JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 20, No. 3, May–June 1997

Prediction of Pilot-in-the-Loop Oscillations Due to Rate Saturation

Holger Duda*
DLR, German Aerospace Research Establishment, 38022 Brunswick, Germany

Rate saturation in modern flight control systems has been shown as a main contributor to triggering of pilot-in-the-loop oscillations (PIOs). Oscillations with significant rate saturation effects are classified as category II PIO. A new method was developed to predict stability problems of rate-saturated closed-loop systems based on the rate-limiting element describing function. Jump phenomena are observed in the closed-loop system describing function after rate-limiting onset, which have been shown as highly correlated with location of the open-loop onset point (OLOP) of the rate limiter in the Nichols chart. The OLOP criterion and its background, physical significance, and determination are presented. Its relation to the negative inverse describing function technique is discussed. Application of the OLOP criterion to closed-loop aircraft-pilot systems in the roll axis was investigated by using aircraft models from in-flight simulations flown on the NT-33 and the YF-16 first flight configuration. A high correlation was found between the OLOP criterion and the PIO susceptibility based on numerical investigations in the time domain with simple pilot models. Rate limiters in the forward path and feedback loop of the flight control system were investigated.

Nomenclature

$A(\omega)$	= amplitude of frequency response
dfc	= commanded differential flap deflection
$dfcl$	= limited differential flap deflection
$F_c(j\omega)$	= closed-loop frequency response
$F_{u_c}^{u_{\mathrm{rle}}}(j\omega)$	= closed-loop frequency response from closed-loop system input to rate-limiter input
$F_0(j\omega)$	= open-loop frequency response
fas	= roll stick force
$G(j\omega)$	= linear transfer function
K_p	= pilot gain
$N(j\omega, u_0)$	= amplitude- and frequency-dependent describing function
$N_{\mathrm{rle}}(j\omega, u_0)$	= rate-limiter describing function
n_y	= lateral load factor
PR_{180}	= phase rate at −180 deg phase angle
p	= roll rate
q	= pitch rate
q_c	= commanded pitch rate
R	= maximum rate of the limiter
t	= time
u_c	= closed-loop system input signal
u_{OLOP}	= input signal for open-loop onset point determination
u_{rle}	= rate-limiting element input signal
u_0	= input amplitude
y_{OLOP}	= output signal for open-loop onset point determination
δ_f	= differential flap deflection (YF-16)
δ_t	= differential tail deflection (YF-16)
η	= elevator deflection
ξ	= aileron deflection
ς	= rudder deflection
Φ, phi	= bank angle
Φ_c	= crossover phase angle
Φ_{com}, phic	= commanded bank angle
$\Phi(\omega)$	= phase angle of frequency response
ω	= frequency
ω_c	= crossover frequency
ω_{onset}	= rate-limiter onset frequency
$\hat{\omega}_{\mathrm{onset}}$	= rate-limiter closed-loop onset frequency

Presented as Paper 95-3304 at the AIAA Guidance, Navigation, and Control Conference, Baltimore, MD, Aug. 7–10, 1995; received June 21, 1996; revision received Feb. 12, 1997; accepted for publication Feb. 12, 1997.

*Scientist, Institute of Flight Mechanics.

Introduction and Background

THE pilot-in-the-loop oscillation (PIO) problem has been known for years, but the introduction of high-gain, full-authority, digital fly-by-wire flight control systems has increased the potential for PIO. This fact is demonstrated by several spectacular incidents with advanced aircraft, such as the YF-22 (Ref. 1) and the JAS-39 (Ref. 2). In the past, the phenomenon basically has been limited to high-performance fighter aircraft, but the latest transports with modern fly-by-wire flight-control systems have demonstrated PIO problems during their development phase, such as the C-17 (Ref. 3) and the B777 (Ref. 4). These incidents caused much concern and prediction of PIO has become an important issue for development of new aircraft.

Several different types of oscillations forced by the pilot are known, which differ by frequency and amplitude. In the roll axis, high-frequency low-amplitude oscillations are known, called ratchet.[5] Such oscillations basically occur at frequencies above 10 rad/s and are caused by interactions between the cockpit controls and the pilot's neuromuscular system. They are characterized by pilot comments about some potential PIO problems but will not result in a catastrophe. The corresponding phenomenon in the pitch axis is called bobble, which mainly is caused by low damping (e.g., elastic modes). Lower frequency high-amplitude oscillations represent the common meaning of the expression PIO. For understanding and analysis, a further classification was introduced[6,7]: category I, essentially linear aircraft-pilot oscillations; category II, quasilinear aircraft-pilot oscillations with series rate or position limiting; and category III, nonlinear aircraft-pilot oscillations with transitions.

