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Piloted simulation tools for aircraft departure analysis

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This paper presents the piloted simulation tools and methods used on the Defence Evaluation and Research Agency (Bedford) flight simulators to investigate departures predicted by theoretical bifurcation analysis. In particular, the use of head down displays showing bifurcation diagrams, nonlinear dynamic inversion control, specific piloting approaches and 'spin templates' to classify departure modes is described. Piloted simulation time histories for autorotation, upright spins and deep stall of various aircraft are also presented. The paper concludes with recommendations on the 'optimum' combination of theoretical analysis and piloted simulation for complete departure analysis.

Keywords: departure prediction; bifurcation analysis; piloted simulation; combat aircraft

1. Introduction

The use of nonlinear bifurcation analysis to investigate aircraft departures has been examined by many researchers over the last three decades. Numerous analytic studies (Mehra *et al*. 1977; Zagaynov & Goman 1984; Adams 1972; Guicheteau 1990; Lowenberg 1996; Planeaux *et al*. 1990; Jahnke & Culick 1994) have demonstrated the capability of the technique to pinpoint departure-prone regions of the flight envelope by determining all steady-state conditions attainable by the aircraft. This form of analysis requires experience, and detailed inspection of the bifurcation diagrams, to interpret and provide a reliable prediction of what departure modes can be anticipated at different angles of attack (AOA).

However, bifurcation analysis of nonlinear aircraft is computationally intensive, time consuming and often cannot determine the transient behaviour leading to departures or indeed the exact nature of the departure. Thus, theoretical predictions must be supplemented by off-line simulation and/or piloted simulation for complete departure analysis. Three distinct stages of investigation are required:

1. predict departures using theoretical bifurcation analysis;
2. validate and investigate the nature of predicted departures in off-line or piloted simulation; and
3. collate, classify and perform off-line analysis of all departure modes investigated during piloted simulation.

Each stage requires a judicious amount of investigation to ensure an efficient approach to departure analysis. Insufficient bifurcation analysis leads to poorly focused piloted simulation, while excessive piloted simulation is of little value without the proper tools and methods to collate and analyse piloting data.

Given this background, the main objective of the work at the Defence Evaluation and Research Agency (DERA), Bedford is to develop tools and methods to enable rapid investigation of the departure characteristics of aircraft both with and without control laws. In particular, to identify the optimum combination of theory and piloted simulation for cost-effective departure analysis.

To achieve this objective, the departure characteristics of a number of aircraft, with different geometry and controls, have been investigated using theoretical analysis and piloted simulation trials (Patel 1996). Each trial has advanced an understanding of how to interpret bifurcation results and what departures to anticipate within specific angle of attack regions, in addition to putting into place piloted simulation tools and methods necessary for efficient departure analysis. Progressively more challenging aircraft have been examined to develop both simulation tools and analysis methods.

Studies at DERA (Bedford) have applied bifurcation analysis to different aircraft configurations, both with and without control laws (Littleboy & Smith 1997; Patel & Smith 1996), and taken a preliminary look at piloted-departure recovery. DERA has also sponsored the development of software code and theoretical studies at TsAGI, Russia (Goman *et al*. 1996; Goman & Khramtsovsky 1995), Bristol University (Lowenberg 1996) and Reading University, UK (Gibson *et al*. 1997).

The work reported here focuses on piloted simulation investigation of aircraft without flight-control laws, i.e. the open-loop aircraft and subsequent off-line analysis. Comprehensive departure analysis of the open-loop aircraft identifies all departure modes of the aircraft and is invaluable in pinpointing 'difficult' regions of the flight envelope and defining performance objectives for control-law design. Departure analysis of the closed-loop aircraft is performed to validate the control law design.

The problems posed by the piloted simulation aspects of departure analysis are:

1. presentation of bifurcation analysis data to the pilot in an easy to assimilate form;
2. uncontrollability of highly unstable open-loop aircraft;
3. methods to induce specific departure modes; and
4. rapid off-line collation and analysis of piloted simulation time-history data.

The solution of the first problem had to satisfy both simulation and pilot briefing requirements. Bifurcation-analysis results are generally presented as a set of state portraits showing the variation in the steady-state behaviour of aircraft states as a critical parameter (e.g. control surface deflection) is varied. Such bifurcation state portraits or 'maps' can, at first glance, be difficult to interpret by both pilots and researchers.

A tool that proved invaluable in addressing the second problem was nonlinear dynamic inversion (NDI) control. NDI is renowned for its ability to generate 'ideal' control laws which prescribe perfectly decoupled aircraft responses (Smith 1994). NDI control is used in this work to enable the pilot to attain departure-prone flight conditions in a controlled manner without gross modification of the open-loop bifurcation maps. The NDI control laws were switched in to reach the departure flight condition and then switched off to investigate the open-loop departure modes.

The paper is organized as follows: § 2 describes the bifurcation-analysis approach used to predict the departures investigated in piloted simulation and presents bifurcation maps for an open-loop combat aircraft, known as the hypothetical high incidence research model (HHIRM) (Goman *et al*. 1995), which exhibits the typical departure characteristics of configurations similar to the F-16 Falcon; § 3 describes the piloted simulation tools and methods; § 4 demonstrates the principles of NDI by bifurcation analysis of HHIRM with NDI control laws (Littleboy & Smith 1997); § 5 presents piloted simulation time histories and spin templates for autorotation, spin and deep-stall modes of a three-surface canard-wing-tail aircraft and a canard-delta aircraft. Conclusions and recommendations are presented in § 6.

2. Bifurcation analysis

The objective of bifurcation-analysis methods is to determine the steady-state flight condition and stability of an aircraft for different control inputs. The control inputs may be for either the open-loop or the closed-loop aircraft, i.e. for pilot demands connected either directly to surface deflections or via a flight-control system. The work described here concentrates on open-loop aircraft dynamics.

The approach used is to determine steady-state flight conditions for varying longitudinal control with all lateral controls set to zero. Potential departures exist in regions of the flight envelope where perturbations in the longitudinal controls induce lateral motion. Such coupling may cause wing rock, nose slices, spins and autorotation. Deep stall, which is predominantly a short-period pitch oscillation, is not usually characterized by longitudinal/lateral aerodynamic coupling but can readily be recognised by a change in the stability of aircraft modes.

(*a*) *Analysis assumptions*

The analysis examines a basic aircraft configuration without the flight-control system, engine dynamics and unsteady aerodynamics or flexible aircraft modes. Aircraft with redundant control surfaces in the pitch axis are analysed by varying one control surface with all other controls fixed at constant deflection. While conventional control laws are not used in this work, extensive use is made of NDI control to help the pilot reach a given flight condition before departure; these are described in detail in § 4.

(*b*) *Aircraft models*

To simplify the study of nonlinear aircraft dynamics, bifurcation analysis of a reduced-degree-of-freedom aircraft model precedes full six-degree-of-freedom (DOF) analysis. The work of Goman & Khramtsovsky (1995) examines three-DOF and five-DOF aircraft models as a precursor to six-DOF analysis. Piloted simulations based on both five-DOF and six-DOF analysis results have been conducted at DERA (Bedford) (Patel 1996). Both aircraft models are described below.

