Appraisal of Rotorcraft Handling Qualities Requirements for Lateral-Directional Dynamics

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Introduction

Civil and military rotorcraft design standards [1, 2] define the acceptable amount of relative damping of the Lateral Directional Oscillatory mode (LDO). Figure 1 shows the Handling Qualities (HQ) boundaries for the LDO frequency (vertical axis) and damping (horizontal axis) from these standards.

The civil standard, CS-29 [1], contains a list of requirements, and acceptable means of compliance, that must be satisfied for large rotorcraft to be certified for operation in a range of flight conditions e.g. Category A vertical operations, day/night. CS-29 states that the rotorcraft must be stable for flight in Visual Meteorological Conditions, represented by the vertical zero damping line in Figure 1, whilst in Instrument Meteorological Conditions, different damping levels are defined depending on the frequency of the LDOs.

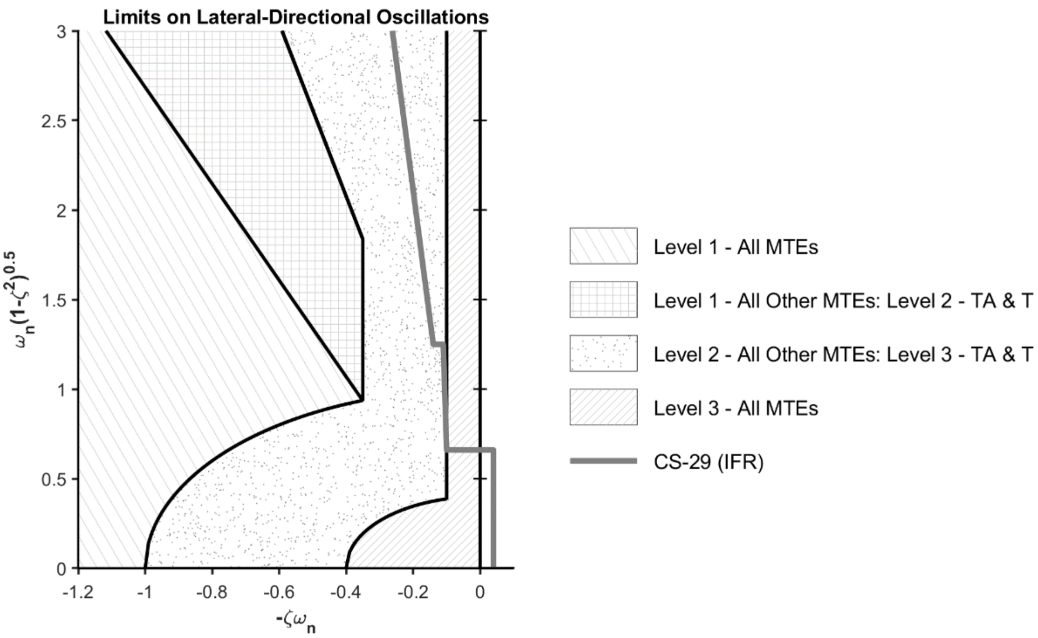


Figure 1. ADS-33E and CS-29 LDO boundaries

The military standard, ADS-33E-PRF [2], defines three different Handling Qualities (HQ) regions for LDOs that relate to the mission of the aircraft. The boundaries for 'All Other Mission Task Elements (MTEs)' are aimed at cargo/utility aircraft while Target Acquisition and Tracking (TA&T) boundaries are for scout/attack rotorcraft. As with CS-29, ADS-33E-PRF LDO damping requirements are dependent on the frequency of the oscillation.

Ref. 3 notes that "*no supporting data for these boundaries relevant to helicopters have appeared in the open literature since publication of ADS-33*"; this is also true for the CS-29 standards. The rotorcraft HQ boundaries are derived from fixed-wing standards developed many decades ago, whose relevance to current rotorcraft operational needs is questionable, and further investigation is warranted. The objective of the research presented in this paper is thus to examine the 'veracity' of current civil/military LDO HQ boundaries by assessing characteristics across the stability chart. This paper will describe the development of the test configurations in the pilot-in-the-loop simulation assessments using Liverpool's HELIFLIGHT [4] moving-base simulation facility, Figure 2. The paper will discuss in detail the correlation between the results and the current LDO standards.