The main effects causing category I PIOs are well known as excessive lags due to time delays and various digital filters in the flight control system leading to high-frequency phase rolloff. The established frequency domain PIO criteria by Neal and Smith,[8] Gibson,[9] Smith,[10] and Hoh and Hodgkinson[11] are well suited to predict category I problems in the pitch axis as well as in the roll axis.[12] Their validation is based on linear aircraft models, but an extension to the nonlinear effects of rate limiting would be very complicated. Therefore, the development of a new category II PIO criterion is required, which is confirmed by the fact that most of the catastrophic PIO occurrences included the effects of actuator rate limiting.[13]

It is very difficult to predict category III problems, but the nonlinear effects of rate saturation can be analyzed in the frequency domain by the describing function technique.[14] This technique already has been applied in the early work of Ashkenas et al.[15] to analyze the PIO of the X-15 aircraft. Current work at DLR, German Aerospace Research Establishment, presents a new method to determine the describing function of rate-saturated closed-loop systems.[16,17] Application of the method to highly augmented aircraft showed jump phenomena in the frequency domain after rate-limiting onset, which have been verified by instabilities observed in the corresponding time domain investigations. It has been shown that these jump phenomena are highly correlated with the location of the open-loop onset point (OLOP) of the rate limiter in the Nichols chart. Therefore, a new category II PIO criterion was proposed based on the OLOP parameter.[18]

This paper presents the background, physical significance, and determination of the OLOP parameter. Several aircraft models based on the YF-16 first flight configuration[19] and the lateral high-order system (LATHOS)[20] and F-18A[21] in-flight simulation programs are used to demonstrate the applicability of the OLOP criterion to closed-loop aircraft-pilot systems in the roll axis.

Describing Function Technique

A nonlinear system can be represented by a quasilinear system using the describing function and the remnant.[14] The describing function can be interpreted as the quasilinear frequency response for sinusoidal inputs. The remnant is a high-frequency signal, which can be neglected if the linear part of the system has low-pass character.

Rate-Limiting Element Describing Function

The rate-limiting element describing function was derived by using the onset frequency, which is defined as the frequency where the rate limiter is activated for the first time. It is dependent on the maximum rate R and the current input amplitude u_{rle}:

$$\omega_{\mathrm{onset}} = R / u_{\mathrm{rle}} \tag{1}$$

The describing function was calculated by using a Fourier series for the fully developed rate-limiting situation[17]:

$$N_{\mathrm{rle}}(j\omega, u_{\mathrm{rle}}) = \frac{4}{\pi}\frac{\omega_{\mathrm{onset}}}{\omega}\exp\left[-j\arccos\left(\frac{\pi}{2}\frac{\omega_{\mathrm{onset}}}{\omega}\right)\right] \tag{2}$$

Figure 1 shows the Bode plot of the rate-limiter describing function for an onset frequency of 1 rad/s, demonstrating the strong increase in phase delay and the slight decrease in amplitude in the transition region.

Rate Limiters in a Closed Loop

Figure 2 shows two typical positions, where rate limiters are installed as software elements in the flight-control systems of highly augmented aircraft. The limiters in the feedback-loop of the flight-control system have the task of protecting the actuators against overload. Otherwise, the oil supply of the actuation system could break down. The limiters in the forward path of the flight-control system are installed to protect the system against high-input rates by the pilot, preventing a saturation of the feedback loop rate limiters. This protection is particularly important for unstable highly augmented aircraft.

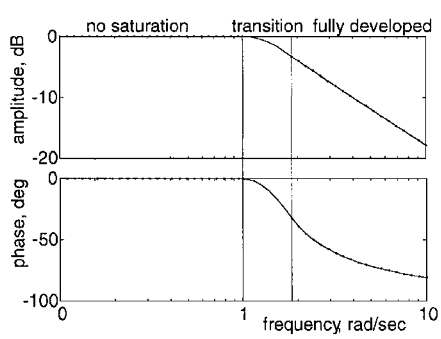


Fig. 1 Rate-limiting element describing function.

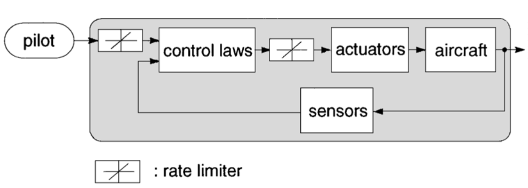


Fig. 2 Typical implementation of rate limiters in modern flight-control systems.

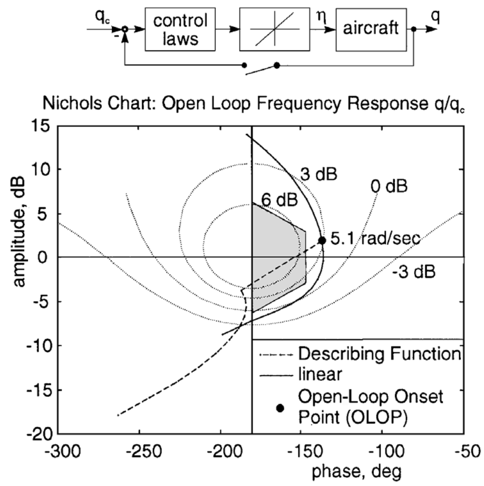


Fig. 3 Jump phenomena due to rate-limiting onset in highly augmented aircraft.

Jump Phenomena

For calculation of the describing function of a rate-limited closed-loop system, an iterative method was derived and verified by means of comparison with the results of nonlinear simulations in the time domain. Application of this method to a highly augmented aircraft with a rate limiter in the feedback loop is presented in Fig. 3. The closed-loop system describing function is characterized by a jump phenomenon after rate-limiting onset, which can be recognized in a Nichols chart as a phase jump. In the example presented in Fig. 3, the phase jump leads to a dramatic loss of phase and amplitude margin, indicating the potential for instability of the closed-loop system. This instability was verified by a nonlinear simulation in time domain by using a sinusoidal input signal with increasing frequency.[17]

