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FLIGHT TESTING OF A RATE SATURATION COMPENSATION SCHEME ON THE ATTAS AIRCRAFT

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ABSTRACT

This paper presents the application of a rate saturation compensation scheme to the DLR Advanced Technologies Testing Aircraft (ATTAS) and the results of the subsequent flight tests at DLR, Braunschweig in July of 2006. Details of the design philosophy and the flight tests, termed SAIFE (Saturation Alleviation In-Flight Experiment), which employed the HQDT (Handling Qualities During Tracking) test technique developed at the USAF Test Pilot School, as well as pilot flight test reports (PFRs), are presented. The compensators were designed based on the anti-windup (AW) control philosophy, with the aim to reduce the effects of rate saturation on the piloted aircraft dynamics, and hence provide an increased flight envelope (operating envelope) for acceptable aircraft handling qualities and reduced (Pilot-in-the-Loop Oscillation) PIO tendencies. The achievement of this goal was quantified by flight test data and subjective pilot ratings. The results show that the compensation scheme greatly reduced the level of rate saturation in all instances (flight conditions) making the aircraft less PIO prone in almost all investigated cases, while exhibiting either unchanged or improved handling qualities. Most notably, the flight tests demonstrated the definite potential for well designed AW compensators to improve the safety and handling qualities of aircraft during rate saturation, with some flight conditions exhibiting dramatic improvements.

1. INTRODUCTION

It is well known that rate limits present a problematic nonlinearity, whether superimposed on the surface deflection commands in a flight control system or defined by the physical constraints of the actuation system itself. Rate limiting adversely affects both the stability and performance properties of the system, potentially catastrophically. A number of spectacular accidents during the development phase of fly-by-wire (FBW), 4th generation fighter aircraft, such as the JAS 39 Gripen and the YF-22, have been attributed to the destabilising effects of actuator rate limiting. These destabilising effects have been determined to be a major factor in CAT II PIOs. CAT II PIOs are predominantly quasi-linear pilot vehicle system (PVS) oscillations with rate and/ or position limiting as the only explicitly non-linear elements. PIO behaviour associated with rate limiting has been observed in both civilian and military aircraft, with the alleviation of such PIO tendencies being an objective of the aeronautical community over the last 15 years (see, e.g. (Mitchell and Klyde 2004)). Subsequently, the issue of PIO proneness of an aircraft, including the specific effect of rate saturation, has become an important design consideration in modern FBW aircraft.

Within the GARTEUR (Group for Aeronautical Research in Europe) framework, Action Group 15 (AG15) is currently involved in advancing PIO research in the field of analysis and test techniques, as well as online rate saturation compensation algorithms, which are the focus of this research. Online algorithms, such as nonlinear filters, phase compensators and feedback schemes have already been proposed (Rundqwist and Hillgren 1996, Mitchell and Klyde 2004). However, while these methods have been implemented successfully, they are typically designed in an ad-hoc manner, and thus may not provide reasonable guarantees for system stability and performance. One key objective of AG15 has been to develop methods to rigorously and systematically design rate saturation compensation algorithms that provide stability and performance guarantees, and hence are more likely to alleviate the effects of rate saturation in practice. This paper presents the results from the design of such an algorithm, as proposed in (Sofrony *et al.* 2006), that is based on the anti-windup (AW) philosophy, and its evaluation via flight tests, termed SAIFE (Saturation Alleviation In-Flight Experiment), on the DLR Advanced Technologies Testing Aircraft (ATTAS) at DLR, Braunschweig, in July of 2006. Notably, in the experiments, in order to fully exploit the AW compensator capability, the software imposed rate limits within the experimental control laws were reduced to a degree that rate limiting would occur during high frequency, large amplitude pilot inputs. This degradation was only applied to the roll axis, since the ATTAS testbed is comparatively agile in roll, whereas structural load limits would have compromised a rigorous evaluation of the pitch axis. Testing was conducted in a build-up approach in three phases at various flight conditions, allowing for a thorough analysis of system dynamics at up-and-away and landing-approach flight conditions.

The paper is outlined as follows. Initially, an overview of the effects of rate limiting on the aircraft dynamics is given that serves as motivation for the research undertaken. This is then followed by a discussion of SAIFE and a description of the experimental test aircraft (ATTAS) as well as the test methods employed, providing both handling qualities ratings (HQRs) and PIO ratings

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(PIORs). The subsequent test results are to be used to determine the effects of the AW scheme on the piloted-aircraft system and the ability to improve handling qualities and reduce PIO susceptibility. The AW design philosophy is presented thereafter, where it is shown how this aims to alleviate the affects of saturation in a theoretically rigorous manner. The design of the AW controllers for the ATTAS aircraft is presented, which gives an overview of the design trade-offs involved in the synthesis and the specific methodology employed. Finally, the results for the experimental evaluation of the AW controller on the ATTAS aircraft for a range of up-and-away flight conditions and offset landing tasks are presented. These results are discussed with reference to pilot flight reports (PFRs), time domain data and preliminary analysis. Conclusions are given in Section VII.

2. MOTIVATION: AIRCRAFT WITH RATE LIMITING

The effects of rate limiting of aircraft actuators have been well studied (see (Klyde and Mitchell 2003, Mitchell and Klyde 2004, Duda 1997, Gatley *et al.* 2006) and the references therein). The following review provides the technical basis for the discussion of rate limiting effects in the paper, while also motivating the compensation philosophy employed in the present research. The problem of saturation is ubiquitous, with all physical systems subject to constraints on their inputs and outputs at some level. Both amplitude and rate limitations will be present, both physically and often as software limits. However, for aircraft systems, and specifically PIO phenomena, the effects of rate saturation have been identified to be a leading factor in degraded aircraft response and stability (Klyde and Mitchell 2003). This is because, unlike amplitude saturation, rate saturation is a dynamic nonlinearity, and as such contributes additional phase lag to the response of the system. It is this phase lag that is often the major cause of degraded system performance during saturation, as it can greatly reduce the stability margins of the closed-loop system, potentially giving rise to unstable or oscillatory (limit cycle) responses by significantly affecting the magnitude response of the closed loop system. Such observations have led to successful analysis tools for PIO behaviour, notably the OLOP criterion developed at DLR (Duda 1997).

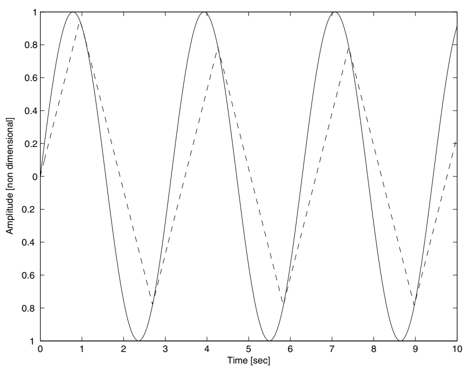


FIG 1. Phase lag caused by rate limit. Slew rate limit of ±1 unit/second; sine wave of 2 rad/s applied

The dynamics of full rate limiting can be quantitatively observed in *Figure 1*[2]. This shows the response to a sinusoidal input and the standard saw tooth triangle shape of the output of the rate limiter when it is completely activated (full saturation). Note that, in addition to the reduced amplitude of the signal, there is a phase difference between the peaks which gives rise to the detrimental phase lag.