Figure 2. UoL Heliflight-R Simulation Facility (Ref. 4)

Test Aircraft and Development of a Baseline Simulation Model

The reference aircraft is the National Research Council Canada's Bell 412 (B412) Advanced Systems Research Aircraft (ASRA) [5], Figure 3. The ASRA has recently completed extensive upgrades that include new engines with improved torque dynamics.

Figure 3. NRC Bell 412 ASRA

The multi-body-dynamic modelling and simulation environment FLIGHTLAB [6] was used to create a baseline simulation model (F-B412) of the B412 ASRA aircraft, using data measured on the aircraft from several flight test campaigns at NRC by the University of Liverpool to support control law design [7] and simulation fidelity research [8-16]. Two of these measurement and flight test campaigns have taken place during the current Rotorcraft Simulation Fidelity (RSF) project. The first flight trial provided data from clinical inputs while the second focused on measuring LDO characteristics.

The F-B412 [16] features a blade-element main rotor with non-linear aerodynamics and a Bailey tail rotor. The hingeless rotor is represented by rigid blades with center-spring analogues for flap and lag dynamics. The fuselage and empennage aerodynamic forces and moments are derived from non-linear look-up tables.

System IDentification (SID) has been used to derive a linear model and predict LDO characteristic at a 90kts flight test condition [16] as indicated by the solid black star in Figure 4, whilst the baseline F-B412 LDO point is indicated by the hollow circle. The F-B412 LDO damping is approximately 30% higher than the aircraft and the frequency is about 70% larger. Predicting the LDO characteristics through simulation has proved notoriously difficult as noted by previous studies [3, 17]. One method to improve the fidelity of the baseline simulation model, to make it more representative of the test aircraft, is to apply the renovation technique developed at Liverpool [8], whereby the mismatch between flight and simulation is corrected with incremental forces and moments as 'delta' derivatives. These deltas are derived from comparisons of the derivatives identified using SID with those from the F-B412. The renovation method selects the derivatives which are effective at improving the match between flight test and the model response. For this study, the renovated model, designated the RF-B412, shown as a solid circle in Figure 4, was created to reflect the ASRA's LDO characteristics using a set of four critical stability derivatives - ΔL_v, ΔN_v, ΔN_p and ΔN_r. This process will be described further in the paper.