The five-DOF model of the aircraft comprise equations of motion for angle of attack (AOA), sideslip angle (β), roll rate (p), pitch rate (q) and yaw rate (r). This model describes fast aircraft modes, i.e. the short-period, Dutch-roll and roll-subsidence modes, and omits all information on the slower phugoid and spiral modes, speed, gravity effects and aircraft orientation in space.

The five-DOF bifurcation analysis results provide salient departure information at constant airspeed. They are a good starting point for nonlinear analysis of the six-DOF dynamics but must be interpreted with some care. In particular, the pitch-rate bifurcation diagram depicts a fixed-speed and no-gravity scenario and hence is not representative of true six-DOF motion. All other state diagrams are representative. The five-DOF representation does, however, provide a good indication of where departures are likely to occur to spins and autorotations, albeit with overestimated angular body rates in spin regions.

Full six-DOF motion can be investigated by bifurcation analysis of an eighth-order model of the aircraft which comprises equations of motion for AOA, sideslip angle (β), roll rate (p), pitch rate (q), yaw rate (r), bank angle (φ), pitch attitude (θ) and speed (Vt).

In addition to the short-period, Dutch-roll and roll-subsidence modes in the five-DOF model, the eighth-order model also includes the slower phugoid and spiral modes. This model contains all the qualitative information necessary for analysis of six-DOF aircraft motion with only heading and aircraft orientation in space (i.e. X position, Y position and height (H)) being omitted. Hence, nonlinear analysis of the eighth-order model will yield accurate departure information of the aircraft at a fixed altitude. The work of Patel & Smith (1996) gives an indication of the differences that may be expected between five-DOF and six-DOF bifurcation-analysis results.

(*c*) *Bifurcation analysis of a high-AOA aircraft*

The equilibrium flight conditions are represented by bifurcation diagrams which show plots of longitudinal-control surface deflection versus aircraft states. The bifurcation diagrams for a five-DOF mathematical model of HHIRM at a speed of $150\ \mathrm{m\,s^{-1}}$ and height 5000 m are shown in figure 1.

The merits of the HHIRM aircraft are that it is unclassified and has representative aircraft aerodynamics modelled in a smooth spline curve form; the latter feature simplifies and speeds up bifurcation analysis. Note that figure 1 is presented to indicate the interpretation of typical bifurcation results and does not show all departure modes exhibited by the aircraft. The results do not show an autorotation mode, which exists at low and negative AOA.

(*d*) *Interpretation of bifurcation diagrams*

The stability classification used on the bifurcation plots is summarized as follows.

1. *Stable*: all modes stable.
2. *Divergent unstable*: one exponential mode unstable.
3. *Oscillatory unstable*: one oscillatory mode unstable.
4. *Otherwise unstable*: any other form of instability.

The elevator deflection (η) versus AOA plot is examined in detail to identify departure characteristics. In particular, the main trim-branch gradient, changes in stability, and general branch shapes are noted. In figure 1, the main trim branch (in green) is in the angle of attack range $-25° < \mathrm{AOA} < 25°$. Inspection of this branch shows

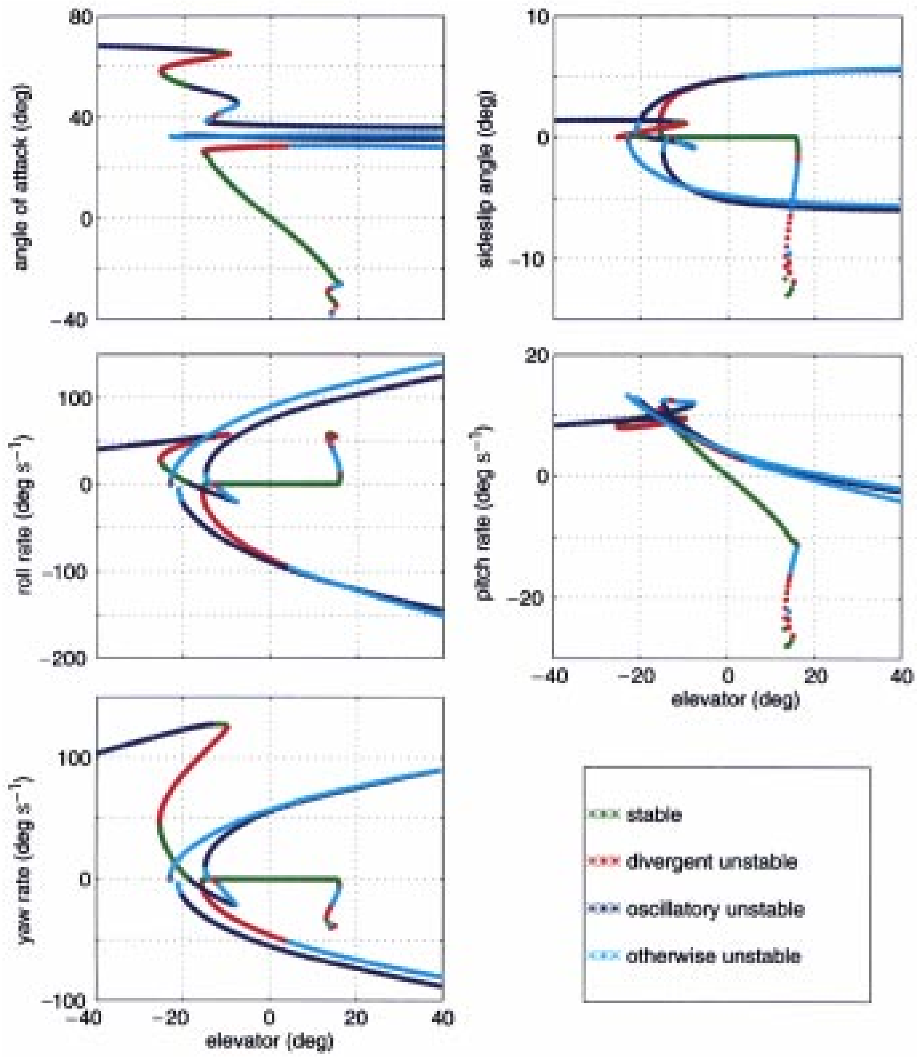

Figure 1. Bifurcation diagram of the open-loop HHIRM aircraft.

that pulling the stick back increases trim AOA (note that negative elevator deflections denote stick aft of neutral position) and that the aircraft is stable in this flight region. A positive main trim-branch gradient in the plot of η versus AOA indicates a pitch instability.

Spin branches are denoted by horizontal branches in the plot of η versus AOA, with little change in AOA for large changes in η. The major effect of η is to vary roll and yaw rates. The spin branches in figure 1 are in the AOA range $27° < \text{AOA} < 38°$, achieving maximum roll rates of $\pm 150°\ \text{s}^{-1}$ and maximum yaw rates of approximately $\pm 100°\ \text{s}^{-1}$. There are generally two sets of branches for each spin, the lower and upper branches on lateral plots. Each set of branches represents the excursion from low η to high η and back again on the (η versus AOA) plot. The lateral branches are examined in some detail to classify both type and severity of spin modes.

