THE SIMULATION OF AIRCRAFT LANDING GEAR DYNAMICS

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ABSTRACT

In an aircraft design programme development of the landing gear requires the integration of various components and sub-systems; tyre, wheel, bogie, leg, oleo, braking, anti-skid control, steering. The design and integration procedure is aided by computer simulation of dynamic interactions between the sub-systems. To provide this a comprehensive and versatile landing gear modelling and simulation software package has been developed. The package encompasses all dynamic properties to a high level of detail, from runway interaction to whole aircraft response, and can simulate take-off, landing, braking to a stop with anti-skid, steering and taxiing.

The mathematical basis for the individual models and the manner in which they can be combined to form a range of complete systems are described. Extensive validation against test results has been completed, giving a high level of confidence in the simulation fidelity. A consistent set of example results is presented for single leg drop tests and dynamometer tests, and also for a whole aircraft during touchdown. The results illustrate that a detailed understanding of the total landing gear dynamic behaviour, including sub-system interactions, can be obtained from this type of analysis.

1. INTRODUCTION

During the development of an aircraft many components and sub-systems are integrated to form the landing gear system. Often major sub-systems are procured from different sub-contractors by the airframe manufacturer, who must ensure that no adverse dynamic interactions occur. It may not be until late in the design and development process, often when hardware has been procured, that undesirable dynamic interactions are identified. To avoid this it is advantageous to be able to simulate the behaviour of both the individual sub-systems and the full interactions between sub-systems in a methodical fashion, so that problems can be predicted and solutions identified.

The need for a comprehensive integrated dynamic analysis of the landing gear system with its sub-systems was identified by the Systems Department of British Aerospace Airbus Limited, who have funded the programme described in this paper. The primary objective was to provide a powerful analysis tool for the integration of landing gear and braking sub-systems with other aircraft dynamics during all phases of design. This has been achieved by the simulation of aircraft ground contact dynamics, including take-off, landing, braking to a stop with anti-skid, steering and taxiing. The important flexibilities of the landing gear, together with tyre-runway interaction and braking and steering control systems were considered to be essential modelling goals, and are included. The requirements dictated the need for a capability to model general aircraft ground contact dynamics without the need for the design engineer to program any equations or mathematical relationships directly.

These factors led to the production of the self-contained computer software package for landing gear analysis described in this paper. The package consists of a series of modules in which the integrated system model can be evolved during the development of a landing gear design. It is capable of representing all of the standard hardware rig tests, such as dynamometer and drop tests, as well as flight tests involving ground contact. Expected benefits are improved design and development capability and avoidance of costly design changes at late stages in an aircraft programme.

2. SCOPE

An aircraft landing gear system has to be designed to meet various requirements over all ground-based operating conditions. It must be capable of absorbing the impact of a severe landing case as well as the kinetic energy of forward motion on landing to bring the aircraft to rest. The braking and steering control systems have to provide the required ground manoeuvring and control capability and the whole assembly must remain stable throughout the ground envelope. In most aircraft programmes the detailed design of the leg and the braking and steering systems is done primarily by the sub-contract suppliers selected to provide the production hardware, although many studies are carried out by the airframe manufacturer.

The aim of the software package described in this paper is to support the airframe manufacturer's landing gear design activities throughout the development of the aircraft. To do this the package is capable of modelling each of the sub-systems to several levels of detail depending on the analysis being performed. Different sub-systems can be mixed in suitable combinations to create a system configuration tailored to the needs of the user. The system configurations which can be simulated are designed to support the important integration tasks and tests carried out during a development programme. The following test scenarios can be simulated:

- Drop tests which have only one landing gear leg defined with the associated bogie, wheels and tyres. This test can be conducted as a standard drop test with no forward speed and an initial wheel spin, or with a forward speed. The spin-up and shimmy characteristics can thus be extrapolated to the moving aircraft case from test scenarios. Brakes can be used on the forward moving drop test which can thereby provide a useful simple model for brake and anti-skid evaluation.
- Dynamometer tests involving a tyre, wheel and brake and braking control system loaded onto a dynamometer drum.
- Whole aircraft touchdowns can be simulated by defining an aircraft with the correct number of legs, wheels and tyres attached. This can be used to analyse full aircraft wheel spin-up characteristics, landing g loads, bounce characteristics, spoiler deployment schedules, etc.

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- Whole aircraft braking tests can be simulated with various runway characteristics. Braking and anti-skid performance can thus be analysed for a wide range of situations.
- Take-off simulations for a whole aircraft can be carried out. These can look in detail at tip-up at brake release, tail scrape on rotation, minimum unstick speeds and lateral controllability, including minimum ground control speed.
- Steering rig tests can be represented by a landing gear leg with wheels, tyres and the necessary steering actuation system.
- Whole aircraft steering simulations can be performed.

At the beginning of a project the data available for the sub-system definitions may be very limited. Nevertheless the package can be used to obtain useful results by selection of models with a suitable level of detail. As development progresses the data can be updated and the models validated against test results. Thus the software package will contribute to:

- An enhanced specification procedure and support for the initial conceptual design stage.
- Early prediction of dynamic performance and interaction between sub-systems.
- Interpretation of test results and extrapolation to cases which are not tested.
- Straightforward evaluation of proposed design modifications.

3. SOFTWARE ORGANIZATION

The software is organized as a series of individual modules that correspond to the components and sub-systems. This allows easy upgrading of any particular module, and also the capability of providing different standards of model for the same sub-system. The number of sub-systems and standards of models give the ability to analyse a very large number of possible configurations. The cases can range from, say, a single wheel/leg/oleo to a whole aircraft, with multiple main gear and nose gear. Studies can range from high frequency dynamic effects to whole aircraft take-off, landing and ground manoeuvring. The package is written in standard Fortran 77. It is self-contained and is readily adaptable to any computer operating system.

3.1 Specifying the Model Configuration

During the course of a project many levels of model may be developed and analysed. A project-oriented data base is provided to assist in the methodical build up of models and to permit the traceability of model standards. The user is able to update and modify existing files from the data base within the package, shortening the time taken to develop new models, since these can be adapted from existing ones.

Once the sub-system models have been defined the user builds up a configuration file which links the sub-system models into a viable total system model. The configuration is specified in this file by a series of command statements which reference the sub-system files to be used. Flexibility is incorporated into this command structure. For example one command can be used to specify the same tyre to be used on all four positions of a bogie. Alternatively it is possible to specify different tyres on the same bogie. In this way, a burst tyre definition could be included to assess the effect of this condition. It is also possible to specify a leg system with bogie, tyre, etc. to be based on the mirror image of one already defined, so that port and starboard legs can use the same data files. The configuration specified in the file is rigourously checked for consistency prior to any simulation runs.