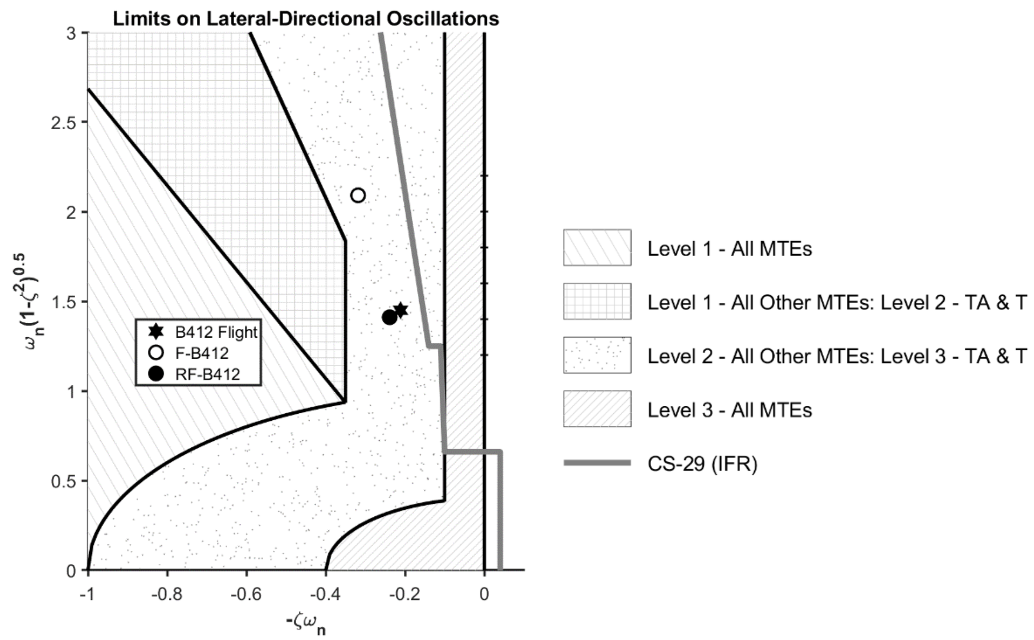


Figure 4. F-B412 renovation to RF-B412 on the LDO stability chart

Achieving Level 1 HQs for non-LDO criteria

To isolate the effects of LDO stability from other HQs, the test configurations should exhibit Level 1 for the non-LDO HQs. Typically, such HQ improvements are implemented through a stability augmentation system (SAS). However, in the present work, the HQs have been 'supplemented' using the renovation technique to, e.g. improve the pitch and roll damping and pitch-from-heave and roll-from-pitch cross couplings, which were not Level 1 in the baseline F-B412. The advantage of this approach is that it allows a targeted HQs to be supplemented to improve a selected HQ instead of several derivatives being augmented by a single SAS channel. An example of the pitch-from-heave coupling HQ supplement, achieved by supplementing M_{col} by $\Delta M_{col} = -0.07$, is illustrated in Figure 5. Six different configurations corresponding to points across the stability chart are shown.

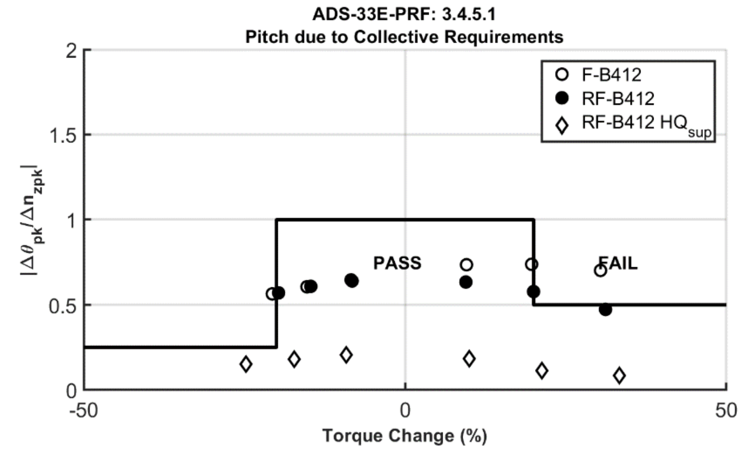


Figure 5. Impact of renovation and HQ supplement on ADS-33E-PRF pitch from heave criteria

LDO test Configurations

LDO test configurations were selected based on frequency and damping to cover a range of HQs on the ADS-33 and CS-29 LDO charts (Figure 6). The first set of configurations (C1-C3) represent aircraft with approximately the same LDO frequency (1.5 rad/s) as the B412, allowing the effect of LDO damping across the ADS/CS HQ regions to be examined. A second group (configurations C4-C6) represents an increased LDO frequency of 2 rad/s. The damping range is greater to maintain a similar spread of LDO HQs. Finally, configurations C7-C9 is used to examine the effect of damping changes at an LDO frequency of 2.5 rad/s.

LDO test configurations have been developed from the baseline RF-B412 with supplemented HQs using the weathercock stability derivative N_v and the yaw damping derivative N_r. The magnitude ratio of the roll and yaw LDO components of the test configurations was maintained constant to ensure that only frequency and damping characteristics defined in the standards were varied. This was achieved by modifying the dihedral effect, L_v, to maintain the B412 ratio p/r of 0.6. In addition, N_{ped} was varied to give the same yaw control sensitivity as the B412 (16deg/sec.inch) across all configurations; this also ensures performance greater than the minimum ADS-33E-PRF Level 1 yaw control power requirement.

