

Mitigation of the structure response based on inertial shock-absorber

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ABSTRACT

The goal of this paper is to present further development of the inertial shock-absorber called SPIN-MAN. Application of the device in mitigation of structures response is investigated and selected case study is discussed.

The specific construction and operation of the device is introduced and explained. In reference to the impact absorption problems, the SPIN-MAN is a concept of adaptive inerter device with two phases of operation. The first of them includes energy absorption and accumulation. External energy of the load is converted to kinetic energy of rotational motion of the mass. During the second phase, accumulated energy is dissipated by inverse spinning of the second mass powered by the remaining part of the impact energy. To obtain this type of operation, special switchable actuators are used.

Applicability of the device in mitigation of impact-born structure response, especially in case of space systems, is investigated. General concept of the device construction and operation is adjusted to meet the requirements for space systems. This results in a fluidless, passive-like solution but adaptable to the load conditions. Tuning of the shock-absorber may be realized by manual or easily automated mechanical adjustments. Effectiveness of the solution is based on the specific on/off type of control, which is responsible for the optimal energy flow in the system and efficient dissipation of impact energy inside the SPIN-MAN. Results of numerical simulations confirmed quick and effective operation of this device.

Keywords: structure response mitigation, adaptive impact absorption, adaptive inerter, semi-active control, shock-absorber.

1 INTRODUCTION

In recent years, mechanical structures with embedded active and adaptive absorbers or dissipators have received much attention in the area of vibration and impact control of structures. Large output bandwidth, efficient conversion or dissipation of energy and ease of integration of various time-oriented control algorithms make these devices very attractive for research. Semi-active and active methods of control for absorbers and dissipators can be used to absorb impact load at the source of this excitation, reduce the impact-born free vibrations or to limit continuously externally forced vibrations.

Despite the increase in the number of research, it is still challenging to design appropriate absorbers and dissipators. At the present, new generations of absorbers and dissipators are built

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based on the so-called smart materials such as magneto-rheological fluids, electro-rheological fluids, piezoelectric materials, shape memory alloys or granular materials (cf. [6-11]). Still older solution can also be satisfactory effective e.g. oil damper with gas spring in a regular landing gear (cf. [12, 13]). For predictable externally forced vibrations, so-called tuned mass-dampers TMD, with properly selected location for extra mass on the spring can be also effective [14]. However, when the excitation is variable or random, the characteristics of damping devices should be adapted to the identified on-line load conditions.

A separate type of devices with embedded inertia elements used to accumulate and absorb energy of impact or vibration were proposed by Chen M. Z. Q. et al [3], Smith [4], Gomuła et al. [5] and Lazar et al. [1, 2]. They proposed an application of the inerter as an absorber of vibrations (as an equivalent of tuned spring–mass system) attached to the main body of a mechanical structure, or a vehicle suspension as a strut that replaces traditional struts with springs and dampers, or the use of the inerter to simulate an additional mass element in a structure, or as a device able to absorb an impact acting on the structure.

Another problem is related to the control on the whole structure with these devices, especially in the case when sources of energy are strictly limited. Generally, the problem in all activities devoted to stabilization of dynamic response of the structure is identification (usually in real time) of dynamic excitation and changes in properties of structure with use of controllable absorbers and dissipator with assumed strategy [15]. This is especially a challenging issue for the impact loads lasting a few milliseconds. Many researches (Mikułowski et al. [12-14], Makowski et al. [8], Bajkowski et al. [9]) provided specific know-how in the field of design of effective active or semi-active suspension systems of vehicles, aircraft or other mechanical structures, based on various smart material technologies under proposed different optimization criteria.

The goal of this paper is to briefly describe the results obtained during the development of a new shock-absorbing device and to discuss the considered semi-active control strategies for structure equipped with this device. The newly invented *adaptive inerter* [6] is based on switchable actuators, which allows accumulating and absorbing impact energy by rotating inertial parts with a controllable spinning orientation [7]. Control of spinning – Spinning Management technique is demonstrated to be an effective way to mitigate the response of structures equipped with Spin-Man device.

