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Optimization of the Passive Shock Absorber of a Military Aircraft

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Summary:

For a large military transport the potential is assessed to improve its behavior during touch down and ground run by optimization landing gear parameters. Four oleo force parameters were chosen for the optimization: the damping coefficients at compression and expansion, the pre-load, and the length of the gas spring. With respect to feasibility the variation of the parameters is restricted to a band of 20% about the nominal value.

Aim of the optimization is the reduction of the vertical acceleration at touchdown. During ground roll the ride index has to be minimized. Touch down and ground run were first treated separately. Thus a basis is provided to assess whether switching the damping can satisfy the requirements of both phases. In addition the complete cycle from touch down to roll out was investigated.

Concerning the results: It is to be observed that the optimal performance is achieved with the parameters at their limits. The performance in terms of reduction of acceleration, respectively improvement of ride comfort is enhanced by an amount between 20% and 30%.

List of Symbols:

f_{damp}	oleo damping force
f_{gas}	oleo gas spring force
f_{g0}	pre-load force
d	damping coefficient
d_{com}	damping coefficient at compression
d_{exp}	damping coefficient at expansion
decel	deceleration of ac at touch down in vertical direction
$height_{jump}$	height of third wheel above ground
Ride-Index	ride comfort = weighted RMS of vertical acceleration
RMS	root mean square
s	oleo stroke
$\dot{s}$	oleo stroke rate
s_{gas}	length of gas chamber
k	polytropic exponent

Indices, Abbreviations:

ac	aircraft
mean	mean value
max	maximum
nose / n	nose of ac = pilot station/ nose landing gear
main / m	main landing gear

1.Introduction:

The designer of a landing gear is confronted with a host of often conflicting requirements. Its strengths must be sufficient to survive hard landings. When operating on a rough airfield the shocks encountered by the wheels should be absorbed to guarantee a high level of crew and passenger comfort and contribute to long service life of the gear itself and the airframe. All this should be achieved while ensuring reliability, avoiding complexity, and watching for good maintainability. The weight must be low and the dimension small so that the gear can be retracted into a narrow bay. Fulfillment of these and a multitude of additional requirements yields finally into a design which minimizes the direct operating costs. For the time being the airframe and gear manufacturers are still somewhat away from such an all embracing optimization. Up to now the various members of a design team strive to optimize their contribution – without inflicting too much on the requirements of the others. An iterative process between the various contributors issues into a more or less optimal design.

Coming back to the principal task of the landing gear, i.e. to provide the interface between the airframe and the ground: The investigation of the interaction is a complex task which can be attacked in different ways. One approach – probably the most expensive and time consuming – is to test a preliminary design on the aircraft, evaluate its performance, detect the deficiencies, modify some components, and embark on another test. Still rather laborious and prone to misjudgement is the attempt to reduce the problem by linearization and approximation and solve it by a small simulation program. The inaccuracies of such simplifications may lead to wrong answers which might disguise effects crucial for the performance.

In recent years computer simulations gained more and more importance and acceptance – especially for complex nonlinear systems. This method has been applied in the work presented here. The multibody system based simulation tool SIMPACK [1] permits to define the various bodies of a system and to connect them by joints and/or force elements. Excitation by runways is provided, where surfaces between "smooth" and "extremely rough" are available. Elasticity can be included. The optimization package MOPS [2] within SIMPACK facilitates to refine a design rapidly around a set of parameters - a task hardly to solve within reasonable time by manual variation, followed by single simulation runs.

The last remark leads to the approach chosen in this paper: First the variation of single parameters demonstrates their effect on the behavior of the system. Thus the basis for the physical interpretation of the systems reaction is given when the optimization brings all parameters to their optimal value.

2 Model description

Aircraft:

The aircraft is a large military transport in the 100 ton weight class. Span and length are roughly 40 meters. Four turbo-prop engines power the craft. The six legs of the main landing gear are of the swing type, while the nose gear is a cantilever one. Since here only symmetrical cases are treated the two legs of each main gear axle are put together as one "double leg". Correspondingly the values of the relevant data - as e.g. damping coefficients, pre-load, tire constants – have been doubled.
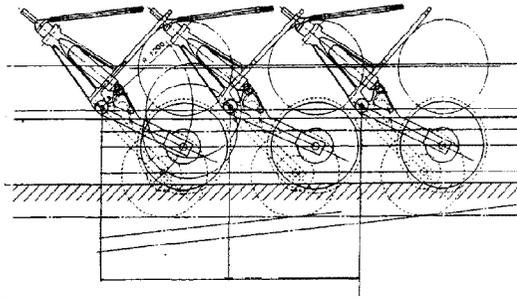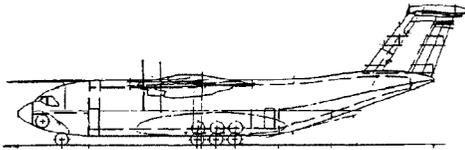
Figure 1: Side view of aircraft and main gear

Aerodynamics:

Though a subroutine with the complete aerodynamics and thrust is available, based on the manufacturers Aerodynamic Data Base, the investigations are made in compliance with the relevant specifications [3]: Before touch down lift is equal to weight, and during rolling lift has to be taken as zero. In this study it is assumed that immediately after touch down lift decays with the decrease of the angle of attack. Due to the hard landing the aircraft jumps. The final touch down occurs about 3.5 s after the initial ground contact. Half a second later the lift dumper and thrust reverse is activated. Within the next second lift and pitching moment are assumed to approach zero.

