ICAS-96-4.11.3

THE SIMULATION OF AIRCRAFT LANDING GEARS DURING USUAL AND UNUSUAL MANOEUVRES

George G. Kapadoukas, Andrew W. Self
Simulation and Control Centre
Kingston University, UK SW15 3DW
Frederique Marteau
Rapid Data Ltd, Crescent Road,
Worthing, West Sussex, UK, BN11 5RW

Abstract

This paper describes the development of full all-axis whole system all-scenario simulation and system integration facility. The facility is used in the paper to analyse aircraft during landing both in terms of time histories and eigen pattern migration. Gear walk and other phenomena are also included.

Current non-linear modelling methods used by the industry provide continuous time histories, but analysis is limited. In-flight linear state space models are described in the literature and regularly used in the industry. This is not the case when the aircraft is in ground-contact. The software facility automatically generates linear state space models from aerodynamic and aircraft data for any in-flight or ground-contact condition thereby allowing numerical analysis and design tools to be used in the design process and throughout the full operating regime from brakes-off, through taxiing, take-off, flight and landing.

The use of a linearised aerodynamic model about a set reference condition provides many insights. It provides correct enough results for engineering purposes but it has its limitations in terms of continuous and non-linear analysis. It is too dangerous to draw conclusions from small perturbation models and in-flight tests. The suite of programmes, called AEROSIM, generates full non-linear block structured models for all in-flight and ground-contact operating regimes and allows the user to examine the robustness of the changes for all conditions and scenarios.

This paper describes the full system integration software facility and includes a ground contact analysis which includes the phenomena of gear-walk and a ground impact modal analysis.

Background

The aim of the work is to develop a full all-axis whole-system all-scenario modelling and total simulation facility. The resulting software allows aircraft manufacturers to model, analyse, and optimise systems both in full simulation and in hardware-in-the-loop real time configurations and thereby reduce the possibility of unpleasant in-service surprises. Designers are able to ensure that total system and subsystems (aerodynamics, hydraulics, braking, control, structure etc.) meet the functional requirements, and to determine how the system and system elements interact and operate for all possible scenarios. The system integration and system modelling facility will allow designers to achieve significant improvements in terms of performance measures such as cost, quality, safety and time to market.

Current non-linear modelling methods used by the industry provide continuous time histories, but analysis is limited. The software facility automatically generates linear state space models from aircraft data for any flight condition. Routines such as Bode, Nyquist, Eigen value and roots locus techniques can then be used for design purposes in the usual way. This linear analysis module links with commercially available packages thereby allowing the designers to use the full range of optimisation techniques such as LQG or H-infinity. The designer is able to view the full taxonomy of modes including (in-flight phugoid short period etc.) and the previously unavailable ground contact modes.

This paper describes the facility generally and includes analysis of gears and tyres using the state space and non-linear simulation modules as a design illustration. The shock-absorbing characteristics of aeroplane landing are normally developed largely as a result of extensive trial drop testing and empirical data or through single axis isolated models. This paper describes a reliable and accurate all-axis method of strut modelling both in isolation and as part of an overall aircraft simulation. The work, apart from facilitating rapid strut prototyping in primary design, will find application in aircraft, brake and flight simulator manufacture.

Motivation for the Work

The reduction in defence budges and market pressures have increased the sensitivity of equipment decisions, both in the public and the private sector. Competition within the world aviation market has been fierce and will intensify still further as major suppliers seek to increase market share, gain a competitive edge and obtain a technological advantage. A lean way of working is needed where rapid and flexible cost-effective solutions are generated within shorter time-frames. Improved modelling and total simulation of systems allows aircraft manufacturers to model, analyse, and optimise systems in an unambiguous way. It allows the designer to ensure that whole system and subsystems meet the functional requirements, and to determine how the system and system elements interact and operate for all possible scenarios. System integration and system modelling allows the designer to achieve significant improvements in terms of performance measures such as cost, quality, safety and time to market.

Systems Integration - a Category one Priority

The aerospace industry has a number of business pressures. Longer service lifetime, increased performance, retrofitting current systems and safety. Advanced aerodynamic and control strategies need to be developed, investigated and analysed throughout the entire flight envelope and for all possible flight conditions before proof of concept is assured. Aircraft need to be strong enough to withstand the predicted ground-contact loads; however, oversizing of structures will impact adversely on operating costs and competitiveness. Designers need to gain an understanding of the subsystems and total system interaction during normal and worst case scenarios and make informed decisions on system improvements. A system wide method is needed to facilitate whole system optimisation, aid subsystem and total system design, provides a co-ordinating facility between subsystem manufacturer and rapid prototyping and agile manufacture.

The aeronautical industry is an amalgam of companies, each making a separate but linked contribution to the health of the whole industry. The 1992 UK DTI National Strategic Technology Plan for Aeronautics (NSTAP) reports that past improvements generally have been dealt with on a piecemeal basis with individual companies sponsoring research into their particular product lines(1). Fragmented structures are unresponsive to customer demand. The document states that a system integration and analysis facility is needed to show how each of the aircraft subsystems or elements (landing gear, tyres, braking, steering, structures engines, aerodynamics and flight control systems etc.) interact collectively. The facility is aimed at satisfying that need and allows the user to foresee potential difficulties and show where the overall system can be interlinked and optimised without compromising safety.

