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Adaptive aircraft shock absorbers

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Typically, aircraft shock absorbers are designed as passive devices with characteristics adjusted to the most frequently expected impact loadings. However, in many cases the variation of real working conditions is so high, that the optimally designed passive shock absorber does not perform well enough. Variation of impact conditions affecting landing gears in various landing conditions is a good example of such a situation.
In contrast to the passive systems, the proposed approach focuses on the active adaptation of energy absorbing structural elements where the system of sensors recognizes the type of impact loading and activates energy absorbing components in the scenario that guarantees optimal dissipation of impact energy.
The term "active control for impact" refers to the methodology used to formulate laws that determine the required signal produced in response to the measured output of the sensors (e.g. radar or accelerometers). This control signal is sent to the actuators (e.g. tuning characteristics of Magnetorheological Fluid), thereby applying corrections of mechanical properties of structural members.
The corresponding methodology (and the software package) will be developed in the proposed approach. As a result, the optimal distribution of non-linear material characteristics (realized through actively controlled shock absorbers) can be designed for the predicted impact scenarios.

Key words: *smart structures, magnetorheological fluid, MR Damper.*

1. Introduction

In most cases the proper performance of typically used shock absorbers is achieved by introducing orifices equipped with metering pins, which are devices that are able to control the internal fluid flow depending on the deflection of the piston. Such a solution is always optimized for a particular type of touching down without taking into account variation of the landing conditions. The classically made struts are expected to be designed to perform in everyday exploitation, as well as in emergency situations, which is objectively unachievable.

In aircraft technologies recognition of each particular case of landing conditions is a fundamental requirement for introducing a system that would be able to tune the landing gear characteristics properly. Such a system of sensors would also be very effective during landing in bad weather when the airplane can become uncontrollable at any moment. The intelligent landing system could then be very helpful for pilots in bringing passengers safely to their destinations.

The introduction of the element based on magnetorheological fluid into the aircraft landing gear as a smart shock absorber is being taken into consideration. The device would enable an active control of impact. The approach requires us to look into the behavior of magnetorheological damper under impact loading. To achieve this goal an experiment was conducted, in which an MR Damper produced by Lord Company was exposed to an impact load.

Magnetoreological fluids (MRF) belong to a group of controllable fluids whose properties may be changed by applying an external magnetic field. The viscosity of the fluids can be changed in a wide variety of values: MRF may change its properties in the range from engine oil like liquid to plastic like solid under magnetic field exposure. Removing the field allows the fluid to return to the normal liquid state. MR fluids consist of micron-sized particles suspended in a carrier fluid, which may be water, oil or gel.

2. Preliminary experiments conducted by the Institute of Aviation

The Institute of Aviation in Warsaw conducted a study of a light aircraft landing gear prototype that was built as a device utilizing advantages of MR fluids. The device was a single acting shock absorber with two chambers filled with the MR fluid that were joined by an cylindrical orifice. One of the orifice walls was a coil placed around the piston. There was a pressured gas spring of nitrogen in the upper chamber that played the role of a stiffness element of the device (Fig. 1(a)).

During dynamic loading the MR fluid was pressurized and moved from the lower chamber to the upper chamber through the orifice surrounded by the electromagnetic coil. While the fluid was flowing it was under the influence of the generated magnetic field. Characteristics of the device behavior could be changed thanks to a variety of magnitude of the applied magnetic field.

Tests of the device were conducted on the laboratory drop test machine in the Institute of Aviation (Fig. 1(b)), where forces under drop suspension can be measured.

Three heights of drop were chosen for the tests: 150 mm, 200 mm, 250 mm, which corresponded with impact velocities: 1.71 m/s, 1.98 m/s, 2.21 m/s.

