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SEMI-ACTIVE CONTROLLED SHOCK ABSORBER FOR LARGE FLEXIBLE AIRCRAFT

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Abstract

The development of aircraft landing gears has lead from simple bicycle-type wheels supported on rubber-and-spring devices to oleopneumatic shock absorbers with fixed nonlinear characteristics. Concepts for future landing gears provide solutions with actively or semi-actively controlled shock absorbers for load alleviation and enhanced ride comfort.

Aircraft dynamic loads and vibrations resulting from landing impact and from runway and taxiway unevenness are recognized as significant factors in causing fatigue damage, dynamic stress on the airframe, crew and passenger discomfort, and control problems to the pilot during ground operations. The application of active-control technology to the landing gears is a method for improving operational characteristics and to reduce ground loads applied to the airframe. Conventional design improvements showed only small improvements.

Thus the concept of an active landing gear for improved ground roll is evaluated. It was decided to investigate a semi-active nose landing gear. This layout promises low weight penalties from additionally required parts and low system complexity compared to other non-conventional solutions. The controller is designed using a multibody model-based multi-objective parameter optimization process. A detailed and verified mechanical model is derived for an existing aircraft (Airbus A 300).

The simulation was performed within SIMPACK, DLR's prime multibody computer code. SIMPACK has the major features to allow for arbitrary complex elastic mechanical systems including active components.

The optimized design was compared with the conventional production landing gear. A general performance gain can be seen for the whole frequency band under consideration with the biggest amelioration between 3 and 4 Hertz.

Introduction

Landing Gear Requirements

Among the numerous complex components that make up an aircraft the landing gear is often regarded only as a bothersome, but necessary attachment. It must not be forgotten that, while the predominant task of an aircraft is without doubt to fly with the best performance achievable, it will also spend a good part of its life on the ground. Typical cases are taxiing as well as take-off and landing. According to today's airlines' specifications an aircraft should reach up to 90 000 take-offs and landings as well as 500 000 km of ground roll during its life time. Statistics also show that accidents prior to or directly after take-off and touchdown relate their fair share (more than 50%) to the overall numbers. Hence, the importance of aircraft ground handling and therefore of landing gear design should not be underestimated.

Tests on life-size aircraft are obviously expensive and risky, and tests on test-rigs (namely drop-test facilities) allow only limited deduction of information about the landing gear's dynamics; especially the interaction between aircraft and landing gear is difficult to assess. On the contrary, simulation offers a means to examine the behavior of the airplane as a complex system in its environment at a reasonable cost.

The conventional landing gear type for large aircraft, consisting of a set of tires, sometimes a bogie, and almost always an oleo pneumatic shock absorber (often abbreviated as "oleo") today is a highly sophisticated device that leaves only limited room for improvement. With the advent of microelectronics both in digital computers and in controller development the idea of a controlled landing gear gained new momentum. Both systems controlling strut stiffness and damping coefficient (fully active) and controlling only the damping parameters (semi-active) are subjects of current research.

The landing gear must on one hand absorb vertical and horizontal energy during landing impact, and on the other hand keep the aircraft in a stable position during ground maneuvers. Commercial aircraft should also provide a smooth ground ride during taxiing both for passenger comfort and safety reasons.

Landing Gear Simulation

The simulation used in the work presented in this paper was based on the Multi-Body-System (MBS) simulation tool SIMPACK. SIMPACK is *the* central MBS-tool of DLR and it is being applied there for aircraft (landing gears), robots, spacecraft structures, railway and road vehicles [1].

SIMPACK offers fast numerical analysis capabilities due to an extended $0(N)$-algorithm for tree-configured rigid body MBS. Dealing with closed loop systems the equations of motion are accompanied by a minimal set of algebraic constraint equations, resulting in a differential-algebraic description of the system.

For the examination of elastic vibration control it is of course necessary to use elastic instead of rigid bodies in the model setup. In SIMPACK the kinematics of elastic bodies as well as stress stiffening effects of elastic deformations are taken into account.

Extensive libraries of coupling elements like joints and force elements as well as excitations aid the engineer in setting up a model. This includes the kinematics of different suspension systems or other complex joints, force models for hydraulic components, various tire models etc.; subsystem modelling techniques enable the user to establish complex non-standard kinematic and force laws. User written subroutines extend the modelling options.

Landing Gear Control

Passive suspensions, mostly consisting of a spring and a damping device, today have a high standard, they suffer from a disadvantage that lies in their principle. Optimized to isolate the vehicle body from the ground best at a certain frequency range, their performance often diminishes at other frequencies. Additionally, the need to retain tire ground contact at all times poses a design conflict with comfort requirements.

For an aircraft the implications of the phenomena mentioned above is noteworthy: designed to absorb the energy of a hard landing impact, aircraft suspensions perform quite poorly in reduction of ground-induced loads during taxi and take-off. Not surprisingly, supersonic aircraft and a new generation of stretched civil transport aircraft suffer the most under ground-induced structural vibration because of their increased structural flexibility inherent in their design with slender bodies and, at supersonic aircraft, their relatively thin wings.

Active and semi-active suspensions promise a solution to this problem. An active suspension can be defined as a suspension layout which controls the forces acting in the shock absorber by control of energy dissipation, or, if required by the control law, by generating additional force. The usual means of control is a closed-loop control with a control law acting with respect to measured states (often velocities or accelerations) at certain points of reference. A suspension termed "semi-active" has the restriction that it cannot input energy into the system. Usually realized as damping control, it is therefore only able to control the amount of energy dissipation. Only forces of the same direction as that of the instantaneous relative damper velocity can be generated. Nevertheless, since fully active control systems usually require a heavy and costly force generation device (for aircraft landing gears mostly pressurized oil reservoirs have been proposed) they are unlikely to be quickly introduced in production aircraft. Semi-active suspension systems offer considerable advantages of light weight and less complicated mechanical requirements without suffering a great loss in performance.

Summarizing, the main reasons for the introduction of semi-active landing gear control are:

1. Minimize the load on the airframe structure, minimize force peak values and vibrations that can result in fatigue and reduce the life of the airframe.
2. Minimize accelerations acting on pilot and passengers since the induced vertical and horizontal accelerations and vibrations can lead to passenger discomfort and crew disorientation.