An automatic trim routine is provided that establishes the appropriate initial conditions prior to the start of a run. This can be in the air or on the ground, and ensures that the response does not include any unwanted starting transients. The trim procedure is generalized and will cater for all combinations of modules without requiring any special set-up procedure.

For the larger scale simulations there is potentially a very large number of possible output parameters. These are all available to the user, but normally a smaller set would be selected as being of most interest, and these can be plotted for analysis. Once a simulation configuration is set up the inputs and timing of the run can be specified and the case executed on-line or in batch mode. Events which act as inputs to the simulation during a run, such as runway profile and friction (e.g. wet runway), speed brake deployment, reverse thrust, can be scheduled with time, distance or speed, as appropriate. Upon completion of a run the required output is stored together with a file which logs the configuration and associated initial conditions to give complete traceability.

3.2 Total System Integration

Before carrying out a simulation run a series of preliminary operations are carried out. This sets up the input data, calculates constants, and calculates the aircraft and leg dynamic equation coefficients. The leg dynamic equation matrices are linked to the aircraft matrices by suitable boundary and compatibility conditions. However, it is simpler to preserve each of the sub-system models in their own axis set. This means that the off-diagonal matrix blocks containing the couplings between the aircraft and leg structure sub-system models also incorporate axis transformations between the leg axis systems and the aircraft axis system. These constants and matrices are then passed to the simulation.

Each sub-system model code incorporates the appropriate options for the modelling level. The different data required by different sub-systems of the same type, for example main and nose legs, are accessed within each model by vectorization of all the parameters. State variables and their derivatives are stored in vectors for access by the integration routine.

The primary objective is the evaluation of response time histories to a range of external input excitations. The physical nature of a landing gear assembly does not lend itself readily to linear analysis, and many of the problems arising in design tend to be related to nonlinear characteristics. However, the dynamic properties of many of the sub-systems can be assessed by linear analysis. For either case, a facility is available to produce a set of linear state space matrices at any operating point by small perturbations in each of the states. These matrices can then be used for standard classical linear analysis in other software external to the main package.

3.3 Time Response Evaluation

Since the system contains many nonlinearities the most appropriate technique for implementing the simulation is in the time domain using numerical integration. The dynamic equations of the sub-systems form a set of nonlinear differential equations, which are arranged in a first order form. For a particular case, whether a sub-system or an assembly of components up to the whole aircraft, the appropriate first order equation sets are automatically concatenated to define a single state derivative vector. The primary numerical integration method within the software package is a standard fourth order fixed step Runge-Kutta algorithm. This routine was found to give the best compromise between accuracy and run time, although a number of other integration techniques, including variable step, are available within the package.

Each of the inertial sub-systems is evaluated in its own body axis reference frame. Determination of the total inertial motion of these systems involves two stages:

- Using the velocities and displacements from the integration of the state derivatives the equivalent variables of the sub-systems are calculated by transformations to appropriate axis frames from the aircraft downwards. This enables the calculation of the positions, orientation and velocities of the tyres in the axis system, which allows the calculation of the forces induced by the tyre motion.
- The tyre forces are then used via appropriate transformations to calculate the forces on the oleo, bogie, leg and aircraft, to determine a consistent set of state derivatives for the complete model.

4. SUB-SYSTEM MODELS

For a particular simulation run a model is built up by the user from a number of sub-system models. These sub-system models have been designed as far as possible to be generic, so that by appropriate choices a specific configuration can be simulated. So far the classes of sub-system represented are typical of large transport aircraft, since this was the immediate application for the work. Major advantages of this approach are that the models can be set up relatively quickly, simplifying assumptions can be made by users in the early stages of a project and proposed solutions to problems can be formulated and analysed without requiring detailed design information.

4.1 Aircraft Model

The runway forces are transmitted through the landing gear assembly to the airframe. The inertia of the aircraft and the aerodynamic forces acting on it are represented in different ways, depending on the type of analysis to be carried out. The three models currently available are:

- A simple mass corresponding to the proportion of the aircraft mass on a single leg. Horizontal and vertical freedoms are allowed for simulation of braking, dynamometer and drop tests. An external vertical force can be applied, which is programmed as a function of time.
- A three degree-of-freedom longitudinal aircraft model for studies of take-off, landing and braking. In this case the assumption of symmetry is used to lock out lateral degrees-of-freedom, thereby avoiding unnecessary computation. Linear longitudinal aerodynamics are included, with spoiler and elevator inputs, and different flap settings can be specified.
- A five degree-of-freedom aircraft model intended for low speed steering simulation. Roll freedom is not included at present and will be added in future development. Linear aerodynamics are used and inputs can be spoilers, elevator and nose wheel steering.

In the last two of these the aircraft can be selected as a rigid body or as a flexible aircraft with the first six simple wing/fuselage vertical bending and fuselage torsion modes represented. A full six degree of freedom model is planned which will incorporate lateral as well as longitudinal controls. In later development it is proposed to link the software package with full flutter and dynamic load models of the airframe, symmetric and antisymmetric. These will provide accelerations to permit assessment of crew and passenger ride quality.

The whole aircraft cases can be trimmed with either a specified rate of descent and pitch angle or a specified rate of descent and forward velocity. Sideslip and roll angles can be specified for asymmetric landing cases. The required aerodynamic control angles and engine thrust are calculated by the trimming routine for run initialization, whether in the air or on the ground.

4.2 Leg Structure Model

The generic model developed for the leg structure was formulated for a typical large civil transport aircraft. An example of such a leg is shown in Figure 1. For relatively long legs flexibilities can be significant and the lower modal frequencies can be well within the range of interest of the model, and should be included. The flexible modes can influence the loads experienced in the leg and aircraft, and they are essential to the evaluation of shimmy modes and other sub-system interactions.

To allow for a wide range of possible configurations a simple finite element model has been built in to the package to represent the leg structure. The first stage of formulating the model is the calculation of the mass and stiffness matrices for a stack of beam finite elements(1), representing the top (fixed tube) and the bottom (sliding tube) of the leg. Each element node has five degrees of freedom. The sixth (axial) freedom is not included since this is assumed to be dominated by the oleo, which is calculated in a separate sub-system model. The mass and stiffness matrices for the basic leg are calculated from basic geometric data entered by the user. These matrices are then augmented by further beam elements representing a built-in stay, two rod elements with only axial compression freedom representing the pin-jointed stay with a fold joint, and a special torque link element which carries the torsional load between the upper and lower legs. The user has complete freedom to specify the size, stiffness and orientation of these components within the appropriate data file.