The starting point or mid-point of the spin branches is where the upper and lower branches meet. The offset from zero lateral activity of the spin-branch midpoint is an indicator of aircraft asymmetry (either due to aircraft geometry or asymmetric vortex-flow breakdown). Gross asymmetry is indicated if this midpoint lies far from zero roll rate, yaw rate and sideslip angle, or, indeed, if the branches do not converge to the same region at all. Asymmetry is also denoted by unequal maximum roll and yaw rates and sideslip angle for upper and lower spin branches.

Figure 1 shows modest asymmetry in the spin branches, denoted both by unequal maximum roll rate, yaw rate and sideslip angle, and by non-convergence of the upper and lower lateral spin branches.

3. Piloted simulation tools

DERA (Bedford) has two main simulators available for piloted simulation, the advanced flight simulator (AFS) and the real time all vehicle simulator (RTAVS). The AFS is a pilot-in-the-loop large-motion simulator which can be operated with and without a motion cueing system. It is primarily used to assess aircraft-handling qualities. RTAVS is a low-cost, fixed-base, pilot-in-the-loop simulator. Both simulators can be configured to represent a range of high-fidelity fixed-wing and rotary-wing aircraft models in real time. Departure analysis requires no motion, hence for this work both simulators have been used in fixed-base mode.

The following subsections describe the piloted simulation tools and analysis strategy used for piloted simulation investigation of aircraft departure characteristics.

(*a*) *Head-down display*

The (η versus AOA) bifurcation diagram is used as a 'road map' during piloted simulation to investigate departure characteristics. Early piloted simulation trials relied on detailed briefings using bifurcation diagrams to guide pilots to departure characteristics of interest. Current piloted simulation trials make use of a head-down display (HDD) showing the (η versus AOA) bifurcation map and clear elevator and AOA readings to alleviate the workload of both pilot and trial directors.

During simulation, a trace of the piloted-aircraft flight condition is superimposed onto the base HDD bifurcation plot to indicate to the pilot where he is currently with respect to departure-prone regions and what piloting action is needed to reach departures. To minimize visual clutter, the trace length displayed on the HDD, i.e. the time history of the piloted-aircraft transient and steady-state flight condition, is adjusted according to whether 'fast' or 'slow' departure motion is anticipated. An external view of aircraft motion is also used by trial coordinators to establish the departure modes under investigation.

To assess the usefulness of the HDD, two pilots were asked to enter specific departure modes with and without the HDD. A comparison of the piloting workload associated with and without HDD showed lower workload with the first pilot and a relatively small difference in workload with the second pilot. The difference between the two pilots was the 'gain' they exhibited. The first pilot exhibited typical high-gain response, with rapid and frequent application of controls, while the second pilot displayed typically low-gain response, with less-frequent and measured use of controls. Both pilots recognized that the HDD provided a good reference indicator of what to aim for during investigation of specific departures.

Some initial problems were encountered with pilot interpretation of the transient piloted simulation data on bifurcation maps which show steady-state conditions only. There was a natural tendency for the pilot to 'chase' the AOA transients when investigating oscillatory modes, rather than maintain the steady-state AOA of interest and let the departure develop fully. High-gain pilots are particularly prone to chasing transients. However, once the problem is recognized, the pilots were able to investigate specific departure modes in an efficient manner.

(*b*) *Nonlinear dynamic inversion control laws*

Unstable airframes pose controllability problems in flying open loop along highly unstable branches of the bifurcation diagram. A solution to this problem is to use the NDI control described in § 4. NDI allows the pilot to attain specific departure flight conditions in a controlled manner without gross modification of the bifurcation diagram.

The NDI control laws were switched in and out via a button on the stick. The control laws were engaged, via button press, to reach specific points in the flight envelope and then disengaged, via button release, to allow the aircraft to depart to the modes of interest. This scheme enabled both the use of NDI and the investigation of hands-off recovery from spins.

(*c*) *Methods of analysis*

A two-pass method of piloted simulation investigation is adopted. On first pass, the aircraft is trimmed in straight and level flight and the pilot is requested to fly to AOA extremes, without exercising any lateral control, to trace out the main trim branch. During this first pass, all departures are avoided, if possible, but the AOA at which the aircraft tends to nose slice or depart and its susceptibility to departure is noted. The aircraft will tend to depart at very high/low AOA but a rapid pull back/push forward on the stick will help avoid all departures until deep stall/autorotation at AOA extremes.

Having validated the main-trim branch, the second pass investigates specific departures. Two piloted simulation approaches are used. The first approach is to initialize the aircraft at a specific flight condition close to departure and then either allow the aircraft to depart naturally or apply pilot action to induce departures. The second approach is to allow the pilot to 'fly around' the bifurcation map, either open loop or with NDI control, to locate departures. A mixture of both approaches is recommended for efficient investigation. Piloted simulation trials which use the first approach only are often unrewarding, from the perspective of both pilot and trial directors, due to frequent initial condition 'reset'.

The incipient conditions and severity of the departure will determine which of the above two approaches is required to investigate each departure mode. Pilot action may be required to induce some departures. Autorotation can generally be induced by the pilot by pushing stick into the lower corners of its envelope to point the aircraft nose down and to encourage it to roll.

4. Nonlinear dynamic inversion control laws

The use of exact NDI for prototype-flight control-law design has received considerable attention (Smith 1994). The term 'ideal' control or 'exact NDI' is used to convey decoupled high-bandwidth response. The exact-NDI approach enables functional full-flight-envelope control laws to be worked up, including switching, blending and logic strategies, with no investment in conventional control-law design. This form of control adds no extra dynamics to the aircraft and hence does not contribute any additional problems (such as integrator windup), as with conventional control laws, and can be rapidly taken into real-time piloted simulation.

(*a*) *NDI control laws for pitch axis*

This subsection describes the basic principles of NDI control by considering the pitch axis only. Control for the roll and yaw axes can be derived in a similar manner, with some modification, as highlighted later. For more detail see Smith (1994).