Oleo:

The gas spring force given by

$$f_{gas} = f_{g0} / (1.0 - s / s_{gas})^{\kappa}$$

shows an exponential climb towards the end of the stroke. Thus it is not surprising that all parameter changes of the optimization try to avoid that the gear approaches the steep end of the gas spring curve accompanied by force and acceleration spikes. A high value for the pre-load f_{g0} and for the length s_{gas} of the gas spring tend into the desired direction.

The damping force

$$f_{damp} = sign(\dot{s}) d \dot{s}^2$$

is proportional to the square $\dot{s}^2$ of the stroke rate. By the closing of valves the damping coefficient at the expansion of the oleo is given a value d_{exp} which is usually by a factor of 10 higher than the d_{com} during compression. The high damping at expansion reduces the tendency that the aircraft is thrown off the ground. However, for comfortable rolling a low expansion damping would be beneficial.

Tire:

The tire force is modeled here as

$$f_{tire} = c_{tire} z_{tire} + d_{tire} \dot{z}_{tire}$$

The force is proportional to the compression and its rate as measured vertically below the wheel hub. Obviously this simplification would give inaccurate results when rolling over steps, since the model does not reflect the smoothing effect of a real tire which „flows around and over" the obstacle. Since the runways considered here do not have steps the simplification does not compromise the simulation results.

Elasticity:

The preprocessor BEAM [4] allows an easy inclusion of the calculation of elastic motions in SIMPACK. The component, the elasticity of which is to be modeled, e. g. the wing, is split into a number of sections – large enough the achieve a sufficient accuracy and small enough to keep the effort in tolerable limits. For such a section the relevant properties – like mass density, cross sectional area, area moment of inertia – are taken as constant. The number of elastic modes can be selected. The validity of the elastic model can be checked by comparison with the modes given by the airframe manufacturer.

Pilot procedure during landing:

The military specifications prescribe a touch down sink rate of 3.66 m/s. After some deliberations a flat landing with a pitch angle = 0, is selected as the worst case yielding into a higher impact acceleration (20 m/s^2) than with a pitch angle of e.g. 6^0 where the successive touch down of the three axles attenuates the acceleration (15 m/s^2). Touch down speed lies at 70 m/s.

After the hard landing the aircraft lifts off again. Especially the nose is thrown back off the ground. It is assumed that the pilot does not start a recovery action, but keeps the elevator fixed in the trimmed condition. Shortly after the second touch

down the lift dumper and the thrust reverser are activated. Half a second later braking of the wheels (of the main gear) commences.

Runway roughness:

Military transports operate frequently on airfields which are neither paved by nor covered by smooth grass, but they are un- or semi-prepared airstrips. In the first case flags mark a strip on a halfway suitable terrain. Given that the roughest unevennesses are eliminated the field is classified as semi-prepared. For a large variety of more or less rough fields MIL-SPEC defines the amplitudes of the unevenness as a function of their wave length [5]. After conversion of [5, fig.1] into metric units the amplitude a depends on the wavelength Λ as:

Semi-prepared field:

$$a_{semi} = 0.0254 + 2.0 \ 10^{-3} \Lambda \quad ;$$
$$\text{for } \Lambda > 305 \text{ m is } a_{semi} = 0.63 \text{ m}$$

Unprepared field:

$$a_{unpre} = 0.05 + 8.9 \ 10^{-3} \ \Lambda$$
$$\text{for } \Lambda < 46 \text{ m}$$

$$a_{unpre} = 0.406 + 7.5 \ 10^{-4} \ \Lambda$$
$$\text{for } 46 < \Lambda < 305 \text{ m}$$

The term on the right hand side of the equations, which does not depend on the wave length, approximates single rocks lying on the runway.
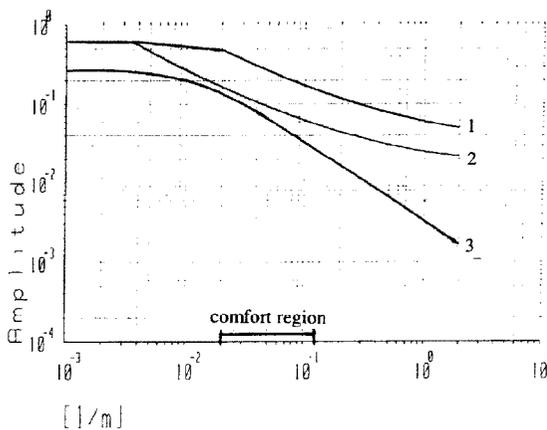
Figure. 2.1: Continuous amplitude spectra

1 : Unprepared airstrip (MIL-SPEC)
2 : Semi-prepared airstrip (MIL-SPEC)
3: „Very bad macadam", SIMPACK
  Comfort relevant frequency range at 70 m/s:
  $1/\Lambda = 0.03$ to 0.14 [1/m]

For our study a roughness was chosen close to that of a semi-prepared field in the frequency range from 2 to 10 Hertz. That interval defines the frequency band which is relevant for the ride comfort (fig. 2.1). SIMPACK offers a spectrum „Very bad macadam", which corresponds to this condition.

The dependence of the amplitude on the wavelength is given by

$$a = \left| \ F(j\Omega) \ \right| = \left| \ 0.705/\{2.66 + 34.2 j\Omega + (j\Omega)^2\} \ \right|$$

with the spatial frequency

$$\Omega = 2\pi / \Lambda \quad [\text{rad/m}].$$

The roughness of the ground is developed as a series of sine-waves

$$z_{ground}(t) = \sum_i A_i \ \sin(2\pi f_i t + \Phi_i) .$$

The frequencies f_i lies in the range from f_{min} to f_{max} which is divided by n equidistant steps. The amplitude A_i is determined by the formula above for the proper frequency f_i whereas a random number generator contributes the phase angle Φ_i between $-\pi$ and $+\pi$.