Once the complete leg mass and stiffness matrices have been formulated in this way the equations are transformed into the principal modal coordinates. The dynamic equations are thereby more efficiently solved within the total system model by numerical integration of the diagonal form. Since it is unnecessary and computationally inefficient to include all the leg modes, a modal reduction procedure is employed to eliminate unwanted modes. The user is able to select from zero (i.e. a rigid leg) up to five modes. The discarded modes are removed by simple row and column deletion, but their static distortions are retained by including them in the transformation from modal coordinates into the leg displacement coordinates during evaluation of the dynamic responses. This is equivalent to assuming that the higher frequency modes respond without any lags. Finally a diagonal principal damping matrix is added to the reduced structural model.

Leg models are formulated in this way for several oleo closure positions. During a simulation run the mass, damping and stiffness matrices used for a particular oleo closure position are determined by linear interpolation between these models.

4.3 Oleos

Modelling of the oleo requires consideration of the hydraulic and pneumatic stiffness and damping characteristics. There are many possible arrangements for oleos which give different damping properties. Two forms of model are provided to cater for this.

The first model is a development of the hydraulic equations for a standard single stage oleo(2), a schematic of which is given in Figure 2. Hydraulic fluid flow through compression and recoil orifices are modelled together with the adiabatic gas compression. The user enters the orifice sizes, volumes, piston areas and fluid properties as basic data defining the model. The pre-processor section of the code evaluates the equations for the data values given and produces look-up tables for damping vs. velocity and stiffness vs. displacement. This makes the running of the dynamic equation code more efficient than evaluating the basic equations at each cycle of the numerical integration.

Alternatively the user may elect to enter the look-up tables directly, to investigate more complex arrangements. Inclusion of displacement as well as velocity in the damping look-up table allows variable damping with displacement such as might be obtained when a needle valve is used to control damping. This modelling allows investigation of different damping and stiffness curves without the need to specify the physical configuration. In this way design studies can be conducted relatively simply.

Seal friction and load-dependent friction are included in the model to get the correct representation of stiction breakout. This is particularly important when considering low force inputs below the breakout level which increase the vertical stiffness of the gear to that obtained from the tyres.

4.4 Bogie

A four wheel bogie model is provided which evaluates the motion of the bogie beam. The rotation of the bogie is restrained by either a pitch damper or an actuator acting through a linkage. A typical arrangement of a pitch damper and its linkage is shown in Figure 3. The method used for bogie restraint can introduce significant nonlinearities into the bogie equations of motion. Two arrangements are modelled; a standard damper system and a more advanced pressurized hydraulic actuator system. Only rigid motions are included at present, but a flexible model of the bogie is under development. Also, a simple two-wheel configuration is included, which is essentially a simplified version of the bogie model.

4.5 Brakes and Wheels

Each tyre, wheel and brake is represented individually within the simulation. An illustration of a typical braking arrangement is given in Figure 4. The mathematical model of the brake and wheel is based on the work described in References 3, 4 and 5. This includes the hydraulic pressure acting on the brake pistons, and the brake pack, the wheel inertia and the brake stator. The wheel and stator models include the stator mode dynamics and nonlinear stiction/friction between brake and stator.

The variations of brake stack coefficient of friction with brake pressure, wheel speed and temperature are included as look-up tables. Work described by Biehl(4), showed that the friction vs. speed characteristic of the brake has a dominant role in the excitation of "squeal" (stator vibration) and "chatter" (leg walk) modes. Validation work with dynamometer tests illustrated further that brake friction was also a combined function of brake pressure and brake temperature (or energy absorbed, since the two are closely related). The former of these effects is due to brake distortion under load, causing a reduction in the effective brake radius. The latter is due to the influence of temperature on the material friction properties. Since neither of these effects is easily predictable the brake friction properties were derived empirically from test results. A first order lag model of the temperature variation during braking is used to allow the coefficient of friction to vary realistically without the need for a full thermal model.

4.6 Braking Servo and Control System

The brake actuators for each wheel are driven by electro-hydraulic brake control servo systems, each of which is controlled by an anti-skid system(6,7). A basic anti-skid system model is included, but, because of the wide range of proprietary anti-skid algorithms, a facility is provided for the user to code appropriate control laws directly.

A full nonlinear model of the servo system, including the hydraulic servos and their loads, is provided and is illustrated in Figure 5. Nonlinear volumetric compliance of the brake actuators due to compression of the brake pack and nonlinear modelling of the brake pressure control servo valve, including flow saturation, are included.

For reasons of safety and reliability the brake pressure control valve is often mounted high on the leg. The long pipe from the brake pressure control valve to the actuator can lead to significant hydraulic transmission line dynamics within the frequency range of interest and consequently these have been included in the model. This was achieved using the so called "method of characteristics", a finite difference modelling approach described by Streeter(8). This technique accurately simulates the transmission delays and pressure wave reflections within the brake pipe. These finite difference equations are interfaced with the continuous time equations via the boundary condition equations for the pipe. A detailed model of the brake actuator supply gallery with pressure balancing orifices is provided, mainly for detailed brake investigations such as might be conducted using the simulation of the dynamometer system.

4.7 Steering Actuation and Control System

Steering commands from the pilot system are applied as inputs to the steering control and actuation system. The steering system model includes the steering servo-system, the hydraulic circuit and the actuation linkage geometry. The model enables inputs to be made from simulated handwheel or rudder pedal inputs, both of which are gain scheduled with aircraft speed. A castoring mode is also included.

Two alternative actuation systems are provided. The first is a push-pull actuation system, as illustrated in Figure 6. The second is a rack and pinion arrangement. The steering model includes the servo valves, nonlinear shimmy damper valve and hydraulic actuators, with the tyre and leg loading included. A schematic diagram of the steering servo loop is given in Figure 7.

4.8 Tyres

A key requirement of the tyre model is the capability to model the shimmy phenomenon(9,10). This is an oscillatory wheel mode induced by a mechanism similar to that of a wing in flutter. Essentially the phenomenon is due to the presence of flexibility between tyre footprint and the wheel plane. Other factors such as wheel speed, tyre geometry and wheel torsional constraint have a contributing effect. The shimmy mode is important not only because it can lead to dynamic stability problems, but also because it is a significant factor in determining the dynamic leg loads.

The shimmy mode model is based on the work of Stevens(10), in which the equations of motion of the tyre footprint over the ground are expressed in terms of tyre yaw velocity, forward speed and two tyre relaxation constants. Assuming the tyre is a linear elastic toroidal membrane, the relaxation constants can be estimated in terms of the basic tyre properties. The equations in this form can be expressed as a second order equation in the tyre sideslip velocity, in which the forward speed appears as a factor. The dependence of the roots of the equations on forward speed are thus evident. These equations are coupled to the motions of the leg by the inclusion of the leg rate of angular distortion in the tyre yaw velocity.

The tyre model includes the correlations of Smiley and Horne(11), so that cross-ply tyre stiffnesses can be estimated from such basic tyre properties as radius and pressure. Since these data are not applicable to modern radial tyres the ability to include manufacturer's data is included. Tyre bottoming and rebound can also be simulated.