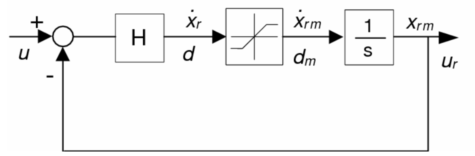


FIG 2. Feedback representation of the rate limited actuator

To model the rate limiter, time domain equations can be derived. However, to facilitate control system design and frequency domain analysis, two approaches can be used. The first is to analyse the time domain response of the system using harmonic balance methods, which provides a quasi-linear frequency domain model of the system (Klyde and Mitchell 2003). The second is to model the rate saturation element as a first order feedback system, as shown in *Figure 2*. This simplified actuator model gives an accurate description of the low frequency behaviour, and is suitable for model based control. This can also be analysed based on harmonic balance methods to give a similar quasi-linear model of the system (Duda 1997). This model, termed the describing function of the rate saturation, is described by the following equation (Duda 1997):

$$N(a,\omega) = \left(4r/\pi\,\omega\,a\right)\, e^{j\arccos\left(\frac{\pi r}{2\omega a}\right)} \tag{1}$$

where ω and a are the frequency and amplitude of the sinusoidal input, and r is the rate saturation limit. *Figure 3* shows the Bode plot of the magnitude and phase characteristics of this quasi-linear model of the rate limiter. Note the phase and magnitude loss at higher frequencies where rate saturation is more pronounced.

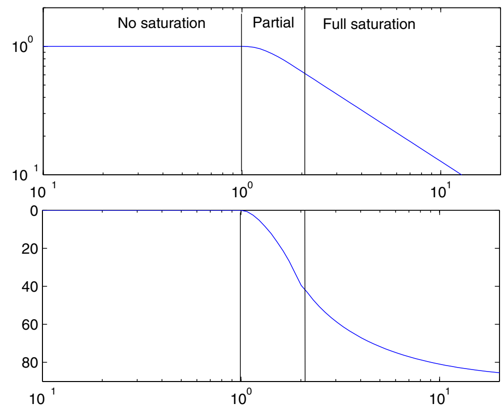


FIG 3. Rate limiter describing function Bode plot

Based on these models of the rate limiter, analysis can be performed to determine the effect of rate saturation on the piloted aircraft. For example, in (Duda 1997, Rundqwist and Hillgren 1996, Klyde et al. 1997) it is shown how the frequency response of the aircraft changes during full rate saturation and the subsequent effects on stability and handling qualities. A particular concern is sustained or divergent oscillations in the aircraft response, as associated with PIO behaviour, and for this limit cycle analysis based on the describing function provides a useful, albeit approximate, first order analysis, which can be supplemented with analysis based on nonlinear

[2] The rate limiter can operate in three modes: no limiting, partial limiting, where the limiter only acts over part of the signal period, and full limiting, where it acts continuously on the signal over several periods, as depicted in *Figure. 1*. The frequency ranges of these modes are also shown in *Figure 3*.

simulations and bifurcation theory. The difficulty with such analysis is the fidelity of the models of the pilot behaviour during the demanding tasks where rate limiting often presents severe problems. Often simple gain or first order models are employed, with the overall piloted aircraft system being represented as in *Figure 4*. As the accuracy of the pilot model is always questionable, high fidelity analysis of piloted-aircraft behaviour is difficult. However, existing analysis techniques, such as OLOP and other more recent derivatives, have been found to give a good indication of the PIO tendencies (Mitchell and Klyde 2004). From such analysis it has generally been agreed that the effect of the additional phase lag, as seen in *Figure 3*, is a leading cause of poor aircraft behaviour during rate saturation. Furthermore, rate limiting, potentially combined with other nonlinear effects, can evidently have a drastic and sometimes catastrophic effect on the piloted aircraft behaviour, mandating its consideration in FCS design for FBW aircraft. Based on the above, methods have been proposed to alleviate its detrimental effects. Examples are nonlinear pilot input filtering and smart rate limiters that preserve phase, and more advanced techniques, such as phase compensators and AW techniques (Rundqwist and Hillgren 1996, Gatley et al. 2006, Mitchell and Klyde 2004). Of these, those based on the AW philosophy have often been successful. Such an AW approach is employed herein, with details of the design philosophy given in Section V. In short, it aims to reduce the effects of rate saturation on the overall aircraft response, which implicitly includes reducing the error (magnitude and phase) between the input and output of the rate limiter, and more importantly explicitly includes the provision of improved stability properties (margins) and performance (handling qualities) during saturation.

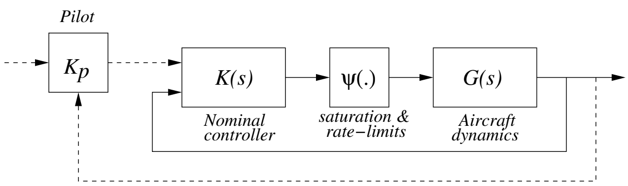


FIG 4. Control Loops in PIO analysis

3. ATTAS AIRCRAFT

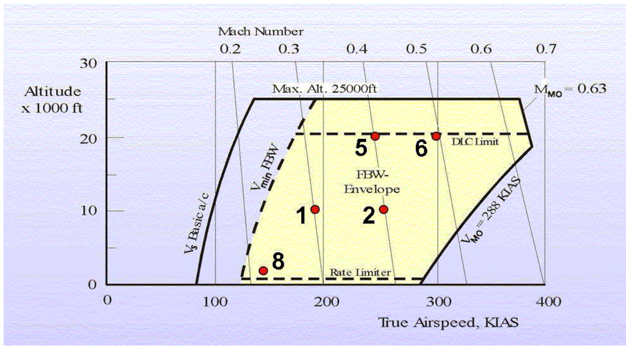
The ATTAS (Advanced Technologies Testing Aircraft) is a highly modified VFW 614 aircraft which has been operated by DLR as testbed and inflight simulator since 1986 (see *Figure 5*). It features various customized systems such as direct lift control, enabling rigid body manipulations in 5 degrees of freedom, an adaptive fly-by-wire flight control system, capable of hosting different controller designs and emulating vehicle dynamics of model-based virtual aircraft (In-Flight Simulation - IFS), an experimental cockpit and extensive flight test instrumentation.