The NSTAP document identifies total system integration, modelling, design and manufacture of hybrid and mechanical systems as a category one priority(1). Category one being those technologies without which the future viability of the aerospace industry would be in doubt. The Defence and Aerospace Technology Foresight Document identifies System Integration as a key skill(2). To an industrial prime contractor, for example, with the responsibility for the performance of a major platform, system integration refers to an ability to understand and model the overall requirements and the interaction of the system elements in an unambiguous way, accommodating the various technologies. To a subsystem manufacturer system integration and total system modelling provides an insight into the dynamic and interactive behaviour of the system element 'in situ' for all possible scenarios.

The aim is to give individual aerospace companies the opportunity to investigate and predict the effect of product changes on the total hybrid systems, prevent unpleasant surprises after manufacture, and operate in a changing world of total quality, rapid prototyping and fierce competition. The facility would enable the user to link customer requirements with system improvements, cost reductions with safety, and fundamentally rethink and radically redesign the total system to achieve significant improvements in terms of critical performance measures such as cost and time to market.

ACSL Approach

AEROSIM is based on the Advanced Continuous Simulation Language (ACSL). This has two advantages. Firstly all the ACSL procedures are called automatically from the software allowing the user to use the well proven ACSL tools to model and analyse aircraft systems. Secondly users can easily add ACSL code to the core AEROSIM model and generate product specific models almost directly. ACSL is an industry standard simulation tool. The language was originally developed in 1975 for aircraft and weapons simulation and has over 5000 users world wide. The software extends ACSL to allow the user to quickly develop large aircraft dynamic models and test prototypes in a thorough and rigorous way.

A Real-time Hardware-in-the Loop Prototyping Facility

With the ACSL real-time platform it is possible to use the software to model and design the whole system, then isolate an element for hardware-in-the-loop real-time testing. Prototypes can be quickly and more thoroughly tested, particularly when the tests are too costly or dangerous to perform with the real aircraft. For example. market forces dictate faster landing speeds, heavier payloads, and consistently shorter stopping distances under all types of runway and landing conditions. From a safety point of view, a scrubbing tyre in an undetected skid can, in seconds, burn through its many plies and blow out. In an even shorter time, the tyre can 'flat spot' and have to be removed and scrapped. These problems are eliminated by anti-skid control systems that combine mechanical, electrical, hydraulic and control engineering technology. More effective braking systems create more strut bending forces and the possibility of gear bending or collapse and unacceptable reflected vibrations through the gear to the cockpit. A full all-axis all-scenario real time aircraft hardware-in-the loop simulation and analysis facility is needed to allow the designer to identify and eliminate this problem in the development stages whilst meeting the customer requirements. The systems integration and testing facility is shown in figure 1. The linear and non-linear modelling and design facilities are shown in figures 2 and 3.

The aim is to provide a combined and integrated approach where the user can generate linear models, non linear models and analyse the aircraft from brakes off, through take-off, flight, landing, taxiing and parking for any scenario. Data is transferred between analysis tools allowing the user to run smoothly through the design stages without making clumsy conversions. Each stage can be completed, progressed and revised throughout the product development, thereby allowing the user to make informed decisions and confirming the suitability of the design for all conditions and scenareos.

Ground Handling Models

Unlike the in-flight situation ground contact models are not well understood, particularly during the transition between the 'soft' aerodynamics and 'stiff' undercarriage dynamics. This serious omission needs attention if aircraft are to be fully modelled from brakes-off through taxiing, take-off, landing and parking. Current undercarriage and ground handling models contain approximations that lead to errors. Often simplified erroneous assumptions are made to avoid the time consuming and exacting task of developing full and accurate ground handling models. Linear gear models, static and single axis tyre models and single axis aircraft ground handling models lead to inaccuracies, sub-optimal solutions to braking and gear designs that have resulted in unpleasant surprises after manufacture. The linear ground handling model allows the user to dynamically and accurately analyse the aircraft modal behaviour during all ground contact scenarios and thereby design systems for usual and unusual manoeuvres including those too dangerous to practice with the real aircraft. The model simulates gear walk and anti-skid braking systems for all landing scenarios. The non-linear facility analyses the system throughout the entire range of operation. Both the linear and non-linear approaches will provide insights that were previously available. Both the linear and non linear approaches are described below. The model encompasses the complete six degrees of freedom aerodynamic. gravitational, thrust and undercarriage strut and tyre forces and moments(3). The modelling methods used allow the analyst to observe and track the aerodynamic. strut and tyre modes of motion (eigen values) throughout the in-the-air and on-the-ground envelope. This alternative approach enables the user to identify and track the eigen value migration, a technique regularly used for in-flight design and previously unavailable for ground handling.