Activities

There have been several preceding efforts to the improvement of aircraft of ground ride. A typical measure to adopt the landing gear force-deflection curve toward a lower slope is the use of a two-chamber-oleo. In 1977, Somm/Straub/Kilner [2] proposed an adaptive landing gear system for several military transport aircraft to improve taxi performance on rough runways. They worked with a secondary air chamber that could be pressurized shortly after touchdown in order to generate the desired softer pneumatic spring rate as a function of aircraft weight. Today, with reliable, inexpensive and powerful electronic signal processing available, research has moved toward computerized closed-loop control. In 1984 a feasibility study for a series-hydraulic active control landing gear intended for supersonic military aircraft was published by McGehee and Morris, [3]. Additionally to theoretical analysis a number of tests had been performed on a test-rig to permit experimental verification of the concept. The setup is typical for a fully active control system and has before and since been investigated several times. The gear force applied to the airframe is regulated by the hydraulic pressure in the piston of the oleo which is used as an actuator.

Another somewhat more recent approach is the analysis of improvements gained with closed loop semi-active oleo control. Studies by Karnopp [4] for automotive applications show that the performance of a semi-active damper is only marginally smaller than that of a fully active system, provided that an adequate control law is used. Catt/Cowling/Shepherd [5] come to a similar result in a simulation study of aircraft suspensions.

Control Laws

Suitable control laws have to be robust against these changes. Several solutions to the problem exist and have been discussed thoroughly, ranging from sky-hook damping to nonlinear and adaptive control laws (for a state-of-the-art review see [6]).

For many problems the algorithms have to go further than to solely observe center of gravity motion. Other points influencing the results are maximum applicable actuator force and suspension travel limitations.

For the problem discussed in this paper, the sky-hook damping approach has been chosen.

Motivation

The Problem

Ride Comfort Assessment

The improvement of crew and passenger ride comfort will be of growing concern for manufacturers of large aircraft.

As base measurement for ride comfort assessment the vertical accelerations are widely used. Since the individual perception is additionally influenced by other factors of the biomechanical human system, scales have been developed to weight the fact that certain frequencies are perceived to be more uncomfortable than others for a given amplitude. In ISO 2631, the frequencies between 4 and 8 Hertz are denoted as the most crucial for comfort (figure 1). Ride comfort improvement has therefore to concentrate on vertical accelerations in this frequency range, measured in the cockpit and passenger compartment.

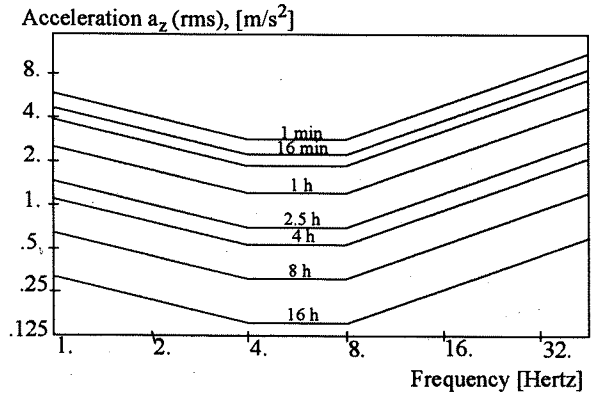

Figure 1: Fatigue-Decreased Proficiency Boundary (ISO 2631-1974(E))

Airframe Eigenfrequencies

Normal accelerations of the airframe originate in longitudinal rigid body modes as well as in elastic airframe eigenmodes.

Rigid body eigenmodes:

The important rigid body eigenmodes are found at frequencies where humans are less susceptible. The rigid airframe eigenmode of large aircraft in vertical direction is likely to be at a frequency below one Hertz, whereas the eigenfrequency of the unsprung mass (i.e. wheels, brakes, bogies), also denoted as wheel hop frequency, is found in the range above 50 Hertz.

Elastic airframe eigenmodes:

Five eigenmodes display frequencies where the human body is most sensitive, with an additional four eigenmodes in a two Hertz band above and below the critical range. A list of the rigid and flexible eigenmodes can be found in [7].

An actively controlled landing gear introduced to improve the ride quality of a large aircraft would therefore have to concentrate on reduction of vertical accelerations due to elastic body oscillations in the 4 to 8 Hertz frequency range. The excitation of these oscillations is caused by runway roughness either due to wear and tear or to other unavoidable reasons. Typical excitations used in the simulations are presented in the next chapter.

Multi-Objective Parameter Optimization using MBS Models

The design strategy for multi-objective parameter optimization is briefly sketched in figure 2. As usual the dynamic system is defined by the plant and the controller models; both are completely free and can be linear or nonlinear as appropriate.

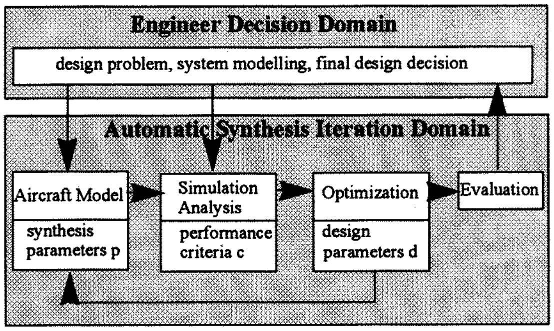

Figure 2: Synthesis Loop of Optimization

A number of so-called synthesis-parameters, $\underline{p}$, are set free within certain limits; they are "tuned" to yield an optimal design. It is indeed arbitrary whether these are some (or all) control law parameters or some parameters characterizing the mechanical system, e.g. damping or stiffness parameters of passive suspension. The various performance criteria c_i, with respect to which the parameters should be optimized (minimized), are summarized in a criteria vector:

$$c = [c_1, c_2, \ldots, c_l]^T \qquad (1)$$

The complete strategy exists of two imbedded loops. The outer loop is initialized by the system definition and the criteria. The inner loop starts on the basis of simulation and analysis initialized by a provisionary parameter vector $\underline{p}^0$ with a corresponding criteria value $\underline{c}^0$.