2 CONSTRUCTION AND OPERATION OF THE SHOCK-ABSORBER

Adaptive SPIN-MAN shock-absorber was introduced in previous works i.e. [7]. Further development of the device resulted in a bit simplified version of it (Fig. 1a) due to construct demonstrator (Fig. 1b) and test operation of the SPIN-MAN in laboratory as soon as possible. Moreover, such a solution can be used in space systems. General concept of the shock-absorber operation is based on the conversion of linear motion of the rod excited by the impact to the rotary motion of threaded outer ring. Significant part of the impact energy is absorbed and accumulated in rotating part and then further motion of the rod is used to rotate the inner ring in opposite direction to the outer ring. In result we use the further movement caused by the impact to dissipate the energy that was accumulated in the first phase of system operation.

Construction of the shock-absorber is based on threaded sleeve placed on the rod that is positioned in a frame and three threaded rings. Inner ring is screwed to the sleeve and has, on its inner surface, a thread compatible with the thread on the sleeve; its outer surface is cylindrical. Middle ring has, on its outer surface, a thread compatible with a thread on the inner surface of the outer ring. Thread of the sleeve and thread of the middle ring provide a rotary motion in the opposite directions. Inner surface of the middle ring and outer surface of the outer ring are cylindrical. A connecting element, so-called energy dissipation surface (EDS), is placed between cylindrical surfaces of the inner ring and the middle ring. This part is a dissipative connection and it

can be realized based on elastomeric ring or frictional connection. For no space applications EDS can be filled with viscous fluid, magneto-rheological or electro-rheological fluids.