The shimmy equations determine the lateral motions of the tyres. Rolling resistance and friction coefficient vs. slip ratio are required to calculate the drag forces arising from the tyre motion. These data can be included in the tyre definition. However, standard data can also be used(12,13,14). Tyre runway surface friction characteristics can be varied during a simulation to represent wet runway and other surface effects. Drag loads due to tyre spin-up are also included.

Since the model can include leg roll angles the loads on the tyres on opposite sides of the leg may be different, implying a need to model individual tyre radii. The accuracy of this aspect of the model is improved by including centrifugal growth effects due to tyre rotational speed and the effect of braking on tyre radius. The asymmetric loads inherent in the leg can be modelled more accurately by taking these effects into account, particularly in cases where there is asymmetric spin up.

4.9 Runway Profile

Landing gear are required to be able to ride over bumps without imposing high loads on the aircraft and to provide good ride in the presence of surface roughness. To allow for an analysis of this, two kinds of input are provided. The first input type is a variation from a flat runway. This can incorporate discrete obstacles and sinusoidal profiles to act as input to the leg forces. Each tyre can be subjected to an individual runway profile, or to the same profile. The correct modelling of the spacial positioning of the tyres relative to the runway profile ensures the correct timing of the encounters with the bumps by each tyre.

The tyre motion over the runway profile is calculated using a "stylus" model for the tyre radius, which ignores the actual geometry of tyre indentations due to the surface profile. The consequence of this is that bumps below a certain speed-dependent length cannot be resolved accurately. To cater for higher frequency, lower amplitude inputs, a low amplitude oscillatory load can be applied to the wheel axles to match test data or to assess ride quality.

5. VALIDATION

Throughout the development of the software package a high level of attention has been given to validating the simulation against actual sub-system or aircraft test results. For the most part this has been aimed at current aircraft development programmes and so has focused on rig tests carried out by the sub-system suppliers. For those aspects of the software that relate to prediction of characteristics where no test data are available, results from earlier aircraft programmes have been used.

The first stage of validation carried out was to set up and run a drop test simulation of a single leg assembly, for two aircraft types, main and nose gear, for a range of speeds and weights. This was followed by dynamometer test cases, with and without the anti-skid control system operating. Here empirical brake friction data were used to obtain accurate results. Steering rig tests were used to validate the steering system model, including the actuation system and control laws. Several full aircraft simulations were run and compared with actual flight test results. These included take-off rotation, touchdown and braking to a stop for a range of flight conditions.

Wherever appropriate the lessons learned from the validation exercises have been incorporated into the software. This has been done with a view to gaining insight into the factors affecting fidelity, so that the lessons have general application rather than simply for a particular test case. In all cases the validation exercises proved very satisfactory. There is a good level of confidence in the current software standard and continuing validation is being maintained in further developments.

6. TYPICAL RESULTS

To illustrate the usage of the model a series of example simulations has been carried out. These show the build up of the test scenarios from simulations of hardware tests to simulation of the whole aircraft. The examples are based on a typical large commercial transport aircraft with two main landing gear, each with a four wheel bogie and an offset side stay, and a nose gear. A simple antiskid system, based on the Mark II controller of Hirzel(6), is used. Its performance is not ideal, but it illustrates brake cycling and dynamic interactions with the leg modes at low speed. These features have been deliberately introduced into the example simulations to illustrate some of the capabilities of the software.

6.1 Drop Test

Figure 8 shows a simulation of a drop test of the main landing gear, which is representative of the design limit load test required by JAR Part 25. For this test half the aircraft mass is attached at the top of the landing gear, with a lift force applied equal to the weight. Initially the simulation is trimmed to a specified steady descent velocity with the wheels spun up to match the assumed aircraft speed. At the time of impact the wheels begin to spin down, inducing drag loads in the landing gear structure, which excite the leg vibration modes. On the configuration analysed here the offset side stay causes a coupling of the fore and aft, lateral and torsional vibration modes of the leg, which are in turn influenced by the shimmy mode. A simulation of this type may be used for a number of studies, such as drag load prediction or leg vibration analysis, which involve interaction between the sub-systems.

By using the data from this simulation, oleo energy absorption characteristics and efficiency can also be analysed. This can be best illustrated by cross-plotting vertical reaction force with oleo closure, as shown in Figure 9. The area enclosed by the curve is the energy absorbed by the oleo over the compression-recoil cycle. The efficiency of the energy absorption is improved the closer the shape of this curve approaches a rectangle.

6.2 Dynamometer Test

Dynamometer tests are carried out to evaluate and optimize the performance of the braking and anti-skid systems over a range of operating conditions. Figure 10 shows a simulation of such a test. A single wheel is forced onto a rotating drum, which has an inertia and contact speed representative of the aircraft. The energy of the drum is then absorbed by application of the brakes. The wheel is held in supports that are arranged to have a fore and aft stiffness similar to that of the landing gear leg. From the initial assumed speed of 73 m/s the run is allowed to proceed for a period of 1 second before the brakes are applied. A region of low tyre-to-dynamometer friction is introduced after an equivalent distance of 300 m, representing a 100 m stretch of wet runway, to which the anti-skid system responds. The simple anti-skid system used here begins to cycle towards the end of the run because it is velocity-sensitive and thus susceptible to skidding at low speed. As the dynamometer comes to a halt a longitudinal leg walk vibration is induced, as described in Section 4.5.

6.3 Single Leg with Braking

Although the dynamometer test provides a good indication of the operation of a single wheel in isolation it does not give a view of the more complex situation of a four wheel bogie. In order to assess this case the relevant sub-system models are combined to set up a simulation of a single landing gear during a landing roll-out with braking. This enables the study of a complete leg with braking, without needing the full aircraft model. An example is shown in Figure 11. The system is trimmed on the ground to a steady forward speed of 73 m/s and brakes are applied after 0.5 seconds. As before, a region of low tyre-runway friction representing wet runway is introduced and the anti-skid system responds. Anti-skid cycling and leg walk vibrations can be seen, with full coupling between the leg motions being evident.

6.4 Whole Aircraft Landing and Braking

Figure 12 shows a simulation of the whole aircraft, starting in flight, proceeding through touchdown, and braking to a stop with anti-skid. Spoilers and reverse thrust are deployed on fixed schedules during roll-out. A 100 m stretch of wet runway is set up after the reverse thrust is completed. There are 350 possible outputs, of which 40 are shown in the figure. This type of simulation is useful in that it enables a complete view of the aircraft landing and braking performance. The range of outputs selected can include whole aircraft parameters as well as detailed system parameters, and this is illustated by the selection given here.