A number of 51 waves was chosen for the series. As smallest wave length a value close to the wheel diameter respectively wheel base should be selected to cater for a good representation of vibrations at the high end of ground excitation. The value of 4 meters taken here deviate from this recommendation regarding the nose wheel, but are agreeable for the main gear with its long wheel base. A smaller wave length turned out to be detrimental to computing time. The longest wave with $\Lambda = 200$ m yields in a frequency of 0.35 Hz at a speed of 70 m/s being sufficiently below the lowest aircraft mode. The height of the roughest bumps and depth of the holes measure 0.15 m. For the check of equilibrium each run begins on a flat stretch.
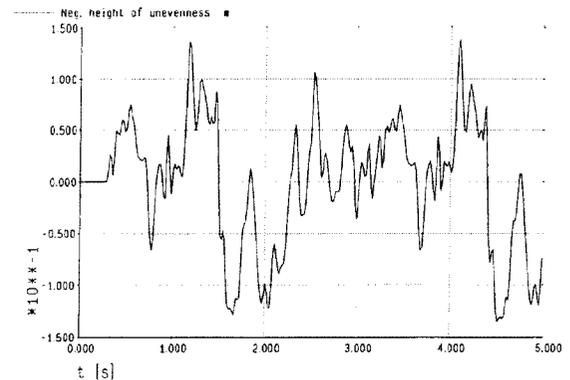
Figure 2.2 Unevenness of the airfield ("Very bad macadam")

3. Results

Before the optimization over all parameters - damping coefficient for compression and expansion, the pre-load, and the length of the gas spring – is started, they are varied one after the other to demonstrate the tendencies and explain their physical effects on the criterion.

3.1 Landing impact

3.1.1 Parameter variation

One of the major tasks of the gear is to reduce safely and comfortably the sink rate of the aircraft to zero. The deceleration in the vertical direction should be as small as possible. Jumping and violent heave and pitch should be avoided. During a rather short time span a large amount of energy has to be dissipated – being proportional to the high sink rate and a considerable aircraft mass.

For the analysis the whole process is here divided into two sections. The initial part, the compression of the gear, ends when the aircraft is closest to the ground the and compression rate reaches zero. During the compression energy is partially dissipated by damping, partially stored in the gas spring. The stored energy initiates the second phase – the expansion of the gear which lifts the aircraft. Whether the upward motion comes to an end before some or all wheels lift off, depends among other parameters on the touch down sink rate, the strength of the gas spring, and the damping. The higher the damping versus the gas spring force the smaller the tendency for the aircraft to jump off the ground after a hard landing (Hence the gears of most carrier based aircraft are dampers only. Jumping up and failing that the arrester hook engages could be fatal. Rolling on rough terrain does not occur, thus discarding the necessity for a spring). On land based aircraft a high value of the damping coefficient slows down the expansion of the gear and counteracts the jumping tendency. Generally the coefficient at expansion exceeds that at compression by a factor of ten. However, a expansion coefficient which is too high is detrimental to the comfort at rolling.

Though the investigation focuses on the acceleration at the pilot station a short deviation to the centre of the aircraft is taken here because the effects during touch down are more pronounced there in the vicinity of the main gear. When the damping (of the main gear oleos) is low, the gas spring has to absorb the bulk of the energy. The force climbs up the steep end of the gas spring curve and reaches high values (Line 1 in fig. 3.1a). The opposite holds for very high damping. The initial damping force exceeds the gas spring force (Line 3 in fig. 3.1a). The optimum with respect to the minimisation of the force and the deceleration would be attained when the two peaks generated by damping and gas spring show the same height (Line 2 in fig. 3.1a). Thus the ideal of a constant and low force during compression would be approached. However such a flat force curve is accompanied by a sudden onset of deceleration which is experienced as objectionable by most pilots. Hence a somewhat lower damping will be chosen as compromise.
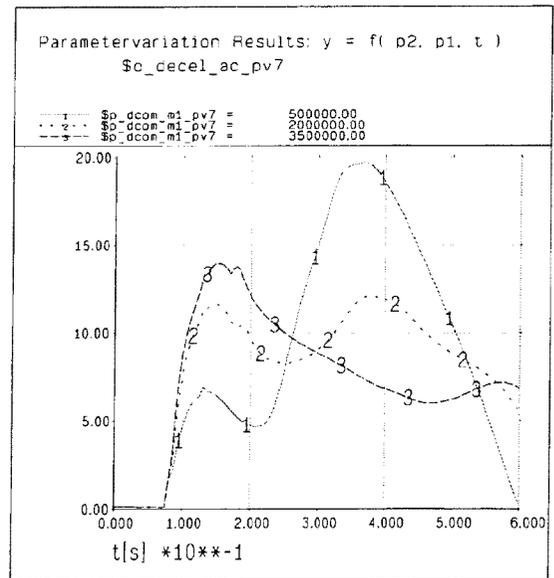
Figure 3.1a Effect of the damping at compression d_{com} on vertical deceleration of the centre of the aircraft