In the Nichols chart, the OLOP can be identified as the point where the phase jump starts. It must be noted that in this case the aircraft becomes unstable even without the pilot in the closed loop (no PIO). (In this context the expression aircraft means the complete aircraft system including the flight-control system.) For systems with lower feedback gain (e.g., in the lateral axis), it is unlikely that such jump phenomena cause aircraft instability, but they lead to a strong misadaptation of the pilot, resulting in instability of the closed-loop aircraft-pilot system (PIO). This was demonstrated for the YF-12 aircraft.[18]

OLOP Criterion

Background

The OLOP is defined as the frequency response value of the open-loop aircraft or aircraft-pilot system at the closed-loop onset frequency $\hat{\omega}_{\mathrm{onset}}$. This is defined as the frequency where the rate limiter is activated for the first time under closed-loop conditions and maximum pilot input amplitude. It is determined by the following equation:

$$\left|F_{u_c}^{u_{\mathrm{rle}}}(j\hat{\omega}_{\mathrm{onset}})\right| = \frac{R}{\hat{\omega}_{\mathrm{onset}}} \tag{3}$$

Calculation of $\hat{\omega}_{\mathrm{onset}}$ means determination of the intersection of the frequency response amplitude $|F_{u_c}^{u_{\mathrm{rle}}}(j\hat{\omega}_{\mathrm{onset}})|$ (from the input of the closed-loop system u_c to the input of the rate limiter u_{rle}) and a straight line with a slope of -20 dB/decade, which crosses the 0-dB line at the maximum rate of the limiter R.

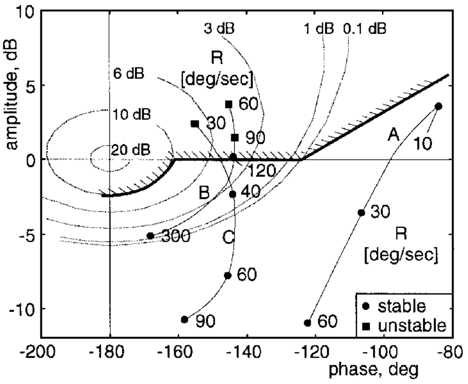


Fig. 4 Proposed OLOP boundary[17]: Nichols chart.

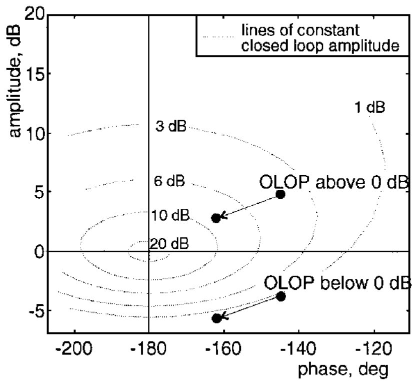
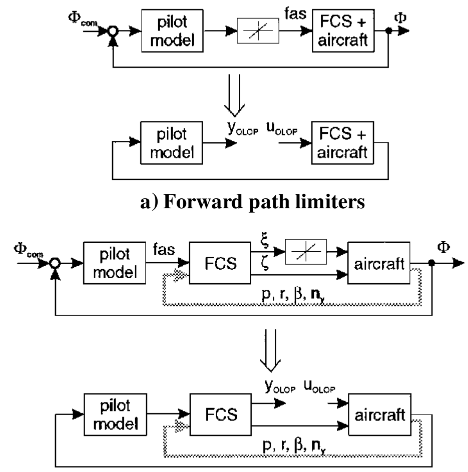


Fig. 5 Physical significance of the OLOP parameter: Nichols chart.



a) Forward path limiters

b) Feedback path limiters

Fig. 6 Determination of the open-loop frequency response required for the OLOP parameter.

The OLOP parameter can be used to predict stability problems of rate-saturated closed-loop systems. It was developed by using the describing function technique with application to a great number of rate-saturated aircraft systems. It has been shown that the jump phenomena in the frequency domain and the corresponding instabilities observed in the time domain are highly dependent on the OLOP location in the Nichols chart. Three highly augmented aircraft systems have been investigated (systems A, B, and C).[17] Figure 4 presents the open-loop frequency responses of these configurations and the OLOP parameters for different maximum rates. A provisional stability boundary was defined based on nonlinear simulations in the time domain. The investigation demonstrates the effects of the flight-control system feedback gain. For system C (low-gain flight-control system) the maximum rate can be significantly reduced in comparison to system B (high-gain flight-control system) to get a stable behavior after rate-limiting onset.

Significance

Evaluation of the rate-limiter describing function has shown that the primary effect caused by activation of a rate limiter is a strong increase in phase delay and a slight decrease in amplitude (Fig. 1). If OLOP is located above 0 dB, the phase delay causes an increase in the closed-loop amplitude as demonstrated in the Nichols chart (Fig. 5). This increase in closed-loop amplitude provokes a stronger rate saturation and, therefore, further increases phase delay. This mechanism can lead to closed-loop instability.

For an OLOP located clearly below 0 dB, the increasing phase delay does not cause an increase in closed-loop amplitude, so the rate-limiting effects are less dramatic. This indicates that a low flight-control system feedback gain can reduce the category II PIO potential.

Application to Aircraft-Pilot Systems

In view of OLOP application to closed-loop aircraft-pilot systems, the required open-loop frequency response $F_0(j\omega)$ is determined by opening the system loop at the rate limiter and treating the system with the rate limiter removed. The output of the rate limiter is defined as the input of the open-loop system u_{OLOP}; the input of the rate limiter is defined as the output of the open-loop system y_{OLOP} (Fig. 6). This procedure can be applied to rate limiters in the forward path and feedback loop of the flight-control system.