The main gear landing impact occurs about 0.5 seconds into the run, followed by de-rotation and nose gear contact at about 4.5 seconds. Angle of attack drops quickly and becomes erratic as the airspeed approaches zero. The leg vibration following touchdown is similar in amplitude to that in the drop test, although some differences are evident, mainly due to the aircraft rotation and lift characteristics. The braking response is similar to that in the single leg braking case, with the effects of the wet runway and the anti-skid system cycling showing on the brake torque. As before, a leg walk mode is excited as the aircraft comes to a stop.

7. CONCLUSION

Design, development and integration of an aircraft landing gear can be aided significantly by use of computer simulation. For a simulation capability to be suitable for use in a major aircraft project it must be produced to a high standard of fidelity in all areas that can influence the static and dynamic performance. Also it must be validated against previous rig or flight test results both at component and assembly levels. Such a simulation capability has been described herein and the results given show typical responses that can be generated for a range of realistic cases. All system parameters have been generalized to a high degree, permitting rapid assessment of the impact of design changes on all aspects of landing gear performance for either the sub-systems or in the whole aircraft environment.

Future development of the software package is planned to continue from the present position. The intention is to improve the overall capability and the relevance to a broader range of aircraft types. The areas that are considered important include symmetric and antisymmetric flexible aircraft dynamic load models, full six degree-of-freedom nonlinear aerodynamics in ground effect for the rigid aircraft models, and relevant aircraft systems, such as the hydraulic supply and the flight control system.

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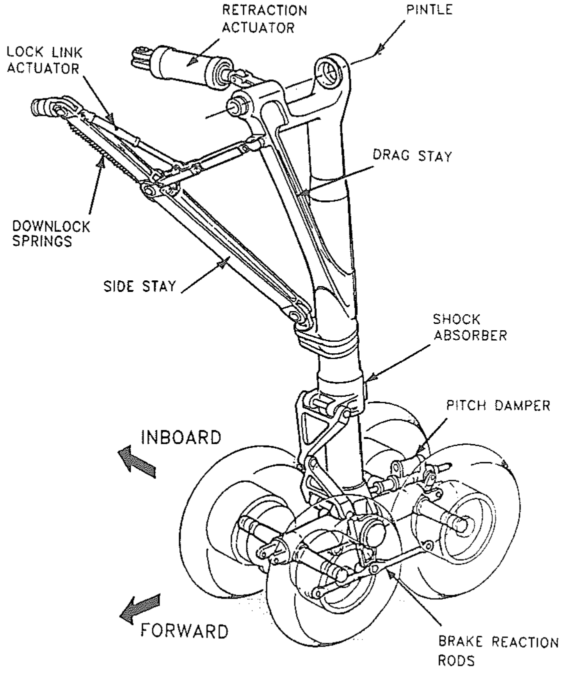

