DESIGN OF CONTROL LAWS FOR ALLEVIATION OF GROUND - INDUCED VIBRATIONS

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1 Summary

An aircraft is subject to a great number of different loads during one operational cycle. For the aircraft, not only the flight loads but also the ground loads are of importance. A crucial point is therefore the development of airframe and landing gears in an integrated design process.
Semi-active landing gears are able to effectively suppress fuselage vibrations which have been excited by an uneven runway. During the design process of such control structures the dynamics of landing gear and airframe have to be known.
At the example of the control design for a semi-active damper it will be shown how existing design tools can be used for the integrated design process. The design process will be described and simulation results for aircraft with semi-active landing gears controlled by a skyhook controller and a state feedback controller.

2 Introduction, Problem

2.1 Landing Gears as a Source of Resonance Problems for Elastic Aircraft

An aircraft is subject to a large number of different loads in its lifetime. During an operational cycle, not only flight maneuvers and gusts but also the ground operations add their share to the loads acting on the aircraft. Obviously, ground loads are design factors for the landing gears, but, less evident, also for large parts of the airframe. Next to the loads of the touch-down further load peaks result from the accelerations induced by single obstacles (e.g. repaired patches of runway or thresholds) or rough runways. These accelerations might well be of higher amplitude than those resulting from the landing impact.
For operation on an aircraft the landing gears have to comply with the certification requirements, which deal mainly with landing gear strength by rather rough estimations of ground loads acting on the aircraft, but the resulting dynamics of the aircraft on the landing gears is also of great importance and not addressed in those requirements. If the design has weaknesses in the interaction of the components, runway undulations can induce vibrations into the fuselage which can become so large, especially if a resonance frequency of fuselage or wings is excited, these vibrations are not only bothersome but can become a serious danger for a safe aircraft operation.
The lighter and the longer a transport aircraft becomes, the greater is the danger that it will encounter such a resonance problem. One reason for the large number of slender aircraft today is the airframers' standard procedure of stretching existing aircraft by introducing fuselage sections while retaining as many components of the original type as possible to reduce development time, costs and certification effort. However, a combination of system parameters that performed well for the original design might perform unsatisfactorily for a derivative type.

2.2 The Conventional and the Integrated Design Process

Airframers very often assign the design and manufacturing of landing gears to specialized companies. As a rule, the basic aircraft configuration will be determined at a very early stage in the development process. With these basic data, the specialist develops a landing gear. In parallel, the airframer develops the airframe structure which is in part - e.g. around the landing gear attachments and at the rear fuselage - itself dependent on the layout of the landing gear.
However, the optimization of single system components does not guarantee the optimal layout of the integrated system. The later problems of dynamic interaction between airframe and landing gears are discovered, the more difficult and expensive an alternative solution will become, if a completely satisfactory solution can be obtained at all.
It is clear that the consideration of the influence of components on each other has a significant impact on the design process. Neither the airframer nor the landing gear manufacturer can expect the design data to remain constant over the design time. Significant factors, as e.g. aircraft weight and airframe natural frequencies, are subject to constant changes. The design strategy has to be do flexible that model changes can be quickly intro-

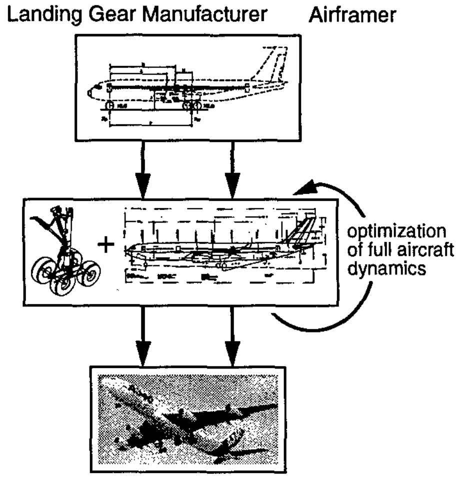

Figure 1: Integrated airframe / landing gear design [1]

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duced. The management of data of decentralized origin is essential, and the modifications in calculation methods must be included into the design process immediately. The "integrated design" requires a close coordination of all companies and engineering disciplines involved.

Numerical simulation is an invaluable tool for the integration of system components. It allows the user to analyze his system up to any chosen degree of complexity, to determine physical variables (e.g. forces, acceleration) at any given point of the system, to change design parameters and perform numerical optimizations, and, by doing so, to keep the costs of the aircraft design down.