State space model structure

The state space model shown in figure 2 simulates the aircraft response to control surface deflections, runway surface variations, steering and braking during taxiing. take off and landing. The six degrees-of-freedom rigid body Euler equations of motion are used to determine the aircraft acceleration along and about all three body axes. The aerodynamic forces and moments are defined in terms of aerodynamic derivatives and control parameters. The landing gear shown in figure 4, 5 and 6 consists of a shock strut, a wheel and a tyre. The shock strut opposes deformation with a gas spring and a hydraulic damping force. The elastic and damping forces depend on strut and tyre deformities, stroke rate and physical parameters. The tyre mass and parts of the shock strut participate in the motion of the wheel. The tyre deforms as shown in figure 5. These deformities are significant and transmit the forces to the body during ground-manoeuvres.

Aerodynamic model.

The aerodynamic forces and moments for the motion are derived along and about the respective body axes in terms of aerodynamic derivatives and control parameters (4).

Gravitational model

The aircraft gravitational forces and moments for the perturbation motion about equilibrium are included as described in reference 4.

Tyre model

The aircraft tyre shown in figure 5 is subjected to a range of non-linear xyz forces during landing and taxiing. These forces result in longitudinal, lateral and normal tyre deformities and characteristics. These include lateral relaxation length, pneumatic castor or trail, normal tyre sinking due to longitudinal and lateral deformation, change in stiffness due to tyre velocity and tyre type. These parameters cause the undercarriage eigen values to migrate during the bounce and are illustrated below. The tyre model and full system model data is described in references 3, 4 and 5. The tyre xyz distortions generate forces that result in gear walk and other phenomena that needs accurately simulated for all scenarios if a full and optimum design is to be completed.

Strut model

The single and two stage oleo pneumatic shock struts shown in figure 6 are used in modern aircraft. The lower chamber of the strut contains hydraulic fluid and the upper chamber contains gas (Nitrogen) under pressure. As the strut compresses a piston moves up into the main upper housing. As this happens oil flows through the main orifice into the upper chamber. The hydraulic pressure drop generated across the orifice resists the telescoping of the strut and the turbulence created provides a means of absorbing impact energy on landing. In some struts the orifice area is constant, where in others a metering pin or rod is used to govern the damping effect of the strut. Flapper valves ensure oil flow from the upper to the lower chamber during strut expansion. The compression of the strut produces an increase in gas pressure which also produces a resistance to closure. In addition to the hydraulic damping force and air stiffness force there is an internal seal friction and a bearing friction which affect the behaviour of the strut (6).

The undercarriage configuration used for the analysis is shown in figure 7. The undercarriage forces and moments responsible for the aircraft dynamic behaviour from touchdown to full stop are described in reference 3.

Total State Space Aircraft Simulation Model

The aircraft motion is considered to be the sum of two components, a steady state or trimmed motion and a perturbation motion. The model formation is described in reference 4. The above aerodynamic, gravitational, engine, strut and tyre perturbation equations are expressed in the following state space form:

$$\dot{X} = AX + BU$$

where:
A - state matrix
B - input matrix

The model inputs are the aircraft control deflections, engine thrust, ground profile, steering and braking. The resulting dynamic motion of the aircraft is described by the states. After each iteration the A and B matrices are updated from a set of feeder equations to form a non-linear dynamic state simulation. The advantage of the non-linear multi-variable state space approach is that the model can be frozen at any point, to form a pseudo linear model and the ACSL Jacobean matrix facility used to track the eigen values. Other methods of identifying eigen values or modes in large non-linear models were found to be inaccurate.

Results - Linear state space approach

The model provides time histories and eigen value migrations for all in-the-air and on-the-ground scenarios. Sample model output is described below. The data used is for a Boeing 747 Jet Aircraft.

Time histories. The aircraft normal velocity and displacement on landing are shown in figure 8. The nose and starboard wheel tyre compression and stiffness during landing are shown in figures 9 and 10. The tyre stiffness varies considerably during landing indicating that constant values would lead to modelling errors. The aircraft pitch angle and wheel hub height response to a starboard gear runway height increase of 0.1m is shown in figure 11 and the lateral velocity v and yaw rate r response to a skewed landing is shown in figure 12. The aircraft lateral velocity and nose wheel tyre relaxation deformity due to steering are shown in figures 13 and 14.

Eigen value migration. The eigen migrations, during landing, for the port undercarriage station and hub are shown in figures 15 and 16. The hub eigen values are real on impact and become oscillatory when the aircraft settles. This is due to the metering pin, the strut velocity and the tyre stiffness variation. The eigen values migrate around the 10Hz pilot feel regime and need to be included in high fidelity flight simulator models.

Non-linear Model. A nested block structured approach is used to form the model. Each block contains major units in the simulation such as the EULER, aerodynamic, anti-skid braking, engine, steering and a management elements.

The aerodynamic, strut and tyre models are as described above with the exception of the aerodynamic forces being derived from the usual equations.

Brake equations Aircraft braking algorithms are normally based on tyre slip. Slip is defined as the ratio between the forward velocity of the aircraft and the velocity of the rolling perimeter of the tyre. If slip is below five percent the brakes are fully applied. If slip is above say 25% the brake pressure is significantly reduced. In the aircraft a simple slip equation is used with an integrator, representing ground speed, runs down from an initial condition set at the point of touch down. An average tyre radius is used to convert the hub rotation into forward velocity.