FIG. 1 TYPICAL MAIN LANDING GEAR

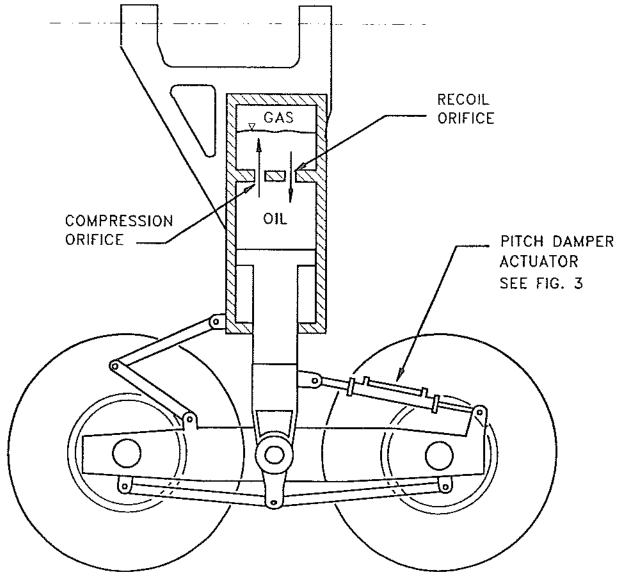

FIG. 2 MAIN LANDING GEAR SCHEMATIC

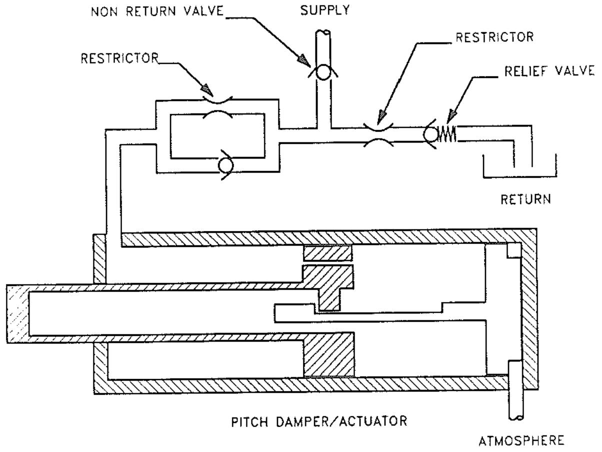

FIG. 3 BOGIE PITCH DAMPER SCHEMATIC

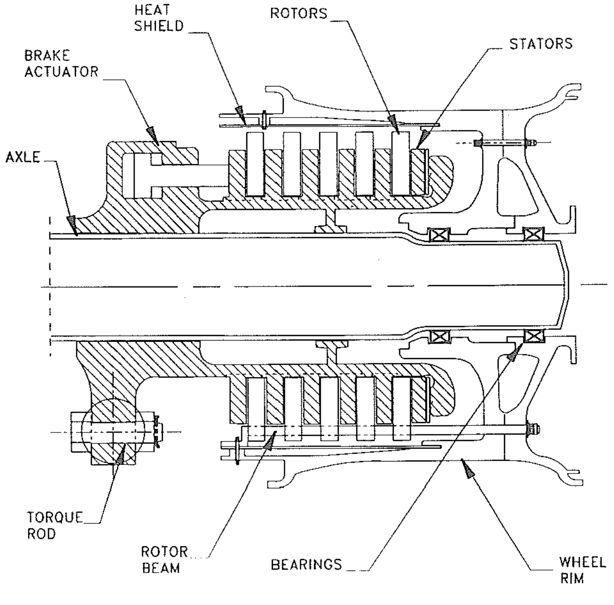

FIG. 4 WHEEL AND BRAKE ARRANGEMENT

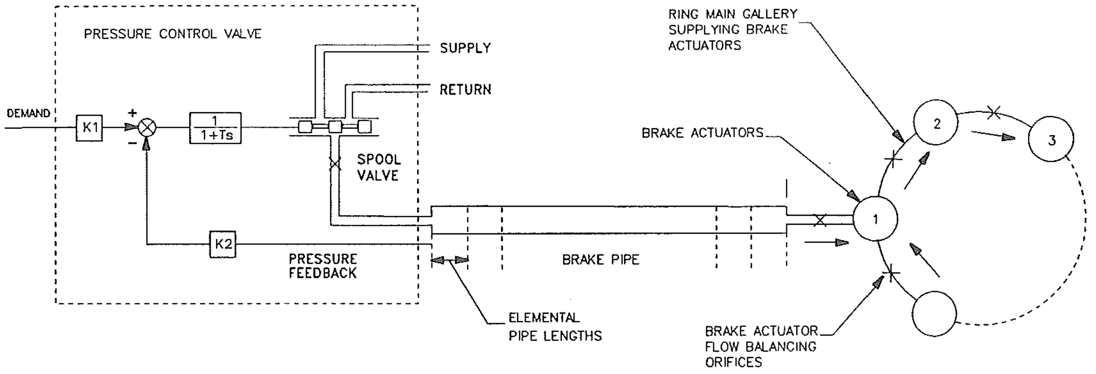