The desired "design-direction" is defined by a design parameter vector ("design director"), d:

$$d = [d_1, d_2, \ldots, d_l]^T \qquad (2)$$

where d_i is a chosen design command level corresponding to criterion c_i; d_i are upper limits for the desired stepwise descent of the corresponding criteria:

$$c_i(\underline{p}) \le d_i \qquad i = 1, \ldots, l \qquad (3)$$

As a design comparator for detecting "better" designs the max-function

$$\alpha = \max \frac{c_i}{d_i} \qquad i = 1, \ldots, l \qquad (4)$$

is chosen. The strategy is to find a minimum for this α in varying the synthesis parameters p:

$$\alpha^* = \min_{\underline{p}} (\alpha(\underline{p})) \qquad (5)$$

The implemented strategy does not only guarantee the monotonous descent of all criteria but also tries to solve efficiently the optimization goal for which $\alpha(p)$ is minimal. After a sufficient number of steps within the automatic synthesis iteration loop, an improved design is reached which is Pareto-optimal, i.e. no criterion can be further improved without deteriorating others.

At this stage certain decisions are possible, e.g. to change the design director in order to change the design direction. Thereby the designer gains experience which criteria can be easily improved and where the critical design conflicts (within the chosen structure) are located. Other decisions may be the change of the criteria or of the controller structure or the synthesis parameters. Within a number of such "experiments" the potentials of the chosen structure is accumulated.

The software modules and their interrelations as used for this paper are shown in figure 5. The optimizer module controls the computational process. The time domain analysis and the actual optimization and the iterative update are prosecuted here, whereas the model data of the MBS model are acquired from the MBS module.

The end product of the optimizing process, the satisfactory compromise, is then used to visualize the final model behavior.

The following chapters will cover the model setup and the optimal controller design as result of the optimization process.

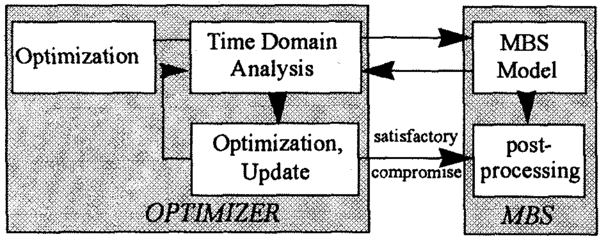

Figure 5: Software Interaction in the Multi-Body Simulation (MBS) Design Environment

Modelling

Aircraft Model Built-Up

Modelling Approach

The AIRBUS A300, which was selected for the model buildup, represents a configuration widely used for commercial airliners: two wheel nose gear, two four wheel bogie main gears, wide body fuselage, two engines and a maximum take off weight around 140 metric tons.

The literally central body of the AIRBUS model is the *wing spar frame*, the fuselage frame situated at the connection of the aft wing spars to the fuselage. It is modelled as a rigid body without mass or geometric extent. It serves as connection point between the elastic airframe bodies and the inertial reference frame. The landing gears, built up by several smaller entities, are linked up to the airframe bodies on the one side. On the other side no joints, but tire force laws form the attachment to the runway surface.

The Elastic Airframe Bodies

For the incorporation of elastic bodies, the MBS package SIMPACK contains the possibilities to include FEM and beam-like structures. For the use of the BEAM preprocessor the body is divided up into several sections with piecewise constant stiffness, damping and distributed mass. This feature and the shape of the four airframe members modelled as elastic bodies (two wings, front and aft fuselage) made its usage feasible for the A300 model.

Fuselage:

The fuselage model consists of a front fuselage part with connection to the nose landing gear and the aft fuselage part with the rigid elevator and horizontal stabilizer bodies. Both parts are linked to the wing spar frame with zero degrees of freedom joints. They are divided into five sections each. The characteristics of the fuselage were derived from design material provided by the airframe manufacturer.

Wings:

Like the fuselage, the wing is partitioned into five sections, connected to the wing spar frame on the inner side and left free on the outer. The engine is linked rigidly to the third node, the second node includes the attachment point for the main landing gear. Only bending in z is taken into account for the wing bodies.

Fed with this data, the BEAM preprocessor calculates the desired eigenmodes of the four airframe members. These eigenmodes are then used by SIMPACK to evaluate the aircraft eigenmodes implemented in the simulation. The selection of the number of eigenmodes plays an important role. High structural vibrations result in small integration stepsize and thus increase CPU work. On the other hand the SHANNON theorem determines the maximum eigenfrequency implemented in a certain model to be at least twice the maximum frequency under consideration [8]. The eigenmodes for the taxi analysis were chosen in a way to guarantee a safe analysis up to 25Hz. In figure 6, the first two fuselage bending eigenmodes are shown.

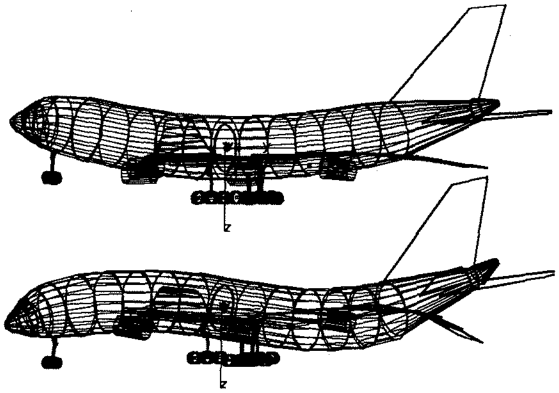

Figure 6: First and Second Fuselage Bending Eigenmode

Force Laws

To simulate the dynamic behavior of the A300 airplane, SIMPACK had to be given a set of force laws. With the aid of the relative displacements and velocities at the specified node points of the multi body system, the according forces were derived. The force laws are realized as user routines within SIMPACK and are explained in detail in [7].

Tire force law:

The tire force model has to yield the longitudinal and lateral forces and the torque moment acting between the road surface and the wheel and depending on the slip between tire and ground. Nevertheless, even with a relatively simple model, computational effort has proven to be substantial for an aircraft with ten or more wheels. Depending on the simulation case it proved to be helpful to linearize the tire behavior if possible. For an aircraft taxiing on ground without cornering or braking, a linear spring model was incorporated. The following suppositions apply:

- negligible slip (no braking),
- no side slip
- no loss of ground contact for any tire
- load variations small enough to allow linearization of deflection curve.

This tire model was used for most of the taxi simulations.