In the model a more accurate method is used. The tyre compression is a function of rolling radius, sinking due to lateral distortion, relaxation length, the inflated tyre pressure, forward velocity, centrifugal growth and instantaneous load. x and y axis distortions are reflected into the instantaneous normal tyre instantaneous force and, with runway friction, effect the onset of skidding considerably.

The x-axis hub displacement is a function of the tyre variables above, hub mass, footprint, centre of pressure, tyre rotational dynamics, strut bending stiffness and the various aircraft forces. The resulting strut longitudinal forces result in 'gear walk', that is the transitional movement shown in figure 4. This phenomena is of serious concert to strut, gear and aircraft manufacturers who wish to ensure that individual elements such as new braking algorithms or less rigid struts do not generate other difficulties such as excessive 'walk' and gear collapse.

Results - Non-linear model

The following results are for a twin engine transport aircraft. The simulation run starts at the point of touchdown, where the brakes and reverse thrust are applied. The aircraft height, nose and main gear wheel hub displacements are shown in figures 17, 18, and 19. Figure 18 shows the nose gear is above the ground(negative displacement) on touchdown. Figures 20 shows the undercarrage station displacement. Figures 21 and 22 show the reduction in forward speed and reverse thrust. The nose and main gear tyre deflected radius is shown in figures 23 and 24 and angular velocities in figures 25 and 26. The nose wheel is not braked and is lowered gently onto the runway. The main gear impacts, carrying the weight of the aircraft. The main gear tyres initially skids, and rapidly pick up speed as the gear compresses and the friction turns the wheel. As the aircraft oscillates the frictional force is reduced, slip occurs and the hub velocity momentarily returns to zero.

The gear x-axis and bending displacements are shown figures 27 and 28. This phenomena known as gear walk is of fundamental inportance to aircraft and gear designers. AEROSIM plots the gear walk, and other essential characteristics, for all usual and unusual scenarios.

Conclusions

The original brief by Rediffusion and BAe was to build an accurate model that could be used to anal;yse all-scenario all-axis non-linear situations. The aim being to analyse the total system in a holistic senses and test elements such as struts 'in situ' for a range of usual and unusual manoeuvres. AEROSIM allows a similar analysis to be completed for all elements of the integrated system, allowing aircraft manufacturers to adopt a total systems approach to design modifications and examine the effect of weigh/stiffness reductions on the total system.

To date, ultra-large or holistic system modelling has been inhibited by the capacity of the computer to execute the programme in a reasonable time scale. The combination of modern PCs and recently available modular software allows the user to run total system in near real time on modern PC-based systems thereby providing the designer with a previously unavailable facility. The full all-axis all-scenario aircraft simulation and analysis facility allows the designer to identify and eliminate problems in the development stages whilst meeting the customer requirements.

The tendency in the industry has been to simulate the model elements that are understood and brush over the model elements that are ill-defined, such as the behaviour of the aircraft and its components during touchdown, the transition between soft aerodynamics and 'hard weight on wheels' dynamics. The software simulates the entire all-axis system during both usual and unusual manoeuvres. The overall aim is to provide a 'whole system' simulation facility that will allow aircraft subsystems to be collectively linked, analysed and improved throughout the product life cycle - from the preliminary design stage, through certification and further enhancements. Both linear state space and non-linear models are used to provide the maximum use of design and analysis techniques.

The availability of in-flight linear models control engineers to design autopilots that, by process and use the aircraft transducer signals to drive the electrically driven hydraulic actuators. These systems known as autpilots modified the aircraft inflight behaviour in aircraft such as the F4 Phantom. The combination of moden control and in-flight models allowed the designers to go a step further and 'configure' the dynamic behaviour of a lightly damped and ill-behaved aircraft to meet the design specification. The result is that the 'configured' aircraft behaves as if it were constructed differently. These systems, known as FLY-BY-WIRE, are commonly used in modern aircraft such as EFA. The availability of full ground-contact and in-flight models now allows the designer to 'configure' braking and gear systems in a similar and optimal fashion and design BRAKE-BY-WIRE systems to produce a system that will behave as if the system were constructed differently, with stiffer gears, minimum pitch when braking, reduced slewing when runway surfaces are contaminated and the aircraft is yawed on landing.

The software has been developed as a result of contracts with Redifussion Simulation, British Aerospace and Dunlop Aviation. AEROSIM is currently being made commercially available through RAPID DATA Ltd.

References

1. National Strategic Technology Acquisition Plan for Aeronautics. DTI UK 1992
2. Technology Foresight Aerospace and Defence DTI UK 1995.
3. G Kapadokas and A Self et al.
4. D. McLean. Automatic Flight Control Systems. 1990. Prentice Hall International UK Ltd. ISBN 0-13-054008-0.

5 C. Hogg. Simulation of Ground Handling of Taxiing Aircraft. Control and Dynamics Research Unit, Department of Mechanical and
Manufacturing Engineering, PhD thesis. June 1993.