The importance of this topic has led to a project in the course of the German aerospace research program, "Flexible Aircraft: Integrated Airframe / Landing Gear Development". An overview over the project and its results has been given in [1].

2.3 Landing Gear Control

Suspensions, not only of aircraft, but also of other ground transport vehicles, are subject to a so-called "design conflict". Many requirements which have to be fulfilled are partially contradictory. In the case of the aircraft, the requirements for the landing impact (a landing with high sink speed; to keep the structural weight as low as possible, the shock absorber will be designed such that the loads for the certification case are minimized) lead to a relatively soft damping factor allowing the use of the full shock absorber stroke. For taxiing, however, a high damping factor is desirable to reduce aircraft pitch and heave motions. Obviously, only one of these conditions can be fully met with a fixed-orifice shock absorber. To satisfy both requirements, modifications at the shock absorber can be made. Possible alternatives to the fixed-orifice shock absorber are systems with stroke-dependent damping (the so-called "metering pin", which is also used to optimize the shock absorber performance at touch-down) [2] or a double-stage shock absorber which varies either the air spring stiffness or the damping factor as a function of the load. A variable damping system (the so-called "taxi-valve") is used in the main landing gears of large aircraft. While taxiing, a high damping factor is used, at high loads (e.g. at the landing) a spring-supported valve is opened to obtain a small damping coefficient. Such a taxi-valve has been investigated in the course of the above-mentioned "Flexible Aircraft" project.

One way to avoid such a design conflict is the use of a semi-active damper. As a conventional oleo, this damper is set up of a gas spring and, in parallel, an oil damper. However, the damper makes use of a variable valve which can be controlled to allow arbitrary damping factors (figure 2). Such a semi-active damper cannot introduce energy into the system aircraft / landing gear. Only for the valve motion a small amount of external energy is needed. It is possible to use such systems for an optimization of the landing impact [3], the study presented here, however, only deals with the rolling case. Semi-active shock absorbers are state-of-the-art in automotive, truck and railway applications [4]. For aerospace applications, though, no system is, to our knowledge, commercially available. In the EU-project ELGAR, the landing gear manufacturer Liebherr Aerospace Lindenberg has built a test-rig with a modified production landing gear which was able to demonstrate the feasibility of the technology [5].

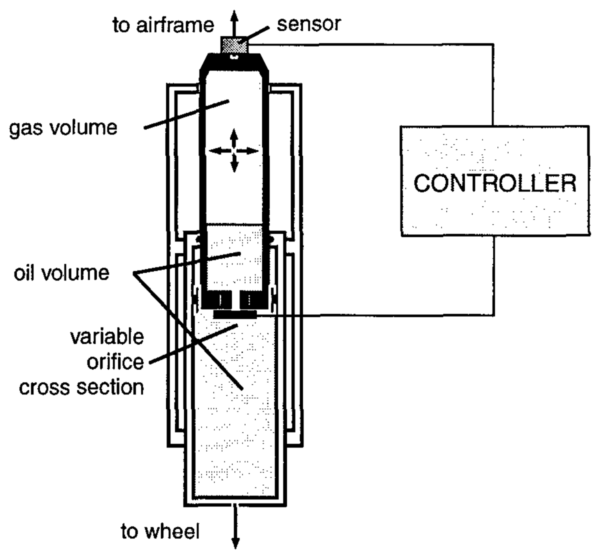


Figure 2: Semi-active oleo [1]

3 System Analysis Tools

3.1 Multibody Systems

For a thorough analysis of a technical system the results of a number of engineering disciplines from the areas of computer aided manufacturing (CAE) have to be introduced into the simulation. A powerful tool for the development of dynamic systems is the method called multibody simulation (MBS). In the DLR, the multidisciplinary simulation program SIMPACK has been developed which allows the integration of models from different CAE products as CAD (Computer Aided Design), FEA (Finite Element Analysis) and CACE (Computer Aided Control Engineering). Specialized programs of other disciplines, e.g. hydraulics or CFD (Computational Fluid Dynamics) can be connected by co-simulation. Thus, the calculation and evaluation of a complex system can be achieved with the desired precision and high calculation speeds. The multibody simulation forms the core of such a multidisciplinary design environment.

