FINE-TUNING HANDLING QUALITIES ON A HIGH-PERFORMANCE AIRCRAFT: MAXIMISING ROLL ACCELERATION WHILE AVOIDING ROLL RATCHET

M. Hanel, EADS Deutschland GmbH
S. Fallon, BAE Systems Plc.
81663 München
Germany

OVERVIEW

This paper presents an important aspect of the roll axis control law design for High-Performance Fighter Aircraft: Maintaining high agility without causing roll-ratcheting: a pilot-aircraft coupling phenomenon leading to severely degraded handling qualities.

The roll ratchet phenomenon can be encountered when aggressive roll stick inputs are translated into a high level of aircraft roll acceleration. Due to the inertia of the pilot-stick combination, the pilot’s body is then moved relative to the airframe thereby generating a lateral stick input in the opposite sense. This input causes further aircraft roll acceleration and coupling between the aircraft control system dynamics and the pilot's neuromuscular system. A subsequent sustained, high frequency, low amplitude roll oscillation or "roll ratchet" can develop. In some cases, this phenomenon is considered more of a nuisance, while in more severe cases it can be very uncomfortable and makes aggressive tracking tasks almost impossible.

Clearly, limiting the roll acceleration of the aircraft will reduce its susceptibility to roll ratchet but will also reduce aircraft agility. Therefore, the roll-axis control law design for fighter aircraft has to avoid roll ratcheting while preserving impressive roll acceleration (i.e. agility) characteristics.

1. INTRODUCTION

Roll ratcheting is an unwanted, sustained, high frequency, low amplitude roll oscillation encountered on high performance aircraft during rapid rolling manoeuvres ([1],[2],[4]). This oscillation is superimposed on a high level of aircraft roll rate (typically > 100°/s) with the oscillation amplitude taking up less than 5% of the overall roll rate. Roll acceleration and roll rate do not change sign due to the oscillation but the pilot feels the changing roll acceleration levels. Comparison to driving bolts with a ratchet brings about the name "ratcheting". The roll ratchet oscillation is caused by lateral stick inputs inadvertently executed by the pilot. This makes roll ratcheting an aircraft-pilot-coupling problem.

1.1. Aircraft-Pilot Coupling

Aircraft-pilot-coupling can become safety-critical if the pilot's control inputs excite an oscillation (pilot-induced-oscillation, PIO), i.e. if the pilot is acting as an active feedback element at a phase and amplitude setting which is destabilising the system. In the case of high-frequency (> 1Hz) phenomena however, such as pitch bobbling (in the longitudinal axis) and roll ratcheting, handling qualities and aircraft performance are degraded but flight path and aircraft attitude control are still possible.

In this context, it is important to investigate whether the pilot's body can be described as a passive element during roll ratchet, only propagating aircraft accelerations into stick deflections, or whether an active pilot feedback as a reaction to sensed accelerations, rates or deflections has to be considered.

In the case of the latter theory ([1],[4]), roll ratchet could be influenced by the pilots' reaction delays, the stick force/displacement characteristics or (in the case of visual information feedback) by the quality of the visual information (e.g. latency of the Head-up-Display). An investigation on a fixed base simulator [1] suggests that some or all of these factors may contribute to roll ratcheting.

Other studies [2], however, concentrate on the theory that inertial forces and moments acting on the pilot's neuromuscular system are the root cause of roll ratcheting. This approach is the starting point for the investigation described in this paper. The theory gives explanation as to why roll ratcheting is only found for aggressive inputs (i.e. when high acceleration values are present). It also accounts for the observation that roll ratchet occurrences have increased with the advent of fly-by-wire flight control systems which are partly characterised by much lower required stick forces for commanding aggressive roll accelerations.

1.2. Aircraft-specific Contributions

Based on the theory that roll ratcheting is caused by inertial forces and moments on the pilot's body and the stick, then the position of the pilot relative to the aircraft roll axis and the mass-balancing of the stick are considered important contributors to roll ratcheting.

Two different types of stick were installed on the high-performance fighter aircraft discussed here. Aircraft of this type generally feature a mass-balanced stick but the stick installed on some prototype aircraft was unbalanced. With the same control law software, roll ratchet susceptibility is expected to be higher for the aircraft equipped with the un-balanced stick (see also section 3.1). The pilot is sitting above the aircraft roll axis. Therefore, roll acceleration is causing additional lateral acceleration on the pilot's body.