6. R. F. Smiley, W. B. Horne. Mechanical properties of pneumatic tires with special reference to modern aircraft tyres.
Technical report R-64, Langley research centre, Langley field, Va11.
7. C. Rodney, C.R. Hanke and D. R. Nordwall. The Simulation of a Jumbo Jet Transport Aircraft. Vol. 2, Modelling Data, D6-30643, September 70.
8. K. Robert, C.R. Hanke and W. F. Jewell. Aircraft Handling Qualities Data. NASA CR-2144, Washington, D.C. December 1972.
Tecknical report R-64, Langley research centre, Langley field, Va11.

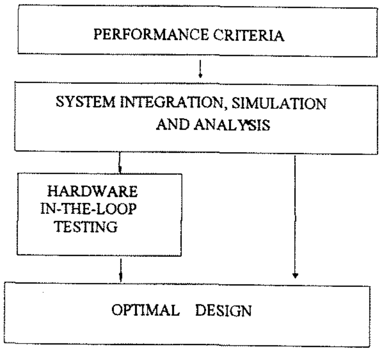

Figure 1. System Integration and Testing Facility

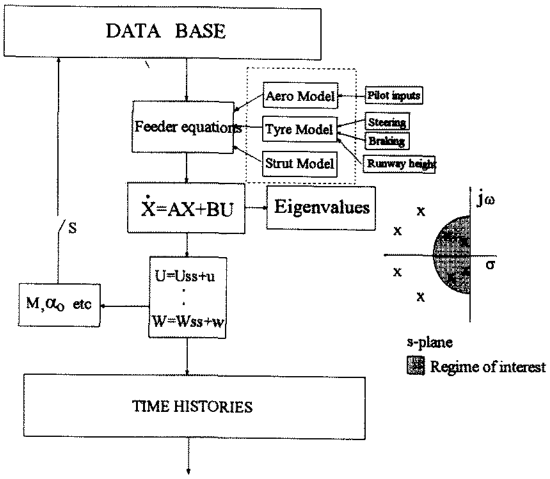

Figure 2. The aircraft linear simulation model

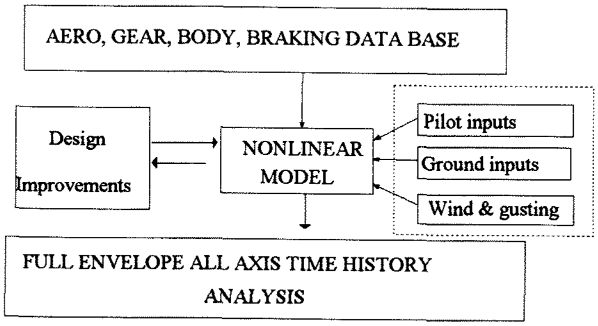

Figure 3. Nonlinear Modelling and Time History Analysis

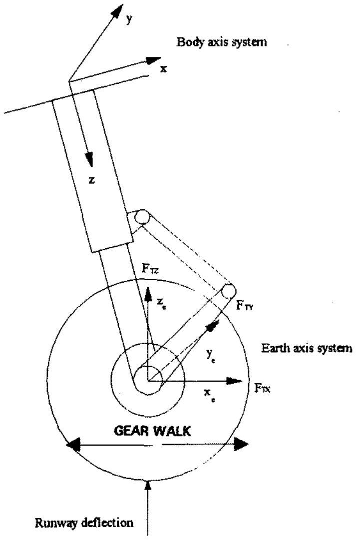

Figure 4. The undercarriage station

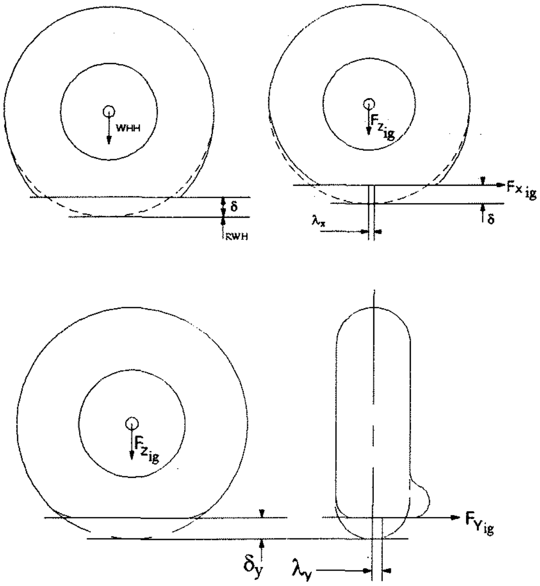

Figure 5. Normal, longitudinal and lateral tyre deformities