In figure 3.1a for demonstration's sake a large variation of damping coefficients has been chosen. Within the small boundaries of ± 20 % the improvement is naturally much smaller (Fig. 3.1b and fig. 3.2).
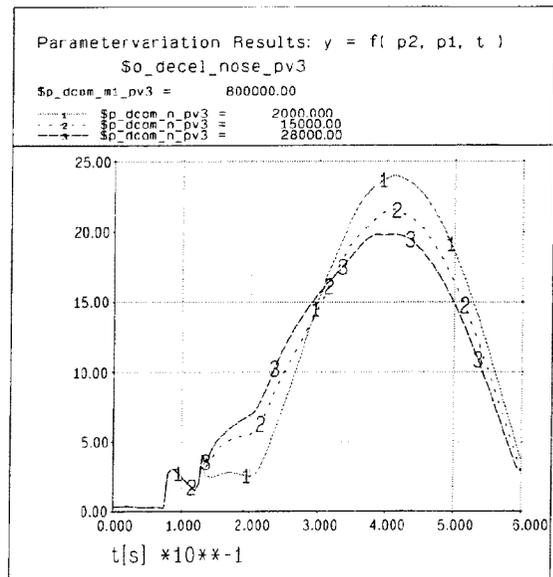
Figure 3.1b Effect of damping at compression d_{com} of nose gear on deceleration at cockpit
(Variation of d_{com} only ± 20 %)

Figure 3.2 Maximal deceleration at cockpit as function of
damping coefficient at compression of nose and
main gear

Jumping of the aircraft:

After a hard and flat touch down the aircraft is thrown back
into the air. As a gauge for the jumping the root mean square
RMS of the height of the third main wheel is taken. This
wheel reaches a maximum height of 0.65 m (Fig. 3.4). Its
time off the ground is about 3 seconds. Height and time off
the ground decrease with increasing damping coefficient at
expansion (Fig. 3.4 and 3.5).

Figure 3.4: Height of third gear above ground as function of
the damping coefficient at expansion for main
gear

The pre-load of the gas spring is another parameter to shape
the deceleration at touch down. An increase raises the force at
the begin of the touch down and reduces the tendency of the
oleo to climb up the steep end.

The increase in gas spring length keeps the oleo away from
the steep end of the force curve by permitting the damping to
dissipate more energy over a longer stroke. A lengthening by
20% yields in a 13% improvement of the deceleration (Fig.
3.3)

Figure 3.3: Effect of gas spring length s_{gas} on maximum
deceleration at the cockpit
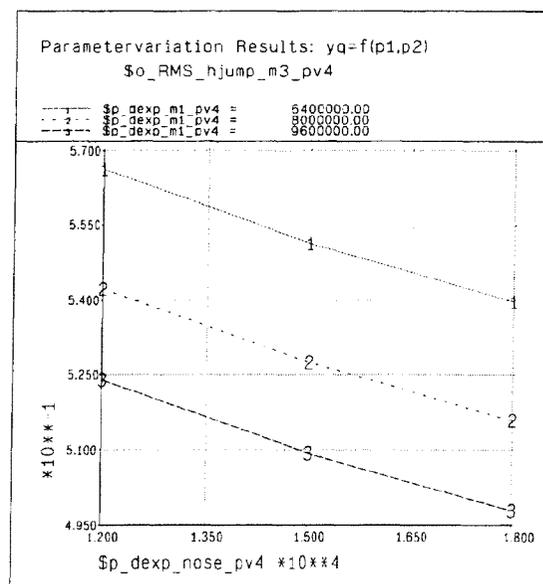
Figure 3.5: Height of third gear above ground as function of
the damping coefficients at expansion for nose
and main gear

3.1.2 Optimization of all oleo force parameters:

Returning to the compression phase of the landing, the optimization over all parameters – except the expansion coefficient – lowers the maximum of the deceleration at the cockpit from 21.3 m/s^2 to 16.8 m/s^2 or by 21% (Fig 3.6a and b).
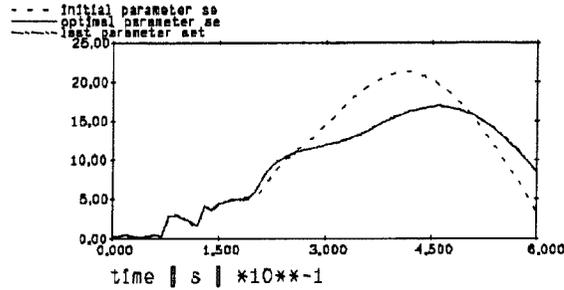
Figure 3.7a: Vertical deceleration at cockpit before and after optimization
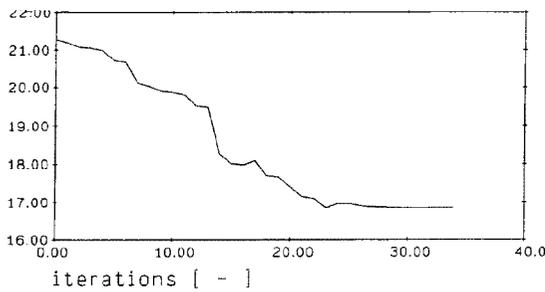
Figure 3.7b: Maximum of vertical deceleration at cockpit versus iterations