Oleo-Pneumatic Shock Absorber Force Law:

Conventional (Passive) System: as primary force generating element each aircraft landing gear is equipped with one central oleo, acting on the principle of a one stage or single slope oleo like those used in the landing gears of the A300 aircraft. The passive oleo displays two separate force generating elements, the gas chamber that generates the spring force and the set of orifices responsible for the damping force. The total oleo force is composed of a gas spring part (calculated using the general gas law), a damping part and a friction part.

Friction forces are difficult to assess and depend on a multitude of parameters. Especially for the landing impact case, longitudinal forces increase the friction and can in fact block the gear and prevent spring deflection, leading to high structural loads and even structural failure. The gas chamber pressure influences the fitting pressure on the outer oleo wall, resulting also in higher friction forces. For the taxi condition the gas pressure variation and applied x-forces remain small, so a constant friction term supplied by the landing gear manufacturer was incorporated.

Semi-Active System: the main difference between a semi-active and a conventional oleo is found in the oil orifices responsible for the damping force. To provide control over the damping force, the oil flow and thereby the damping coefficient is regulated. This can be achieved by variable diameter orifices or by implementation of a servo valve. Since the actual design may exhibit quite different oil flow regulators, but all of them control the damping coefficient, this coefficient was chosen as control variable. The control range, i.e. the maximum and minimum damping coefficient values achievable, was deliberately chosen to lie between 20 and 500% of the original value used in the conventional A300 oleo because this range was considered to be technically feasible.

Aerodynamics Force Law:

Stationary motion of an aircraft through the air results in an aerodynamic force acting on the aircraft. Taken into account the small influence of the aerodynamic forces and moments on the overall dynamics of the system, the aerodynamic force user routines were limited to the longitudinal motion. To account for non-stationary moments, the pitch damping coefficient was calculated.

Runway surface

To analyze the dynamic behavior of a general nonlinear MBS model, time histories have to be evaluated for a broad range of frequencies. The excitations used on the model should include a wide frequency range. Additionally, single frequencies of special concern might be agitated separately.

The following existing runway disturbances have been taken into account in the present investigation:

- General roughness: Especially on older airports and on airports in the countries of the former Warsaw Pact, the run- and taxiways display undulations of all frequencies and with higher amplitudes than those measured on airports in western countries, [9]. These conditions have reportedly led to dangerous situations. Pilots of aircraft equipped with Cathode Ray Displays (so called "glass cockpits") experienced difficulties to read the instruments due to vertical oscillations during the take-off run.
- Concrete Plate Deforming: A widely used method to construct fortified runways is the casting of large plates using liquid concrete. These plates are separated from each other by gaps filled with rubber. Aging of concrete runways causes the plates to settle unevenly, leading to long wavelength bumps and steps at the gaps.
- Center Line Lights: All run- and taxiways are equipped with lights indicating the middle line during night time operation. These lamps extend a few centimeters from the ground (figure 7) and exert a shock when hit by a tire. They are spaced regularly and can induce oscillations.

a: Housing Height (2... 5 cm)
b: Length (15...30 cm)
c: Spacing (5... 15 m)

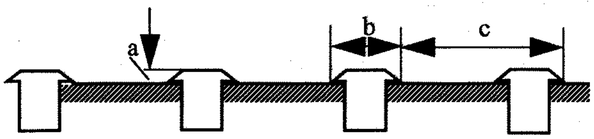

Figure 7: Center Line Light Housings in a Runway

To simulate these runway surface conditions, the following three distinct models have been programmed.

Quasi-stochastic Runway Model

Thompson [9] gave a list of a number of measured Power Spectral Densities (PSD) of runways in NATO countries. These were used to build up a deflection curve using a set of harmonic functions. The runway elevation curve resulting from this process is displayed in figure 8.

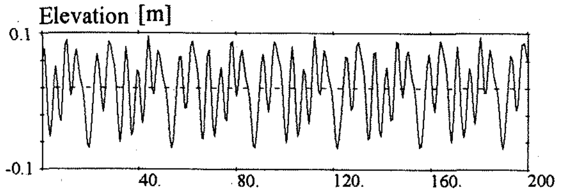

Figure 8: Quasi-stochastic Model Runway Surface

A comparison between four measured runway PSD's (thin lines) and the PSD of the implemented model runway (solid line) is shown in figure 9.

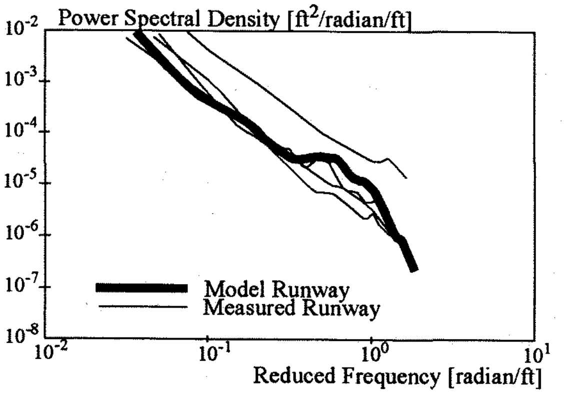

Figure 9: Power Spectral Density of Measured and Model Runway

Multiple Pulse Runway Model:

Step and pulse model inputs are especially suitable to induce a broad band of frequencies into a model. In practical ground operation, pulse inputs can result from concrete plate gaps or from center line light housings. In figure 7, a light housing built into the runway is sketched. In reality, the tire hitting the housing will deform, so that the impact of the heave motion of the bottom of the tire spring will be muffled. The multiple pulse runway model uses this kind of pulse shape. Housing dimensions and spacing are programmed as variables and are defined in the experiment model setup.

Harmonic Wave Runway Model:

The harmonic wave as excitation was included in the system analysis to perform a sort of "worst case" evaluation. With this runway model, a distinct frequency acts on the landing gear to induce potentially problematic oscillations like the main fuselage bending eigenfrequencies. A simple sinusoidal wave was used for the model. In figure 10, an example runway surface is given used for the excitation of the 3.6 Hertz fuselage bending eigenmode of the A300 at a speed of 20 m/s.