FIG. 5 BRAKE SERVO CONTROL SYSTEM SCHEMATIC

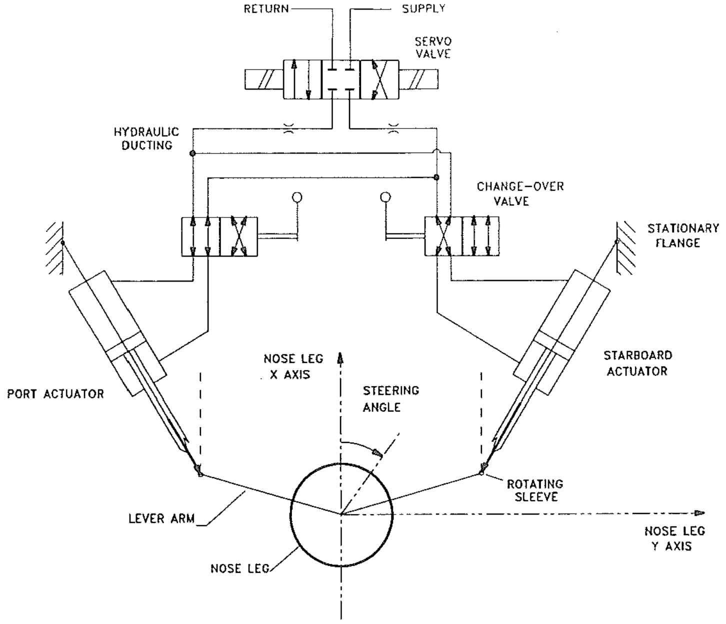

FIG. 6 STEERING ACTUATION SYSTEM

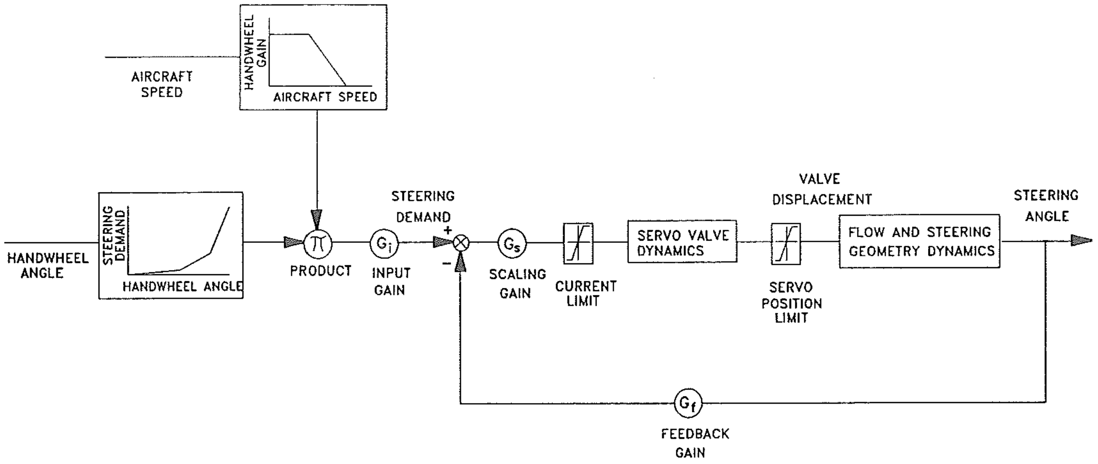

FIG. 7 STEERING SERVO LOOP BLOCK DIAGRAM

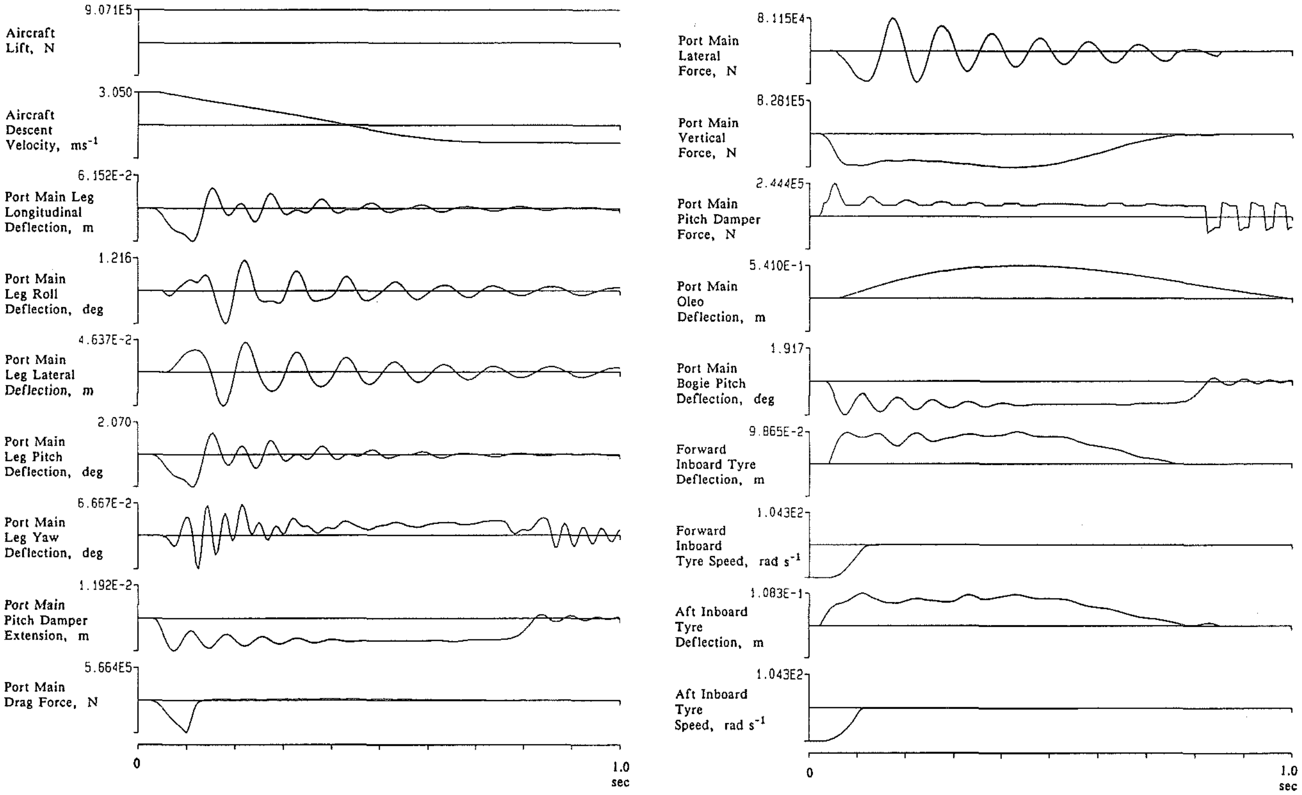

FIG. 8 MAIN GEAR DROP TEST

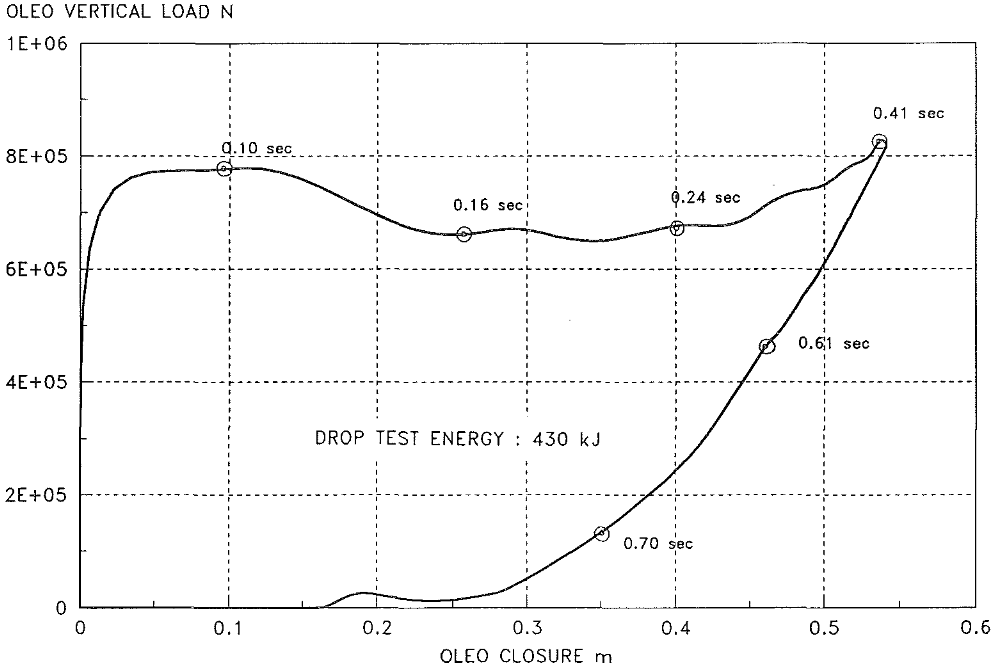