During the optimization all parameters move to their upper boundaries (Fig 3.8). The parameters are the damping coefficient at compression, the pre-load, and the length of the gas spring, both for the nose and the main gear. Since the first phase of the landing – considered here – ends before the expansion begins this coefficient stays unchanged.
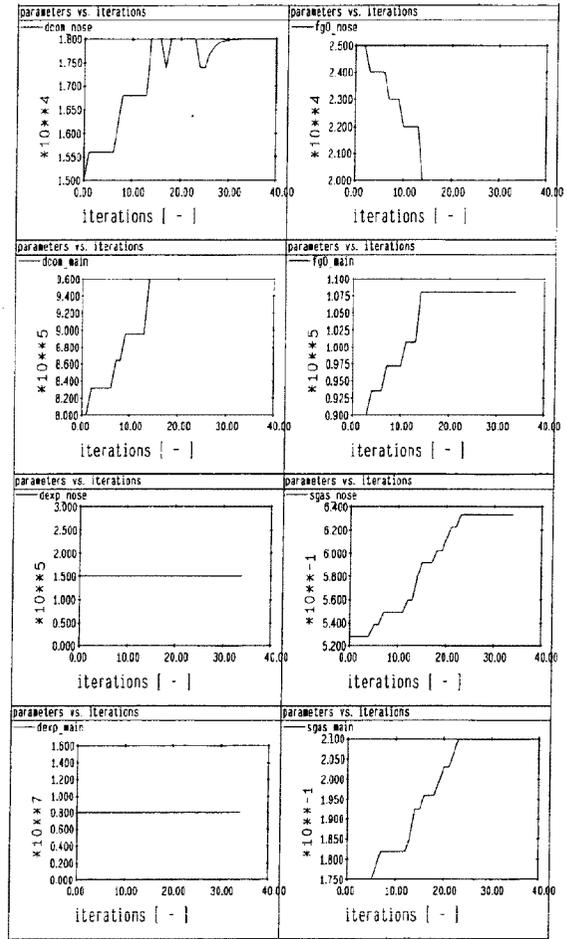
Figure 3.8: Development of parameters versus iterations of the optimization

As a rough guess: an increase of the parameters by 20% is accompanied by 20% reduction of the deceleration.

3.2 Ground roll

Rolling with touch down or take off speed over the rough runway subjects the aircraft to shocks up to 15 m/s^2 – accelerations in the same order of magnitude as those at landing impact, posing a lot of discomfort on passengers and pilot. As a measure for the discomfort – and as criterion for the optimization – the ride index at the cockpit is chosen. Basically it is the root mean square of the vertical acceleration weighted by human sensitivity to vibration. Due to bio mechanical factors man perceives certain frequencies to be more comfortable than others for a given amplitude. The International Organization for Standarization [6] specifies frequencies between 4 and 8 Hertz as most detrimental to comfort [6]. Hence the optimization of comfort has to concentrate on this frequency range.

3.2.1 Parameter variation

Damping coefficient for compression:

A change of the coefficients for both the nose and the main gear affects the comfort only slightly. An increase of 20% of the nose gear coefficient diminishes the ride index by 0.5% only. The low influence could be expected because the stroke rate of the oleo is rather small during ground roll - a remark which holds even more for the damping force which is proportional to the square of the low rate. In the investigated parameter range the highest values for nose and main gear give the best result. Similar to the tendency observed at the landing impact, an increase in damping flattens the force versus stroke diagram and keeps the oleo force curve away from the steep climb at the high end.
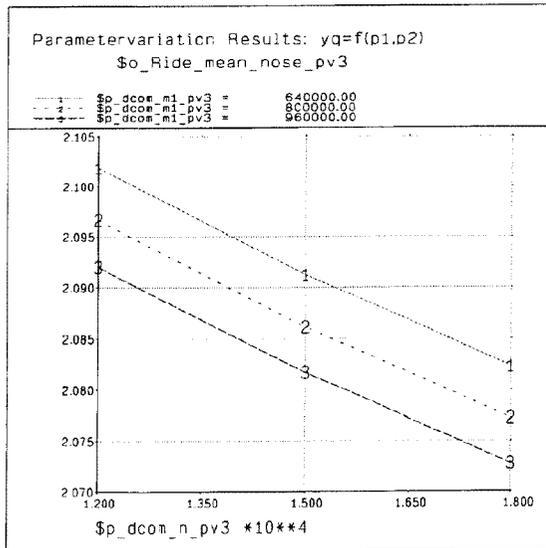
Figure 3.9: Ride comfort as function of damping coefficient at compression of nose and main gear

Damping coefficient for expansion:

A decrease of the damping during expansion allows the gear to follow rapidly declining slopes of the runway surface. Thus the wheels do not loose ground contact and can support the aircraft. Thus its downward motion is diminished and the shock reduced when the next ascending slope is encountered. The best comfort can be expected for the lowest values of the coefficient. For a 20% change of the nose gear coefficient 1.3% alteration in ride comfort are obtained.

Some warning is appropriate here: The criterion for comfortable ride during rolling is conflicting with another one concerning the jumping of the aircraft. Immediately after the touch down during a hard landing the gear is highly compressed. The ensuing expansion would throw the vehicle up off the ground. To counteract the tendency for jumping the coefficient for expansion is usually larger by a factor of 10 than that for compression. Switching of the damping coefficient between touch down and rolling could take care of the conflicting situations.
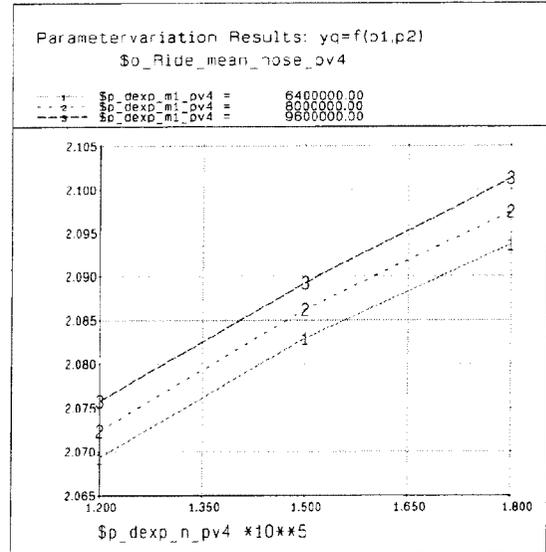
Figure 3.10 Ride comfort as function of damping coefficient at expansion of nose and main gear