2. FLIGHT TEST OCCURRENCES

Roll ratcheting was encountered on a prototype aircraft of the high performance aircraft discussed here during flight test of a development software load. At that time, the flight control law had been redesigned with the goal of achieving higher agility. As expected, full roll stick inputs delivered the expected agility improvement. However, partial roll stick inputs (between 60% and 90%) were found to generate roll ratcheting which, in some instances, were quite severe.

FIG 1: Roll Ratchet Occcurrence - Aircraft equipped with un-balanced stick (250kt)

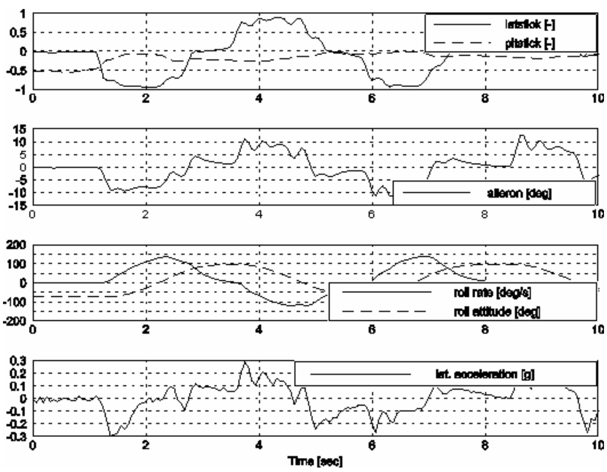
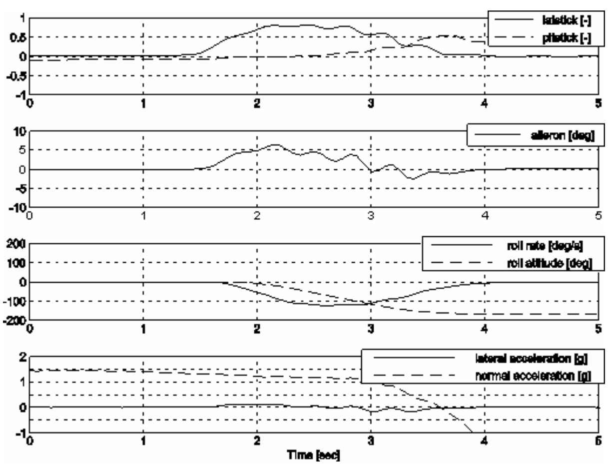


FIG 2: Roll Ratchet on Aircraft equipped with balanced stick (350kt)



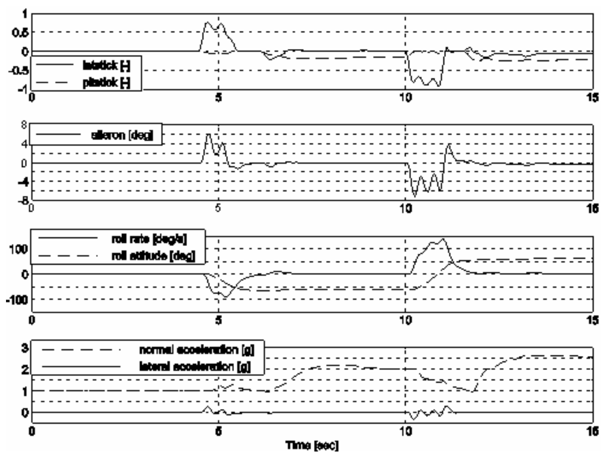
The first occurrence was on an aircraft (see Figure 1) equipped with an unbalanced stick (see section 1.2). It was initially hoped that roll ratcheting would not be encountered on the balanced stick - equipped aircraft. However, when the same control law was loaded onto aircraft equipped with balanced stick some weeks later, roll ratcheting was again observed, albeit only at higher speeds, where higher roll acceleration values can be generated.

Figure 2 shows a typical example for roll ratcheting experienced on an aircraft equipped with balanced stick. The pilot uses roughly 80% stick command for rolling to an inverted position. A small amplitude oscillation in roll acceleration and lateral stick deflection develops. When the pilot centres the stick, the damping of the oscillation increases and only stops when the roll acceleration levels fall below 100°/s².