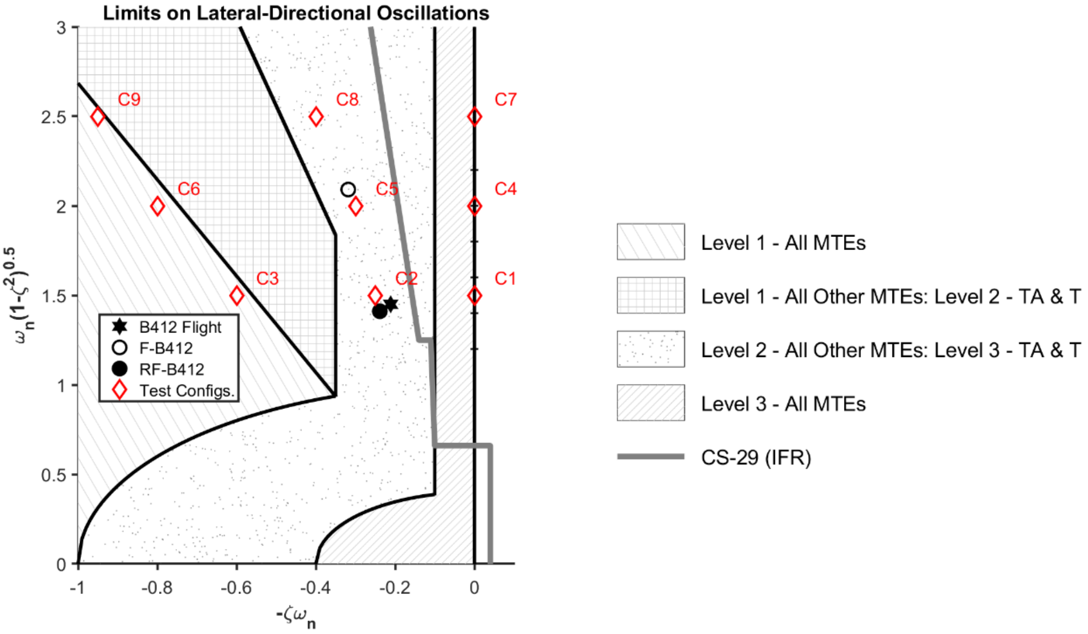


Figure 6. LDO test configurations

In addition to the LDO stability characteristics, ADS-33E-PRF characterises the bank angle changes in relation to the phase of the roll-sideslip oscillation. An example of the roll-sideslip coupling time history for C2 is illustrated in Figure 7. The *y*-axis parameter (ϕ_{osc}/ϕ_{av}) in Figure 8 is calculated from the ratio of peaks and troughs while the *x*-axis parameter ψ_β is the phase angle between roll rate and sideslip. The roll oscillations remain within Level 1 for all test configurations as illustrated in Figure 8, with the maximum sideslip to roll rate phase difference of 62 degrees being between C3 and C7. Further configurations will be developed and reported in the paper where a predefined phase can be achieved by modifying L_v.