FIG. 9 LANDING GEAR ENERGY ABSORPTION CURVE

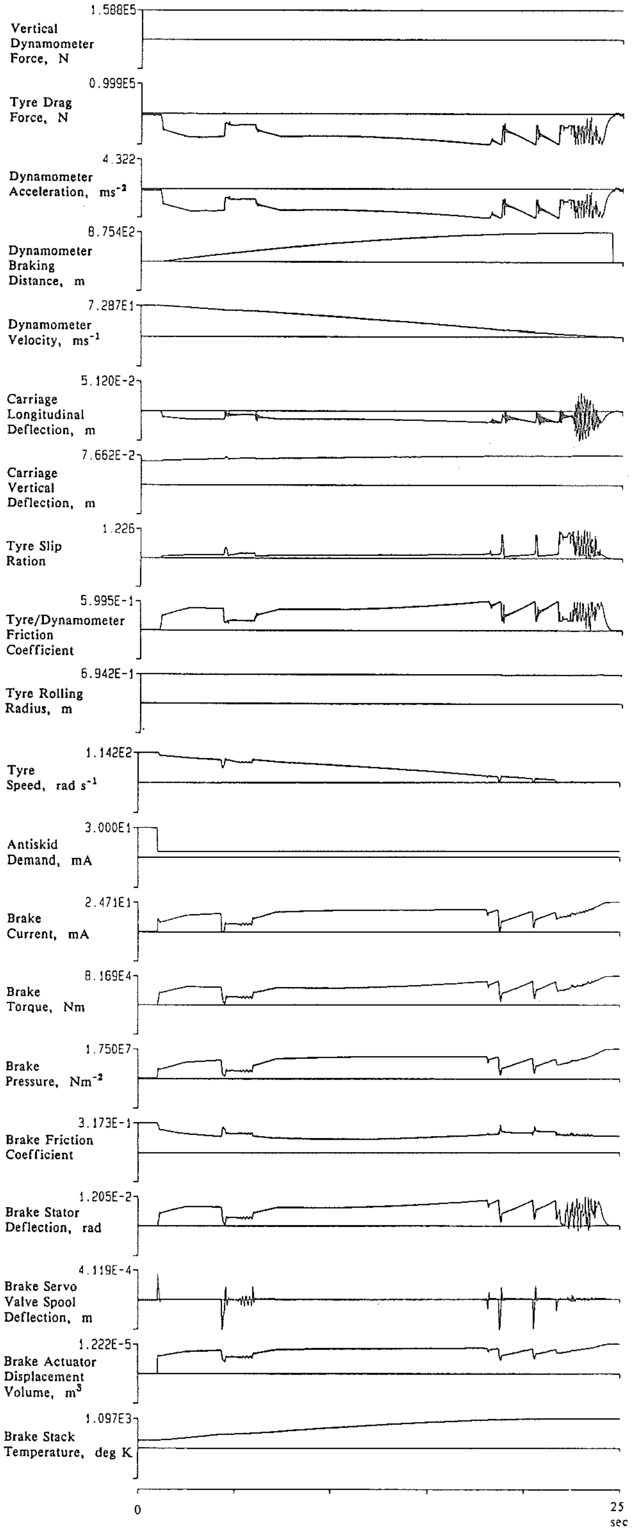

FIG. 10 SINGLE WHEEL DYNAMOMETER TEST

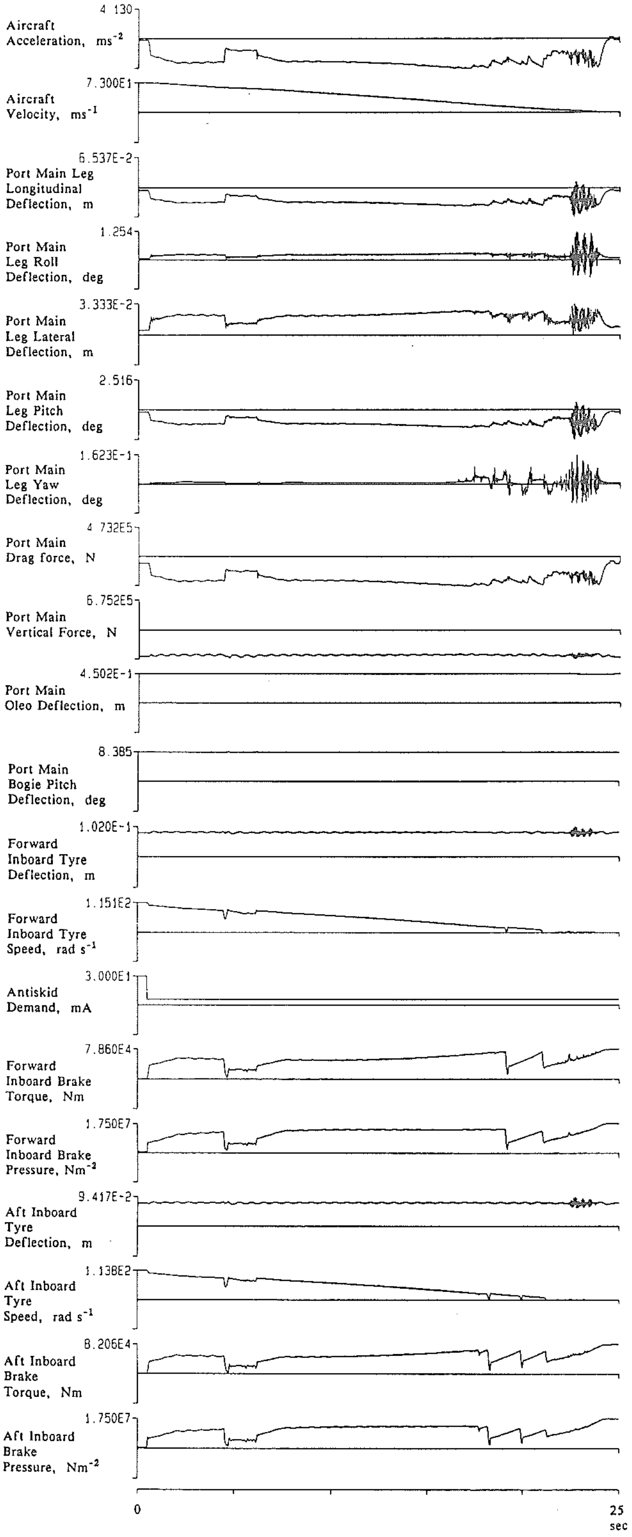

FIG. 11 SINGLE LEG AND BOGIE WITH BRAKING

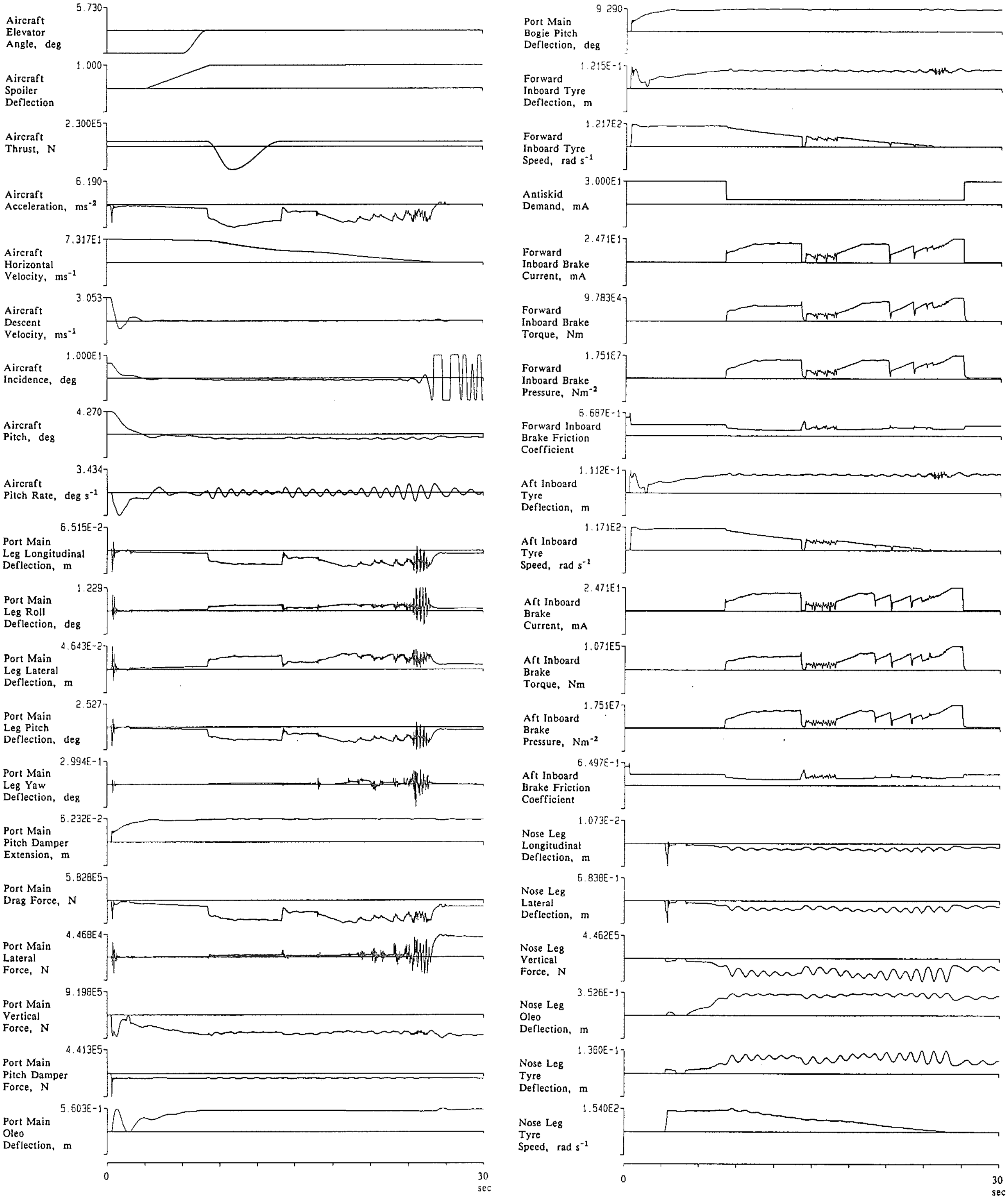

FIG. 12 WHOLE AIRCRAFT LANDING AND BRAKING