Oleo pre-load:

A large pre-load proves to be favorable for comfort. It lifts the oleo force to a high level and refrains the oleo to climb up the steep end of the force curve at compression. During expansion it pushes the wheels down, supports thus the aircraft and prevents a sharp acceleration when hitting the next bump. A 2.5% improvement accompanies a 20% increase of the nose gear pre-load.
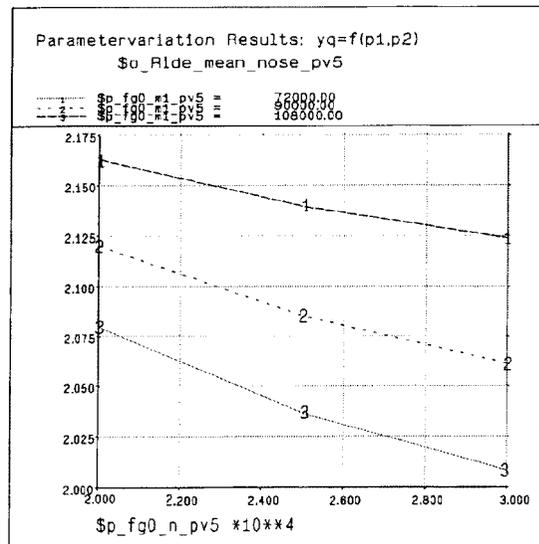
Figure 3.11 Ride comfort as function of oleo pre-load

Length of the gas spring:

The changes of the oleo, discussed so far, can be performed without a major effort. This is not true for the length of the gas spring. Its change has repercussion on the whole aircraft.

Obviously features like the height of the floor above ground, the size of the gear bay, or weight are involved. But also the dynamics e.g. heave and pitch motion of the aircraft are affected.

The results confirm the physically plausible expectation that an increase of the length of the gas spring enhances comfort. Increasing the nose oleo by 20% improves the ride by about 5%.
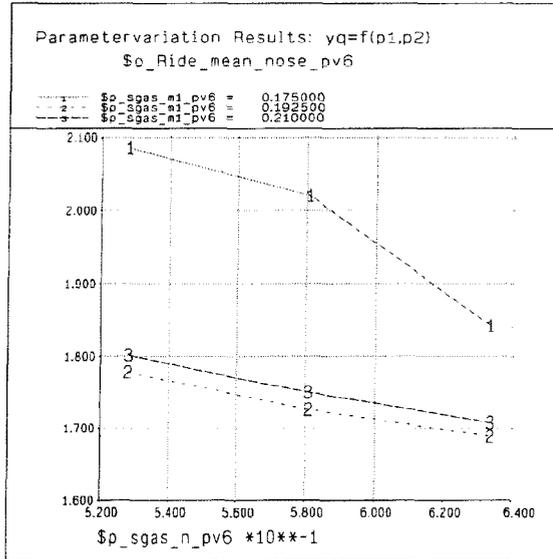
Figure 3.12 Ride comfort as function of gas spring length

3.2.2 Optimization of all parameters

All parameters move towards the boundaries, with the exception of the length of the main gear gas spring which stays slightly under the maximum possible (Fig. 3.13). They follow the tendencies shown by the variations of the single parameters.

While the improvements are quite small, when the parameters are varied one by one, the results for a simultaneous optimization of all parameters indicate that the effects are amplified and a significant improvement is achieved. The mean of the ride index decreases from 2.108 to 1.52 – or by 25% (Fig. 3.14). The peaks of the vertical acceleration at the cockpit are reduced by an amount between 10 and 20%, whereas the alleviation in the center of the aircraft is less pronounced (Fig. 3.15).