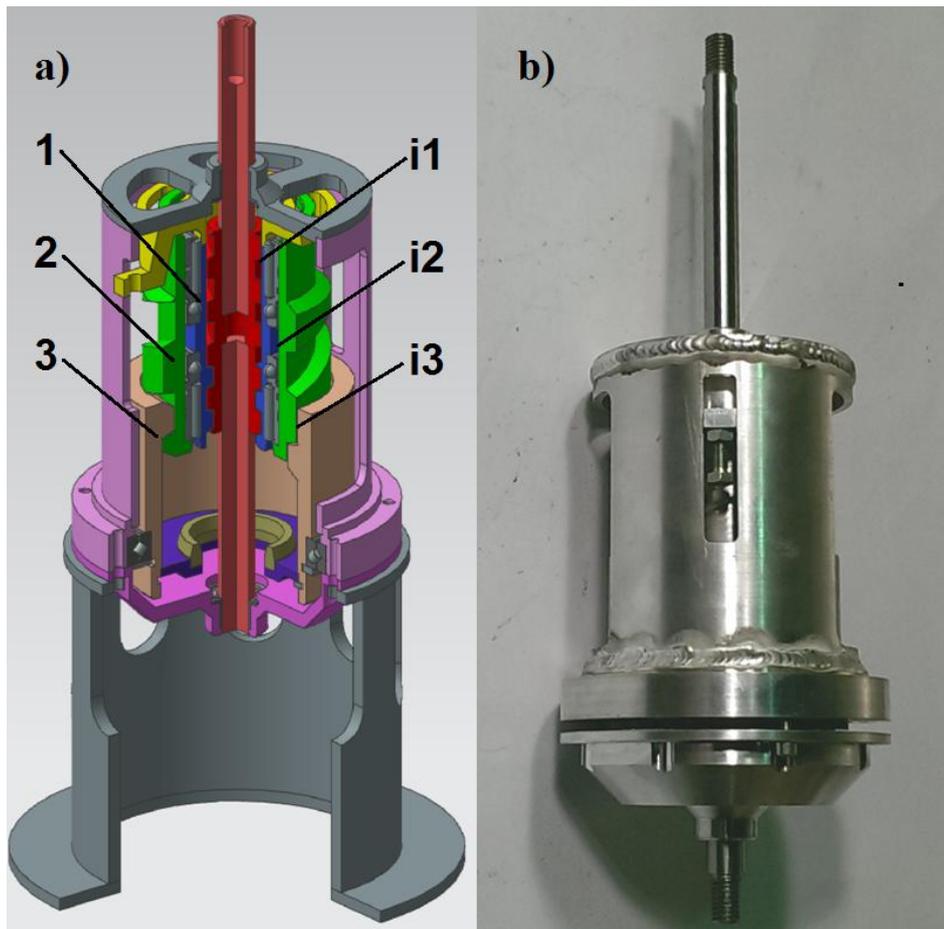


Figure 1 - Construction of the SPIN-MAN shock-absorber a) simplified concept, b) demonstrator

Connections of the main components as well as mass parameters have a significant influence on the SPIN-MAN's performance. Each connection is called an interface. A threaded connection of the sleeve with inner ring 1 is the interface i1 and it allows linear and angular relative displacements. Interface i2, between inner ring 1 and middle ring 2 as a dissipative connection – EDS, allows only angular relative displacements. Interface i3 connecting middle ring 2 with outer ring 3 is a threaded connection – thread opposite oriented to the thread of the interface i1. Third connection enables rotation and move in the direction of the rod axis of the middle ring. Outer ring can rotate and cannot move along the rod axis because of the positioning connection with the frame. Each interface is equipped with a blocker of the relative rotary motion that can be separately turned on and turned off leading to a desired sequence of relative rotary motions. According to the Fig. 1, all described constraints and blockers turn on/off actions are performed mechanically.

A system of sensors, required for effective system adaptation to the system excitation, should identify precisely main characteristics of the shock. For known parameters of the impact – instant velocity growth and energy of impact, control system selects appropriate control strategy ensuring demanded response of the system. Mechanical adjustments can be automatically performed to adapt the system to the actual load conditions.

3 MITIGATION OF THE STRUCTURE RESPONSE

Let us consider a system composed of two frames with common hinge. This system was assumed to be a model of solar panel of a satellite that is unfolded on the orbit. To mitigate the structure response during unfolding, system was equipped with the SPIN-MAN device as shown in Fig. 2. The shock-absorber is integrated with one rod of first frame which is subjected to the impact in point A when point B of the second frame is combined with point A of first frame. First frame is fixed to the satellite. Simulations of such a system were conducted in ADAMS software environment and some results are presented below.