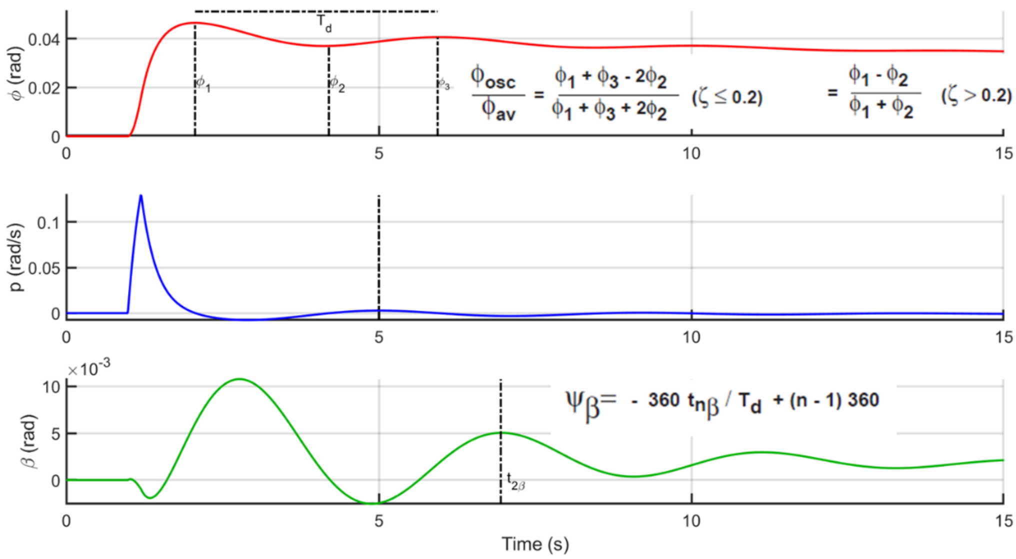


Figure 7. C2 Time history for calculating ADS-33E-PRF bank angle oscillations criteria.

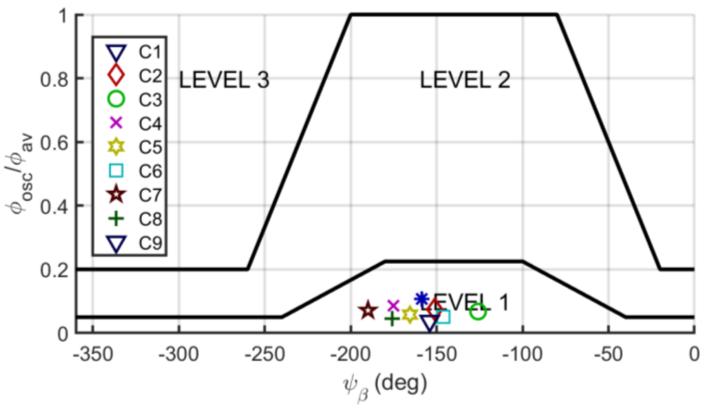


Figure 8. Roll from sideslip coupling for the nine test configurations.