3.2 SIMPACK

The MBS tools SIMPACK, [6], has been developed at the DLR as a tool for the analysis of dynamic structures for aerospace applications as well as for ground transport vehicles and robotics. By continuous development the program has evolved into a mechatronic simulation and design tool. The basis of SIMPACK is formed by efficient algorithms for the generation of equations of motion of the model [7], which can be set up by using a graphical interface. The equations of motion can be or-

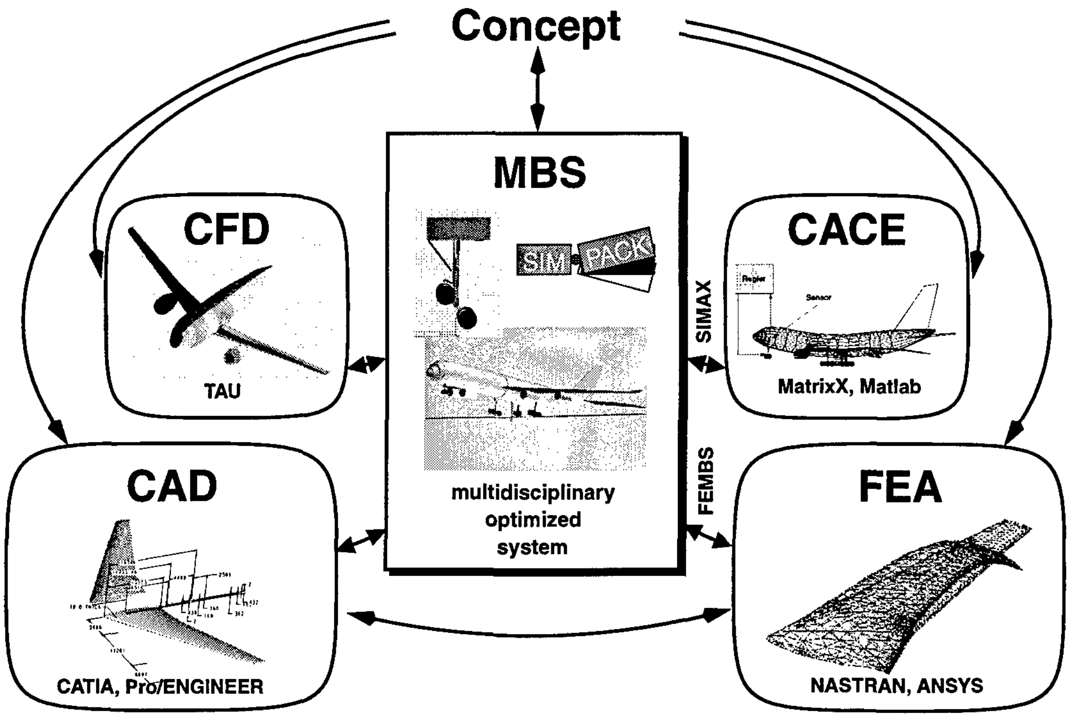


Figure 3: Tools for the integrated design

dinary differential equations of differential-algebraic equations (e.g. for closed kinematic loops). Several fast and specialized integrators for the solution of those (nonlinear) equations are available, [8], as well as all the "classical" methods for linear system analysis, e.g. linearization, eigenvalues, frequency response, stochastic analysis in the time and frequency domain. Methods of parameter variation and a multi-objective parameter optimization [9] have become an invaluable tool for many research and industrial applications.

SIMPACK has bi-directional interfaces to many CAE tools, cf. figure 3. For this work, the three interfaces that are most important are the integration of elastic bodies from FEA models, the controller definition in MATLAB or MATRIXx, and the connection to the multi-objective parameter optimization. As an example, the following paragraph will present those interfaces to MATRIXx that have been used in the control design and optimization for the semi-active damper.

3.3 MATRIXx

MATRIXx by ISI (Integrated Systems) is a tool for control design and system analysis which comes with a block-oriented simulation environment ("SystemBuild"). The package is similar in structure and complexity to MATLAB / Simulink by MathWorks, which is no coincidence, since both programs evolved from the same roots, the original Matlab by Little and Moler (cf. [10]).

MATRIXx / SystemBuild has different interfaces for model import and export which have been connected to SIMPACK via the interface package "SIMAX".