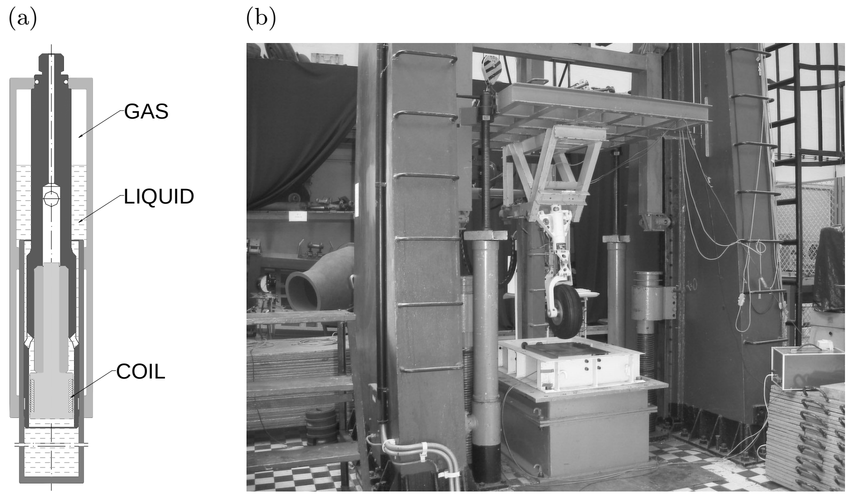

Figure 1. (a) Shock absorber prototype scheme. (b) Drop test machine – Institute of Aviation.

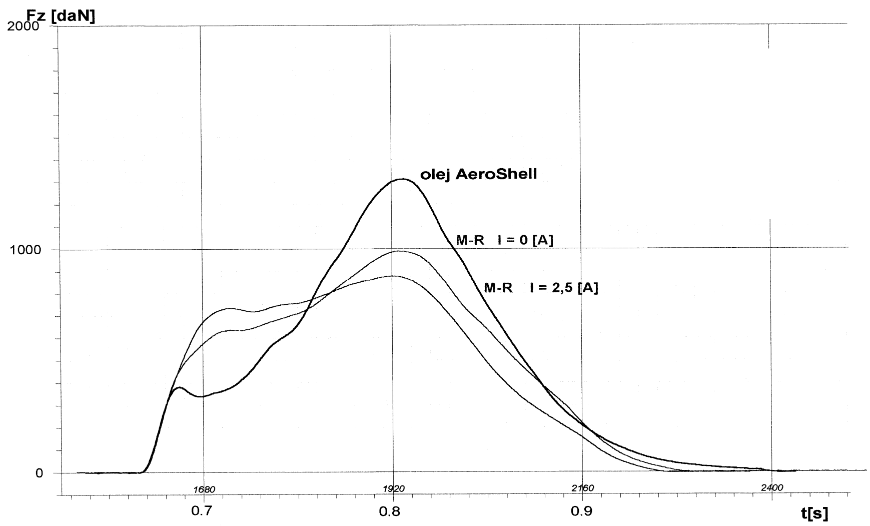

Figure 2. Results of experiment conducted in IA.

The following values were measured:

- displacement of drop landing gear,
- velocity of drop landing gear,
- forces generated by drop landing gear.

The tests were conducted in three modes: with coil supplied with a constant current, with coil not supplied with a current and a special mode for the shock absorber filled with standard Aeroshell Fluid.

As a result, curves presented in Fig. 2 were obtained. The Horizontal axis depicts time and the vertical axis shows the value of forces measured under the wheel at the moment of impact. The thickest line on the graph depicts forces in time that are transmitted on the fuselage during landing using shock absorber filled with standard oil. Thinner lines depict values of the forces when the strut was filled with MR fluid, one for steering current equal to 0 A, and another one for steering current equal to 2.5 A. It can be seen that using the MR fluid in that prototype allowed us to decrease the maximum level of generated forces by about 30%. These results were obtained without introducing any control strategies for steering current magnitudes, which is a very hopeful prognosis for a further development of smart landing gear based on MR fluids.

3. Experiment assumptions

The presented research contained two main groups of activities: conducting the experiment with a magnetorheological damper excited with impact loading and numerical implementation of the rheological model of the damper. Moreover, a series of numerical experiments were conducted, which led to the identification of the numerical model's parameters and obtaining knowledge about possibilities of controlling the MR Damper exposed to fast dynamic loads.

3.1. Experiment

MR Damper RD-1005-3 manufactured by Lord Company was introduced as an adaptive dissipative element in the experimental setup. The damper was placed vertically inside a frame that was a housing for drop mass (Fig. 3(a)). Tests contained dropping mass on the MR Damper from the height of 100 mm to 300 mm; the mass was changed in the range of 10 kg to 32 kg, which gave the maximum impact velocity on the level of 2 m/s. Displacement of the damper's piston was measured by means of inductive displacement sensor placed in a parallel position to the MR device. The experiments were conducted in a time domain. Experimentally obtained results are presented in Fig. 3(b).