Further flight testing was subsequently performed in order to identify worst-case conditions and to give different test pilots a chance to assess the aircraft behaviour.

Figure 3 shows roll-ratcheting experienced during a dedicated ratchet assessment task. Roll ratcheting occurs during bank-to-bank acquisition at high speed on an aircraft equipped with balanced stick. The ratchet frequency is approx. 2.3Hz and maximum roll acceleration values of up to 500°/s² are registered. It is also apparent that the ratcheting is only present within a narrow band of stick travel and stops immediately as the stick is centred.

FIG 3: Aircraft equipped with balanced stick, 450kt – Dedicated Ratchet Testing



The software load was obviously unfit for delivery to the customer but there were no safety implications and therefore, no flight limitation had to be imposed. Most other roll ratchet occurrences were of much smaller intensity but all test pilots flying with this software load were able to excite roll ratcheting.

From these results, it was concluded that the roll ratcheting was caused by deficiencies in the roll command path design, with the balanced stick only partially mitigating the effect.

3. MODELLING ROLL RATCHETING

In order to analyse the problem encountered in flight, a model of the pilot-stick dynamics was added to the non-linear simulation model of the augmented aircraft.

3.1. Two Point-Mass Pilot-Stick Model

A two point-mass pilot-stick model was developed for representing the excitation of the roll stick by inertial forces. Figure 4 illustrates the two point-mass pilot-stick model.

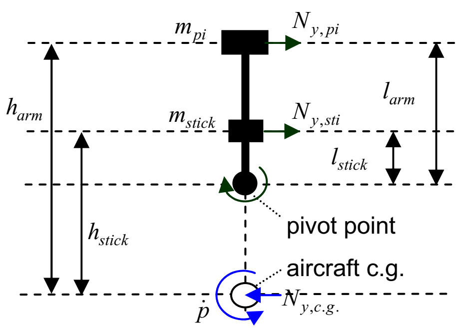
The hinge-line of the stick is defined as the pivot-point for stick rotations in the lateral (roll) direction. The stick is modelled as a point mass (m_{stick}) installed at a distance l_{stick} above the pivot point. For a balanced stick, the inertial moment about the pivot point is close to zero.

For the pilot dynamics, it is assumed that the pilot's body is strapped to the seat and therefore only the pilot's arm will move relative to the aircraft. A second-order lag filter characterised by frequency and damping is used to model the transfer function of the pilot's body-arm system. Stick forces are neglegted.

This leaves three parameters for characterising the properties of individual pilots:

- the mass m_{pi} of the pilot's arm
- the frequency ω_{pi} of the pilot's body-arm transfer function
- the damping ζ_{pi} of the pilot's body-arm transfer function

FIG 4: Two Point-Mass Pilot-Stick Model



The lateral acceleration acting on the pilot's arm and the stick respectively is derived from:

$$(1)\quad \begin{aligned} N_{y,pil} &= N_{y,c.g.} + \dot{p}\cdot h_{arm} + \dot{r}\cdot x_{arm} \\ N_{y,sti} &= N_{y,c.g.} + \dot{p}\cdot h_{stick} + \dot{r}\cdot x_{stick} \end{aligned}$$

where $\dot{p}$ and $\dot{r}$ denote roll and yaw acceleration at the aircraft c.g., and x_{arm} and x_{stick} are the longitudinal distances from pilot's arm and the stick, to the c.g. Consequently, the inertial moment on the stick, relative to its pivot point, can be calculated as:

$$(2)\quad L_s = \left(N_{y,pil}\cdot l_{arm}\cdot m_{pil} + N_{y,stick}\cdot l_{stick}\cdot m_{stick}\right)\cdot 9.81$$

The inertial moment is passed through the second-order lag filter and consequently the stick deflection can be derived from

$$(3)\quad \delta_{R,c} = \frac{-c\cdot L_s}{s^2 + 2\zeta_{pi}\omega_{pi} + \omega_{pi}^2},$$

where c denotes a constant conversion factor from angular stick motion to stick units.

3.2. Relation to other Pilot Models

In a recent study [2], a biomechanical pilot model is proposed for prediction of roll ratcheting. This model comprises four bodies connected by springs. The model parameters are estimated by matching the frequency response to values from literature.