The safety concept realised on the aircraft with a safety pilot and a mechanical back-up control system as primary assets allow for the assessment of flight control software in the authentic environment by an evaluation pilot without having to meet extensive certification requirements. In cases when flight safety may be compromised, the safety pilot can always override commands generated by the experimental control laws via the mechanical back-up system. For the SAIFE flight test campaign, the aircraft was equipped with a passive side stick as primary control inceptor at the evaluation pilot's station to facilitate high frequency, large amplitude inputs and potentially precipitate 'bang-bang' control. The AW compensator design was based on the basic ATTAS VFW 614 dynamics including the scheduled control laws engaged in the fly-by-wire (FBW) mode.

FIG 5. ATTAS testbed

4. PLANNED FLIGHT TESTS

To demonstrate the effectiveness of the AW compensation, four up-and-away flight conditions and one landing-approach flight condition were selected to assess different compensator designs (see *Figure 6* and *Tables 2* and *3*). Two test pilots from the German Armed Forces Technical and Airworthiness Centre for Aircraft participated in the trial and acted as evaluation pilots, one known to be a high gain pilot, the other a low gain pilot.



(1) 10000 ft, Ma 0.3 / (2) 10000 ft, Ma 0.4 /
(5) 20000 ft, Ma 0.4 / (6) 20000 ft, Ma 0.5 /
(8) pattern altitude, 135 kEAS

FIG 6. Test points within the ATTAS envelope

As mentioned earlier, testing focused on the roll axis. To degrade system performance and handling qualities, the software imposed aileron command rate limits were reduced to 50% and 60% of the full authority values for up-and-away and landing-approach test cases, respectively. All test conditions were assessed with the AW compensator engaged and disengaged, while the rate limit degradation was retained throughout. Pilots were not aware if the compensation was active and plainly evaluated aircraft response. Prior to any flight testing, procedures and test methods were trained using the fixed base ATTAS simulator, which also provided an insight into the expected real aircraft response.

4.1. Up-and-Away Testing

Testing at all up-and-away flight conditions was conducted in cruise configuration, in a build-up approach, consisting of three test phases:

− *Phase I* testing comprised semi-closed loop and closed loop bank angle capture tasks, to enable the pilot to become familiar with the aircraft dynamics requiring qualitative pilot comments and PIO ratings (PIOR).

– *Phase II* testing involved the application of the HQDT test technique, which currently is the only method that allows for systematic, high bandwidth PIO resistance testing, and is therefore sometimes also referred to as handling qualities stress testing. This test method was developed to investigate the entire range of possible pilot input commands with respect to frequency and amplitude which may occur during a mission under certain circumstances, as depicted in *Figure 7*.
When tracking becomes necessary, i.e. an error signal exceeds a certain threshold prompting the pilot to close the control loop, pilots by nature adopt the lowest possible gain piloting technique which is consistent with satisfactory task performance. However, when pilots experience stress, anxiety or fear they will assume a high gain control technique.

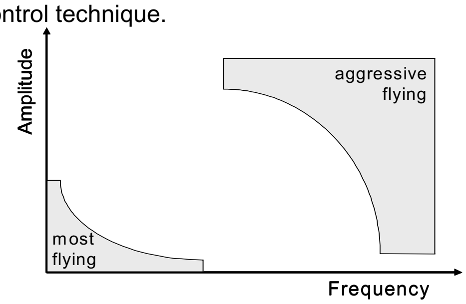


FIG 7. Pilot input schematic

In order to ensure that in such an event system stability is not compromised, possibly promoting PIO, and stability margins are sufficient to accommodate any changes in pilot dynamics, this flight test technique was devised to uncover any deficiencies caused by high gain pilot inputs, including system degradation due to saturation. Its aim is to artificially increase pilot bandwidth, i.e. the frequency and amplitude content, by requiring the pilot to track a precision aim point as aggressively and assiduously as possible, correcting even the smallest tracking error as rapidly as possible. Initially commencing with small amplitude and low frequency inputs, control is gradually tightened, progressing to higher frequencies and amplitudes up to 'bang-bang' control, until finally the pilot behaves like a switching function, reversing the control input in the instant the piper or other aircraft fixed reference moves through the aim point. The degree to which an aircraft follows these violent inputs is quantified using PIOR. During the SAIFE campaign the pilot was tasked to apply HQDT while capturing a wings level roll attitude from an initial 30 deg offset using the roll attitude indicator in the main head down display (MHDD) as reference.

– *Phase III* testing evaluates handling qualities in an operationally relevant context. A target tracking task was defined, requiring the pilot to closely track a generic birdy (aircraft symbol) projected into the MHDD with the aircraft water line (WL) symbol (refer to *Figure 8*).

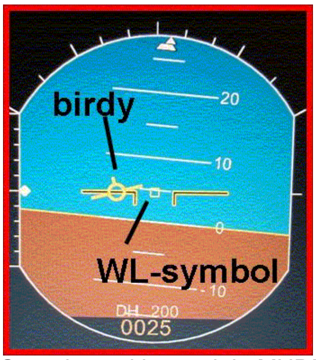


FIG 8. Generic tracking task in MHDD

The birdy performed a predefined sequence of ramp and step-type roll attitude changes, requiring the pilot to perform and assess gross acquisition and fine tracking handling qualities. The birdy tracking task is depicted in *Figure 9* and was originally devised to assess pitch axis dynamics. It has been successfully used by the U.S. Air Force Test Pilot School on the NF-16D VISTA as heads-up display (HUD) tracking task and features a range of large amplitude step and ramp alterations, evoking saturation. For the SAIFE flight tests the task amplitudes were scaled to fit the ATTAS roll capability.

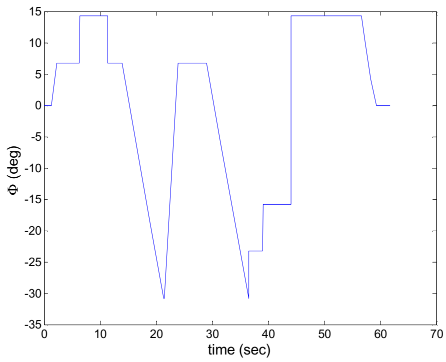


FIG 9. Generic tracking task sequence

Evaluation pilots were tasked to provide Hand Qualities Ratings (HQRs) to quantify system performance during gross acquisition and fine tracking, respectively. Performance criteria were defined as illustrated in *Figure 10*.

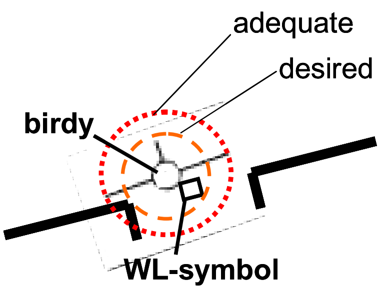


FIG 10. Performance criteria for tracking task

Desired performance is achieved when the WL-symbol overlaps or touches the aircraft symbol, adequate performance is achieved when the WL –symbol can be positioned within the wingspan of the aircraft symbol. Display latency was found to be no factor during the assessment.