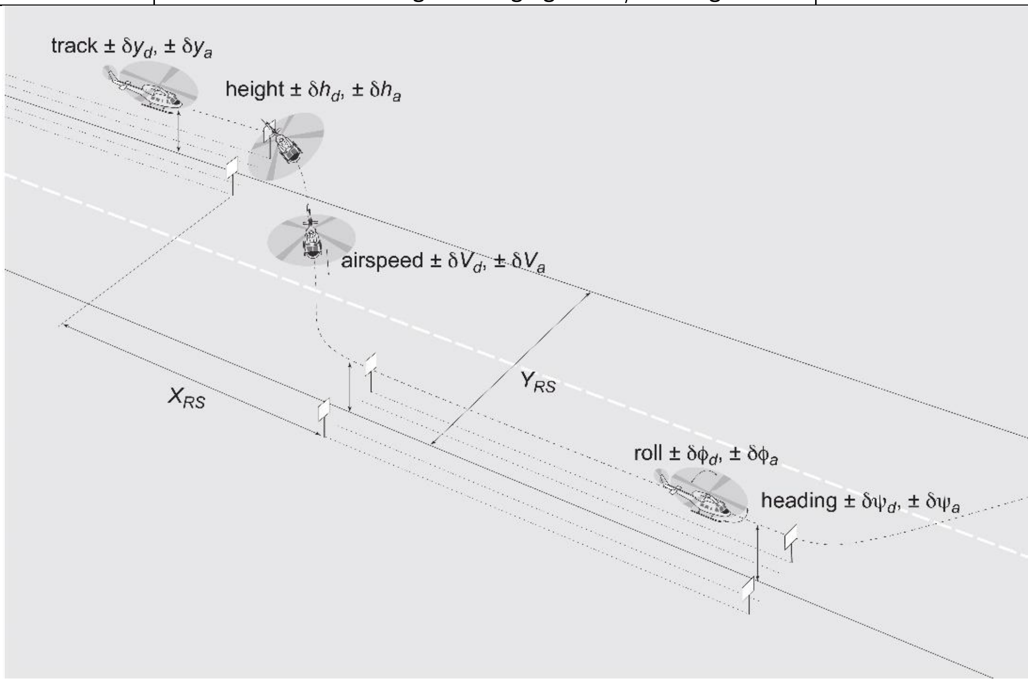
Pilot-in-the-Loop Simulation Trials

The current fixed-wing standards relate to flight phases or, in the case of the civil standards, to the ability to maintain trim flight in either VMC or IMC. ADS-33 is a mission-oriented standard with MTEs used as part of the assessment methodology. The initial investigations in our research have focussed on a typical forward-flight MTE. The Roll-Step [18], described in Table 1, was chosen as it provides moderate roll attitude changes and a flight-path/attitude tracking element. The mission type is described as scout-attack in ADS-33 parlance, but such a MTE could be equally applicable to a utility mission.

Table 1. Roll-Step MTE definition

Title	Roll-step
Mission	Scout-Attack
Critical HQ	HQs associated with lateral-directional stability
Objectives	• Check ability to manoeuvre in forward flight with respect to the ground. • Check roll and heave co-ordination. • Check turn co-ordination for moderately aggressive forward-flight manoeuvring. • Check for objectionable inter-axis coupling during moderately aggressive forward-flight manoeuvring.
Manoeuvre Description	The pilot is required to fly through an ordered series of these gates which form the roll-step task. The manoeuvre starts with the aircraft displaced aft of the runway threshold, lined up with the left-hand edge of the runway at an altitude of *h*ft trimmed at *V*knots. The manoeuvre requires the pilot to traverse the runway, Y_{RS}ft, over a distance of X_{RS}ft and then capture and track the right-hand edge of the runway, before traversing back across the runway and completing the manoeuvre by capturing and tracking the left hand runway edge. Speed and altitude requirements must be maintained throughout the MTE. Roll attitude, $\delta\phi°$, heading $\delta\psi°$, and lateral ground track requirements, within the δyft, are applied between the gates on the runway edges (see figure below).
Test Course Description	200ft wide airport runway which is flanked by a series of numbered gates 500ft apart (see figure below). The lateral separation of the gates indicates the adequate performance requirements; half of this distance is the desired performance requirement.

Performance Standards	Desired (*d*)	Adequate (*a*)
	• Maintain lateral ground track, δy along runway edge: $\pm$15ft • Maintain altitude, h: $\pm$10ft • Maintain speed V: $\pm$5kts • Maintain heading through gates $\delta\psi$: $\pm$ 10deg • Maintain bank angle through gates $\delta\phi$: $\pm$ 5deg	• $\pm$30ft • $\pm$15ft • $\pm$10kts • $\pm$ 15deg • $\pm$10deg



Roll-step performance standards

STATUS OF WORK

An initial set of exploratory pilot-in-the-loop simulations have been carried out. Pilot ratings and comments suggest that the methodology adopted to ensure that the pilots focus on HQ changes in the LDO chart has been successful. Configurations with predicted Level 1 HQs were generally awarded HQR 4; the HQ deficiencies identified that prevented Level 1 related to non-LDO inceptor aspects; these are being further explored.

Configurations with predicted Level 2 HQs for non-tracking (all-other) MTEs (C2, C5, and C8) were assigned Level 2 HQRs. An example result from two test pilots is illustrated in Figure 9 for LDO configuration C2.

Both pilots awarded HQR 5, commenting that '*considerable pilot compensation*' was required to recapture and track the runway edge, particularly after the second runway crossing. Consequently, the pilots did not maintain desired height performance due to the distractions from extra workload in the lateral-directional axis using lateral stick (δ_{lat}) and pedal (δ_{ped}). Further analysis of the data will be presented including pilot attack and frequency analysis.

Test pilots also returned Level 2 HQRs for the zero damping cases (C1, C4, C7) with evidence of susceptibility to Pilot Induced Oscillations (PIO). This aspect is being explored further, including tests in cruise-MTEs with turbulence, and will be reported in the written paper.