A dominant neuro-muscular system pole at a frequency of 2.54Hz and a damping of 0.45 is found. It is not noted whether the remaining neuro-muscular system dynamics interact with the aircraft dynamics.

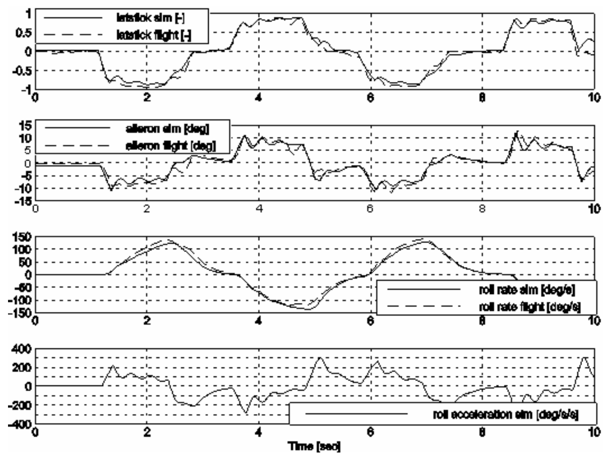
In other studes [1],[4] where the pilot is modelled as an active acceleration or force feedback element with a delay, lag and gain properties, a second-order neuro-muscular system mode of about 2.5Hz is also present.

These results suggest that, independent of the type or complexity of the pilot model, a complex mode which is poorly damped and with a frequency of around 2.5Hz must exist in order to successfully model the oscillatory motion (roll ratchet) seen in flight.

3.3. Flight Test Re-Prediction

The pilot-stick model described in section 3.1 was used to re-predict the roll ratchet occurrences encountered during flight test. The longitudinal stick and pedal inputs recorded in flight were inserted directly into the simulation model. Oscillations in the recorded lateral stick inputs were removed by using simple step and ramp inputs which approximated the intended pilot input. The loop between pilot stick model and lateral stick was closed by adding the output of the pilot model to the lateral stick forcing function.

FIG 5: Re-Prediction: Aircraft equipped with un-balanced stick, 250kt, Pilot A



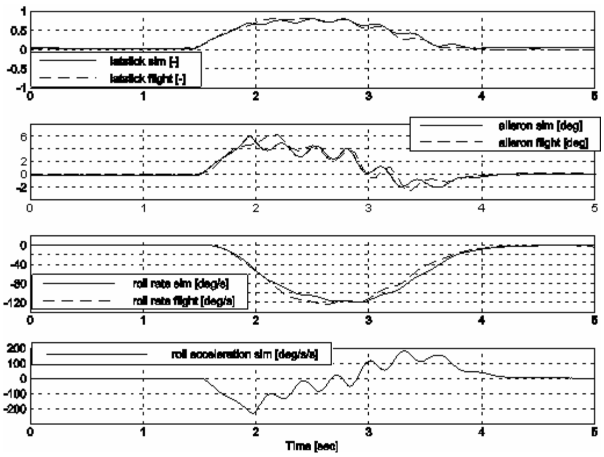
The three pilot parameters were tuned until a good match between flight test results and simulation was achieved (see Figures 5, 6 and 7). It was found that:

- all occurrences on the same flight (i.e. experienced by the same pilot but at different flight conditions) could be matched by using the same parameter combination.

- for each pilot, a different parameter combination was needed, with differences found in all three parameters (see table 1).
- the frequency range for roll ratcheting extends from 1.9 to 2.75Hz, with damping ranging between 0.25 and 0.5.
- the frequency of the pilot model is always very close to the ratcheting frequency.

Additional confidence was taken from the fact that higher estimated pilot-arm masses were found for heavier pilots. It was concluded that the simple two point-mass pilot-stick model of section 3.1 is capable of reproducing the roll ratcheting phenomenon seen in flight.

FIG 6: Re-Prediction: Aircraft equipped with balanced stick, 350kt, Pilot B



Since the pilot model is linear it can also predict small amplitude roll ratcheting for small stick inputs. Judging from the time histories of gentle manoeuvre inputs, no such effects were present in flight. Consequently, it can be concluded that the linear pilot model of section 3.1 is valid only for large commanded roll acceleration values. Under these conditions, the pilot's arm behaves like a simple mass-spring-damper system. Damping is low (in the 0.25 to 0.4 range, see table 1) and does not increase if the pilot strengthens his grip on the stick. Conversely, if acceleration levels are low, the neuro-muscular system is expected to compensate for the acceleration and keep the arm calm, resulting in much higher pilot damping values.