(a) (b)

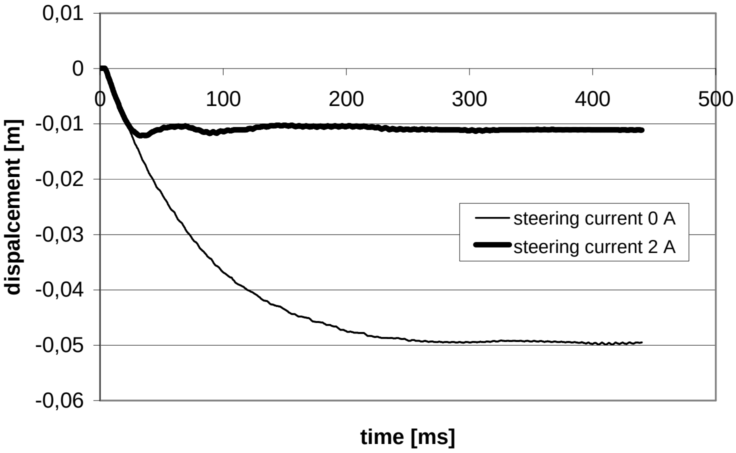

Figure 3. (a) Experimental housing of MR Damper. (b) Experimentally obtained results.

3.2. Assumed rheological model and numerical implementation

For further research development, the rheological model proposed by Spencer *et al.* [2] was chosen. This model is governed by the following set of equations:

$$\begin{cases} f = c_1\,\dot{y} + k_1\,(x_d - x_0), \\ \dot{z} = -\gamma\,\left|\dot{x}_d - \dot{y}\right|\,z\,|z|^{n-1} - \beta\,(\dot{x}_d - \dot{y})\,|z|^n + A\,(\dot{x}_d - \dot{y}), \\ \dot{y} = \dfrac{1}{c_0 + c_1}\left[\alpha\,z + c_0\,\dot{x}_d + k_0\,(x_d - y)\right]. \end{cases} \tag{3.1}$$

Originally, the model was described by the following parameters: f – force; k_1 – accumulator stiffness; c_0 – viscous damping at large velocities; c_1 – viscous damping at low velocities; k_0 – stiffness at large velocities; x_0 – initial deflection; Bouc Wen element parameters: z – evolutionary variable, A, β, γ, – adjustable parameters of Bouc Wen nonlinear hysteretic element; x – mass displacement; y – internal displacement.

In the case considered in the experiment it was necessary to develop Spencer's model by adding an inertial part in order to obtain the possibility of simulating the dynamic behavior. In the expanded model the analytical equations were changed accordingly as follows:

$$\begin{cases} m\,\ddot{x} = -k_1\,x - c_0\,(\dot{x}-\dot{y}) - k_0\,(x-y) - \alpha\,z, \\ c_1\,\dot{y} = \alpha\,z + k_0\,(x-y) + c_0\,(\dot{x}-\dot{y}), \\ \quad\dot{z} = -\gamma\,|\dot{x}-\dot{y}|\;z\,|z|^{n-1} - \beta\,(\dot{x}-\dot{y})\,|z|^n + A\,(\dot{x}-\dot{y}), \end{cases} \tag{3.2}$$

where: m – drop mass; k_1 – gas spring stiffness; c_0 – viscous damping at large velocities; c_1 – viscous damping at low velocities; k_0 – stiffness at large velocities; x_0 – initial deflection; x – mass displacement; y – internal displacement; BW – non-linear hysteretic Bouc Wen element governed by adjustable parameters: A, α β, γ, and evolutionary variable z. Parameters introduced by Bouc Wen element have no physical meaning and they only make the hysteretic behaviour obtainable (cf. Fig. 4).

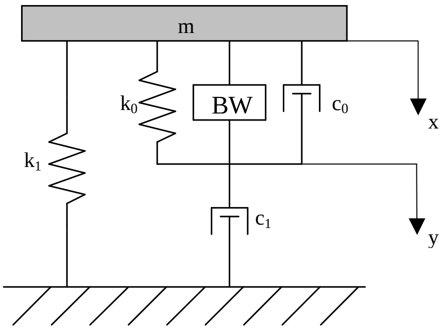

FIGURE 4. Modified Rheological model of MR Damper.