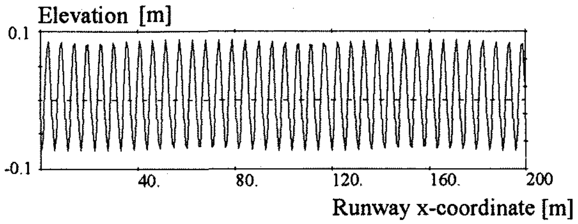

Figure 10: Harmonic Model Runway Surface

Control Concept Analysis

Control System Lay-Out

During the selection process of a control law to be implemented, the rigorous safety requirements in aircraft design have to be taken into consideration. Thus, low system complexity is one of the design drivers for the control system. A single input single output (SISO) control system requires the minimum of one sensor signal and one actuator element and was therefore chosen.

Aircraft currently in commercial operation are in part already equipped with acceleration sensors. To keep additional system requirements low, a single acceleration sensor at the cockpit position was assumed and used for the feedback signal. Figure 11 shows the resulting system lay-out.

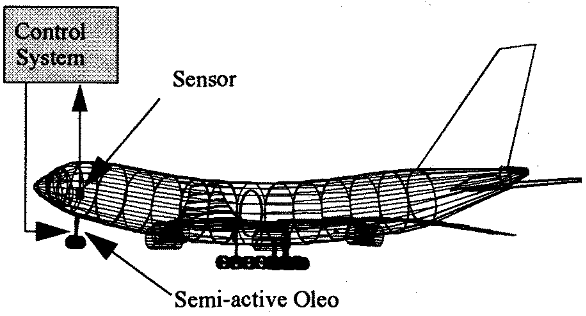

Figure 11: Control System Sensor and Actuator Location

The block diagram in figure 12 shows the general principle of the feedback system. The *Oleo Closure Rate* remains the main input for the *Landing Gear Oleo*. It determines the forces applied on the *Aircraft Structure* depending on the *Runway Profile* inputs and the *Damping Orifice Area Actuator*. The *Aircraft Response* coming from the *Aircraft Structure* is fed back using the *Sensor Signal Processing* and the control algorithm implemented in the *Controller*. The velocity feedback used as controller input

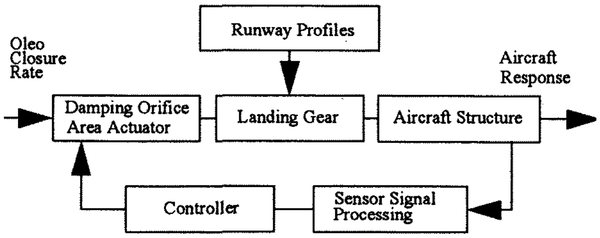

Figure 12: Control System Block Diagram

makes the chosen control concept a variation of the sky-hook approach.

Optimization Process

Criteria Selection

The goal of the implementation of a controlled nose gear is to increase passenger and pilot comfort by reduction of fuselage vibration. The criterion vector c must take into account the necessary states. The aircraft state vector Y

$$\underline{Y} = \begin{bmatrix} y_I & y_{II} & q & \dot{q} \end{bmatrix}^T \tag{1}$$

contains the states describing the aircraft motion. Here,

$$y_I = \begin{bmatrix} y_I^i \end{bmatrix}, \quad i = 1, \ldots, n_G \tag{2}$$

denotes the position states for each of the n_G joints,

$$y_{II} = \begin{bmatrix} y_{II}^i \end{bmatrix}, \quad i = 1, \ldots, n_G \tag{3}$$

stands for the velocity states of the joints,

$$q = [q^i], \quad i = 1, \ldots, n_K \tag{4}$$

describes the deformation position coordinates for each elastic body n_K and

$$\dot{q} = [\dot{q}^i], \quad i = 1, \ldots, n_K \tag{5}$$

expresses the deformation coordinates in the velocity domain. For calculation and analysis the states of several distinct locations on the elastic bodies are needed. Unlike on rigid bodies, where states of any location can easily be derived if the states of the reference system of the body are known, the states of arbitrary locations on the elastic body depend on the deformation position and velocity coordinates.

To observe all interesting eigenmode shapes it is necessary to introduce measurements of suitable locations on all elastic bodies (fuselage and wings). For example, the first fuselage bending mode can be observed by measurements in the far front or far rear end of the fuselage, whereas for the second eigenmode additional information is needed from stations between the front and the center of gravity of the aircraft. As a compromise between the resolution of high frequency eigenmodes and simulation time, 16 locations have been selected on the A300 airframe.

The semi-active landing gear influences primarily the vertical motion of the aircraft. Vertical acceleration was therefore picked as criterion state to be measured. The Root Mean Square (RMS) value is calculated using

$$c_{i,\,RMS} = \sqrt{\int_{t_0}^{t_e} (\ddot{x}_z - \ddot{x}_m)^2 \, dt} \tag{6}$$

with

x_z = vertical acceleration at sensor i

x_m = reference value for acceleration evaluation, to be set by operator

$c_{i,RMS}$ = RMS-criterion for sensor i

t_0 = start of time integration interval

t_e = end of time integration interval

Besides the Root Mean Square value (RMS value), which rates amplitudes and their duration time, peak values are includes as well:

$$c_{i,\,peak} = \max(\mathrm{abs}(\ddot{x}_z - \ddot{x}_m)) \tag{7}$$

where $c_{i,peak}$ denotes the peak-criterion value.

With this double criterion strategy, a trade-in of low RMS values for very high but short peaks is avoided. RMS values and peak values of all sensors were weighted equally, with slight emphasis on the front fuselage part.