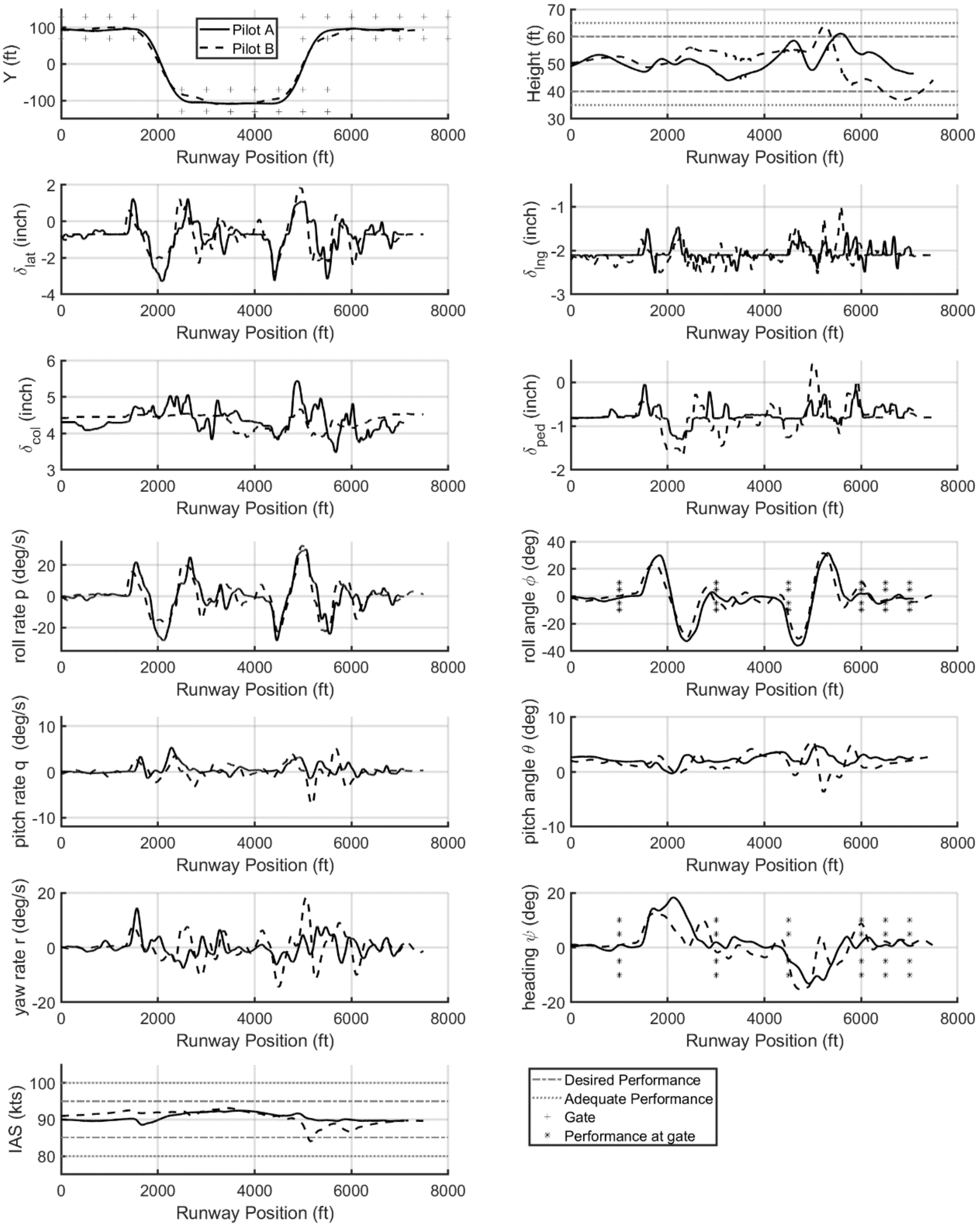


Figure 9. Roll-Step time history for C2 from 2 test pilots

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