NDI control requires simple algebraic manipulation of the standard aircraft equations of motion to determine the angular moments that must be applied to the aircraft to produce perfectly decoupled responses of desired bandwidth in the pitch, roll and yaw axes. Consider the equation for pitch rotational acceleration of a symmetric aircraft with one principal pitch-control surface,

$$I_{yy}\dot{q} = (I_{zz} - I_{xx})rp + I_{xz}(r^2 - p^2) + M. \tag{4.1}$$

The rotational acceleration, $\dot{q}$, is a function of the aircraft aerodynamics, inertias and body rates. The nonlinear aerodynamic equation that gives rise to the pitching moment, M, is a function of the state variables, aerodynamic derivatives, control deflections and control derivatives:

$$M = \mathit{\Lambda} + M_\eta \eta, \tag{4.2}$$

where, in terms of conventional derivatives,

$$\mathit{\Lambda} = M_u u + M_w w + M_{\dot{w}}\dot{w} + M_q q. \tag{4.3}$$

In practice, $\mathit{\Lambda}$ may comprise more derivative terms; NDI can cope with any level of complexity. Substituting equation (4.2) into equation (4.1) gives,

$$I_{yy}\dot{q} = (I_{zz} - I_{xx})rp + I_{xz}(r^2 - p^2) + \mathit{\Lambda} + M_\eta \eta. \tag{4.4}$$

If there is a sensor for $\dot{q}$ and η, indicated by a subscript 's', then equation (4.4) can be rewritten as

$$I_{yy}\dot{q}_{\mathrm{s}} = (I_{zz} - I_{xx})rp + I_{xz}(r^2 - p^2) + \mathit{\Lambda} + M_\eta \eta_{\mathrm{s}}. \tag{4.5}$$

Similarly, if demanded pitch acceleration, $\dot{q}_{\mathrm{d}}$, and elevator deflection, η_{d}, are introduced, then equation (4.4) can be rewritten as

$$I_{yy}\dot{q}_{\mathrm{d}} = (I_{zz} - I_{xx})rp + I_{xz}(r^2 - p^2) + \mathit{\Lambda} + M_\eta \eta_{\mathrm{d}}. \tag{4.6}$$

Subtracting equation (4.5) from equation (4.6) defines the demanded elevator deflection to be

$$\eta_{\mathrm{d}} = (\dot{q}_{\mathrm{d}} - \dot{q}_{\mathrm{s}})\frac{I_{yy}}{M_\eta} + \eta_{\mathrm{s}}. \tag{4.7}$$

Thus, provided rotational acceleration and control-surface position can be measured, a demanded pitch acceleration can be met for a rigid aircraft, provided pitch inertia and control-surface effectiveness are known. For this study, equation (4.7)

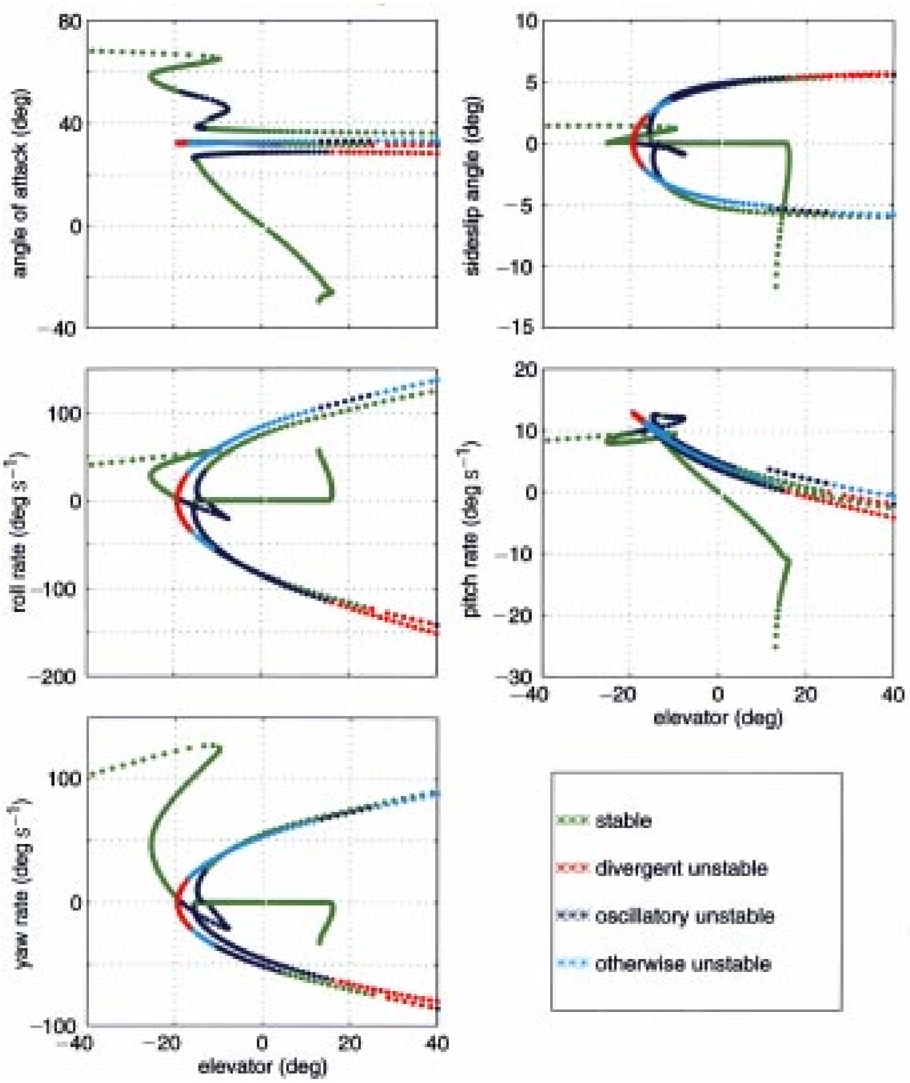

Figure 2. HHIRM aircraft with pitch-rate NDI control.

was implemented assuming a simple first-order response for the demanded body rate accelerations,

$$\dot{q}_{\rm d} = (q_{\rm d} - q_{\rm s})q_{\rm bw}, \tag{4.8}$$

where $q_{\rm bw}$ is the response bandwidth. Thus the commanded pitch rate can be directly mapped into a commanded pitch acceleration, which in turn determines the required control deflections.

The above procedure requires simple manipulation of the pitch-acceleration equation to achieve exact responses in the pitch axis. The same approach can be applied to the roll- and yaw-rate axes, assuming that secondary effects of the primary lateral control surfaces are negligible, i.e. rolling moment due to rudder and yawing moment due to aileron are both small.