3.4 SIMAX

Using SIMAX, models can be set up in SIMPACK, and made available to MATRIXx for control design and simulation.

The Linear System Interface

SIMPACK models can be linearized and exported in the form of linear system matrices in a MATRIXx-readable format. Inside SystemBuild, the model can be used directly in a state-space block. This interface allows a very fast model export, a restriction is that it is, as the name says, limited to linearized models and a re-transfer of the results is not possible.

Symbolic Code Interface

Models with non-negligible nonlinear effects can be exported in a platform independent way in the form of so-called *Symbolic Code*. Here, SIMPACK generates model dependent, portable FORTRAN code which can be connected to the SystemBuild UserCode Block interface. The symbolic code can also be converted into C to be used in a Hardware-in-the-Loop environment.

Function Call Interface

The most comfortable interface is the Function Call Interface which allows to include SIMPACK in its full functionality. It also works using the UserCode Block. The numerical integration is performed in MATRIXx which calls SIMPACK for the right-hand-side for the equations of motion, the results can afterwards be plotted and animated in SIMPACK. Models with closed kinematic loops can also be integrated separately in the respective packages, using discrete co-simulation, with all SIMPACK post-processing capabilities available. Using inter-process-communication (IPC), MATRIXx and SIMPACK can also run on different platforms.

SIMAX^{-1}: "AutoCode" - Import
After a control design concept is set up in SystemBuild, any chosen parameters can be defined as free and the control structure can be exported. For this kind of model export, MATRIXx offers the - separately licensed - module "AutoCode" which generates C code from SystemBuild models. This code can be used as a user-defined controller and connected to the multibody simulation via the SIMPACK programmable interface.
All these functionalities allow the model setup inside SIMPACK, a model export to MATRIXx in a way adjusted to the desired complexity, a control design inside MATRIXx/SystemBuild, and a re-import of the control structure after the control design for a fast parameter optimization or verification and evaluation simulations in SIMPACK.

4 Control Concepts for a Semi-Active Damper

4.1 Landing Gears of Variable Characteristics

Conventional landing gears are suspensions with fixed spring/damper characteristics. Those passive systems are restricted to generating forces in response to *local relative* motion. To obtain an improved performance with respect to comfort and loads the suspension characteristics can be made adaptable to aircraft parameters, as well as to environment conditions, e.g. the quality of the runway. Active systems may generate forces which are a *function of many variables*, some of which may be remotely measured, e.g. aircraft weight and forward speed. Adaptive suspensions are already state-of-the-art in automotive and railway applications.
Basically, two different adaptive suspension strategies exist. A first step is a non-feedback setting of spring or damper characteristics according to the expected runway quality and aircraft weight prior to touch-down, and keeping those suspension characteristics constant during roll. This variant has been examined by Somm, Straub, Kilner in 1978 [11] who used a gas spring with an adaptive pressure which was used for military aircraft landing on unpaved runways. Another variant of this suspension type are those suspensions of luxury cars which can be switched between sportive and comfortable operating modes.
A further step is the feedback of vehicle motion and, consequently, a suspension control. The basic sensor and control layout is similar for most systems and has already been described in the seventies and eighties by Corsetti/Dillow [12] for aircraft and Karnopp [13] for ground vehicles: a sensor at the vehicle measures acceleration and velocity of the sprung mass and suspension deflections and, via a control law, results in a change of suspension characteristics.
In 1984 an AGARD conference was dedicated to the state-of-the-art of active suspensions [14]. Freymann proposed a fully active nose landing gear for the reduction of ground loads [15]. Most investigations, however, were dedicated to the reduction of peak loads at landing impact. One example was the study of active landing gears for an F-106 fighter [16].