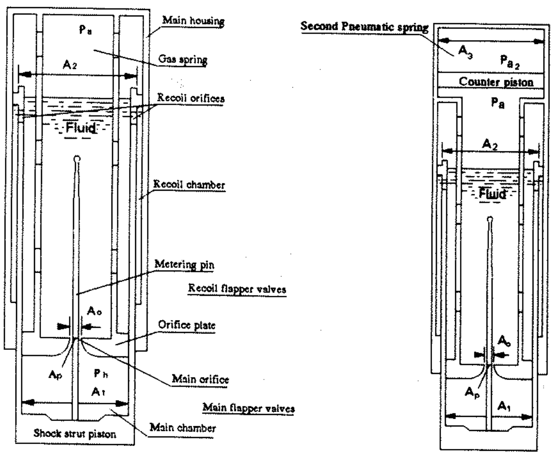

Figure 6. Single and two stage oleo pneumatic shock struts

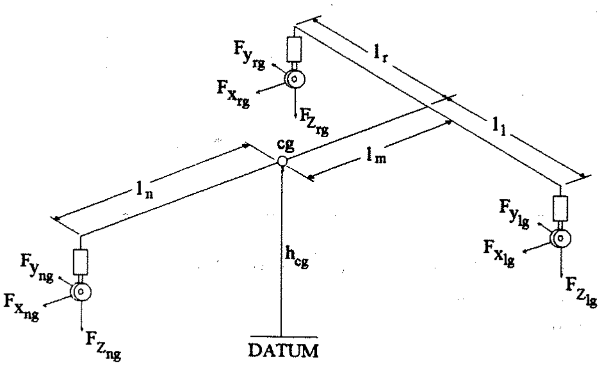

Figure 7. The aircraft suspension layout

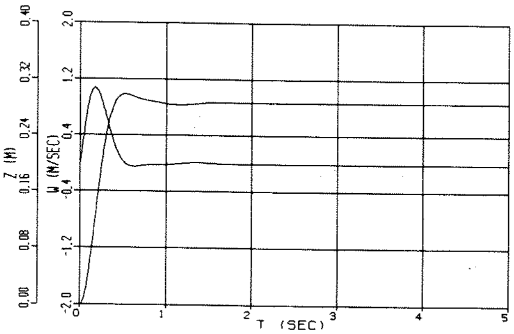

Figure 8. Aircraft normal velocity and displacement for smooth landing

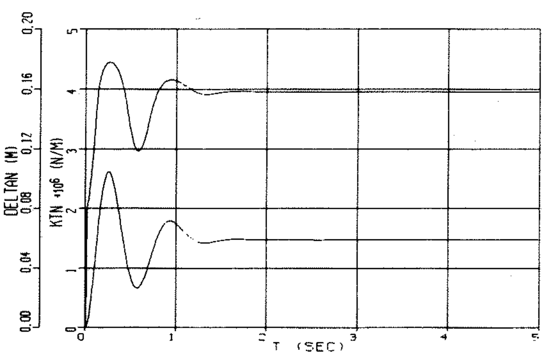

Figure 9. Nose tyre normal deflection and spring constant for smooth landing.

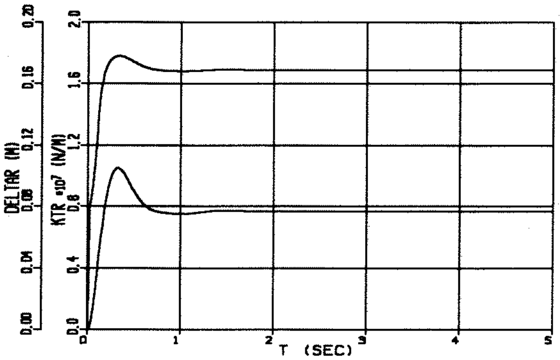

Figure 10. Main starboard tyre normal deflection and spring constant for smooth landing

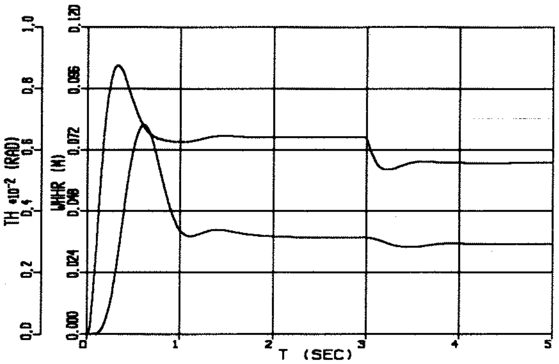

Figure 11. Aircraft pitch and nose hub displacement due to a runway height displacement of 0.1m at the main starboard gear after the aircraft has initially settled

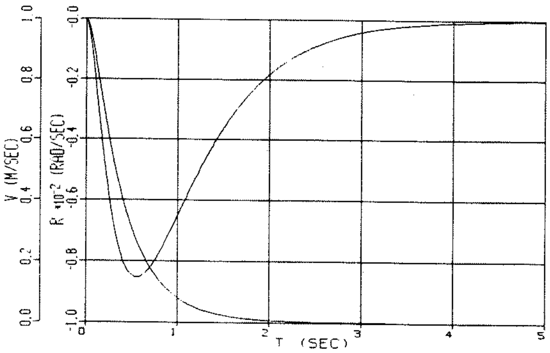

Figure 12. Aircraft lateral velocity and yaw rate due to a skewed landing with Vic=1.0Ms^{-1}

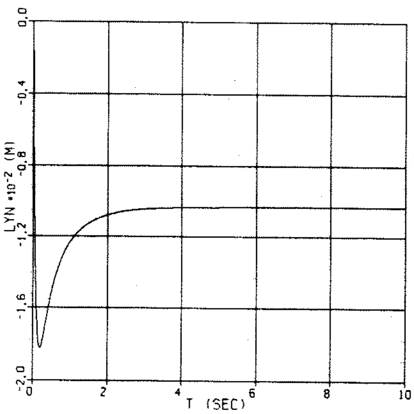

Figure 13. Nose wheel tyre relaxation length for 1 degree steering at 20 m/s forward speed