The pilot model has to be adjusted to the linear aircraft dynamics, which means that the pilot has adapted to aircraft behavior without rate saturation. It is assumed that in a time period after rate-limiting onset the pilot dynamics remain those adapted to the linear aircraft behavior (posttransition retention).[7] The sudden change in closed-loop aircraft behavior can lead to strong misadaptation by the pilot.

It is recommended that simple gain pilot models be used because the pilot usually reacts as a simple gain during a fully developed PIO (synchronous precognitive behavior).[7] The gain has to be adjusted based on the linear crossover phase angle of the open-loop aircraft-pilot system Φ_c. Within this study, a gain spectrum from $\Phi_c = -110$ deg (low pilot gain) up to $\Phi_c = -160$ deg (high pilot gain) is used. This gain spectrum can provide the following results: if an aircraft is rated as category II PIO prone by an OLOP value based on a low-gain pilot model, a PIO is very likely; if an aircraft is rated as category II PIO free based on a high-gain pilot model, a PIO is very unlikely after rate-limiting onset.

In practice the following procedure must be applied for determination of the pilot model gain: 1) calculation of the frequency response from stick force or deflection to pitch or bank angle and separation into amplitude $A(\omega)$ and phase angle $\Phi(\omega)$; 2) searching the index k_c, where the phase angle is equal to the required crossover phase angle $\Phi(k_c) = \Phi_c$; 3) the crossover frequency is $\omega_c = \omega(k_c)$; and 4) the pilot model gain is $K_p = 1/A(k_c)$.

Determination

Determination of OLOP does not require the describing function technique. The following steps are required, assuming that the aircraft model including the flight-control system is available: 1) definition of a simple (high) gain pilot model based on the linear aircraft-pilot crossover phase angle Φ_c; 2) calculation of the linear closed-loop frequency response from the stick input to the input of the rate limiter $F_{u_c}^{u_{\mathrm{rle}}}(j\omega)$; 3) determination of the closed-loop onset frequency $\hat{\omega}_{\mathrm{onset}}$ considering stick and control surface limits [Eq. (3)]; 4) calculation of the required open-loop frequency response $F_0(j\omega)$ (Fig. 6) and separation into amplitude $A(\omega)$ and phase angle $\Phi(\omega)$; and 5) determination of the OLOP parameter $[\Phi(\hat{\omega}_{\mathrm{onset}}), A(\hat{\omega}_{\mathrm{onset}})]$.

Negative Inverse Describing Function Technique

Consider a nonlinear element in series with a linear element involved in a closed-loop situation (Fig. 7). The linear portion is represented by a frequency-dependent transfer function, $G(j\omega)$, and the nonlinear element is represented by a frequency- and amplitude-dependent describing function, $N(j\omega, u_0)$. The

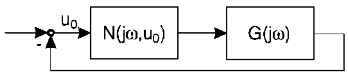


Fig. 7 Closed-loop system with nonlinear element.

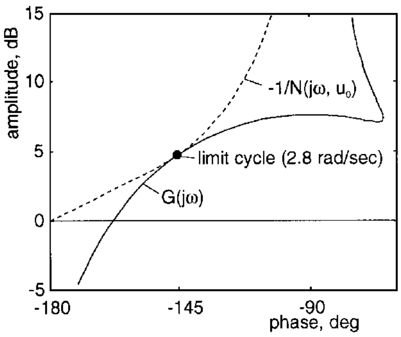


Fig. 8 Negative inverse describing function technique applied to the X-15 aircraft[15]: Nichols chart. $G(j\omega)$, negative inverse describing function and $-1/N(j\omega, u_0)$, linear portion of the X-15 aircraft.

necessary conditions for a limit cycle are that the open-loop amplitude ratio is 1.0 (0 dB) and the phase angle is −180 deg. For an oscillation to persist, the open-loop frequency response must satisfy the following equation:

$$G(j\omega)N(j\omega, u_0) = -1 \Rightarrow G(j\omega) = -1/N(j\omega, u_0) \qquad (4)$$

This equation is commonly solved by a graphical method, whereas the frequency responses of the linear portion and the negative inverse describing function are plotted in a Nichols chart. The intersection of the two curves satisfies Eq. (4) and provides the frequency and amplitude of the limit cycle.

Figure 8 presents the application of the negative inverse describing function technique to the X-15 aircraft, which encountered PIO problems on landing.[6,15] Considering a maximum rate of $R = 15$ deg/s leads to very good agreement between the limit cycle frequency and amplitude predicted by the analysis and observed in flight. But the problem with this method is that an increase in the maximum rate R leaves the $-1/N(j\omega, u_0)$ curve in the Nichols chart completely unaltered.[15] Hence, intersection of the linear and nonlinear portion of the Nichols chart is independent of the maximum rate of the limiter. It is obvious that for a very high maximum rate the limiter will not be activated anymore because of the stick and control surface deflection limits. These limits are considered within determination of the OLOP parameter. Therefore, the OLOP criterion predicts whether a limit cycle is likely. The negative inverse describing function technique can be used as a complementary tool to assess the severity of the limit cycle.