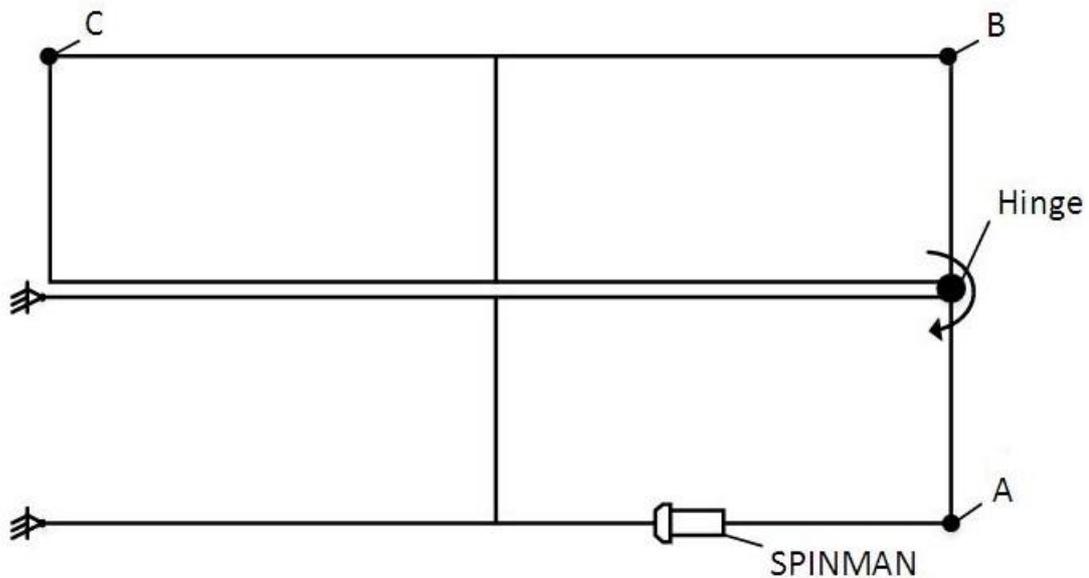


Figure 2 - Structure equipped with SPIN-MAN device

Control strategy performed on the device was adjusted to mitigate structure response under the impact load related to the moment of combining point A of first frame with point B of second frame. Moreover, operation of the device seems to be consistent with the capabilities of prepared demonstrator.

- Operation of the device in analyzed case can be divided into three phases:
- accumulation of the part of impact energy in inertial part of the device;
 - dissipation of accumulated energy on dissipative interface;
 - returning of the structure to desired final position.

According to Fig. 3 maximum acceleration in direction of the impact during combining point A with point B is significantly reduced. Unfortunately, in perpendicular direction maximum acceleration is increased what leads to conclusion that the device should also be placed in vertical rod. Investigations of the SPIN-MAN's application for mitigation of the structure response are on the early stage. In near future system with the shock-absorber placed in two perpendicular directions will be simulated and results will be discussed at the conference.