TAB 1. Roll ratchet pilot model parameters estimated from flight test results

Pilot	m_{pi}	ω_{pi}	ζ_{pi}
A	1.0kg	2.3Hz	0.4
B	1.0kg	2.75Hz	0.25
C	1.5kg	2.3Hz	0.5
all	1.0kg-2.5kg	1.9Hz-2.75Hz	0.25-0.5

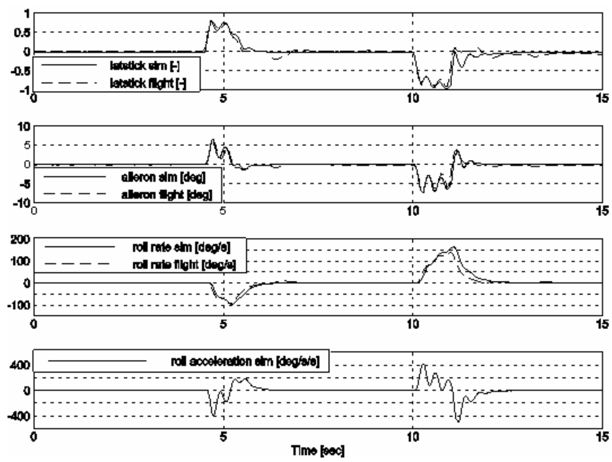
4. A CONTROL LAW SOLUTION

In preparation of a control law design solution, the simulation results for cases with the pilot model in the loop were compared to open-loop simulation results. It became apparent that roll ratcheting increased both rise time and settling time of the roll rate command. Consequently, a less aggressive roll command path design which avoided roll ratcheting would result in more agile overall roll rate responses. The design challenge was, therefore, characterised by the idea of maximising roll acceleration without causing roll ratcheting.

4.1. Roll Command Path

Figure 13 shows the main elements of the roll axis feedback and roll command system. It should be kept in mind that the digital flight control systems installed on high-performance aircraft make it possible to realize complex command path and feedback structures ([3]).
The feedback system shown here features a basic PI-structure with a roll damper (k_p), a roll command direct link (k_d) and an integral roll rate error feedback (k_i). All three feedback signals are summed and distributed to both aileron (ξ) and rudder (ζ). Yaw rate and angle-of-sideslip (AoS) feedback paths (not detailed in Figure 13) complement the lateral axes control law, providing turn coordination and zero steady state control errors in roll rate and angle-of-sideslip.

FIG 7: Re-prediction: Aircraft equipped with balanced stick, 450kt, Pilot C



The roll command path consists of two main elements. In the first element, the stick command (in stick units) is converted into a roll rate command. This is done via a quadratic roll rate command shaping function. It should be noted that the roll rate authority of fighter aircraft is not constant but increases with speed and decreases with angle-of-attack. Using the quadratic roll rate command shaping function makes it possible to obtain a constant stick versus roll rate slope around centre stick (which ensures good tracking properties) throughout the envelope while ensuring that full roll stick command provides full roll authority at each point of the envelope.

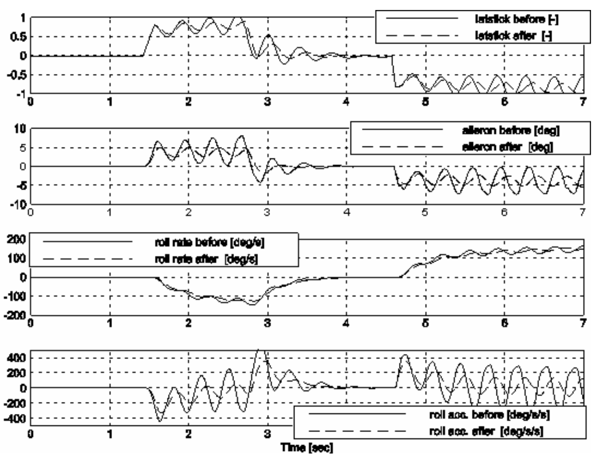
In the second element of the roll command path, the roll rate command is filtered by a first-order lead-lag. Roll damper, integral and direct link gains determine the closed-loop poles of the transfer function from roll rate command to aircraft roll rate. Here, the direct link gain (which determines the position of a zero in the transfer function) is chosen such that the integral roll pole is canceled in the transfer function. The remaining transfer function can then be approximated by a first-order lag system. With the lead-lag filter added, the lead time constant of the lead-lag filter can be determined such that the resulting zero cancels the remaining pole of the closed loop system. Consequently, the lag time constant of the lead-lag filter determines the pole position of the roll rate command to aircraft roll rate transfer function.