4.2 Semi-Active Control

The idea of a semi-active damper for use in suspension systems has already been introduced in the early seventies by Karnopp [17]. Catt/Cowling/Sheppard performed simulation studies on semi-active aircraft suspensions [18]. Wentscher [2] investigated the use of a semi-active Skyhook-controller for an A300 model. Duffek [19] developed a semi-active control concept for landing which could be combined with a control concept for ground ride.
The concept of semi-active control is to use a variable damper to produce suspension forces that can be influenced by a feedback controller. Thus, the force input was is achieved using a servomechanic device requiring an external power supply as in [15] and [16] but rather with a controllable dissipative device (hence, semi-active control is sometimes also known as *active damping*, [18]).
In a semi-active damper the applicable force depends on the sign of the stroke velocity across the damper, see figure 4. Since the damper can only dissipate energy, forces can only be produced in the first and third quadrant of the force / stroke velocity plane, i.e. a positive force F_d in the sense of figure 4 can only be fulfilled while the oleo is compressing, a negative force can be fulfilled by an expanding oleo. If the controller commands a negative force during oleo compression, the best that can be done is to generate only a compression force as small as possible, in other words, to open the orifice as far as possible. Keeping this in mind the semi-active damper is an inherently highly non-linear device which has to be able to switch from force generation to near zero force in a very short time.

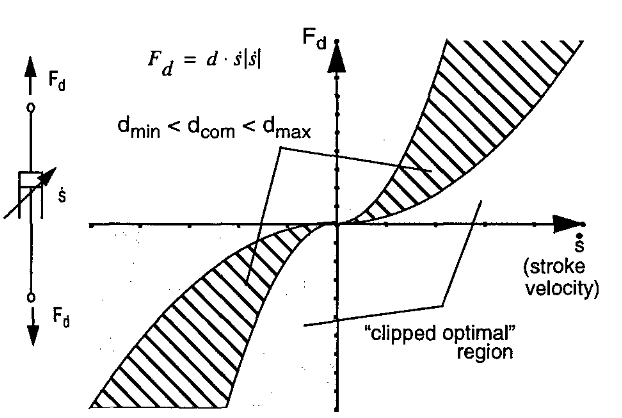


Figure 4: Semi-active control

A controller with a semi-active control scheme is often designed as if it was a fully active system. Control commands that lie in quadrant 2 and 4 of figure 4 are then set to zero. This is known as a "clipped optimal" approach.
A technical semi-active damper, on the other hand, has a minimum and a maximum orifice size for the oil flow, resulting in a respective minimum and maximum con-

trollable damping coefficient. Therefore, a clipped optimal scheme has to be replaced by a realistic, limited system, setting boundaries for the commands for technical realization.

In this work the control has been designed using fully active approaches. The control parameters have then been optimized on the semi-active model with control command boundaries.

It should be noted that the control input for the system by both skyhook (section 4.3) and state feedback (section 4.4) control is a force which is a direct function of the system output, be it measurements or the state vector, and can be positive or negative. The oleo, however, works with an (always positive) orifice cross-section as control input. This requires first a check of the applicability of the control force. The commanded force can only be applied if it acts in the same direction as the current stroke velocity. Second, the force has to be transformed into a damping factor, taking into consideration minimum and maximum damping factor if the control law is not considered to be "clipped optimal":

$$d = \begin{cases} F/\dot{s}|\dot{s}| & \text{if} \quad \operatorname{sgn}(F) = \operatorname{sgn}(\dot{s}) \\ d_{min} & \text{if} \quad \operatorname{sgn}(F) \neq \operatorname{sgn}(\dot{s}) \end{cases}$$

$d_{min} = 0$ for clipped optimum

$d_{min} < d < d_{max}$ for non-clipped optimum

Finally, the commanded damping factor can be converted into a commanded orifice cross section.

4.3 Skyhook-Controller

In the literature several algorithms for active suspension control are proposed. One of the most simple, yet effective approaches is the "Skyhook" controller by Karnopp [13]. At this control scheme the actuator generates a control force which is proportional to the sprung mass vertical velocity. The skyhook principle can be shown on a simple, yet representative example ([20], see figure 5).

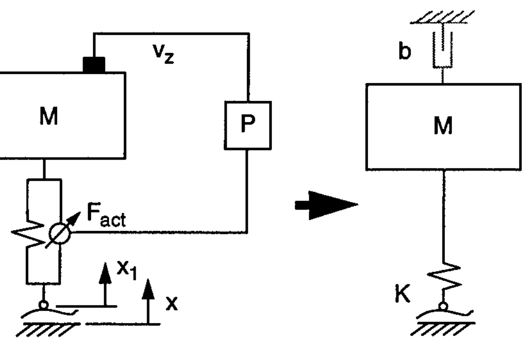


Figure 5: Skyhook control principle

The equation of motion of the one-degree-of freedom model is as follows:

$$m\ddot{x} = F$$

Now, the vertical acceleration of the mass $\ddot{x}$ as well as the suspension stroke shall be minimized. This leads to a classical optimization problem, the solution of which is shown in detail in [21] and [22]. Here, only the solution will be given - the optimal actuator force F_{act} will be

$$F_{act} = K(x - x_1) - b\dot{x}$$

This force law could be realized with a passive system if the mass was connected to the excitation by a spring with stiffness K, carrying the static weight, and to the inertial frame by a damper with damping factor b - the name "Sky-Hook" has been derived from this result. However, for obvious reason this passive solution is not feasible for aircraft. The answer to the problem is to place an actuator parallel to the spring and feed back the vertical velocity of the mass to simulate a fictitious damper to the inertial system.

Even though the derivation of the control law has been done for a single mass system, the same conclusions are true for a two-mass model (in automotive applications also known as the "quarter car model"), the "classic" dynamic model for suspension layout (see figure 7). The limitation applies hat not all control commands can be completely fulfilled by a semi-active controller, however, the commands can be realized in good approximation.

The main advantages of the skyhook damper are its simple implementation and relatively small size which often make the skyhook approach the reference control law which has been implemented in automotive applications a number of times (see [4], [23]).

The proportional gain of the Skyhook controller can be complemented by dynamic control elements. Wentscher, e.g, optimized a lead-lag controller for an A300 model [2].

In this study, the use of a PD-controller has proven to be useful.

4.4 State Feedback Controller

State feedback is a means to control the motion of a system by feeding back the state vector x via a control matrix K into a control signal u

$$u = K \cdot x .$$

The system performance can be modified this way since x contains all information about the process. The desired dynamic properties of the controlled system are obtained by the choice of the matrix K. The performance limits of the actuator concerning maximum frequency and maximum force level have to taken into consideration.

As a rule, in a complex system not all states are directly accessible. Thus, either a limited state feedback control is used or a state observer has to be designed. State observer and state controller can be designed independently.

Taking into consideration the stochastic excitation (e.g. runway unevenness) and measurement noise, the observer used has the form of a Kalman-Bucy filter [10]. A time-invariant (stationary) filter is sufficient for this application. Prerequisite are good estimations about measurement noise and the spectral density of the exci-

tation. For an implementation it is important to remember that the Kalman-filter has the same number of additional states as the model to be observed [10].
If the state vector is known, the state feedback controller can be designed. For this purpose there exist a number of methods, some of the most well-known the Pole Placement and the LQR (linear quadratic regulator) - method which have been used in suspension layout [23]. In this study, from the state vector x a number of states and measurements have been selected via a measurement matrix H which were then multiplied with a weighting vector $q = q_1, q_2, ..., q_n$. The actuation effort was introduced by a criterion r. The cost function which shall be minimized as follows:

$$J = \int_0^{\infty} (x^T H^T q H x + u^T r u) dt$$

Starting values for the parameters q_i and r for a subsequent numerical optimization were chosen according to Bryson and Ho [22].
The design of Kalman-filter and state controller are supported by standard MATRIXx functions, so observer and controller design took place completely in MATRIXx.

5 Control Design

5.1 The Model

The model used for the control design has been derived from the model described in [1]. The aircraft configuration is that of a large civil transport aircraft with a maximum landing weight of 250 tons, a two-wheel nose landing gear, two main landing gears (four wheels, bogie) and a two-wheel center landing gear.

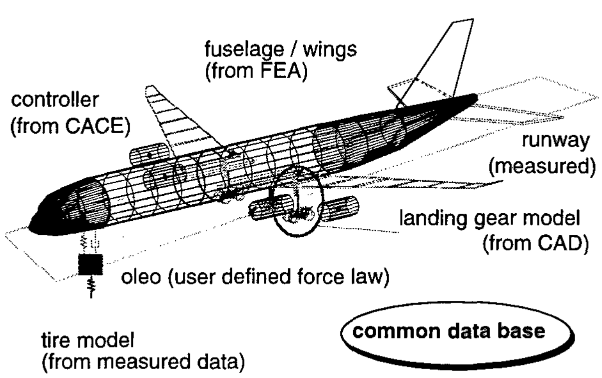


Figure 6: Aircraft model

Airframe
The airframe is described by a single MBS body. The structure has been derived from a NASTRAN finite element model of the complete structure which had been set up for loads and deformation analysis. Inside NASTRAN, a modal analysis was performed and the data transferred into SIMPACK via the pre-processor FEMBS in which the modes of interest for the simulation were selected [24].
Natural frequencies up to 15 Hz were included in the model. By doing that, 14 to 16 equations (16 when using static modes) were added to the equations of motion. A frequency dependent modal damping was introduced for all structural modes.