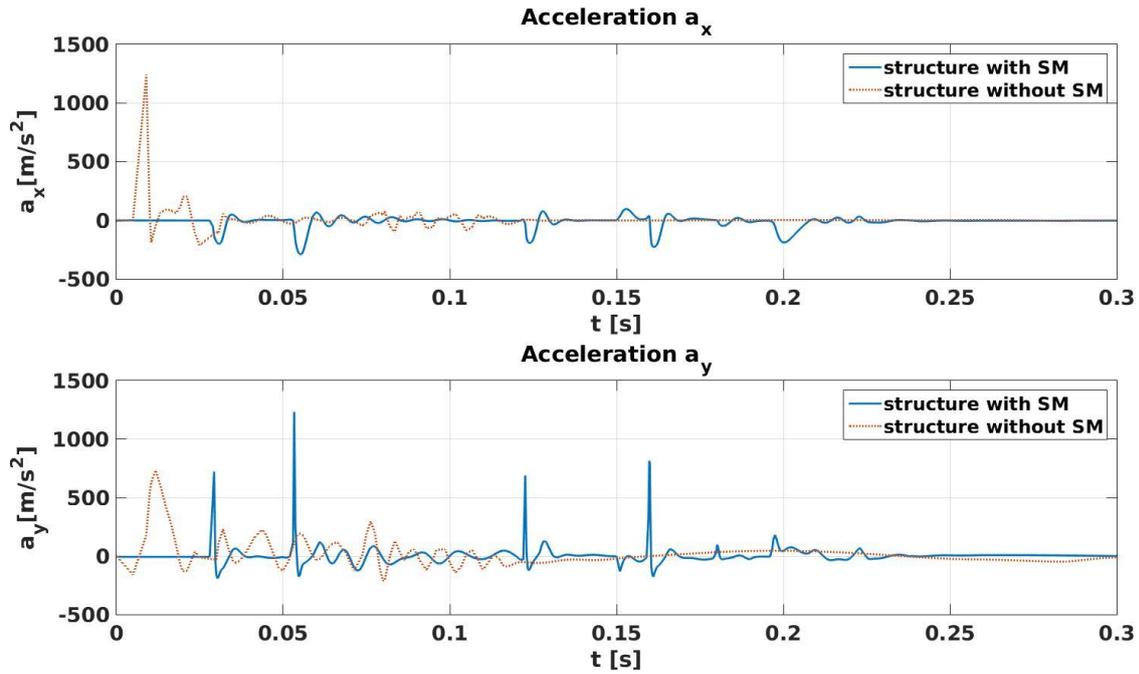


Figure 3 - Acceleration of the point C

4 CONCLUSIONS

This paper introduces a new application of the shock-absorber called SPIN-MAN, the device invented in the Institute of Fundamental Technological Research Polish Academy of Sciences (IPPT PAN). Mitigation of the structure response using this device, based on the impact energy management technique was investigated and simulated in ADAMS software environment. More research in application of the SPIN-MAN for structure response mitigation is needed and operation of the device has to be tuned to obtain desired effects. Currently, first version of the SPIN-MAN's demonstrator is built and tests of the device are under preparation.

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REFERENCES

- [1] Lazar I F, Neild S A and Wagg D J, 2014, Using an inerter based device for structural vibration suppression Earthq., *Eng. Struct. Dyn.*, **43** 1129–47.
- [2] Lazar I F, Neild S A and Wagg D J, 2014, Design and performance analysis of inerter-based vibration control systems, *Proc. 32nd IMAC, A Conf. and Exposition on Structural Dynamics* pp 493–500.

- [3] Chen M Z Q, Papageorgiou C, Scheibe F, Wang F-C and Smith M C, 2009, The missing mechanical circuit element, *Circuits Syst. Mag.*, **9** 10–26.
- [4] Smith M C 2002 Synthesis of mechanical networks: the inerter, *IEEE Trans. Autom. Control*, **47** 1648–62.
- [5] Gomuła S and Łągiewka L 2007 A method of impact and inertia force reduction during collisions between physical objects. Results of experimental investigations *J. Tech. Phys.*, **48** 13–27.
- [6] Holnicki-Szulc J, Faraj R and Mróz A, 2015, A mean of damping of vibrations excited by a mechanical impact and an inertial damper (in Polish: Sposób tłumienia drgań wywołanych udarem mechanicznym oraz tłumik bezwładnościowy), Patent pending, Poland, P 411237.
- [7] Faraj R., Holnicki-Szulc J., Knap L., Seńko J., 2016, Adaptive inertial shock-absorber, *Smart Mater. Struct.*, **25** 035031.
- [8] Makowski M and Knap L 2014 Reduction of wheel force variations with magnetorheological devices *J. Vib. Control*, **20** 1552–64.
- [9] Bajkowski J, Jasiński M, Mączak J, Radkowski S and Zalewski R 2012 The active magnetorheological support as an element of damping of vibrations transferred from the ground to large-scale structure supports, *Key Eng. Mater.*, **518** 350–7.
- [10] Carlson J D and Spencer B F Jr, 1996, Magneto-rheological fluid dampers for semi-active seismic control, *Proc. 3rd Int. Conf. on Motion and Vibration Control* (Chiba, Japan), **3** pp 35–40.
- [11] Makowski M., Zalewski R., 2015, Vibration analysis for vehicle with Vacuum Packed Particles suspension, *Journal of Theoretical and Applied Mechanics*, **53** 1 109-117.
- [12] Mikułowski G and Jankowski Ł, 2009, Adaptive landing gear: optimum control strategy and potential for improvement, *Shock Vib.*, **16** 175–94.
- [13] Mikułowski G and Holnicki-Szulc J, 2007, Adaptive landing gear concept – feedback control validation, *Smart Mater. Struct.*, **16** 2146.
- [14] Mikułowski G, Wiszowaty R and Holnicki-Szulc J, 2013, Characterization of a piezoelectric valve for an adaptive pneumatic shock absorber, *Smart Mater. Struct.*, **22** 125011.
- [15] Sekuła K, Graczykowski C and Holnicki-Szulc J, 2013, On-line impact load identification, *Shock Vib.*, **20** 123–41.