The feedback gains and command path parameters are adapted with Mach-number, dynamic pressure and angle-of-attack, providing harmonisation of the aircraft's handling qualities over the envelope.

4.2. Discussion of Roll Command Path Modifications

The parameters of the roll command system described in section 4.1 all have an influence on roll ratchet sensitivity. The more aggressive the response for which the command path is designed (i.e. the higher the amplitude of the transfer function from stick to aircraft roll rate in the "ratchet frequency range" from roughly 1.9Hz to 2.5Hz) the more ratchet-prone is the system. For a quantitative assessment, the open-loop frequency response is usually displayed in the Nichols-diagram (see Figure 12). Applying this technique to the control law software version loaded when roll-ratcheting was observed, violations of the ratchet criterion could be demonstrated. For this assessment, the pilot model parameters estimated from the flight test results were used. Further analysis highlighted that this control law version features a very high direct link gain k_d which had been designed to optimise time-to-90° bank.

FIG 8: Re-design of command path system: before vs. after case – reduction of roll ratchet sensitivity

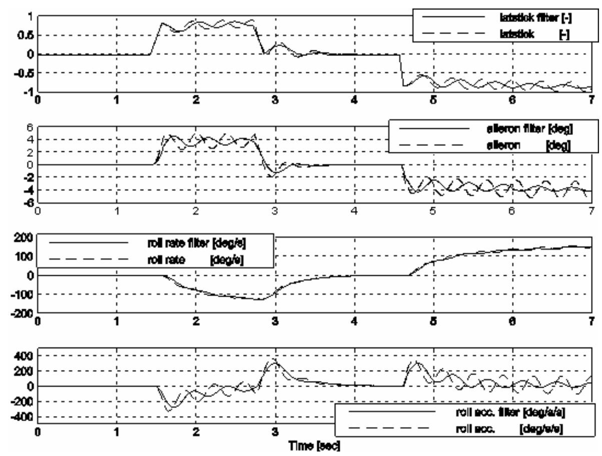


Based on these findings, a re-design of the roll command path was considered appropriate. A general frequency-independent reduction in roll command path amplitude leads to a significant loss of aircraft agility. Therefore, the command path parameters were not optimised to satisfy the ratchet criterion in the Nichols plot but were chosen to deliver the desired roll rate response with respect to rise time and settling time, reducing the peak roll acceleration values and compromising on time-to-90°bank at some points in the envelope. Figure 8 compares simulated time histories before and after command path re-design for a bank-to-bank reversal manoeuvre. Roll ratcheting is still present but the sensitivity is clearly reduced. Worst-case pilot model parameters (1.5kg, 2.3Hz, 30% damping) not encountered in flight have been used here for illustration purposes.

In a second design step, additional control law elements were investigated for eliminating roll ratcheting. Dynamic filtering and rate-limiting are discussed here. A second-order lag filter is proposed by some researchers for roll ratched mitigation [2]. With the filter included, the open-loop roll command path frequency response can be shaped so that the roll ratchet criterion in the Nichols plot is satisfied.

Aircraft agility measured by roll acceleration potential is, however, reduced if a significant lag is introduced into the command path. In addition, a delay in the command path increases the risk of pilot-induced-oscillations (PIO). Therefore, only moderate high-frequency attenuation is sought. Figure 9 compares simulated time histories for the system after command path re-design with and without a second-order lag-filter in the command path.

