" which would feed back to the aircraft. The same phenomenon has been related to longitudinal, pilot-induced oscillations.[8] Experiments conducted at the Air Force Aerospace Medical Research Laboratory (AMRL) investigated pilot control performance while experiencing sinusoidal lateral vibrations.[9] A simple roll-bar-tracking maneuver with a well-behaved controlled element was utilized. Figure 14 compares results of this experiment with an analytical model for stick deflection response to lateral accelerations during tracking. Pilot closed-loop tracking was around 5 rad/s, while an oscillatory arm/stick "bobweight" mode occurred at about 12 rad/s (2 cycles/s)—near the frequencies of the observed ratcheting oscillations in the LATHOS experiment.

In summary, a large value of $1/T_R$ appears to result in excessive gain at high frequencies (see Fig. 15), which seems to be the root cause of roll ratcheting. This can be alleviated to some extent by reducing the stick gain for small inputs, that is, most high-frequency control activity occurs with low magnitude; see, for example, configurations 5-3N2 and 5-3N3 in Fig. 11, where an improvement in pilot ratings resulted from a minor change in stick force shaping. However, resisting the temptation to overaugment $1/T_R$ seems to be the best overall solution. Even then, some nonlinear stick shaping will most likely be required.

Sensitivity

MIL-F-8785C specifies a maximum limit for degrees of roll in 1 s/lb of stick force, ϕ_1/F_{as}. For Level 1 operation in Category A flight, $\phi_1/F_{as} \leq 15$. However, as Fig. 2 reflects, pilots prefer a number much smaller than this for fine maneuvering. Clearly, sensitivity involves many more elements than just ϕ_1/F_{as}. Since the primary shortcoming of CAS is oversensitivity (normally characterized by ratcheting), solution of sensitivity problems involves proper integration of all aspects of the CAS.

Guidance for Reducing Roll Ratcheting

Several solutions to the problem of excessive sensitivity have been presented. In summary, these solutions are to: 1) decrease the stick sensitivity around neutral; 2) minimize the augmented aircraft value of $1/T_R$; and 3) add a low-frequency stick prefilter with a break frequency of 10 rad/s or less.

Reduction of stick sensitivity for CAS-equipped aircraft is relatively straightforward. Use of nonlinear shaping (p/F_{as}) on LATHOS reduced the sensitivity only slightly, but improved pilot ratings from 7 to 4 (see Figs. 10 and 11). It is clear that low sensitivity around neutral is essential for acceptable flying qualities.

Prefilters in the forward path were found to alleviate ratcheting on both aircraft A and LATHOS. The time constants of the filters were well into the range of pilot crossover ($1/T_F$ around 3 rad/s), and their effect as observed by the pilot was to smooth aircraft response (i.e., increase T_R). However, this should not be considered as a practical fix to the problem of sensitivity, since the aircraft response to outside disturbances might still be unacceptably abrupt. More importantly, prefilters can add considerable equivalent time delay to the system. In the longitudinal axis, a first-order lag of 3 rad/s adds about 0.1 s to overall τ_e (see Fig. 12). For the T-33 LATHOS experiment, where basic τ_e due to actuators was small (0.028 s), this was not significant. However, on a highly augmented aircraft where structural filters, sensor filters, digital time delay, and so on, may already contribute considerable lag, a prefilter could make the aircraft totally unacceptable due to excessive time delay.

The following guidelines are offered to obtain adequate roll control power for large control inputs without incurring excessive abruptness and/or roll ratcheting for small inputs, or excessive time delay, and hence lateral PIO tendencies.

1) Utilize nonlinear lateral stick shaping in the region specified in Fig. 2.

2) Avoid excessively large values of $1/T_R$ by minimizing the gain on the roll rate feedback. Figure 13 suggests $1/T_R < 4$.

3) Stick filters will eliminate roll ratcheting. However, the break frequency should be carefully evaluated in terms of time delay (see Fig. 12).

Summary and Conclusions

Roll rate command augmentation systems have proven to significantly enhance the handling qualities of fighter-type airplanes. High-gain, high-authority CAS will become more commonplace in the future as the technology is advanced. This review has revealed some of the aspects of CAS necessary for good handling qualities, and has presented some guidelines for avoiding the problems encountered with CAS in the past.

The primary concern about handling qualities of CAS-equipped airplanes relates to roll performance and sensitivity. Performance (or control power) requires a high p_c/F_{as} gradient for large control inputs. Sensitivity requires a very low gradient around neutral. However, excessive sensitivity, leading to roll ratcheting, is not so easily cured. Its solution can involve all of the elements of a CAS.

Acknowledgment

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References

[1]"Flying Qualities of Piloted Airplanes," MIL-F-8785C, Nov. 1980.

[2]McRuer, D. and Graham, D., "Eighty Years of Flight Control: Triumphs and Pitfalls of the Systems Approach," *Journal of Guidance and Control,* Vol. 4, July-Aug. 1981, pp. 353-362.

[3]Monagan, S.J., Smith, R.E., and Bailey, R.E., "Lateral Flying Qualities of Highly Augmented Fighter Aircraft," AFWAL-TR-81-3171, March 1982.

[4]Hoh, R.H., Mitchell, D.G., Ashkenas, I.L., Klein, R.H., Heffley, R.K., and Hodgkinson, J., "Proposed MIL Standard and Handbook—Flying Qualities of Air Vehicles. Vol. I. Proposed MIL Standard. Vol. II. Proposed MIL Handbook," AFWAL-TR-82-3081, Nov. 1982.

[5]Chalk, C.R., "The Ideal Controlled Element for Real Airplanes Is Not K/S," Calspan FRM 554, Aug. 1981.

[6]Creer, B.Y., Stewart, J.D., Merrick, R.B., and Drinkwater III, F.J., "A Pilot Opinion Study of Lateral Control Requirements for Fighter-Type Aircraft," NASA Memo 1-29-59A, March 1959.

[7]Teper, G.L., "Aircraft Stability and Control Data," Systems Technology, Inc., TR-176-1, April 1969.

[8]Ashkenas, I.L., Jex, H.R., and McRuer, D.T., "Pilot Induced Oscillations: Their Cause and Analysis," NORAIR Report NOR-64-143, June 1964.

[9]Allen, R.W., Jex, H.R., and Magdaleno, R.E., "Manual Control Performance and Dynamic Response During Sinusoidal Vibration," AMRL-TR-73-78, Oct. 1973.