4.2. Landing-Approach Testing

As an additional, operational task, offset landings were performed at Schwerin-Parchim airfield (EDOP) to evaluate the effectiveness of various compensator designs during the landing-approach phase of flight. For these landings, the aircraft was reconfigured with flaps set to 14 deg and the landing gear extended. The pilot was tasked to establish a nominal approach flight path on the active runway with an initial 200 m lateral offset to the runway centreline. When passing through 500 ft AGL (Above Ground Level) the pilot was required to aggressively capture runway centreline and maintain the nominal flight path to attempt to hit a specified touch down point within the desired touch down zone marked on the runway. System performance was evaluated by means of HQRs and PIORs. Since the primary focus was on the evaluation of the lateral/ directional dynamics and the combined task proved to be too complex with such a degraded system, the precision touch down requirement was dropped in favour of precise centreline control.

5. ANTI-WINDUP PHILOSOPHY

Section 2 discussed basic properties of rate limited systems and the need to alleviate the potentially deleterious effects. In order to reduce such effects of rate limits on system performance, three obvious choices are available to the flight control system designer:

1. Limit the aggressiveness of pilot reference inputs. This entails either saturating or filtering the pilot command inputs to the controller to ensure that demands which would require control signals of too high rates are not commanded. Effectively this ensures that the rate limits are not excited and therefore the standard linear control system governs aircraft behaviour. The problem with this approach is that aircraft manoeuvrability may be reduced and that external disturbances such as wind gusts are not catered for.
2. Re-design the linear controller to explicitly cater for rate limits. Although feasible in principle, such an approach is potentially fraught with problems. Firstly, it may be difficult to design a controller which simultaneously meets small signal (linear) and large signal (rate limited) performance specifications. Moreover, it may not be cost-effective to perform a complete re-design if much time and effort have been invested in the flight testing of the original linear compensation.
3. Augment the existing linear controller with an additional element which is only active when rate limiting occurs. The advantage of this approach is that the baseline controller can be maintained and this will function normally except in cases when the actuators undergo rate limiting. This allows small signal performance to be handled by the linear controller and large signal performance to be handled by the additional element.

In this paper we take the third approach to catering for rate limited actuators. This approach is arguably the most pragmatic and is probably the one most studied, both within the aerospace industry and within the academic community. In fact, the so-called phase compensation methods developed by SAAB and the former DASA are examples of this latter approach (Wilmes and Duda 1998, Hovmark and Duus 2000). In phase compensation methods, a filter which only becomes active during rate limiting attempts to keep the phase-lag between the input and output of the rate limited actuator to a minimum. In terms of *Figure 1*, the objective of the phase compensation techniques is to minimise the phase delay which occurs between the input sine and the output saw-tooth waveform. As mentioned earlier, although these so-called phase compensation methods, particularly those developed by SAAB (Rundqwist and Hillgren 1996), have had success in coping with rate limited actuators, they also suffer from several drawbacks:

- They are simple, intuitive approaches; rigorous stability guarantees are not provided.
- There are no systematic methods to design or tune these compensators, and the choice of filter parameters is rather ad-hoc.
- They take no account of the aircraft dynamics and simply alter the control signals injected into the actuators.

5.1. An anti-windup approach

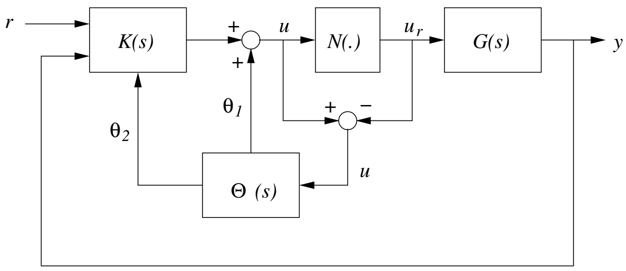


FIG 11. Control scheme with generic anti-windup compensator

The phase compensation method developed by SAAB (Rundqwist and Hillgren 1996) is actually very similar to a class of control augmentation elements called anti-windup (AW) compensators. In the case of rate limits, these are linear filters which become active only when rate limiting occurs and act to retain stability and limit performance degradation during rate limiting. The generic structure of an AW scheme is shown in *Figure 11*. In this figure *G(s)* represents the aircraft dynamics, *K(s)* the baseline controller and *Θ(s)* the anti-windup compensator. The pilot command input is *r(t)* and the aircraft response is represented by *y(t)*. The nonlinear (rate limited) actuators are represented by the nonlinear operator *N(.)*. Note that *Θ(s)* only becomes active when the signal $\tilde{u} = u - u_r$ is non-zero, being when the plant input is different from the controller output (i.e. rate limiting has occurred). Thus the anti-windup compensator remains inactive until rate limiting occurs and, when it does occur, has the authority to modify the controller's behaviour through the signals $\Theta_1(t)$ and $\Theta_2(t)$. Roughly speaking, $\Theta_1(t)$ allows rapid modification of controller output for improved performance and $\Theta_2(t)$ allows the AW compensator to stabilise any unstable (integrator) controller dynamics during periods of saturation.

5.2. Rate limit AW

Although its significance in the control of aircraft has been fairly modest, AW compensation is a standard method in the control field and has been studied by many researchers over recent years. Good summaries can be found in (Kothare et al. 1994, Glattfelder and Schaufelberger 2003, Villota et al. 2006), for example. Most of these studies have concentrated on magnitude limits and studies of the AW technique applied to rate limiting are less common (see (Queinnec et al. 2006) for some related aircraft work). This fact was one of the motivators for the studies in Sofrony et al. (2005a) in which an existing technique for AW synthesis for magnitude limited actuators (Sofrony et al. (2005b)) was extended to systems with actuator rate limits. This scheme makes extensive use of the representation of a rate limit shown in *Figure 2* in which the actuator is modelled by a linear first order low-pass filter with saturation on the rate. For large values of *H*, this serves as a good approximation to a 'true' rate limiter, and also gives a simple model of the linear dynamics of actuators for smaller values of *H*, where *H* represents the actuator bandwidth. For this work it is assumed that the signals either side of the saturation block in *Figure 2* are available for measurement. Although this would rarely be the case for a physical rate limit, software imposed rate limits within the control laws are common and this assumption is plausible in most modern aircraft. In fact, for the ATTAS study described here, the aircraft was artificially degraded using software rate limits and hence the assumption on these measurements was entirely reasonable.