Optimization Method

The numerical procedure used to solve this nonlinear multi objective multi parameter optimization problem is based on the technique of Sequential Quadratic Programming (SQP) described in [10]. The aim is to determine a set of parameters p in a way that minimizes a cost function $f(x)$ under consideration of different equality and inequality constraints $g(x)$. The general form of the cost function can be stated as

$$f(x) = \min \; ; \quad x \in \Re^n \tag{8}$$

with the constraints

$$g_j(\underline{x}) = 0 \quad ; \quad j = 1, 2, \ldots, m_G \tag{9}$$

$$g_j(\underline{x}) \geq 0 \quad ; \quad j = m_G + 1, 2, \ldots, m \tag{10}$$

and the parameter domain boundaries

$$\underline{x}_o \geq \underline{x} \geq \underline{x}_u \tag{11}$$

Cost function and constraints have to be continuous, but no specific structure is required. For the acceleration minimization, the cost function can now be stated as

$$\sum_{i=1}^{16} \sqrt{\int_{t_0}^{t_e} \left(\ddot{x}_z - \ddot{x}_{m_{RMS}}\right)^2 dt} + \sum_{i=1}^{16} \max\left(\mathrm{abs}\left(\ddot{x}_z - \ddot{x}_{m_{peak}}\right)\right) = \min \tag{12}$$

The acceleration itself is determined as

$$\ddot{x}_z = f(\dot{x}(t), x(t), u(t)) \tag{13}$$

with

$$u(t) = f(p, t) \tag{14}$$

where $u(t)$ stands for the model input, a function dependent on time t and the controller parameters p.

To derive the free system parameters, the optimization strategy shown in figure 13 was used. The system was subjected to the three different excitation cases which were described earlier. In the following step, a complete and self-contained simulation run of the nonlinear model was performed for each excitation case. The criteria were evaluated using the steady state time response. After being weighted with the design parameters d, the optimization run was evaluated and the next optimization run initiated using changed parameters.

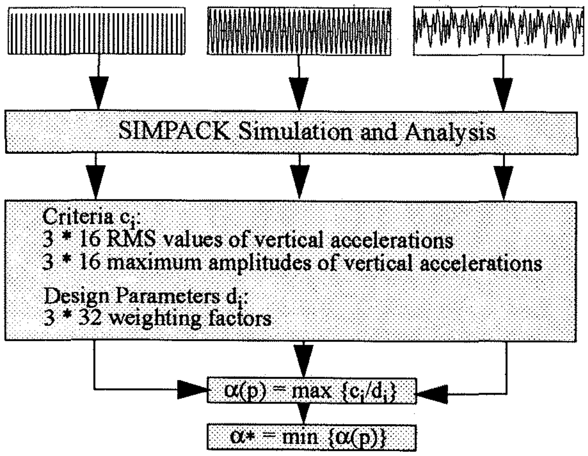

Figure 13: Multi Model Optimization Process

Results

Final Design Evaluation

The optimization process described above was used to derive a set of controller parameters best suited to minimize the design parameters d_i. On the following pages the system performance using those controller parameters is shown for the three excitation cases. The performance is subsequently compared with that of the original conventional type landing gear. A complete presentation and discussion of the results can be found in [7].

Quasistochastic Excitation Performance

In figure 14 the vertical cockpit acceleration response of both the conventional gear (thin line) and the semi-active gear (bold line) in the time domain are shown for a total simulation time of five seconds. The system state at the beginning of the simulation was determined by a pre-analysis time integration to guarantee a steady state response throughout the whole analysis period. It can be seen that no fading oscillations are present. The controlled gear,performs well, the amplitudes of the acceleration are diminished by a factor of five.

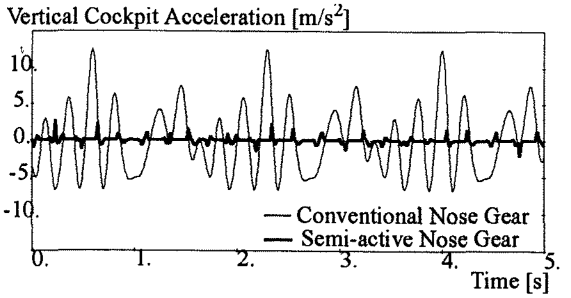

Figure 14: Time Domain Response for Quasistochastic Excitation

The power spectral density (PSD) of the cockpit accelerations of this time history, shown in figure 15 for the frequency range from 0.1 to 30 Hertz, displays significant improvements over the whole frequency range. The influence of the semi-active gear can especially be seen for the first fuselage bending eigenmode at 3.6 Hertz and for the second symmetric and antimetric wing bending eigenmode at 5.6 and 5.7 Hertz, respectively.

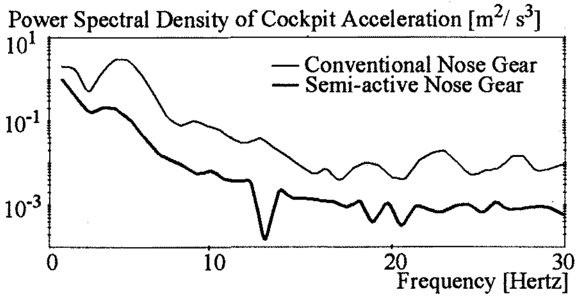

Figure 15: Power Spectral Density of Quasistochastic Excitation Response

Center Line Light Excitation

Figure 16 shows the system behavior for the repeated pulse excitation as exerted by center line light cases or concrete plate gaps.

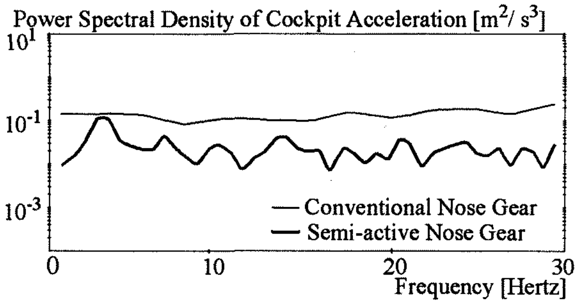

Figure 16: Power Spectral Density of Center Line Light Excitation Response

While the system response of the semi-active gear remains below the one of the passive gear over the whole frequency range, two distinct peaks can be seen below 10Hz for the aircraft structural eigenmodes. At those points the system performance of the semi-active oleo retains only a small advantage over the conventional system. This behavior differs from the one seen for quasistochastic excitation and may be amplified by the total absence of inputs between the bumps and on the main gears.