The optimization has reduced the damping coefficient during expansion. As mentioned above this enhances ground contact when rolling into holes, may however affect adversely the tendency of the aircraft to jump after a hard touch down. Considering only rolling on rough terrain the reduction of these coefficients decreases the time and height of the third gear being off the ground. The criterion, the RMS of the height of the third wheel above ground, decreases considerably (Fig. 3.16). It has to be admitted that rolling on very bad macadam does not cause a big problem of jumping. In the test case there has been only one instant where the wheel lifts off a few centimeters.
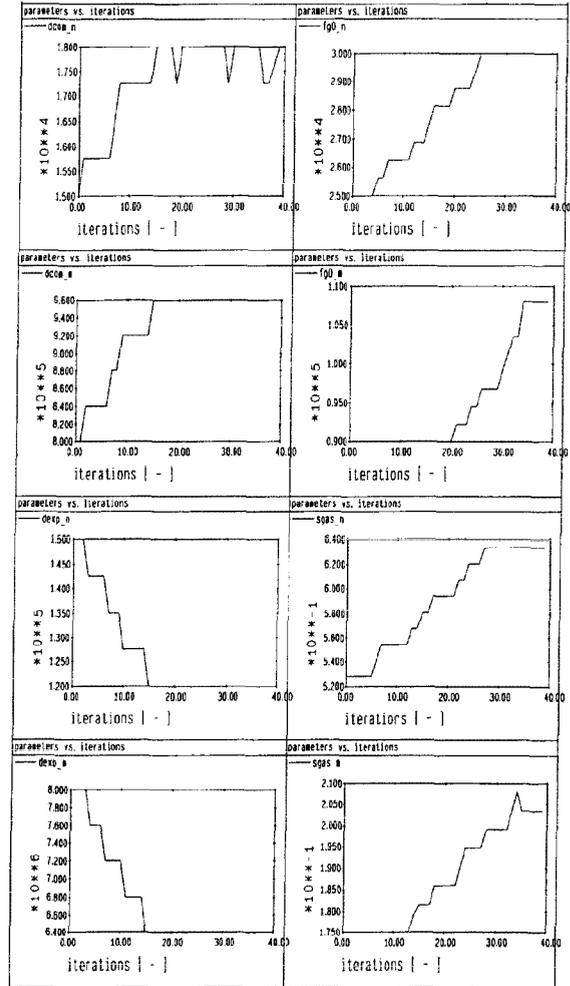
Figure 3.13 Development of parameters versus iterations of the optimization
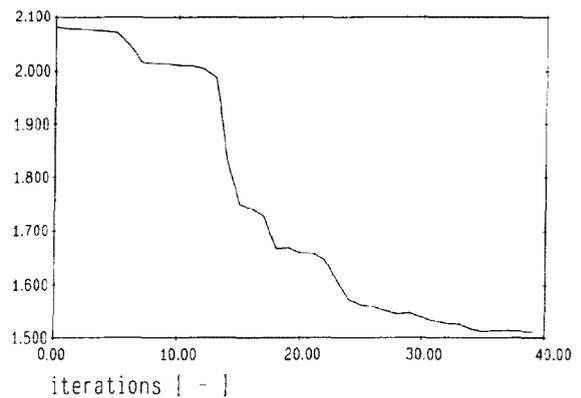
Figure 3.14: Development of ride comfort versus iterations of the optimization
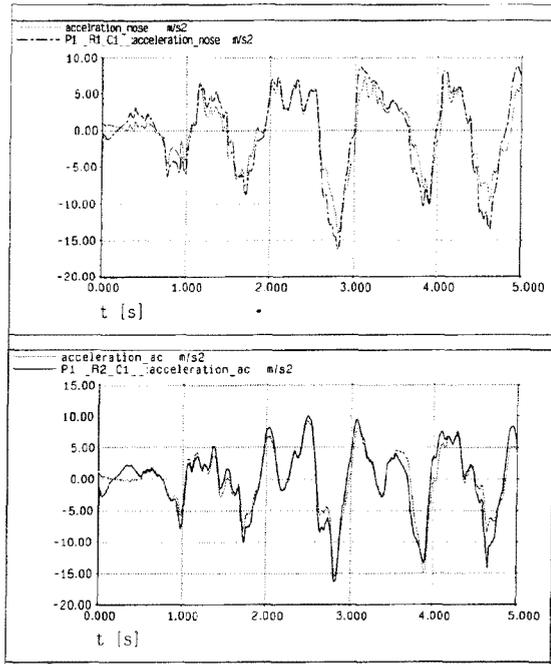
Figure 3.15 Vertical acceleration at the cockpit and at the center of the aircraft
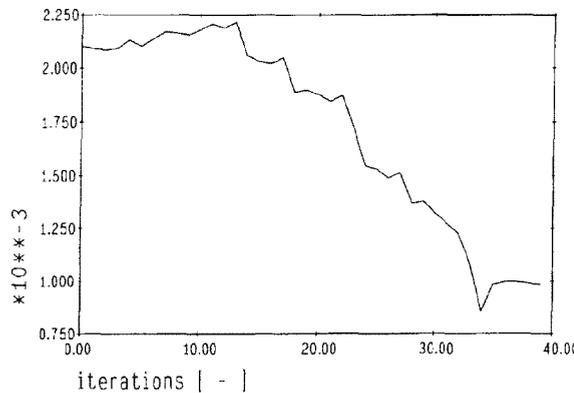
Figure 3.16 Criterion RMS_jump for jumping of the aircraft versus iterations of the optimization

3.3 The complete landing

By this expression the sequence of touchdown, jumping for several seconds, the final touch down and subsequent deployment of lift dumpers, thrust reverse and wheel braking is understood. The first ten seconds of this process are evaluated here. Speed decreases from 70 to about 30 m/s.

As criterion for the whole process the ride index is chosen. The parameters move to the same boundaries as in the two preceding optimizations (Fig. 3.17). Though the criterion for jumping is not activated, it benefits from the improvement of the initial touch down phase. Due to the higher damping more energy is dissipated during compression, leaving less to toss the aircraft up into a large jump. Both criteria improve by about 30% (Fig. 3.18, 3.19). Regarding the time histories: the sharp spikes of the acceleration are clipped off and the height of the jump is somewhat reduced (Fig 3.20, 3.21)