OLOP Application in the Roll Axis

A great number of aircraft models with different flight-control system characteristics and maximum rates were investigated. The models are based on the following databases: YF-16, the famous first flight PIO occurrences of the YF-16 aircraft including the flight-control system modifications[19]; LATHOS, in-flight simulation program on the NT-33 to study the effects of time delay and prefilter lag in the lateral flight control system[20]; F-18, in-flight simulation program on the NT-33 to identify flying quality problems of the F-18A before its first flight.[21]

YF-16 First Flight Configuration

During a high-speed taxi run, scheduled as part of the buildup before the first flight, the YF-16 aircraft inadvertently became completely airborne and a severe PIO occurred. The magnitude and rate of the pilot control inputs were sufficient to position and rate saturate the roll flight-control system. After the PIO experienced on the first flight, the YF-16 aircraft's initial roll flight-control system (IFCS) was modified by reducing the forward path and feedback loop gains and the roll command force gradient, and by lowering the maximum commanded roll rate (MFCS).[19] These two configurations were implemented under Simulink.[21]

Linear analysis of these two configurations has shown that these modifications have adverse effects even on the category I PIO susceptibility of the aircraft, e.g., the phase rate parameter was decreased.[12]

IFCS:

$$PR_{180} = -115 \text{ deg/Hz} \qquad \text{level 2 (boundary to level 1)}$$

MFCS:

$$PR_{180} = -133 \text{ deg/Hz} \qquad \text{level 2}$$

However, it is obvious that the aircraft should be less category II PIO prone because of the gain reduction in the flight-control system, which is proved by the following OLOP analysis.

The YF-16 has two independent roll axis control surfaces, the differential flap δ_f and the differential tail δ_t. Hence, the closed-loop onset frequencies according to Eq. (3) were calculated for the two configurations and control surfaces.

IFCS:

$$\hat{\omega}_{\text{onset}}(\delta_f) = 2.8 \text{ rad/s}$$

$$\hat{\omega}_{\text{onset}}(\delta_t) = 6.6 \text{ rad/s}$$

MFCS:

$$\hat{\omega}_{\text{onset}}(\delta_f) = 3.6 \text{ rad/s}$$

$$\hat{\omega}_{\text{onset}}(\delta_t) = \infty \text{ (no rate limiting possible)}$$

A significantly lower closed-loop onset frequency is obtained for differential flap rate limiter than for the differential tail rate limiter. This means that the differential flap rate limiter is activated at first, which is confirmed by the time histories of the first flight PIO. The determination of the closed-loop onset frequency $\hat{\omega}_{\text{onset}}$ for the differential flap rate limiter is presented in Fig. 9 for the IFCS and MFCS configurations. The straight line with a slope of −20 dB/decade represents the maximum rate of the limiter ($R = 56$ deg/s). The constant amplitude line represents the maximum differential flap deflection of 20 deg. The solid lines in the Bode plot are the amplitude response curves of the commanded differential flap deflection per stick force for maximum input amplitude. The Bode plot demonstrates the high control authority of the IFCS configuration, indicating that for maximum applied stick force the differential flap limits of 20 deg are reached. Hence, the intersection of the 20-deg constant amplitude line with the rate-limiter line defines the closed-loop onset frequency. The gain reduction of the MFCS configuration has the effect that even for maximum stick force no amplitude limiting of the differential flap deflection is possible.

Figure 10 presents the open-loop aircraft-pilot frequency responses and the OLOP parameters of the two YF-16 configurations in the Nichols chart. The pilot gain was adjusted to obtain a linear crossover phase angle of $\Phi_c = -140$ deg, representing a medium pilot gain. Comparing these OLOP locations with the proposed boundary proves the category II PIO potential of the IFCS configuration. Unlike the category I PIO criteria, the OLOP criterion clearly indicates the improvements due to the flight-control system modifications.

The PIO potential of the two YF-16 configurations was investigated in the time domain. The closed-loop aircraft-pilot system is

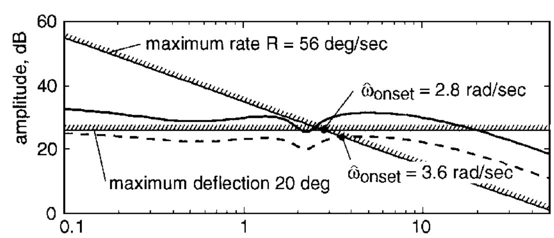


Fig. 9 YF-16 determination of the closed-loop onset frequency (differential flap rate limiter); Bode plot: frequency responses *dfc/fas*. ——, IFCS and – – –, MFCS.

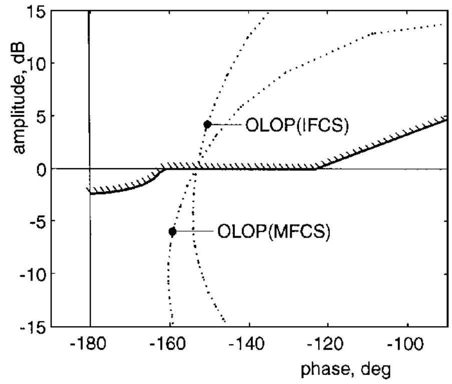
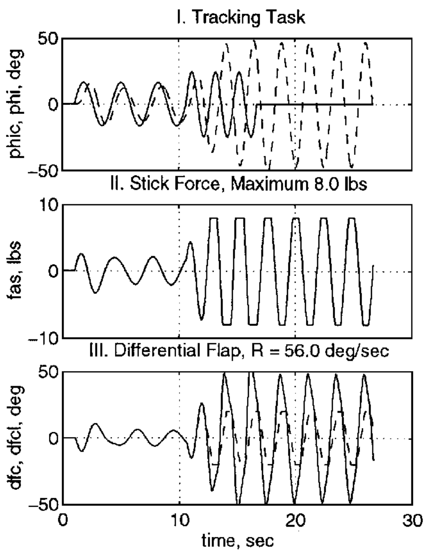
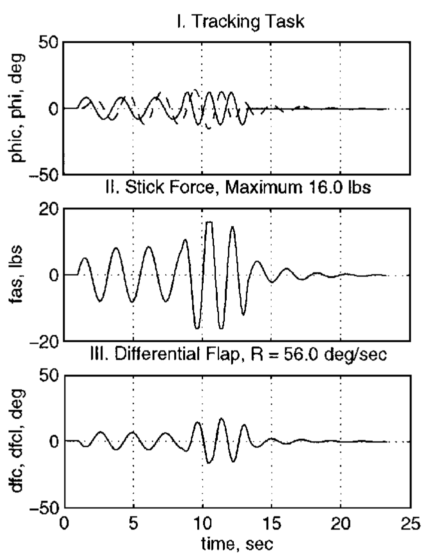