To obtain the dependence of the damper model on the variation of the steering current level, parameters of the model were replaced with expanded parameters α, c_1, c_0 as follows [2]:

$$\alpha = \alpha(u) = \alpha_a + \alpha_b\,u,$$

$$c_1 = c_1(u) = c_{1a} + c_{1b}\,u,$$

$$c_0 = c_0(u) = c_{0a} + c_{0b}\,u,$$

and u was governed by equation of first order filter:

$$\dot{u} = -\eta(u-v),$$

where v was steering signal and η as filter constant.

Equation of first order filter was required to model the dynamics involved in reaching rheological equilibrium and in driving the electromagnet in the MR Damper.

The equations of motion were numerically implemented and integrated by means of Runge-Kutta's fourth order method. Parameters of the model were numerically identified with nonlinear least square optimization routine using the experimentally obtained results of MR Damper dynamic behavior. The objective function of identification problem was defined as:

$$r_{\mathrm{id}}(x) = \frac{1}{2}\sum_i \left|x - x'\right|^2, \tag{3.3}$$

where: $r_{\mathrm{id}}(x)$ is the objective function of identification routine, x is the mass displacement obtained numerically, x' is the mass displacement obtained experimentally.

In the optimization routine the basic idea used to solve this problem was Trust Region Method. The basic idea of the method is to approximate the objective function r_{id} with a simpler function which reasonably reflects the behavior of the function in a neighborhood N around the point x. This neighborhood is the trust region. A trial step is computed by minimizing over N.

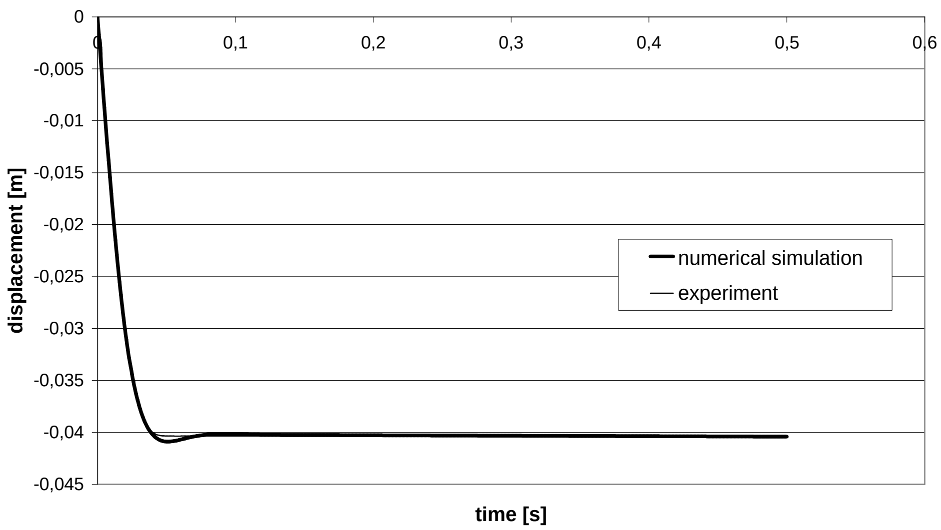

Figure 5. Simulation results after identification.

4. Control strategy

Two types of control realization were considered possible in the experiment. Firstly, the fully active control approach including taking advantages of introducing closed feedback control loop and secondly, the open loop approach, in which determining the most efficient characteristic for each particular landing event would be accomplished before the touchdown moment. The predetermined adjustments would be constant during the rest of the landing process.

The quantity, which describes the landing process most objectively, is aircraft vertical kinetic energy that must be dissipated during the touchdown. The most important issue in evaluating kinetic energy is finding an efficient way for measuring the actual sink speed of an aircraft (the mass is known) just before landing moment. Having the impact energy determined the precomputed optimal solution for the control parameters can be applied.

The parameter that was chosen as the objective function in the signal control optimization was heuristically defined efficiency of aircraft landing gear which is described as:

$$e = \frac{E_{\mathrm{d}}}{L\,S} \quad [\%], \tag{4.1}$$

where: E_{d} is the energy dissipated in single shock absorber stroke obtained by integrating the area beneath the load-displacement curve, L is the maximum load obtained during a test, S is the maximum piston displacement obtained during a test.