The parameters for the complete landing exhibit the same tendencies as for touch down or ground roll. The somewhat deviating behavior of the damping coefficient at expansion, when the importance of jumping is emphasized, is not appearing - mainly because the criterion for jumping has not been activated in this example. The choice of proper weights on jumping and rolling is an awkward task for the gear designer. To ensure comfortable rolling high weight should be put on this phase of the landing and vice versa, when jumping is of great concern a high weight is needed here. To complicate matters further the hardness of the touch down and the roughness of the runway as well as the duration of the ground run are influencing the importance of the various phases. Obviously, the longer and rougher the ground run, the higher the trend to low expansion damping. On the other hand: hard landings on smooth and short runways amplify the tendency towards a high expansion damping. To obtain a valid result the designer has to take into account the collective of all landings and runways the aircraft will encounter in its service life – not an easy task. All these deep deliberations are not performed here, but the potential of the optimization is demonstrated by the example specified above.
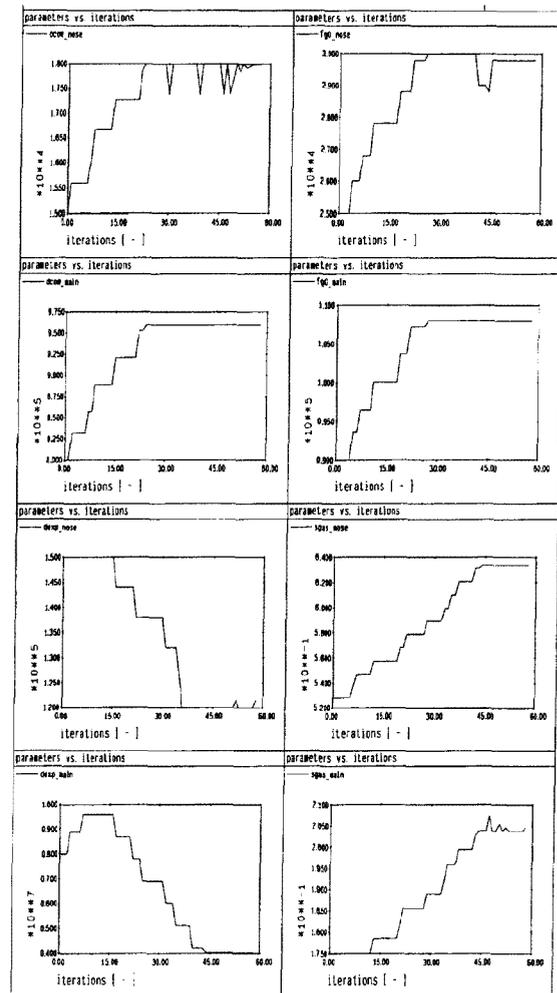
Figure 3.17: Development of parameters versus iterations of the optimization of the complete landing
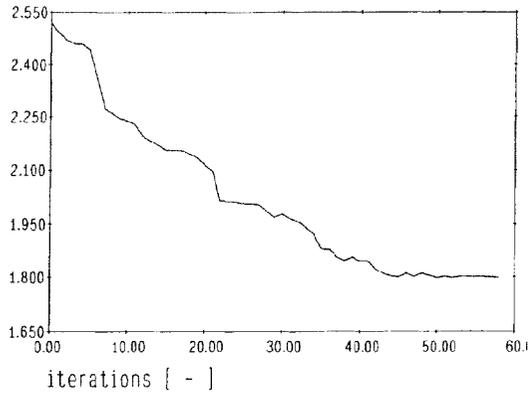
Figure 3.18: Ride index versus iterations of the optimization

Figure 3.98: Criterion RMS_jump for jumping of the aircraft versus iterations of the optimization
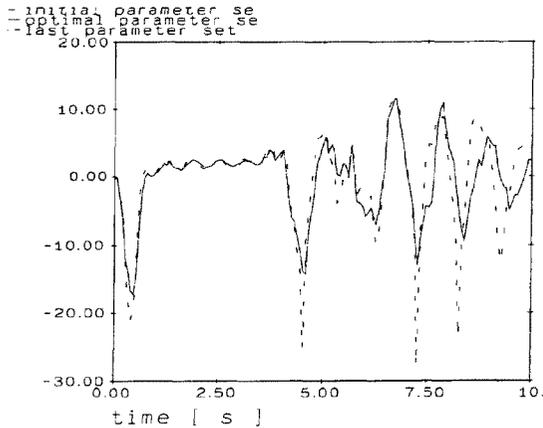
Figure 3.20 Decrease of vertical acceleration at cockpit

Figure 3.21 Decrease of jumping (Height of third wheel above ground)

Parameter:	original	optimal	Ride-index
d_{c,m_n}	0.15 e5	0.18 e5 **	
d_{con_m}	8.0 e5	9.6 e5 **	
d_{exp_n}	0.15 e6	0.12 e6 *	Original:
d_{exp_m}	8.0 e6	6.4 e6 *	2.5
f_{g0_n}	0.25 e5	0.30 e5 **	optimized:
f_{g0_m}	0.90 e5	1.08 e5 **	1.8
S_{gas_n}	0.528	0.6336 **	
S_{gas_m}	0.175	0.2035	
* lower boundary, ** upper boundary			

Table 1: Optimization within boundaries of 20% of the original parameter values

4. Summary:

The design of an optimal gear for a large multi-wheel flexible aircraft operating from a rough airfield is a demanding task, which necessitates the use of a powerful software tool (as e.g. SIMPACK). Thus the potential of the passive gear can be evaluated.

In the example presented here the various phases of a landing – touch down, jumping, ground roll – are analysed, first separately and then as a continuous sequence. As design aim the reduction of the vertical acceleration at the cockpit has been chosen. For the touch down the maximum of the deceleration is taken as the criterion. For the ground roll as well as for the complete landing the ride index measures the performance.

Putting aside for a moment the jumping of the aircraft, in all other phases of the landing the parameters move into the same direction for improved performance For both, the nose and the main gear, the damping coefficients at compression go to the upper boundary, while the damping at expansion settles down at the lower limit. The pre-load adopts the upper values. The gas spring length of the nose gear acquires the maximum value, whereas the main gear stays a few percent below the upper limit. Assessing the jumping after a hard landing as an isolated process, a high value of the damping coefficient at expansion would be optimal. However in the optimization of the complete landing the value of the expansion damping depends on the weight which is put on the criteria for jumping and for ground roll. In this example the jumping criterion has not been activated. Nevertheless, the improvement of the compression phase – high absorption of energy by an increased damping – alleviates the jumping.

To sum it up: The optimization moves the oleo force parameters to the boundaries of ± 20% about their nominal values. The criteria "maximal deceleration" and "ride comfort" improve by 20% and 28%.

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