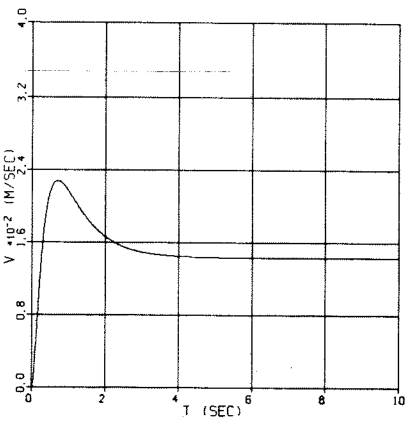

Figure 14. Aircraft lateral velocity for 1 degree steering at 20 m/s forward speed

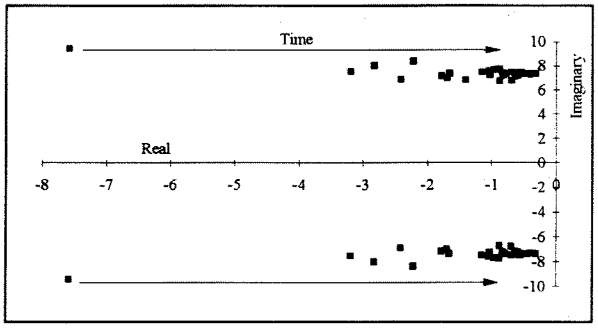

Figure 15. Undercarriage eigenvalues migration

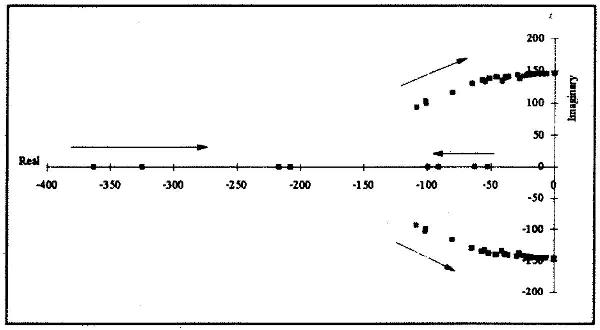

Figure 16. Hub eigenvalues migration during a
during a 4 m/s landing.landing
4 m/s landing