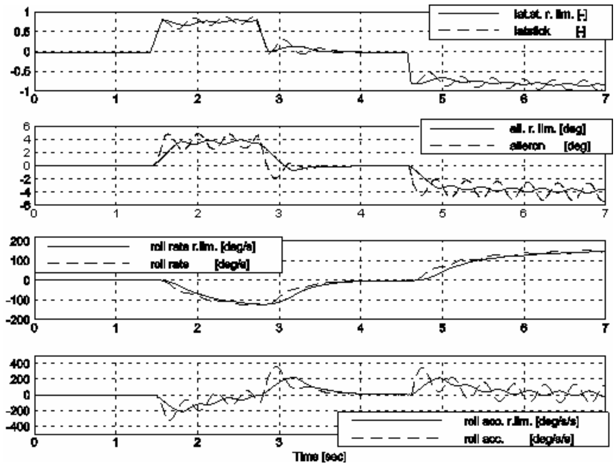
FIG 9: Simulation of closed-loop system with filter in the command path



Here, a high frequency attenuation of 4dB and a bandwidth of 1.7Hz has been chosen. Roll-ratchet sensitivity is reduced and command path damping is increased, but the problem is still present.

Introduction of a rate limit in the roll command path was investigated next. A rate-limit on the roll rate command corresponds to an absolute limit on the roll acceleration command. With such a measure, only large stick inputs generating large roll acceleration commands are affected. High input frequencies are attenuated and the roll rate rise time will be slower for larger stick inputs than for smaller stick inputs. Figure 10 compares simulated time histories for the system after command path re-design with and without a rate-limit in the command path. A limit of 300°/s² has been chosen for this example. Roll ratcheting is eliminated but the system response is now much slower. In addition an important delay is introduced into the command path which again increases the risk of PIO.

FIG 10: Simulation of closed-loop system with rate-limit in the command path



Therefore, a rate-limit alone is not considered a suitable means of removing roll-ratcheting. For the high performance aircraft discussed here, a combined solution consisting of both a second-order filter and a rate-limit has been designed. The rate-limit of 1000°/s² is incorporated into the filter as a limit on the commanded acceleration. This ensures that system delays due to filter and rate-limit are not combined. In addition, the high frequency attenuation of the filter is implemented as a function of commanded roll acceleration. Consequently, only a 2dB high-frequency attenuation is active during tracking inputs around centre stick whereas 4dB attenuation is obtained for large stick inputs.

FIG 11: Simulation of closed-loop system with combined solution in the command path

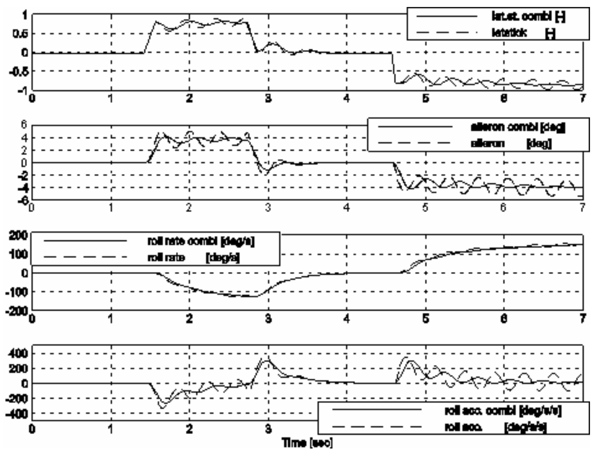


Figure 11 compares simulated time histories for the system after command path re-design with and without the combined solution in the command path. The response looks similar to the filter solution on first glance (not unexpectedly as the same filter parameters are used) but a direct comparison reveals a significantly increased system damping. Rise time and settling time of the roll rate response are preserved, but roll ratcheting is not completely eliminated.

Based on the hypothesis that the pilot damping parameter is a function of the acceleration level (see section 3.3), the combined solution as described above was implemented in the subsequent issue of the control law software.

Flight test results support the hypothesis of the non-linear pilot damping as no roll ratcheting was experienced with the solution in place. With no intermediate values available, a functional dependency of pilot damping on acceleration levels can not be given. This could be an interesting aspect to be covered by future research work.

4.3. Frequency-domain assessment

A frequency-domain assessment (based on [5]) has been performed in support of the redesign process described in section 4.2. The pilot-stick model of section 3.1 has been added to the linearised model of the augmented aircraft dynamics using the parameters identified from the flight test results. The open-loop frequency response has then been calculated. Figure 12 shows the frequency responses corresponding to the 'before' (pre-modification) case software standard for an example 450kt flight condition, a stick command of 80% full roll stick, a pilot arm mass of 1.5kg, a pilot ratchet frequency of 2.3Hz and two different pilot damping values (0.3 and 0.5).