Harmonic Excitation

The frequency domain response for the harmonic excitation in figure 17 shows that a high level of accelerations

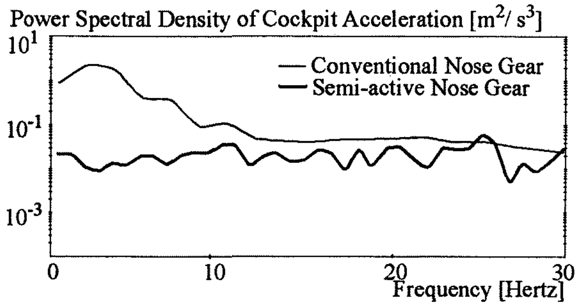

Figure 17: Power Spectral Density of Harmonic Excitation Response (3.6Hz)

at the frequency of the exciting undulations of the runway for the conventional gear has to be expected (thin line). Therefore the PSD in this frequency range exhibits high levels. The semi-active gear (bold line) transforms the response into small amplitudes over a wide frequency range, leading to higher PSD levels at higher frequencies than the conventional gear.

It must be taken into account, though, that the total absence of higher frequencies in the excitation was deliberately chosen to analyze this excitation form and will be accompanied by higher or lower levels of distributed runway inputs in each real runway excitation.

Nevertheless it can be stressed that the semi-active system performance displays an impressive lead in the low frequency range over the conventional gear. This result is even more important bearing in mind the susceptibility of the human body with its emphasis on the low frequency range. To assess the impact of the additional excitation of the main gears, comparative simulations were performed [7].

Application

Operational Requirements and Constraints

The safety standard for a new suspension system has to be at least on the same level than for a conventional solution. Compared to a conventional landing gear the semi-active solution shall not be significantly worse with respect to weight, cost and maintainability. An active suspension system must be able to find the optimum for comfort and safety in each situation. A semi-active aircraft landing gear has to meet all the operational requirements valid for a conventional gear as well. Some operational requirements shall be especially mentioned:

- temperature range (from -50°C to +70°C)
- operation in severe environment
- fail-safe design (semi-active components)
- soft behavior during T/O and landing run
- good landing impact energy absorption
- high safety level (same as a conventional concept)
- maintenance free (semi-active components)

These requirements are expected as most severe for a new concept. But it seems to be possible to meet all of these requirements. In general the technology is well known and already proofed in the automobile industry. The expected difficulties are more related to the specific details of an aircraft application, for example the tendency of „jamming“ of a raked telescopic shock strut.

The designer of a semi-active landing gear has to consider some constraints for the system layout. The interfaces to the airframe structure and other systems (e.g. flight control system) shall be in accordance with the characteristics of the semi-active suspension system. The system performance depends mainly on the hydraulic properties of the shock absorber. These are for example:

- flow rate
- internal pressure
- type of the fluid

Furthermore the system actuation and control components must be able to respond quickly to the excitation inputs. The size of the semi-active shock absorber shall not be larger than the size of the conventional type. And again for such a system only a small amount of additional weight and cost will be accepted.

Possible Actuation Principles

General

In the automobile industry the word „active“ has different meanings. In a car there can be active elements for [13]:

- braking and driving (e.g. anti-lock brakes)
- comfort and safety (suspension)
- directional control (steering)

In this paper the attention is focussed on active suspension systems. This technology is since more than 30 years under development. Four years ago an active suspension system was state-of-the-art in formula one racing cars. Today, some car manufacturers provide an adaptive suspension as an optional feature in series-cars and since 1991 two Japanese manufacturers offer even fully active suspension systems for their upper class cars.

The term „active shock absorber“ has a wide range of meanings as well. One meaning is an „active-spring“ and the other is an „active-damping“ system. In this study an „active-damping“ system is considered only.

Moreover the „active shock absorber“ can work in different ways. As an adaptive, semi-active or full-active element. The common definitions (figure 18) are:

- Adaptive is a principle which acts slow (< 5 Hz) to inputs
- Semi-active is a principle which acts fast (> 5 Hz) to inputs
- (Full-) active is a principle which can act slow or fast to inputs but it needs in any case external energy

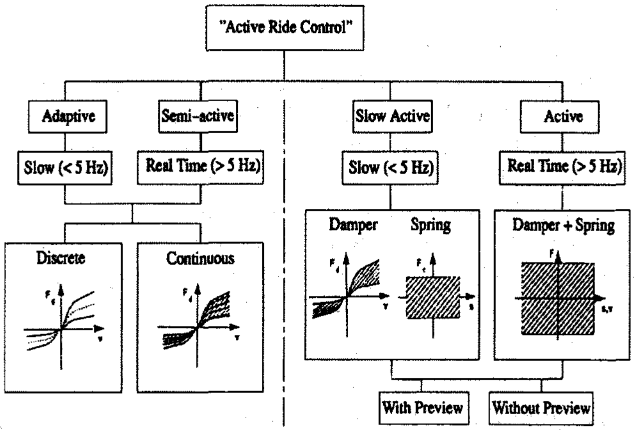

Figure 18: Overview - Active Ride Control

Usually, the aircraft „ground“ operations are less interesting than the „airborne“ operations. Therefore, an active controlled shock absorber does not earn so much attention than a fly-by-wire flight control system for example. In the past there were some active landing gear concepts developed mainly for military aircraft and tested with more or less good results. But, due to the higher weight, cost and system complexity this prototype applications were not considered for series aircraft. In this context a more favorable concept is the semi-active damping device rather than the fully-active device.

The following solutions are considered as semi-active concepts, because the fully active system has for our application only marginal benefits but a high degree of complexity.

To develop a semi-active shock absorber, two physically different concepts have been considered. First, the „classical“ hydraulically solution which controls the flow of a fluid. Second, a relatively new development which controls the viscosity of a fluid (ERF) [14]. A semi-active system can be feasible with various actuation principles. Two of the „classical“ principles are described briefly hereafter and one ERF solution will be introduced as well.

Active orifice

The active orifice (figure 19) controls the oil flow between two chambers. The shape of the moveable element may be a cone (as for example proposed in [15]). Depending on the stroke of the cone the flow varies from zero to maximum. Additional „passive“ holes in the damper ensure a minimum damping capability. The movement of the cone can be done by an electrical linear motor. Due to the relatively high fluid pressure on the cone, the force to move the cone is high as well. This disadvantage requires a very powerful motor.

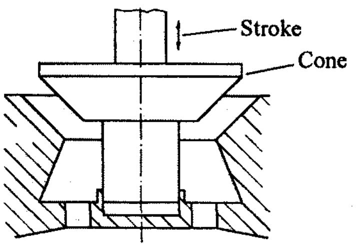

Figure 19: Active Orifice

Active restrictor valve

The active restrictor valve (figure 20) controls the oil flow between two chambers as well. The linear movement of the restrictor varies the cross-section of the holes in a tube. This leads to a flow control from zero to maximum and a minimum damping capability is ensured by additional „passive“ holes in the damper. There are no high loads on the restrictor and the motor of this arrangement can be much less powerful than in the first solution.