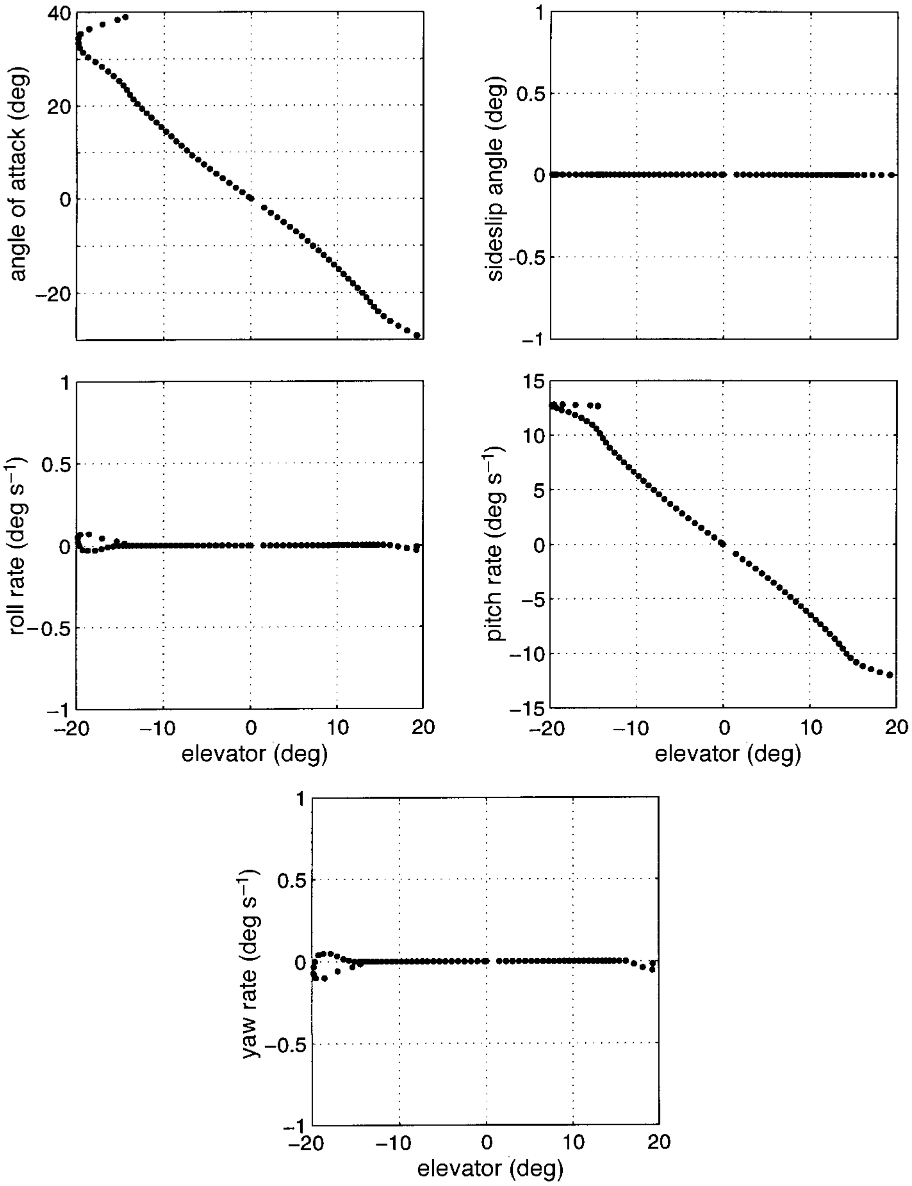

Figure 3. HHIRM aircraft with pitch-rate, roll-rate and yaw-rate NDI control (all steady-state solutions are stable).

(*b*) *Bifurcation analysis of aircraft with NDI control*

This subsection demonstrates how the open-loop HHIRM bifurcation diagrams of § 2 are modified by application of NDI control. Figures 2 and 3 show the results of applying NDI control first only in the longitudinal pitch axis and then in both longitudinal and lateral axes to demonstrate the effect of each on the aircraft departure modes; in particular, to demonstrate that it is the lateral decoupling control laws which remove spins, at high AOA.

Figure 2 shows bifurcation diagrams of the aircraft with NDI pitch-rate control. Note that, since a control law has been implemented, the continuation parameter is pitch-rate demand. However, elevator-deflection variation has been plotted on the NDI bifurcation results to enable simple comparison between the open- and closed-loop results.

A comparison of figures 1 and 2 shows that NDI control removes the instabilities at negative AOA and increases the level of stability at high positive AOA. The most important feature is that the steady-state conditions are the same, only their stability characteristics have altered, i.e. that NDI control retains the stable trim branch that exists for the open-loop aircraft. This result enabled NDI control to be used to enhance the stability of airframes unstable in pitch (e.g. canard-delta configurations) and allow the pilot to fly around the bifurcation diagram during piloted simulation.

Figure 3 shows bifurcation diagrams of the aircraft with NDI control laws for pitch rate, roll rate and yaw rate. This figure shows that the roll and yaw NDI control laws remove the high AOA spins due to longitudinal/lateral coupling and extend the trim flight envelope up to the point where the lateral controls saturate at AOA $= 40°$. The NDI control laws also stabilize the aircraft. Note that the AOA trim branch in the range $27° <$ AOA $< 40°$ joins up the points of origin of spin branches in figures 1 and 2, i.e. it follows the shape of the original open-loop spin region.

Full details of application of NDI control laws to the HHIRM aircraft are presented in Littleboy & Smith (1997). To the authors' knowledge, the work in Littleboy & Smith (1997) is the first demonstration of the global stability properties of NDI. Note that global stability is defined here in the sense that the closed-loop model is stable for slowly varying control demand, not in the sense of robustness to external disturbances or an abrupt change in control demand.

5. Piloted simulation data

This section presents a sample of piloted simulation time-history data for spins, autorotation and deep stall for a canard-delta and a canard-wing-tailplane aircraft configuration. The piloted simulations were conducted to validate and investigate the departures predicted by theoretical bifurcation analysis. These results are presented to illustrate the incipient and developed behaviour of typical departures. Note that these piloted simulation results are not for the HHIRM aircraft introduced in §§ 2 and 4 to illustrate typical theoretical bifurcation analysis data for open-loop and NDI-controlled aircraft.

Spin 'templates', which are used to perform rapid off-line analysis of a large number of piloted simulation time histories, are also presented. The spin template is a three-dimensional plot of roll, pitch and yaw rates (i.e. p, q and r). While these plots are a simple concept, they proved to be very effective for rapid visual identification of different departure modes and for reducing the time taken to analyse piloted simulation results.

The spin templates are examined in conjunction with plots of aircraft position in (X, Y, H) coordinates and/or aircraft trajectory in earth coordinates to help visualize departure modes. The (X, Y, H) plot is used to differentiate between upright spiralling spins and autorotation or tumbling spins; the latter class of spins trace a predominantly straight path with little spiralling. Note that X, Y and height (H)