It can be seen from the definition that the situation closest to optimal would appear when the load-displacement curve is in shape as close as possible to rectangle (Fig. 6). That shape induces the maximum amount of dissipated energy with the minimal level of dynamic loads transmitted onto the fuselage of the aircraft. Maximization of the efficiency parameter could

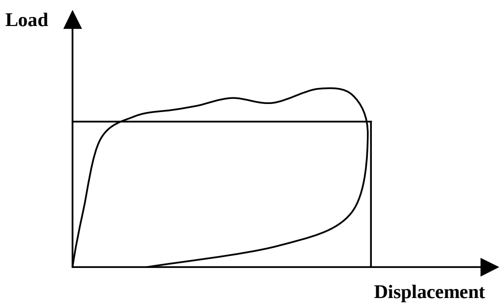

Figure 6. Load vs. displacement curve.

possibly give the most desired characteristic of aircraft shock absorber work during touchdown from the point of view of aircraft durability . This approach can be introduced as a control law in active as well as in open loop control. In this paper the numerical verification of open loop control strategy is presented.

The above approach mentioned was numerically implemented and a series of numerical tests of open loop control strategy were conducted. By means of nonlinear least square optimization routine the maximum value of efficiency factor was tried to be obtained.

The limitation taken into account was maximum displacement allowed from the technological point of view. Results of the optimization process are presented in Fig. 7 as obtained load vs. displacement curves. There are two lines depicted in the figure: the thick one corresponds to the answer of MR damper before the optimization process and the thin one after the process. As can be seen from the graph (Fig. 7) improvement of the landing gear behavior can be obtained only by taking advantage of MR fluids characteristics. These results are very promising, taking into account the very strict time limitations that occur in the functioning of landing gears. The possibility of putting together the advantages of open loop control and semi-active control of shock absorbers in landing gears makes the proposed concept feasible.

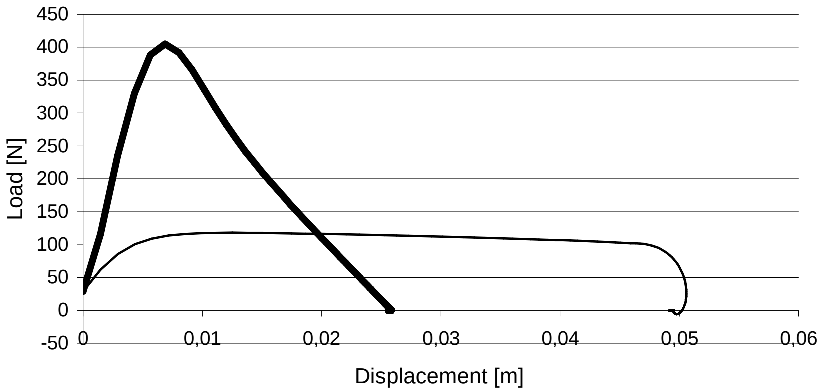

Figure 7. Load-displacement curve – numerical experiment results.

5. Conclusions

5.1. Numerical simulation of MR Damper behaviour under impact loading

A set of numerical and physical experiments proved that Spencer's rheological model of MR Damper (1996) allows to reflect behavior of the device under impact loading properly.

5.2. Control strategy

The experiments conducted have shown that the time required for MR Damper to change its characteristics may be too long to introduce fully active control of shock absorber properties during landing impact. Typically, the touchdown lasts 100 ms and the magnetorheological fluid is able to change its properties in about 25 ms. This would give a possibility of changing the steering current 2 or 3 times per process.

In those circumstances the open loop control strategy, as well as joined strategies of open loop and active control of aircraft shock absorber seem to be applicable in the case of introducing magnetorheological devices to fast dynamic events. The desired damper adjustments for various landing cases may be derived from the definition of aircraft shock absorber efficiency. By optimizing the shape of load – displacement curve development of MR Damper under impact loading behavior was obtained.

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References

1. N.S. Currey, *Aircraft Landing Gear Design: Principles and Practices*, 2nd ed., Washington: AIAA Educational Series, 1988.
2. B.F. Spencer *et al.* , Phenomenological model of a Magnetorheological Damper, *Journal of Engineering Mechanics*, 1996.
3. Y.K. Wen, Method of random vibration of hysteretic systems, *Journal of Engineering Mechanics*, Division ASCE, Vol.102, No.EM2, pp.249-263.
4. J.D. Carlson, Introduction to magnetorheological fluids, *Smart Structures and Health Monitoring, Proc. Int. Conf. SMART'01*, Warsaw 2001.
5. Z. Wołejsza, *Institute of Aviation. Experimental Results.*
6. S.J. Dyke and B.F. Spencer, *Seismic Response to Control Using Multiple MR Dampers*, University of Notre Dame.