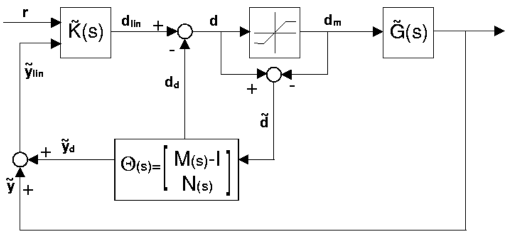


FIG 12. Control scheme with generic anti-windup compensator

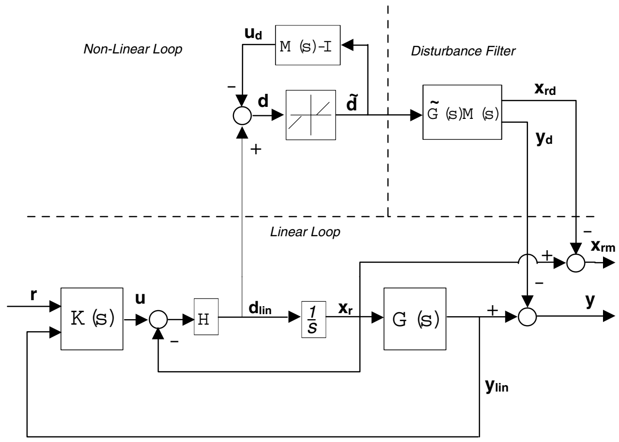


FIG 13. Equivalent representation of System with Anti-windup parameterised by *M(s)*

5.3. A decoupled approach

The anti-windup compensator used in this paper is synthesised according to the methodology described in Sofrony et al. (2005a) (see also (Sofrony et al. 2005b, Turner and Postlethwaite 2004, Grimm et al. 2003) for related papers). The basic architecture is shown in *Figure 12.* In this structure the rate limit is 'broken' into two linear parts and the saturation nonlinearity (see (Sofrony et al. 2005a) for more details). One linear part is then subsumed into an augmented controller, $\tilde{K}(s)$, which is described by the transfer function

$$d = \underbrace{H\begin{bmatrix} K_1 & K_2 & -I \end{bmatrix}}_{\tilde{K}(s)} \begin{bmatrix} r \\ y \\ x_{rm} \end{bmatrix}, \qquad (2)$$

where x_r is the output of the rate limit. The second linear part (the integrator) is subsumed into an augmented linear plant, $\tilde{G}(s)$, which is given as

$$\tilde{y} := \begin{bmatrix} y \\ x_{rm} \end{bmatrix} = \underbrace{\begin{bmatrix} G(s) \\ I \end{bmatrix}}_{\tilde{G}(s)} \frac{1}{s} d_m \quad . \qquad (3)$$

In this scheme, the AW compensator, *Θ(s)*, is now interpreted in terms of a free parameter - the transfer function matrix *M(s)*. The motivation behind this is that through manipulating the block diagram, one can re-draw *Figure 12* as *Figure 13.* Although *Figure 13* does not represent an implementable AW scheme, this figure is mathematically equivalent to *Figure 12* and thus any analysis conducted using this representation also holds for *Figure 13.* The advantage of this second representation is that it gives a more lucid representation of the AW problem. In particular, it is easy to observe that, providing the nominal system (i.e. aircraft plus controller) is stable and *M(s)* is also stable, then the nonlinear stability problem is translated into ensuring that the nonlinear loop in *Figure 13* is stable. Furthermore, the degradation of linear performance can be measured by the magnitude of $\tilde{y}_d := [y_d' \quad x_{rd}']'$, or alternatively, the 'gain' from d_{lin} to $\tilde{y}_d$. For minimal degradation of linear performance, we would like the map $T_p : d_{lin} \mapsto \tilde{y}_d$ to be as small as possible.

6. AW DESIGNDS FOR ATTAS

Considering *Figure 13*, the 'size' of the nonlinear map T_p indicates how performance of the system degrades from linear during rate limiting. A natural design objective would therefore be to minimise T_p (in some sense) while also ensuring that the nonlinear loop was stable. Unfortunately, the integrator in the rate limit creates problems in achieving unconditional global asymptotic stability of the nonlinear loop. In Sofrony *et al.* (2005*a*) a method of designing AW compensators for rate limited systems was introduced. Essentially the method produced an AW compensator, *Θ(s)* which ensured that the L_2 (RMS) gain of T_p is less than a certain value, γ, and that the nonlinear loop is stable in a certain subset, *E*, of the *region of attraction*. The synthesis algorithm is described in detail in Sofrony *et al.* (2005*a*) and in Sofrony *et al.* (2006) the tuning algorithm was refined and nonlinear simulation results involving a prototype AW compensator for the ATTAS aircraft were given. Briefly, the synthesis algorithm requires the designer to pick two parameters, scalars *R* and ε, which are then used to synthesise an AW compensator, $\Theta_{R,\varepsilon}(s)$, which then guarantees an L_2 performance level $\gamma_{R,\varepsilon}$; and stability within the set E_R. The role of these parameters is as follows.

- The estimate of the region of attraction becomes larger as *R* is decreased, the size of the cross-section decreasing at a roughly inversely proportional rate (assuming μ = 1 (Sofrony *et al.* 2005*a*)). Unfortunately the size of the local L_2 gain also increases as *R* is decreased, for large *R* this is at a roughly inversely proportional rate, but for small *R*, the rate of increase is more complex. Typically *R* is chosen small.
- As $\varepsilon \in (0,1)$ is chosen closer to unity, the local L_2 gain bound becomes smaller. For good performance ε is thus chosen close to unity. As ε becomes smaller

the local L_2 gain bound grows and for very small values of ε, the dependency of the *Θ(s)* on ε becomes negligible.

Roughly speaking if ε is fixed close to unity, altering *R* causes the gain of the AW compensator to change; for small *R*, the gain is low, causing the AW compensator to behave in an IMC manner. While initially the tuning logic appears complicated, it was found sufficiently intuitive for compensator design.

6.1. Choice of Parameters

In (Sofrony *et al.* 2006), a single AW compensator was designed for the entire ATTAS flight envelope. The flight condition which was expected to cause the most problematic behaviour during rate limiting was selected as the design point. Simulation then revealed that the AW compensator delivered reasonably robust performance across the flight envelope. However, performance did degrade as the flight condition was varied and it was felt prudent to design one compensator for each flight condition to be tested and to use one compensator per flight condition. All compensators tested were designed using the following choice of parameters: $\varepsilon = 0.97$, $R = 1e\text{-}7$. This yielded compensators which delivered reasonably robust performance (in desktop simulation) over a reasonably large region of the flight envelope. It was found that increasing *R* led to less aggressive compensators which seemed better at preserving linear performance for small amounts of rate limiting but which failed to provide enough protection for extensive rate limiting.

7. FLIGHT TEST RESULTS

7.1. Pilot Ratings

As mentioned earlier, at each flight condition two pilots evaluated a series of tasks (HQDT, birdy tracking task, offset landings, etc.) for the degraded ATTAS aircraft, both with and without AW compensation. At each flight condition, the pilots assigned PIO ratings (on the PIO rating scale) and HQR ratings (using the standard Cooper-Harper rating scale) for the aircraft both with and without AW compensation. The results for the up-and-away flight conditions are tabulated in *Table 2* and the results for the offset landing approach are given in *Table 3*. The notation ‘w/l’ indicates that the rating given was due to the workload involved and ‘n/a’ indicates that this rating was not applicable or was not assigned. The key tasks which were rated are summarised in *Table 1*.