Landing Gear
The landing gear was modeled as a "classical" rigid body MBS system. The elasticity of the landing gear has been introduced as spring elements in the joints. The effects that were taken into consideration were horizontal motion ("gear walk" induced by spin-up of the wheel or braking) and the attachment stiffness between landing gear and airframe. The wheel has a rotational degree of freedom, the tire is modeled as a point follower with a vertical spring and horizontal slip.
The oleo consists of an air spring and a damping element in parallel. The passive damper corresponds to the one optimized in [1] (taxi-valve type). The semi-active damping has been described above in section 3.1 and 3.2.

Two-Mass-Model
For basic considerations and first realization studies the model of a "two-mass landing gear" was used, consisting of the complete landing gear, but replacing the elastic aircraft structure with an equivalent substitution mass (see figure 7). This model also plays a role in the certification rules according to (FAR 25).

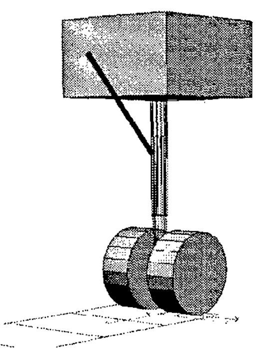
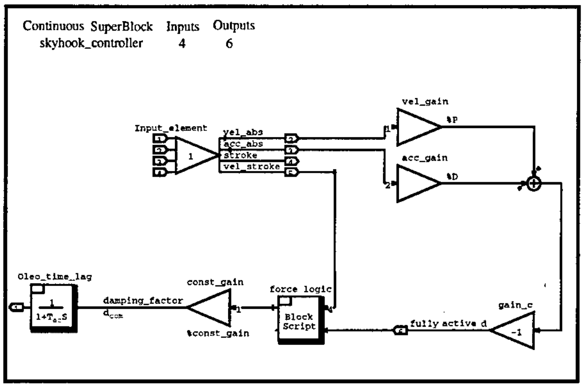


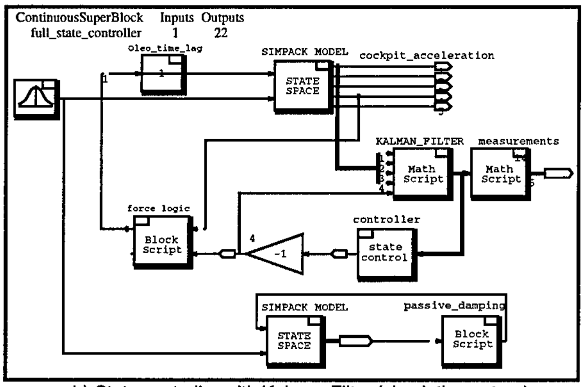
Figure 7: Conventional two-mass model

5.2 Controller Design

The controller design was performed in three steps. In the first step, the control concept was developed and set up in MATRIXx/SystemBuild. The controller was designed using a model exported from SIMPACK. The simulation used for design was based on a stochastic runway. Figure 8 a shows the skyhook controller as a SystemBuild block diagram. The inputs and outputs defined in the block correspond to the inputs and outputs of the SIMPACK programming interface.
Figure 8 b demonstrates the state controller in a SystemBuild simulation environment in a direct comparison to a passive model. In both cases the MBS model was first a two-mass model which was later replaced by a full aircraft model without a change in the control structure.
In a second step, the structure of the controllers was exported from MATRIXx by producing C-code with the help of MATRIXx "AutoCode" which was then implemented as a SIMPACK user force element. The parameters of the controller were subsequently optimized with MOPS, the Multi-Objective Parameter Synthesis tool. The model used was a more complex optimization



a) Skyhook-Filter (controller)



b) State controller with Kalman-Filter (simulation set-up)

Figure 8: Implementation of control laws in SystemBuild

model, the excitation used was a measured runway profile. The free parameters were, in the case of the skyhook controller, the gains P and D, in the case of the state controller the weighting factors r and $q_1 ... q_n$.
In the last step, a large number of comparison runs were undertaken for an evaluation of the semi-active model vs. a passive one using a full evaluation model, different load cases and different speeds.