Fig. 10 YF-16 open-loop aircraft-pilot frequency responses and OLOP parameters (differential flap rate limiter): Nichols chart.



a) Initial flight control system (IFCS)



b) Modified flight control system (MFCS)

Fig. 11 YF-16 nonlinear simulation of the aircraft-pilot loop.

stimulated with an input signal with increasing frequency from 0.7 to 1.1 $\hat{\omega}_{\text{onset}}$. Two cycles after the frequency increase, the input amplitude is set to zero to detect a limit cycle (Fig. 11). This frequency increase leads to activation of the differential flap rate limiter, causing a sustained aircraft-pilot oscillation (limit cycle) for the IFCS configuration, as predicted by the OLOP criterion. For the MFCS configuration, the defined tracking task causes only a very slight activation of the rate limiter, but it does not provoke a limit cycle. These

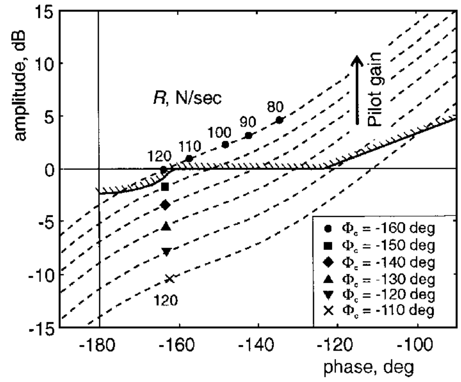


Fig. 12 Influence of maximum rate and pilot gain, LATHOS configuration L1_2T4: Nichols chart.

time domain investigations clearly demonstrate the significance of an OLOP parameter below the boundary, where activation of the rate limiter has nearly no effect on closed-loop system dynamics (nearly no additional time delay is induced).

Forward Path Rate Limiters

To investigate the effects of forward path rate limiters, four characteristic aircraft models have been selected from the LATHOS[20] flight-test program and extended to rate limiters in the forward path of the flight-control system. Several aircraft/limiter/pilot combinations have been investigated with the result that OLOP is applicable to predict category II PIO problems due to forward path rate limiters as well.[22]

Evaluations have shown that pilot gain is an important factor for the OLOP criterion. Figure 12 demonstrates the influence of the maximum rate R and the pilot model gain for LATHOS configuration L1_2T4. The open-loop aircraft-pilot frequency responses are plotted for six different pilot model gains ($\Phi_c = -110$ to 160 deg) and the OLOP parameters have been determined for a maximum force rate of 120 N/s. The influence of the maximum rate is displayed by varying R from 120 to 80 N/s. This graph indicates that PIOs triggered by rate limiters in the forward path of the flight control system are possible mainly for high-gain pilots or extremely low maximum rates. For very low gain pilots ($\Phi_c > -120$ deg) OLOP reaches 0 dB at phase angles > -120 deg, which is compared to the proposed PIO boundary in the safe area. This OLOP value leads to the surprising result that configurations with poor linear dynamics characterized by low gradients of their frequency response curves in the Nichols chart are less category II PIO prone. This result does not mean that those configurations are less prone to PIOs at all, but the sudden change in the aircraft-pilot system dynamics is less dramatic. It becomes clear that the OLOP criterion is not correlated with the classic category I PIO criteria. Therefore, the category I PIO criteria still are required for a flight-control system design, because the OLOP criterion does not optimize the linear performance of the system.

Feedback Loop Rate Limiters

To investigate the effects of feedback loop rate limiters, several aircraft models from the F-18 (Ref. 21) flight-test program are used. In addition, the YF-16 configurations are investigated, and the maximum rates of the limiters are varied. Figure 13 presents the relevant open-loop aircraft frequency responses of the investigated configurations in a Nichols chart. To obtain a wider OLOP spectrum, two additional F-18 models have been defined based on configuration B: B1, configuration B, no time delay in the forward path, decreased feedback gain; and B2, configuration B, no time delay in the forward path, decreased time constant in the feedback loop.