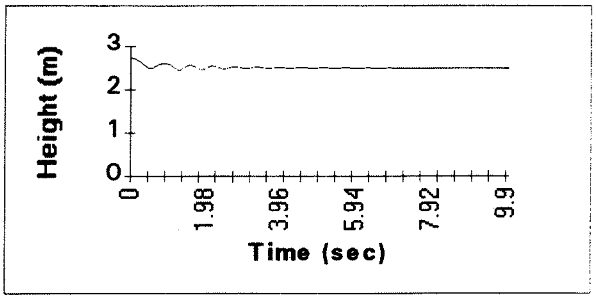

Figure 17. Height displacement

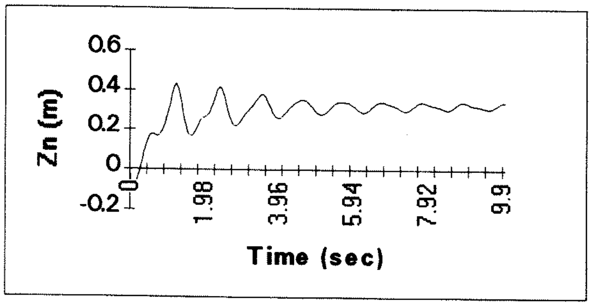

Figure 18. Nose wheel displacement

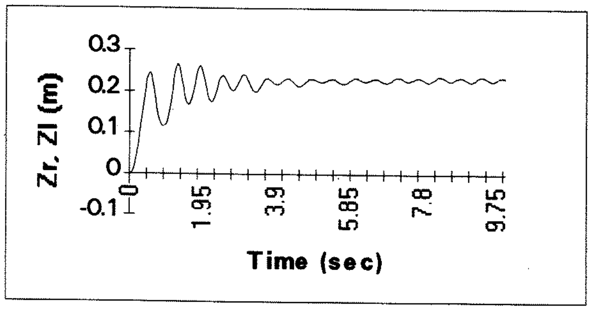

Figure 19 Main gear wheel displacement

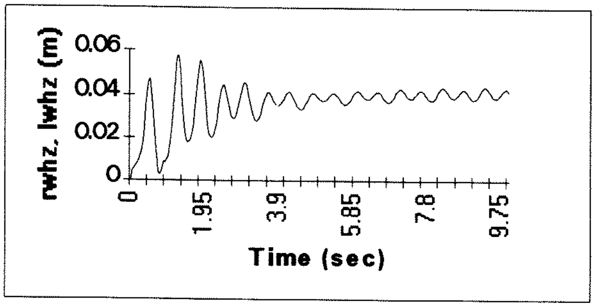

Figure 20. Main gear displacement

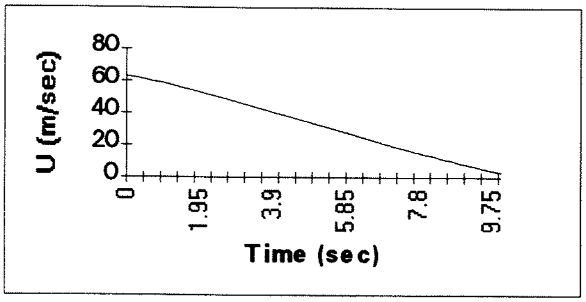

Figure 21. forward speed

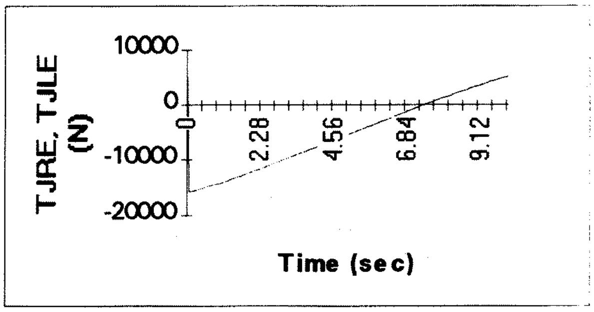

Figure 22. Reverse thrust

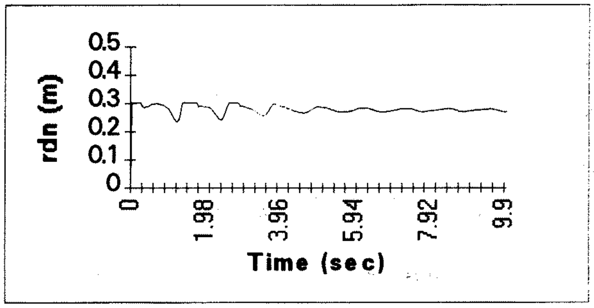

Figure 23. Nose wheel tyre compression

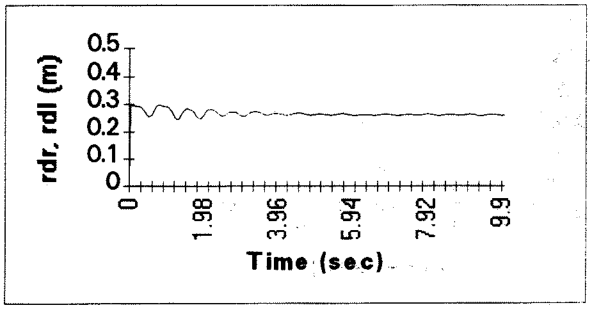

Figure 24. Main gear tyre compression

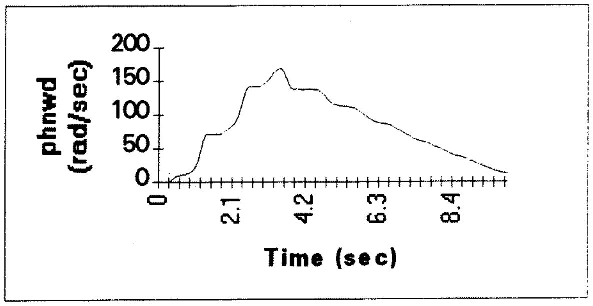

Figure 25. Nose wheel forward velocity

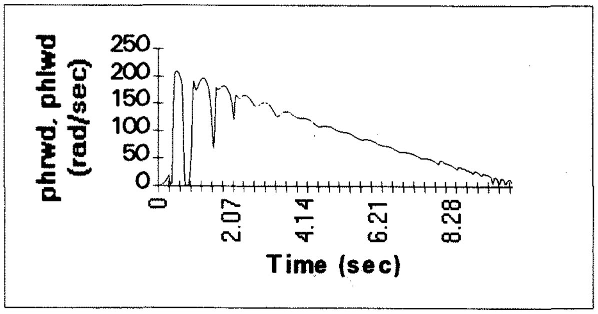

Figure 26. Main gear forward velocity

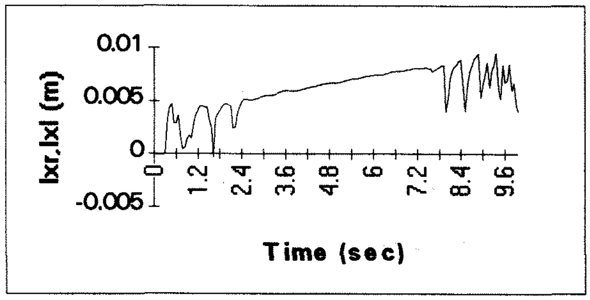

Figure 27. Gear walk under braking

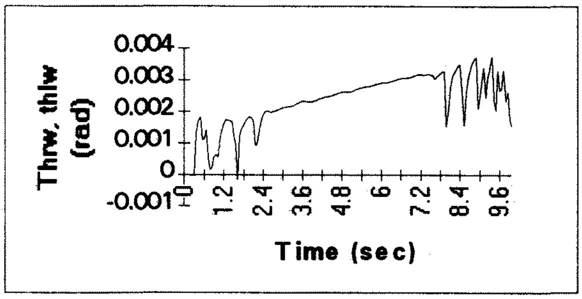

Figure 28. Gear rotation