6 Results

The evaluation was performed on the basis of the vertical cockpit accelerations. Here, the amplitude of the aircraft time response was one of the main criteria. Furthermore, the frequency response was of special interest, since comfort as well as load criteria are frequency dependent. For all cases, the results obtained with the semi-active landing gear were compared with those obtained for the passive reference suspension.
Figure 9 shows a comparison of the time response plots for an excitation by a measured runway. It is interesting to note that both controlled systems remain well below the level of the passive aircraft, however, no great difference can be seen between the skyhook and the state feedback controller. Both systems achieve approximately the same reduction of peak response.
The situation is somewhat different when the accelerations are analyzed in the frequency response (figure 10). Here it can clearly be seen that the skyhook controller can effectively damp the aircraft response in the low frequency range (rigid body pitch and heave motion up

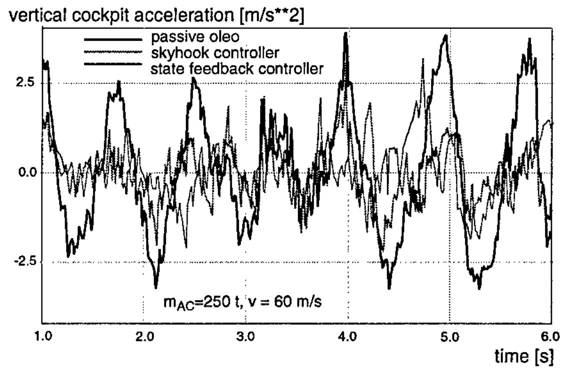


Figure 9: Comparison of simulations, time response

to a factor of 10) but can lead to a response above the passive system for the natural frequencies of wings and fuselage (see figure 10, ca. 3.5 Hz and above). The state feedback controller, on the other hand, can be tuned by the correct choice of the weighting factors such that arbitrary natural frequencies can be damped.

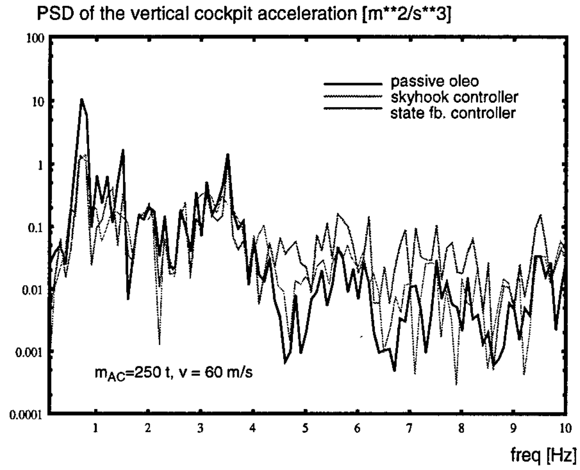


Figure 10: Comparison of simulations, frequency response

Physical limits are set by the performance of the actuator, the maximum size limiting the oil flow and the fact mentioned above that a semi-active controller cannot introduce energy into the system and is thus not able to execute all control commands.

7 Summary and Outlook

The integrated design process of modern transport aircraft includes interdisciplinary simulation and optimization methods as well as data exchange over company and country borders. In the development of landing gears there is still potential for improvement.
It could be shown at the example of a suspension layout how an integrated airframe / landing gear design can be performed using a design environment centered around the dynamic multibody simulation. The key elements are interfaces between the common tools of aircraft and landing gear design, i.e. CAD, FEA, and control design. These interfaces have to be bi-directional to allow not only a fast transfer of models but also a quick re-transfer of the results obtained in the simulation and optimiza-

tion to all involved disciplines.

With the methodology presented alternative suspension concepts as semi-active suspensions can be studied in parallel to conventional designs, and their improvement potential can be assessed. Semi-active systems allow the adaptation of the damper characteristics as a function of aircraft motion and can be used to effectively suppress resonance oscillations of fuselage and wings. In the course of the study a skyhook and a state feedback controller were designed and were subject to a performance comparison. Furthermore it was tested how the used design software is capable to support the design of different control concepts.

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