The open-loop aircraft–flight-control system frequency–response curve of configuration B1 is located at lower amplitudes in comparison to configuration B because of its lower feedback gain. Therefore, its OLOP parameter should be located at lower amplitudes for a given maximum rate as well. The frequency–response curve of configuration B2 is characterized by higher phase delays that tend to get additional OLOPs at higher phase delays. The Nichols chart

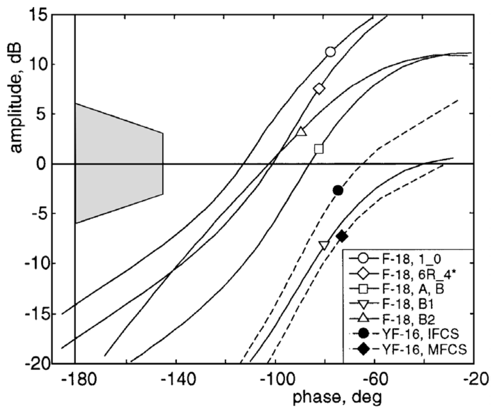


Fig. 13 Aircraft open-loop frequency responses, F-18 and YF-16 models: Nichols chart.

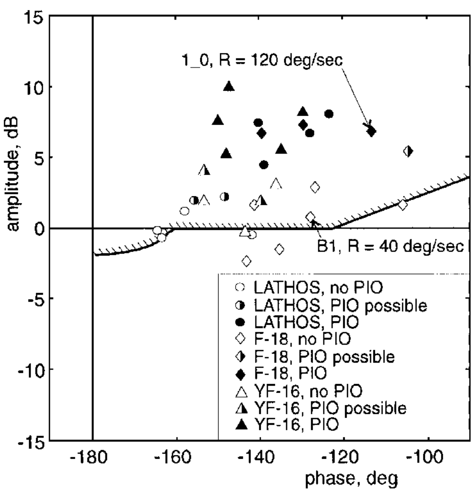


Fig. 14 Verification of the OLOP criterion: Nichols chart.

demonstrates that all aircraft frequency responses have absolutely sufficient phase and amplitude margin compared to the commonly used stability boundary. Hence, its closed-loop stability without rate saturation is not endangered, but it is expected that some configurations are very category II PIO prone because of their high feedback gain, especially the F-18 configurations 1_0 and 6R_4. The high feedback gains of these configurations correspond to OLOP locations in the dangerous area above 0 dB, which is a possible explanation for the extreme scatter in the pilot ratings of F-18 configuration 1_0 (Cooper–Harper rating 10, 4, 5, 5, 3) (Ref. 21). Configuration B1 should be very PIO resistant after rate-limiting onset because of its lowered feedback gain.

PIO Boundary

Figure 14 presents the OLOP parameters of the investigated configurations from the three databases and their category II PIO potential based on nonlinear simulations with pilot models. It is important to note that in this Nichols chart the OLOP parameters of forward path and feedback loop rate limiters are mixed, whereas a high correlation is observed between the OLOP location and the PIO susceptibility. This demonstrates that OLOP is applicable to both forward path and feedback loop rate limiters using the same PIO boundary. The diagram indicates that the proposed boundary seems to be too conservative, but it is not intended to adjust the preliminary boundary until more flight simulator experiments become available.

Two configurations are highlighted in Fig. 14, demonstrating the effects of flight-control system feedback gain: F-18 configuration B1 ($R = 40$ deg/s) and F-18 configuration 1_0 ($R = 120$ deg/s); a crossover phase angle of $\Phi_c = -120$ deg was considered in both cases. It becomes clear that configuration 1_0 is category II PIO prone with a maximum rate three times higher than configuration B1, which is not category II PIO prone. This result is due to the significantly lower flight-control system feedback gain of the configuration B1 in comparison to the configuration 1_0 (Fig. 13). The activation of feedback loop rate limiters provides a very strong category II PIO potential for high flight-control system feedback gains. Aircraft-flight-control system instabilities presented in previous work[17] can be interpreted as PIO with zero or very low pilot gain. For aircraft with low flight-control system feedback gains, the feedback loop rate limiters exhibit a character similar to the forward path rate limiters.

Discussion and Future Activities

The investigations have shown that the OLOP criterion is well suited to understand and predict category II PIO problems. It is applicable to rate limiters in the forward path and feedback loop of the flight control system, whereas the procedure for its determination is independent of the rate-limiter location (forward path or feedback loop) and the complexity of the flight-control system. Therefore, it also should be applicable to fly-by-wire rotorcraft systems.

OLOP can be used as a valuable tool in the early design process of new flight control systems to optimize the feedback gain, the maximum rate of the limiters (dimensioning the actuators), and steady-state gain. In this design process, the category I PIO criteria are still very important. Each flight-control system design must be a compromise: 1) Reducing the steady-state gain leads to an increase of $\hat{\omega}_{\text{onset}}$, but the aircraft performance could become insufficient, e.g., the roll performance. 2) Reducing the feedback gain of the flight control system leads to a shifting of the OLOP parameter toward the safe area below 0 dB, but the linear dynamics can deteriorate, as demonstrated in the case of YF-16. 3) Increasing the maximum rate leads to an increasing $\hat{\omega}_{\text{onset}}$, but cost and weight are also increased.

The basic remaining uncertainty within the OLOP criterion is pilot behavior in the rate-limiting onset situation, but also uncertain is the definition of the pilot gain based on the linear crossover phase angle. For this purpose, special flight simulator experiments are scheduled within the scope of a Swedish/German cooperation on nonlinear effects in flight control systems.

Conclusions

Based on the investigations reported herein, the following conclusions can be drawn.

1) The developed criterion (open-loop onset point; OLOP) is a suitable tool to predict category II pilot-in-the-loop oscillations (PIO) of aircraft with rate limiters in the forward path and feedback loop of the flight-control system. Its determination is straightforward and independent of the flight-control system complexity.