PIO-c	PIO rating: bank angle capture
HQR-g	HQR: gross acquisition, birdy
HQR-f	HQR: fine tracking, birdy
PIO-b	PIO rating: birdy
HQR-cl	HQR: centreline capture
HQR-t	HQR: touch-down zone
PIO-t	PIO rating: touch-down zone

TABLE 1: Key to HQR/PIO ratings

From the tables it can be inferred - at least as far as PIO ratings and HQR's were concerned - that the presence of AW *did not degrade the aircraft* performance at any flight condition. It appears that at the lower speed flight conditions (Conditions 1 and 5) both pilots found that AW compensation typically bestowed some minor improvement in aircraft performance. However for the higher speed flight conditions (Conditions 2 and 6) it is clear that major improvements were detected, again according to both pilots. For instance at Flight Condition 2, both pilots gave the birdy tracking task a PIO rating of 4 with no AW; this dropped to a 2 with AW Compensator 3. Moreover, at this flight condition, the HQR's were also improved with AW compensation. From *Table 3*, the presence of AW seemed to improve the aircraft behaviour for the landing approach on average, particularly in the centreline capture task. However, it must be mentioned that Pilot 2 did encounter two PIO's on the final approach even with AW compensators active. It is not yet clear why this was the case and further analysis is warranted.

7.2. Time histories

The data recorded in the flight tests was gathered in three parts, each of which concentrates on certain areas of the flight envelope; low altitude, landing approaches and high altitude. This section presents data from the high altitude (20*k* feet) flight condition at a speed of 224*kts* (i.e. Flight Condition 6). This set of data was recorded last, and the data without AW compensation was the last manoeuvre sequence recorded, hopefully giving some assurance that the *learning factor* will not play such a large role in the pilot's appreciation of the aircraft's manoeuvrability. *Figures 14* and *15* show experimental time histories of the birdy tracking tasks for the high gain pilot (Pilot 1) and the low gain pilot (Pilot 2) for the cases with and without AW compensation. The signals shown are roll angle ϕ, pilot stick command, conditioned control signal and rate limited control signal. Although the task is very demanding and generally the steps are given in quick succession, the plots give a rough indication of the aircraft's performance. The following criteria are of particular interest:

- PIO tendency of the pilot-aircraft loop and how hard it is for the pilot to maintain stability.
- Level of rate limiting present in the system and how far is the system from linear operation.

Pilot 1 (*Figure 14*). High gain pilots have been generally linked to PIO's and are therefore very useful for test purposes. Initially the system with no AW is considered. The roll angle exhibits some oscillatory behaviour and some high overshoots. There are also instances when it appears that a divergent oscillation may be developing and the pilot is ‘lowering his gain’ to counter this tendency. It is important to notice that the system has very high levels of rate limiting and operates outside its linear range most of the time. Some improvement in the aircraft behaviour can be observed when using AW compensation, perhaps with finer tracking achievable and slightly less oscillatory behaviour. Note the markedly reduced rate limiting in the lower graphs, with the rate limited signal remaining much closer to the commanded control signal.

Pilot 2 (*Figure 15*). This pilot was inherently lower gain, and thought less likely to generate a PIO. With no AW compensation, observe that the roll angle has frequent, large overshoots and fine tracking seems poor. Tracking capabilities of the system are deeply affected by rate limiting; high frequency oscillations develop, especially when the pilot initiates abrupt manoeuvres. Notice that the pilot uses full stick commands most of the time in order to control the system, increasing the work load and tendency to PIO. In addition, the control signal remains rate limited frequently and there is a large difference between the commanded and actual control signal. When AW compensation was introduced, the roll angle has noticeably better tracking properties with overshoot and oscillation dramatically reduced. Although the aircraft appears to be more sluggish, fine tracking is possible but with an increase in the workload. It is important to observe that the conditioned control signal is less aggressive, and therefore, the system is outside linear behaviour for shorter periods of time. Pilot stick commands are reduced and in general, with the exception of fine tracking, the workload is less.

7.3. Discussion

The qualitative pilot ratings clearly show the advantage of adding AW compensation for the degraded aircraft with rate limiting. This seems to be true for all flight conditions, although the advantages of AW are most striking at higher speeds (conditions 2 and 6), where *Table 2* indicates PIO rating improvements by two points in some cases and also improvement in the HQRs. The time-histories most clearly show an improvement due to AW for the case of the low-gain pilot (#2), where a clear reduction in pilot workload and oscillatory response can be observed (see *Figure 15*) when AW is present. It is thus not surprising that Pilot 2 records some of his best PIO/HQR ratings for AW compensations at this flight condition and these ratings are substantially better than those with no AW. The correspondence between the time-domain data and *Table 2* are less clear for the high gain pilot (#1). Although *Table 2* shows that this pilot preferred the response of the aircraft with AW (with ratings similar to Pilot 1), it is less evident how this is manifested within the time-domain data. While some mild improvement in tracking, together with a reduction in rate limiting may be observed in *Figure 14*, the improvement is not striking. However, it should be pointed out that the pilots may consciously or unconsciously adjust their 'gain' and piloting technique as the task progresses. Indeed, close inspection of *Figure 14* reveals that the pilot stick command is zero for short periods, perhaps as the pilot removes himself from the loop to prevent oscillations building up (the pilot remarked on this during the flight). Both pilots remarked that they felt that AW improved the predictability of the aircraft response, although mentioned that the aircraft also felt more sluggish at times. On the basis of these flight tests it is not clear whether AW compensators which preserve the predictability of the aircraft yet reduce the sluggishness could be obtained; an investigation into this aspect would be desirable, yet would require further flight testing.

8. CONCLUSIONS

This paper has presented results from a flight test campaign of a rate limit compensation scheme conducted at DLR Braunschweig. Pilot ratings and inspection of recorded time-domain data clearly show the performance improvement attainable with anti-windup compensation, particularly at high speed up-and-away flight conditions. An important characteristic, and one that was expected, is the reduction in the level of rate limiting of the control signal when AW is present, reducing deviation from linear dynamics. The precise effects of changes in the AW tuning parameters are not clear from these flight tests and further tests would be required to obtain clearer tuning guidelines. Overall, the SAIFE tests were considered very encouraging and the results should contribute towards the development of PIO-free aircraft.

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REFERENCES

[1] Duda, H. (1997). Prediction of pilot-in-the-loop oscillations due to rate saturation. *Journal of Guidance, Control and Dynamics* **20**(3), 581-587.

[2] Flying Qualities Testing. Chapter 22, US Air Force Test Pilot School, Edwards Air Force Base, February 2002

[3] Gatley, S.L., M.C. Turner, I. Postlethwaite and A. Kumar (2006). A comparison of rate limit compensation schemes for pilot induced-oscillation avoidance. *Aerospace Science and Technology* **10**, 37-47.

[4] Glattfelder, A.H. and W. Schaufelberger (2003). *Control systems with input and output constraints*. Springer. London

[5] Grimm, G., J. Hat_eld, I. Postlethwaite, A.R. Teel, M.C. Turner and L. Zaccarian (2003). Anti-windup for stable linear systems with input saturation: an LMI based synthesis. *IEEE Transactions on Automatic Control* **48**(9), 1509-1525.