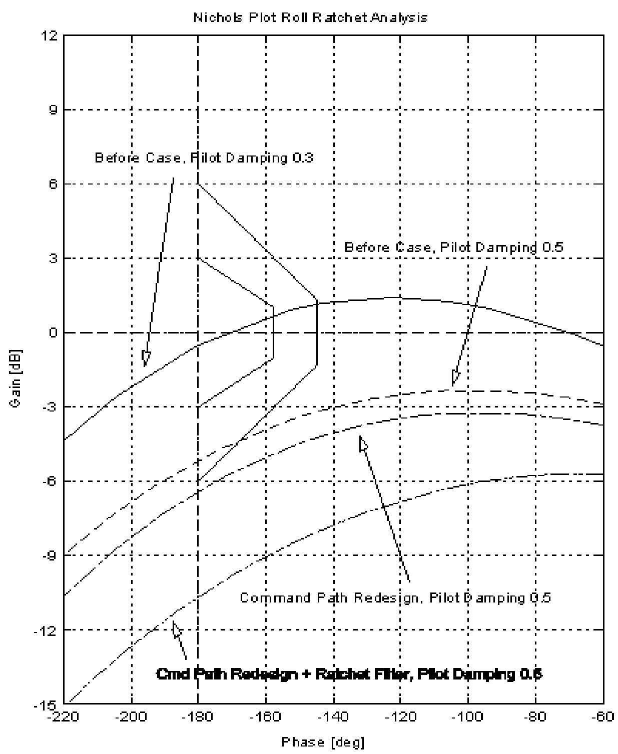


FIG 12: Open-loop frequency response of the roll rate command system formatted as Nichols-plot: before case vs. redesign with and without ratchet filter

Not unexpectedly, the frequency response passes from stable to unstable if the pilot damping is reduced sufficiently. Frequency responses for the system after control law redesign, with and without the ratchet filter respectively are compared for 0.5 damping. It should be noted that the effect of the rate limit has not been considered here. A significant attenuation of the frequency response is apparent, confirming the non-linear simulation results. This kind of frequency response analysis is certainly an interesting tool for predicting ratchet tendencies on aircraft. It should be noted, however, that this frequency response is dominated by the assumptions made on the pilot transfer function. As discussed in section 3, the pilot-stick transfer function varies widely for different pilots and is influenced by aircraft-specific parameters (e.g. how the pilot is strapped to the seat). Designing against this criterion for a worst-case pilot model is, therefore, likely to generate very slow roll responses. Consequently, it is recommended to use average pilot characteristics for this kind of assessment task.

5. CONCLUSIONS

This paper discusses roll ratchet occurrences encountered during flight test of an early control law software load for a High Performance Fighter Aircraft featuring high levels of roll rate and roll acceleration.

The roll ratcheting was caused by deficiencies in the roll command path design. In the case discussed here, an un-balanced stick contributed to and amplified the roll ratcheting tendency but was not the root cause of the problem.

The effect could be re-produced in non-linear simulation by using a simple dynamic pilot-arm model based on 3 main parameters. This approach delivered a match for large levels of roll acceleration but – contradictory to flight test experience - also predicts small amplitude roll ratcheting for lower acceleration levels.

Therefore, a hypothesis is developed that the linear model is only valid for large acceleration values when the neuro-muscular system of the pilot is too slow to damp the oscillation. For lower acceleration values, a feedback contribution from the neuro-muscular system and a much higher pilot damping are assumed.

The ratchet problem was solved by redesigning the roll command path. First, the direct link gain and the lead-lag filter in the command path were chosen to deliver the desired roll rate response with respect to rise time and settling time. Then, a second order lag filter was used for attenuating the roll command path transfer function in the frequency range where roll ratcheting occured for different pilots. In addition, a rate limit was introduced, limiting the maximum commanded roll rate.

This combination of control law measures was tested in simulations using the pilot model derived earlier. A wider range of pilot parameters was considered. Using the linear pilot model, a mild level of roll-ratcheting was still predicted for worst-case pilot parameters, albeit at low roll accelerations levels. The solution was implemented and tested in flight. No roll ratcheting was present. This result supports the hypothesis that pilot damping is lower for higher acceleration levels.

Acknowledgement

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FIG 13: Main Elements of a Roll Command Path and Roll Axis Feedback System