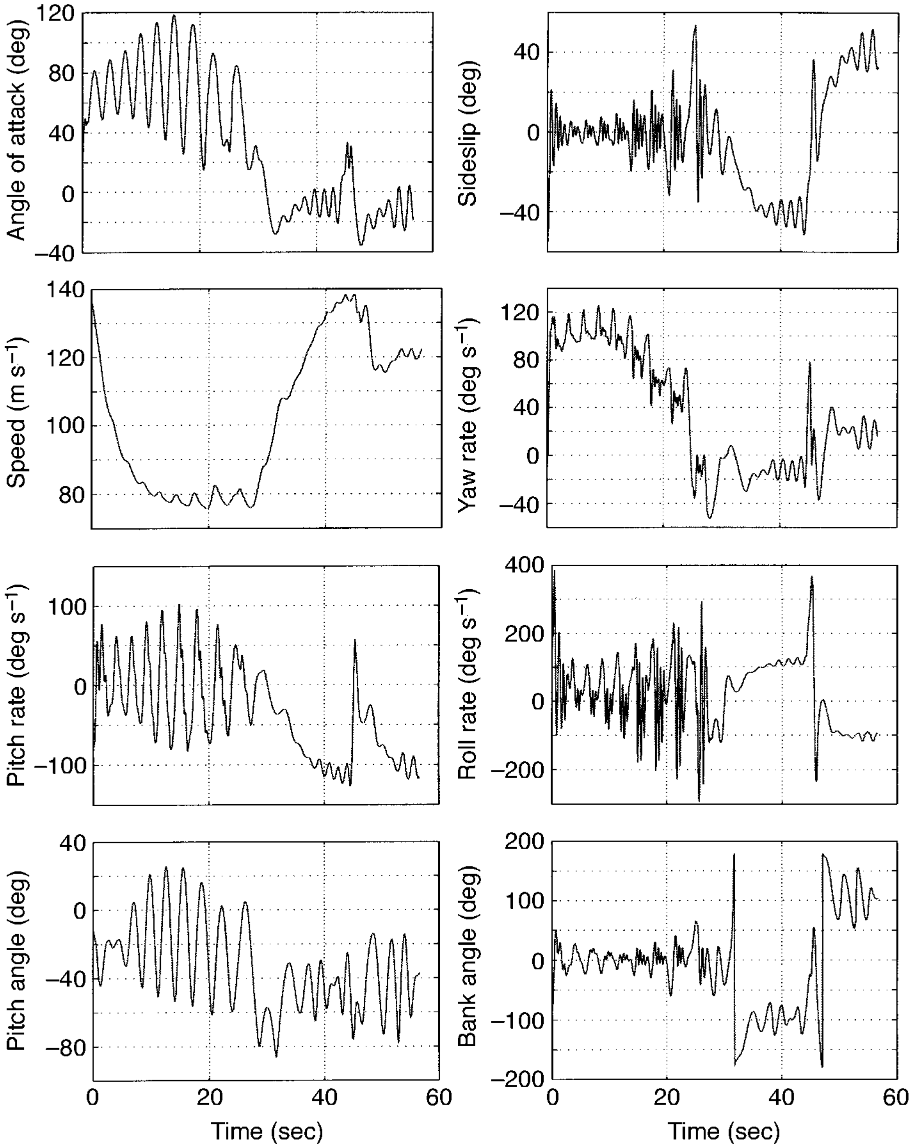

Figure 4. Departure to spins at AOA = 65° and autorotation at AOA = −10° for a canard-wing-tail aircraft.

are measured at the aircraft centre of gravity. The aircraft is not shown to scale in these plots.

(*a*) *Departure to spins and autorotation*

Figure 4 shows piloted simulation time histories for the departure of an open-loop canard-wing-tail aircraft, first to upright spins and then to autorotation. The first departure occurs from AOA = 27° to spins at AOA = 65° from initial stable open-loop flight. The developed spins are flat and fast and oscillate with significant roll

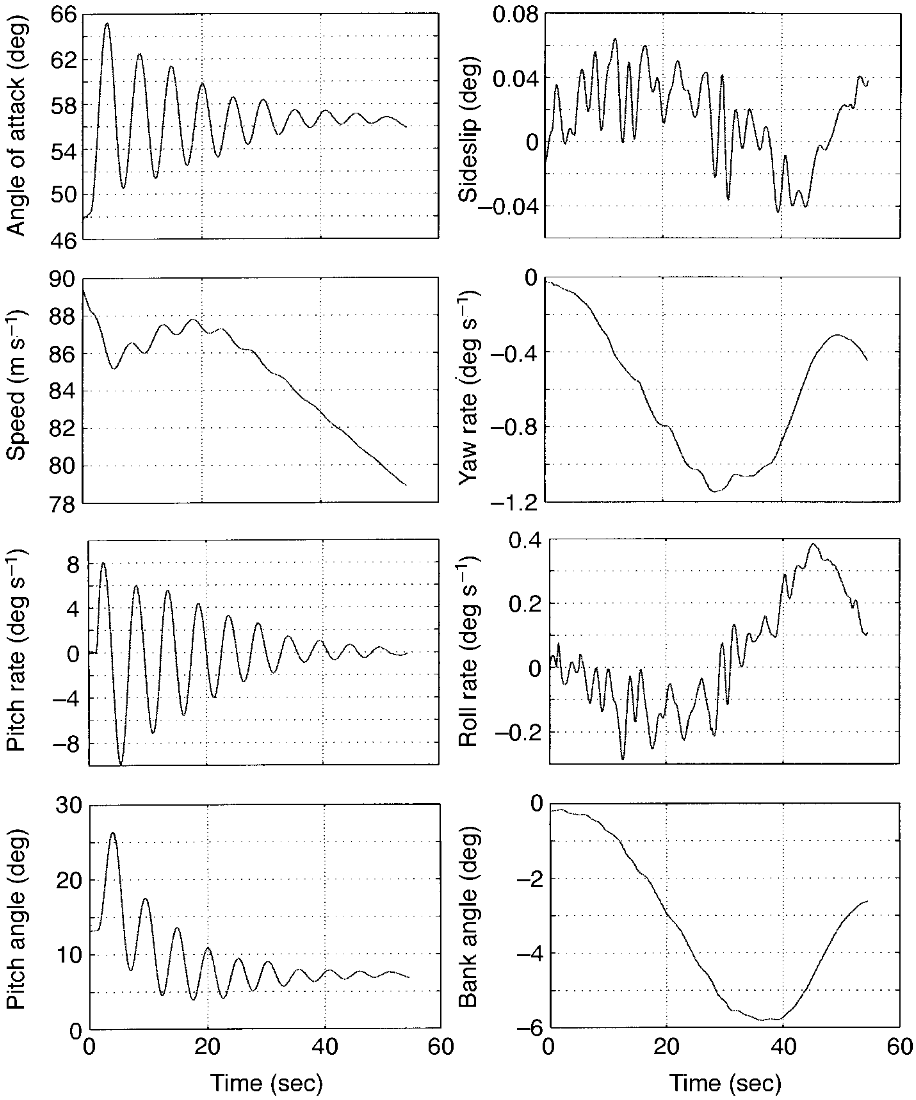

Figure 5. Deep-stall time histories for a canard-wing-tail aircraft.

and yaw motion. After approximately 30 s of spins, the aircraft suddenly departs to negative AOA (approximately $-10°$) to develop autorotation with a high positive roll rate of $100° \mathrm{s}^{-1}$ and moderate yaw rate of $-20° \mathrm{s}^{-1}$. After 12 s, the aircraft autorotation changes direction, with negative roll rate and positive yaw rate of the same magnitude as before.

(*b*) *Deep stall*

Figures 5 and 6 show piloted simulation time histories and the typical aircraft trajectory for deep stall. Deep stall is characterized by predominant pitch oscillation and modest lateral activity. Figure 4 shows a pitch oscillation which gradually dies away at around AOA = 56°.