[6] Hovmark, G. and G. Duus (2000). Experimental evaluation of phase compensating rate limiters in an aircraft's lateral flight control system. Technical Report TP-120-04. GARTEUR.

[7] Klyde, D.H. and D.G. Mitchell (2003). Investigating the role of rate limiting in pilot-induced oscillations. *AIAA Atmospheric Flight Mechanics Conference and Exhibit*.

[8] Liebst, B.S., M.J. Chapa, and D.B. Leggett (2002). Nonlinear prefilter to prevent pilot-induced oscillations due to actuator rate limiting. *Journal of Guidance, Control and Dynamics* **25**(4), 740-747

[9] Kothare, M.V., P.J. Campo, M. Morari and C.N. Nett (1994). A unified framework for the study of anti-windup designs. *Automatica* **30**(12), 1869-1883.

[10] Mitchell, D.G. and D.H. Klyde (2004). Recommended practices for exposing pilot-induced oscillations or tendencies in the development process. *USAF Development Test and Evaluation Summit*.

[11] Oelker, H.-C. and O. Brieger (2006). Flight Test Experiences with Eurofighter Typhoon During High Bandwidth PIO Resistance Testing, *AIAA 2006-6496, Atmospheric Flight Mechanics Conference*

[12] Queinnec, I., S. Tarbouriech and G. Garcia (2006). Anti-windup design for aircraft _ight control. *IEEE Conference on Control Applications* (To be presented).

[13] Rundqwist, L. and R. Hillgren (1996). Phase compensation of rate limiters in jas 39 gripen.

[14] Sofrony, J., M.C. Turner and I. Postlethwaite (2005*a*). Anti-windup synthesis for systems with rate limits: a Riccati equation approach. *Proc. SICE Annual Conference*.

[15] Sofrony, J., M.C. Turner and I. Postlethwaite (2005*b*). Anti-windup synthesis using Riccati equations. *IFAC Congress*.

[16] Sofrony, J., M.C. Turner, I. Postlethwaite, O.M. Brieger and D. Leissling (2006). Anti-windup synthesis for PIO avoidance in an experimental aircraft.. *IEEE Conference on Decision and Control, to be presented*.

[17] Turner, M.C. and I. Postlethwaite (2004). A new perspective on static and low order anti-windup synthesis. *International Journal of Control* **77**(1), 27.44.

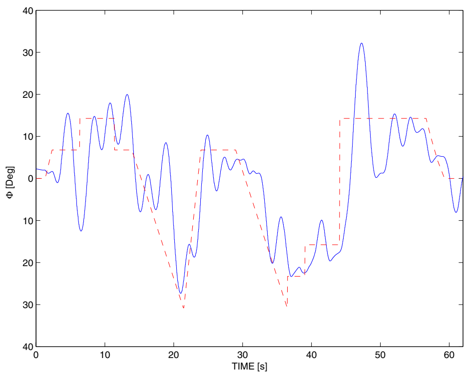
[18] Twisdale, T. Handling Qualities Testing, SFTE Short Course, 14-18 Nov. 2005, Lancaster, CA, USA

[19] Villota, E., M. Kerr and S. Jayasuriya (2006). A study of configurations for anti-windup control of uncertain systems.. *IEEE Conference on Decision and Control (to be presented).*

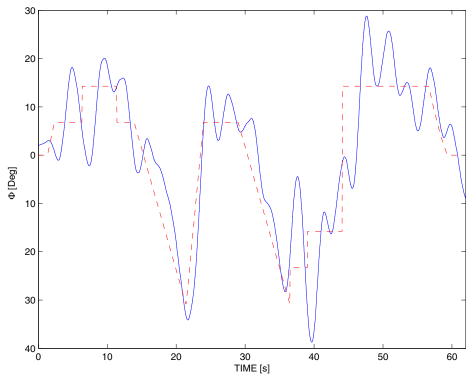
[20] Wilmes, T. and H. Duda (1998). Investigation of electronic filters to prevent aircraft-pilot-coupling. Technical Report IB 111- 98/29. Institut fur Flugmechanik, Braunschweig.

FC	Comp	Pilot 1 (high gain)				Pilot 2 (low gain)				Improvement	
		PIO-c	HQR-g	HQR-f	PIO-b	PIO-c	HQR-g	HQR-f	PIO-b	Pilot1	Pilot2
1	none	4	6	5	3	4	6	5	4	n/a	n/a
1	1	4	5	5	3	3	5	5	3	slight	minor
2	none	5	6	5	4	4	6	5	4	n/a	n/a
2	2	4	5-6	5 (w/l)	3	2	5	4	4	minor	major
2	3	3(good)	5 (w/l)	4	2	2	5 (w/l)	4	2	major	major
5	none	5(good)	7	6	5	4	7 (w/l)	6	4	n/a	n/a
5	5	5	7	6	5	4	5	5	4	none	minor
6	none	5	6	5	n/a	5	6 (w/l)	5	4	n/a	n/a
6	6	3	5 (w/l)	4	3	3	5	4 (w/l)	2	major	major

TABLE 2: Up-and-away flight conditions



ϕ [deg] with no AW compensation



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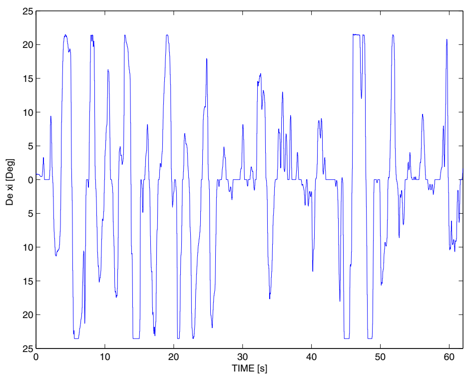
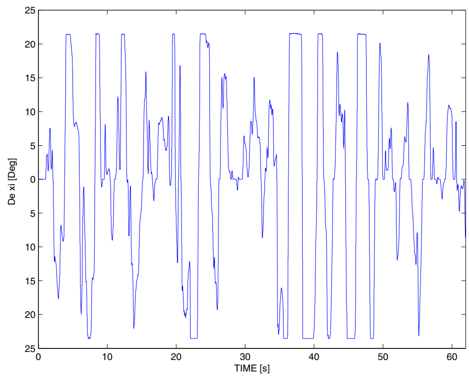
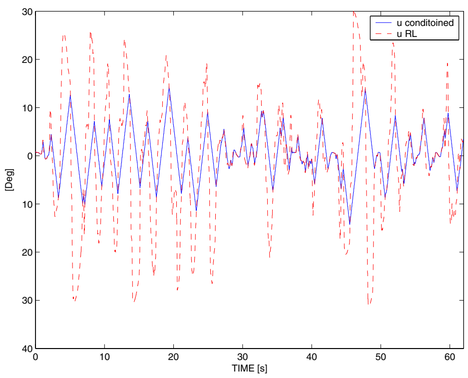