2) The negative inverse describing function technique is a suitable tool to predict the limit cycle frequency and amplitude; it can be used as a complementary tool within an OLOP analysis to assess the severity of the limit cycle.

3) Aircraft with high flight-control-system feedback gains in the flight-control system are absolutely PIO prone after the onset of rate limiting in the feedback loop even for low-gain pilots. PIOs triggered due to an activation of forward path rate limiters are possible only for high-gain pilots or extremely low maximum rates. Therefore, the use of forward path rate limiters, which are designed to prevent a saturation of the feedback loop rate limiters, shall reduce this category II PIO potential.

4) The PIO problem of the YF-16 aircraft during its unintended first flight was predicted by the OLOP criterion as well as the improvements due to the modifications in the flight-control system.

5) The OLOP criterion is well suited to predict flying quality cliffs due to rate limiting, e.g., the F-18 configuration 1_0, which is characterized by a large scatter in the pilot ratings (Cooper–Harper rating 10, 4, 5, 5, 3).

6) The OLOP criterion is applicable to aircraft systems with several control surfaces in one axis, as was shown for the YF-16 aircraft with differential flap and tail. Therefore, it should also be applicable to aircraft incorporating two pitch axis control surfaces, such as canards and symmetric flaps.

7) The uncertain pilot behavior in the rate-limiting onset situation is still subject to further theoretical and experimental investigations.

References

[1]Dornheim, M. A., "Report Pinpoints Factors Leading to YF-22 Crash," *Aviation Week and Space Technology*, Vol. 137, No. 19, 1992, pp. 53, 54.

[2]Kullberg, E., and Elgcrona, P.-O., "SAAB Experience with PIO," AGARD AR-335, May 1994 (Paper 9).

[3]Norton, W. J., "Aeroelastic Pilot-In-The-Loop Oscillations," AGARD AR-335, May 1994 (Paper 10).

[4]Dornheim, M. A., and Hughes, D., "Boeing Corrects Several 777 PIOs," *Aviation Week and Space Technology*, Vol. 142, No. 19, 1995, p. 32.

[5]Mitchell, D. G., Hoh, R. H., Aponso, B. L., and Klyde, D. H., "The Measurement and Prediction of Pilot-In-The-Loop Oscillations," AIAA Paper 94-3670, Aug. 1994.

[6]Klyde, D. H., McRuer, D. T., and Myers, T. T., "Unified Pilot-Induced Oscillation Theory, Volume I: PIO Analysis with Linear and Nonlinear Effective Vehicle Characteristics, Including Rate Limiting," U.S. Air Force Wright Lab., WL-TR 96-3028, Wright–Patterson AFB, OH, Dec. 1995.

[7]McRuer, D., "Pilot-Induced Oscillations and Human Dynamic Behavior," NASA CR-4683, July 1995.

[8]Neal, T. P., and Smith, R. E., "A Flying Qualities Criterion for Design of Fighter Flight-Control Systems," *Journal of Aircraft*, Vol. 8, No. 10, 1971, pp. 803–809.

[9]Gibson, J. C., "The Development of Alternate Criteria for FBW Handling Qualities," AGARD CP-508, Oct. 1990 (Paper 9).

[10]Smith, R. H., "Notes on Lateral-Directional Pilot Induced Oscillations," U.S. Air Force Wright Aeronautical Lab., TR 81-3090, March 1982.

[11]Hoh, R. E., and Hodgkinson, J., "Bandwidth—A Criterion for Highly Augmented Airplanes," AGARD CP-333, April 1982 (Paper 9).

[12]Duda, H., "Analysis of Adverse Aircraft-Pilot Coupling in the Roll Axis Using Frequency Domain Criteria," DLR-IB 111-95/24, July 1995.

[13]McKay, K., "Summary of an AGARD Workshop on Pilot-Induced Oscillations," AIAA Paper 94-3668, Aug. 1994.

[14]Graham, D., and McRuer, D., *Analysis of Nonlinear Control Systems*, Wiley, New York, 1961.

[15]Ashkenas, I. L., Jex, H. R., and McRuer, D. T., "Pilot-Induced Oscillations: Their Cause and Analysis," NORAIR Rept. NOR-64-143 (also Systems Technology, TR-239-2), June 1964.

[16]Hanke, D., "Handling Qualities Analysis of Rate Limiting Elements in Flight Control Systems," AGARD AR-335, May 1994 (Paper 11).

[17]Duda, H., "Frequency Domain Analysis of Rate Limiting Elements in Flight Control Systems," DLR-FB 94-16, Aug. 1994 (in German).

[18]Duda, H., "Effects of Rate Limiting Elements in Flight Control Systems—A New PIO-Criterion," AIAA Paper 95-3304, Aug. 1995.

[19]Smith, J. W., "Analysis of a Lateral Pilot-Induced Oscillation Experienced on the First Flight of the YF-16 Aircraft," NASA TM-72867, Sept. 1979.

[20]Monagan, S. J., Smith, R. E., and Randall, E. B., "Lateral Flying Qualities of Highly Augmented Fighter Aircraft," U.S. Air Force Wright Aeronautical Labs., TR-81-3171, Vols. 1 and 2, March 1982.

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

[22]Duda, H., "Prediction of Adverse Aircraft-Pilot Coupling in the Roll Axis Due to Rate Limiting in Flight Control Systems," DLR-IB 111-96/13, April 1996.