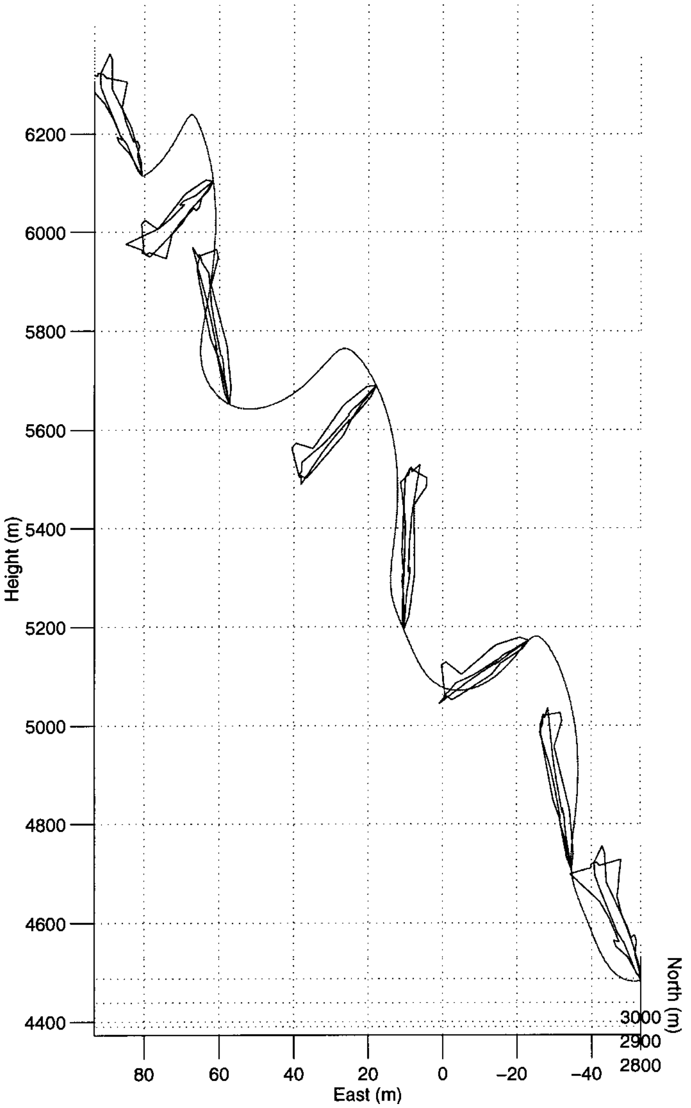

Figure 6. Aircraft trajectory for deep stall of canard-wing-tail aircraft.

(c) *Templates for upright spins, autorotation and tumbling-spin modes*

Figures 7 and 8, respectively, show two sets of typical spin templates for upright spins and autorotation. Note the exaggerated spiral flight path for the upright spin and, in comparison, the relatively straight flight path traced out by the autorotation mode. Another difference between the two types of spin is that the average roll rate for upright spins is approximately zero while high-magnitude average roll rates are observed with the autorotation modes.

Figures 9 and 10 show another form of autorotation, a wing tip to wing tip 'tumbling' spin mode. This autorotation mode is unusual in that it has high pitch and yaw rate in addition to high roll rates. Note also the distinct (p, q, r) spin template.

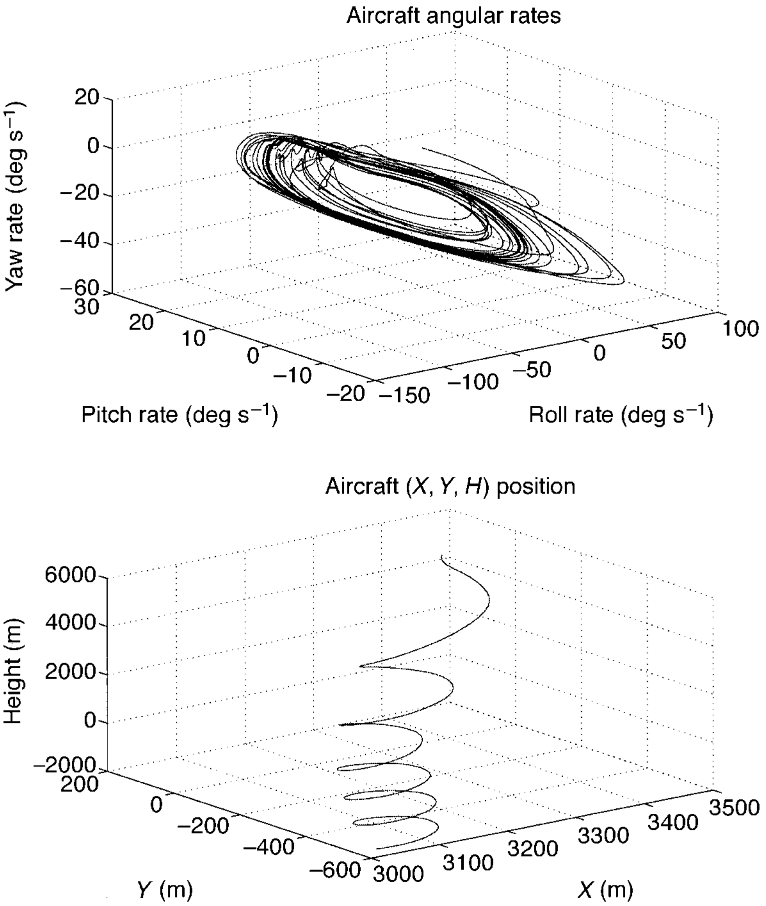

Figure 7. Spin template and (X, Y, H) plot for upright spins of a canard-delta aircraft.

6. Conclusions and recommendations

This paper has described the piloted simulation tools and methods used to validate and investigate further the aircraft departure characteristics theoretically predicted by application of bifurcation analysis. The tools and methods have been developed for the high-fidelity real-time simulation facilities at DERA (Bedford).

The work reported here is the culmination of a number of theoretical studies and piloted simulation trials of progressively more challenging aircraft. The major achievements in the piloted simulation work are: in establishing the use of a HDD which shows bifurcation diagrams as departure 'road maps'; and the use of NDI control. Both developments enable the pilot to reach specific regions of the flight envelope in a controlled manner.

The HDD, in particular, removes a huge overhead in running the trials, from the perspective of both pilots and trial directors. The piloted-aircraft flight condition superimposed onto the base bifurcation plots provides the pilot with a good indicator of where he is with respect to departure-prone regions and what piloting action is needed to reach departures. The HDD also provides trial directors with immediate