Electro-Rheological Fluid (ERF)

The ER-effect has been discovered by W.M. Winslow in 1947 already. He found out that special fluids changed their rheological properties in response to an electrical field. The primary fluid property of interest is the apparent viscosity under shear. Considering a steady shear condition, the equivalent viscosity value can be increased by a factor of ten to a hundred (depending on the shear rate), completely reversibly. The frequency of this process can be at 1 - 2 kHz. The appeal of ERF devices derives from their simplicity, speed, low cost and the innovative possibilities.

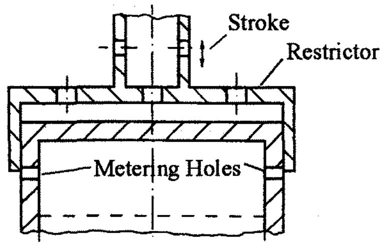

Figure 20: Active Restrictor Valve

Flow controlled solution

This solution based on a nose landing gear which incorporates a semi-active damping control device (figure 21) in a more or less conventional shock absorber. This device can be designed as an active orifice or as active restrictor valve. Technical problems directly associated with the principle have not been identified yet. High contribution of friction loads (up to 10% of the total load) during compression can be observed on some aircraft configurations and load distributions. In some special cases a high amount of friction could make the semi-active system ineffective at very low loads on the nose landing gear.

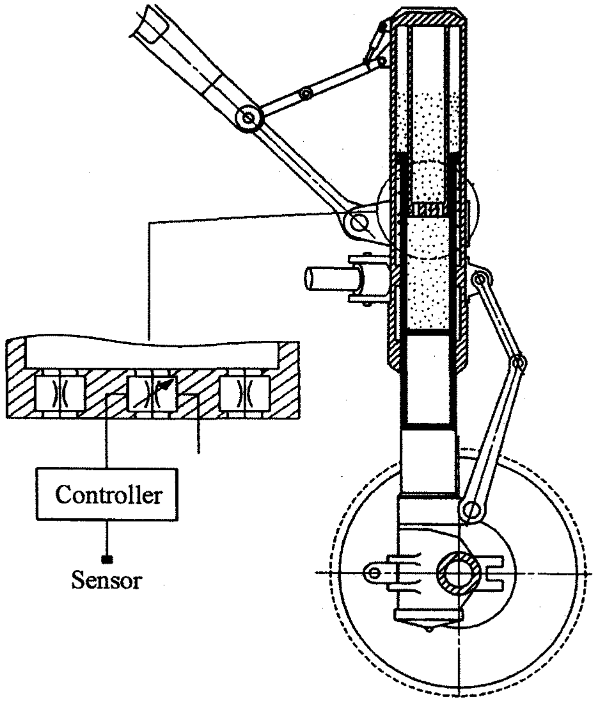

Figure 21: Nose Landing Gear with Semi-active Damping Device

Viscosity controlled solution

This solution presents a new technology for the nose landing gear. The nose landing gear main fitting incorporates all additional equipment for the shock absorber. In approaching the design of an ERF based, semi-active suspension control system, the ERF component can be built as either a flow-mode, mixed-mode or shear mode type of damper. Among the three types, the flow-mode damper is most similar to the traditional shock absorber except that it replaces the conventional orifice with an ERF valve. Scientists from the University of Michigan have carried out an analysis which indicates that the shear-mode damper achieves better dynamic response and more effective control than the flow- or mixed-mode types. They also proposed a design of a general concept for an aircraft ERF shock absorber.

Technical description: The control in the landing gear is realized through the medium of an ERF. The shear-mode damper uses multiple rotational shearing disks („hot" electrodes and „cold" electrodes) instead of translational plates, which form a total control surface area that is constant and independent of the relative position of the landing gear, resulting in good control and a compact size. A translation-to-rotation device converts the translational motion of the shear-mode damper, and vice versa. A specific design proposed by [14] shows an ERF prototype shock strut (figure 22). Problem areas are the volume of the shock absorber (flow-mode damper) and the high voltage required, whereas the benefits include a very fast response time of the fluid characteristic to input signals and low electrical power consumption.

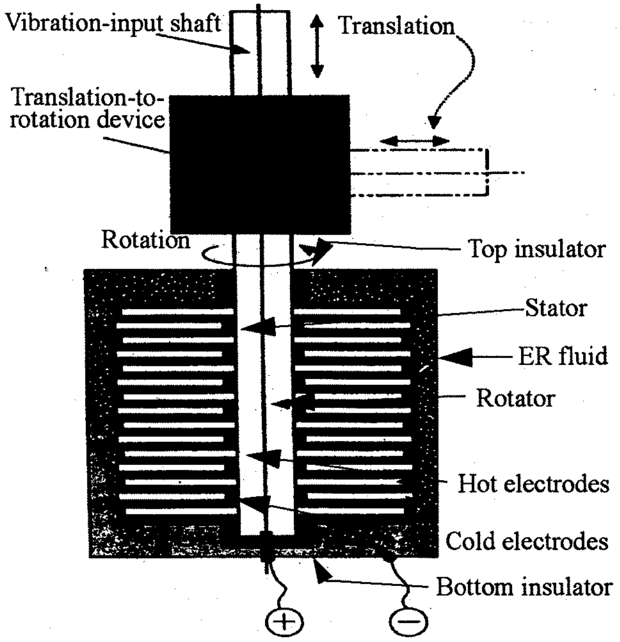

Figure 22: ERF Controlled Shock Absorber (schematic)

Summary

For a semi-active landing gear of a commercial aircraft a controller optimization process was proposed. A multi-model multi-objective controller parameter optimization approach was used on a nonlinear aircraft model, implemented in the MBS-Simulation code of SIMPACK. The result, a pareto-optimal controller, showed important improvements over the whole frequency range under consideration in the vertical accelerations for several, differing excitation types. Several implementation possibilities have been lined out, including conventional as well as ERF technology.

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