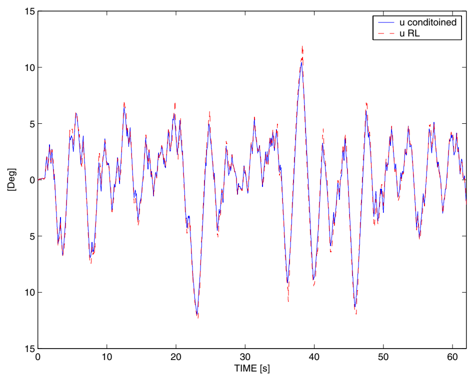
Stick Input Signal [deg] with no AW compensation



Stick Input Signal [deg] with AW compensation



Control signals u and u_r with no AW compensation

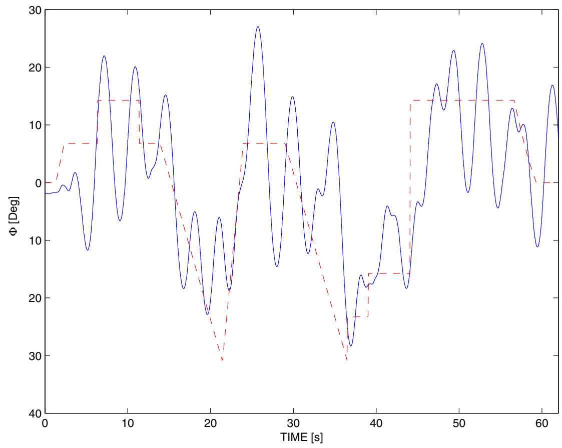


Control signals u and u_r with AW compensation

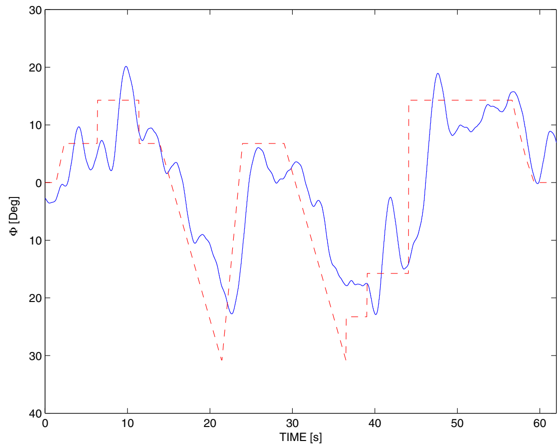
FIG 14. Lateral tracking task for Pilot 1 and flight condition 6 – 20 kft, 224 kts

FC	Comp	Pilot 1 (high gain)			Pilot 2 (low gain)			Improvement	
		HQR-cl	HQR-t	PIO-t	HQR-cl	HQR-t	PIO-t	Pilot1	Pilot2
8	none	5	6	4	6	n/a	n/a	n/a	n/a
8	8	4	5	3	4	n/a	5	some	some
8	9	4	6	4	3	3	n/a	slight	major

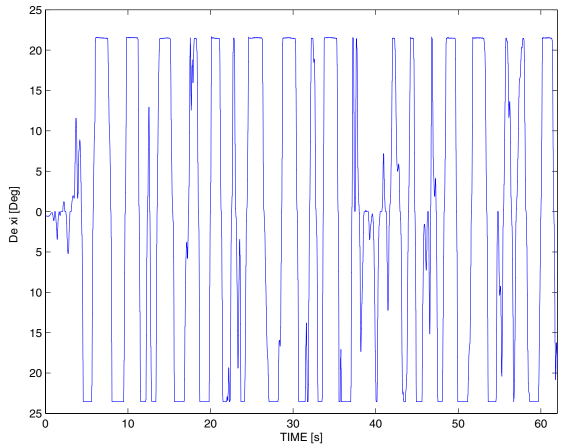
TABLE 3: Landing approach flight conditions



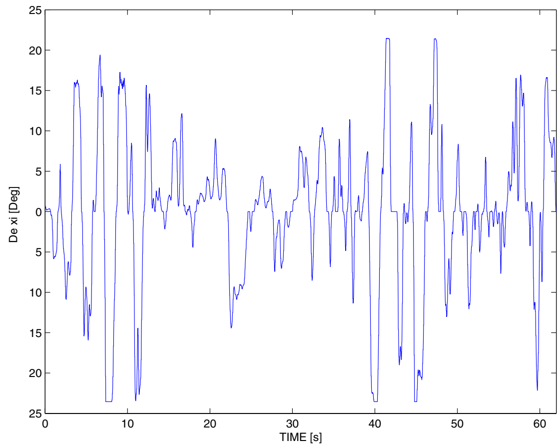
ϕ [deg] with no AW compensation



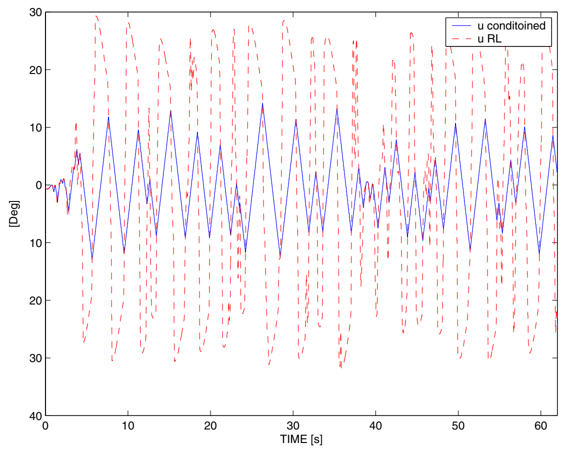
ϕ [deg] with AW compensation



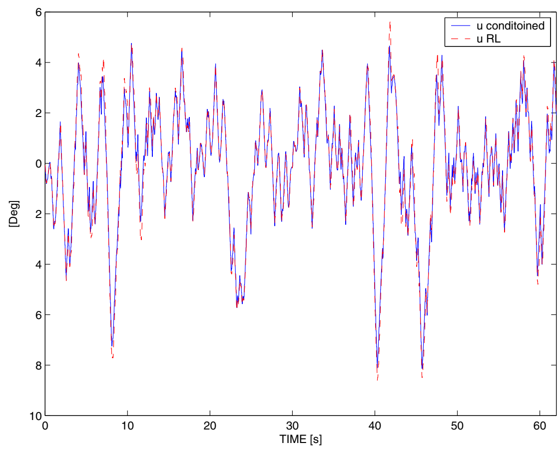
Stick Input Signal [deg] with no AW compensation



Stick Input Signal [deg] with AW compensation



Control signals u and u_r with no AW compensation



Control signals u and u_r with no AW compensation

FIG 15. Lateral tracking task for Pilot 2 and flight condition 6 – 20 kft, 224 kts