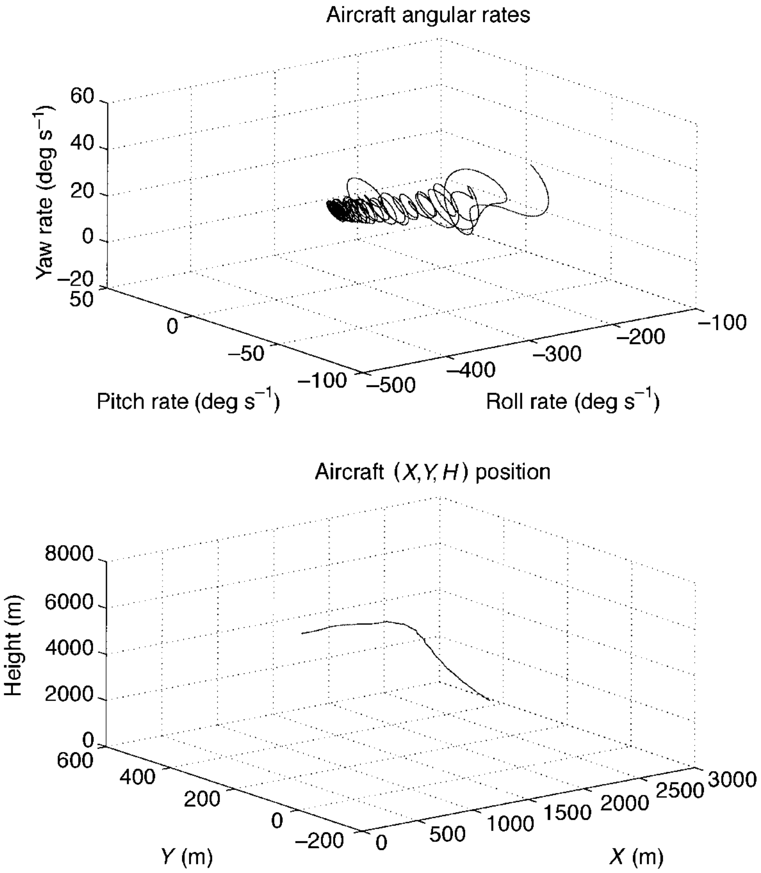

Figure 8. Spin template and (X, Y, H) plot for autorotation of a canard-delta aircraft.

information on aircraft position flight condition and the specific departure modes being exercised without relying on visual or verbal feedback from the pilot.

The paper has presented some of the spin, autorotation and deep-stall modes exhibited by different aircraft configurations. The use of spin templates, which show aircraft angular rates, to classify different departure modes has also been introduced. These templates provide a simple means of rapidly sifting through a large number of piloted simulation time histories.

The combined use of theory and piloted simulation is advocated. The theoretical bifurcation results provide an accurate picture of the departure-prone and carefree handling regions of the flight envelope. Hence, the theoretical results provide a 'reference map' of global aircraft behaviour and an indication of the source of undesirable behaviour. They are invaluable in immediately pinpointing regions of the flight envelope which need detailed investigation without any element of trial and error. Investigation of departure modes, using either piloted or off-line simulation, without the bifurcation maps requires extensive, time-consuming and somewhat arbitrary analysis methods.

However, the equilibrium bifurcation diagrams give no information on the initial conditions and transient response that lead to the steady-state flight conditions.

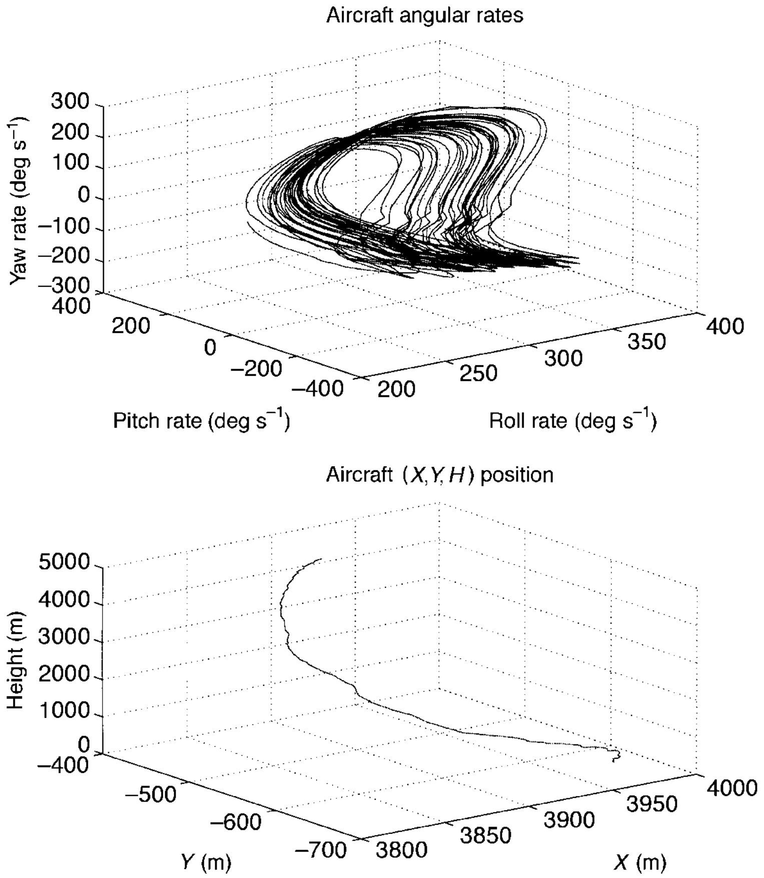

Figure 9. Spin template and (X, Y, H) plot for wing-tumbling spins of a canard-delta aircraft.

Thus, theoretical analysis does not identify the incipient departure conditions or indeed the exact nature of the developed departure (i.e. whether it is an upright spin, inverted spin, wing rock, nose slice or autorotation). Calculation of regions of attraction of stable equilibrium and period solutions, which determine the steady-state convergence of aircraft trajectories to stable flight modes from any given initial flight condition, will provide this information. The regions of attraction can also be used in spin-tunnel tests of departure modes to determine the aircraft initial condition which will lead to particular departure modes.

However, in the absence of regions of attraction, experience and detailed inspection of specific departure-prone regions of the flight envelope will provide some of this missing information. Also, extensive off-line simulation using a judicious choice of initial conditions from consideration of the bifurcation diagrams can provide some additional departure information. However, given the trial-and-error nature of this approach and the computational overheads associated with detailed bifurcation analysis, a more expedient and cost-effective method of investigation is piloted simulation.

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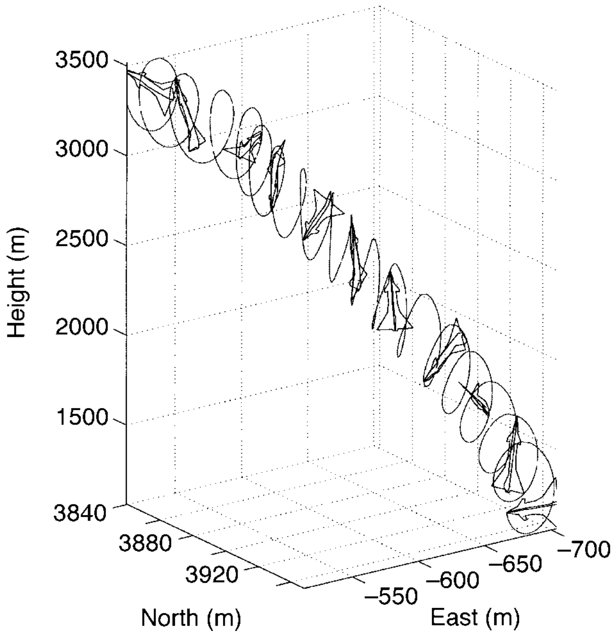

Figure 10. Aircraft trajectory for wing tumbling spins of a canard-delta aircraft.

thanks are due to Mr John Burnell for developing the concept of spin templates. The work was supported by the UK Ministry of Defence. This paper is published with the permission of the DERA on behalf of the Controller of HMSO.

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