Adaptive impact absorption – a benchmark and an example absorber

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ABSTRACT: This paper proposes a benchmark for conceptual devices dedicated to adaptive impact absorption (AIA) and protection against shock excitations. The problem of the exploitation impacts is present in a wide class of applications, and particularly where direction of the object's movement is well-defined, for example: precise docking systems, rail car buffers or landing gear shock absorbers. In those applications the objective is to equalize the values of velocities of the bodies in order to minimize the deceleration peak. The proposed benchmark establishes a comparing procedure for materials or devices in the field of AIA in a simplified regime in order to improve the comparability of the solutions. A drop test device is proposed to be used for testing the proposed devices in the predefined experimental regime. Besides, an example of the adaptive absorber is presented.

1 INTRODUCTION

The task of adaptive impact absorption can be defined as a relatively new class of problem that aggregates knowledge of several fields: mechanics, automatics, control theory and informatics. The objective here is to develop a device or material that is able to respond adequately in various impact conditions. The additional requirement is that energy consumption of the device and its dimensions are minimal and the deceleration peak has the lowest possible value. The presented study proposes a method for comparison the AIA devices in the domain of their performance. The proposed benchmark does not limit the design of the devices or their idea of operation.

2 CLASSICAL EVALUATION CRITERIA FOR IMPACT ABSORBERS

For the purpose of comparison of various types of absorbers and estimation of their efficiency several evaluation criteria had been proposed (Kindervater et al. 1993). The evaluation criteria are based on the force-deflection characteristics which defines energy absorption capabilities of the absorber. The criteria are defined for the axial impact, however they can be easily generalized for the case of arbitrary absorber subjected to random impact loading. The following classical evaluation criteria can be distinguished:

- Specific energy E_s

$$E_s = \frac{E^{abs}}{m}$$

Specific energy is a ratio of dissipated energy to mass of the absorber. The value in denominator is either mass of the part of absorber which is directly included in the dissipation process or, alternatively, the whole mass of the absorber. Specific energy is an important quantity for lightweight design of the absorbers.

- Energy dissipation density E_d

$$E_d = \frac{E^{abs}}{V_0}$$

Energy dissipation density relates dissipated energy to volume of the absorber. These quantity constitutes an important criterion for compact design of the absorbers.

- Mean crushing stress σ_{cr}

$$\sigma_{cr} = \frac{F^{avg}}{A_0}$$

Mean crushing stress is calculated as ratio of average crushing force to initial area of the absorber. An alternative evaluation criteria is specific crushing stress σ_{spec} which is obtained by dividing mean crushing stress by initial density of the absorber material: $\sigma_{spec} = \sigma_{cr} / \rho_0$

- Crush force efficiency AE

$$AE = \frac{F^{avg}}{F^{\max}}$$

Crush force efficiency relates maximal force which is obtained during crushing process to average value of that force. Crush force efficiency close to unity indicates advantageous uniform crushing characteristics (close to rectangular-shaped). In contrast, low values indicate occurrence of high peaks of force during the process of crushing.

- Stroke efficiency SE

$$SE = \frac{s^{\max}}{H^0}$$

Stroke efficiency is a ratio of utilized stroke of absorber to the its whole stroke. Stroke efficiency close to one indicate effective use of the absorber stroke.

3 SYSTEMATICS OF THE PROBLEM

An important feature of the considered solutions should be reusability and versatility. The reusability should be understood that the proposed device shall reconfigure after each impact to be ready for another case. The versatility of the concepts will allow them to operate under various magnitudes of the impact energy.

Among the impact energy absorbing devices the following categories can be specified: a) passive devices, b) semi-active devices, c) semi-active devices with a pre-impact energy recognition functionality, d) active devices, e) active devices with a pre-impact energy recognition functionality. Passive devices are assumed here to have no control system or any energy recognition functionality and breaking the impacting object with the reaction force exclusively. The semi-active devices are considered to have functionality of automatic adaptation of the reaction breaking force during absorption with dedicated control system but without adding any mechanical energy to the system. Active systems are defined here to be adaptive with possibility of acting with external forces except the reaction force (adding energy to the mechanical system) in order to dissipate the energy of the impacting object. Both semi-active and active systems can be equipped with non-contact pre-impact energy recognition functionality. This functionality constitutes another group in the systematic. In accordance to the description above benchmark may contain two categories: 1) systems with the energy recognition and 2) systems without the energy recognition functionality.

Figure 1 Drop-test stand in Smart-Tech Centre

4 DROP TESTING STAND

An appropriate apparatus for conducting the benchmark is a drop-test machine available in laboratory of Smart-Tech Centre (Fig. 1). The device allows to conduct the drop tests with high level of accuracy and repeatability of the acquired results. The device is available for the benchmark purposes in the Smart-Tech Centre (Warsaw).

The stand (Fig. 2) allows to generate initial impact energy up to 1.5 kJ by means of a drop-weight of 100 kg free-falling from the height of 1.5 m.

The stand is equipped with electric motor (1) for lifting the drop-weight and a control switch box (2) used to program a set of drop tests. The tested object with the set-up was the pneumatic absorber (3) fixed in the vertical position (diameter 30 mm, maximum stroke 100 mm) between the frame (4) with drop-weight carriage (5) and the foundation of the test-stand. The lift mechanism contains an electromagnet (6) used for releasing the impacting mass fixed to the carriage (5), which is guided by the rail system (7) embedded in the frame. The mass was impacting onto the tested object via a pneumatic bumper (8). The measured data, which was acquired at 5 kS/s by NI PCI-6251 data acquisition card, included the following signals:

- the optical switch (9), which served as a trigger and allowed to determine the vertical velocity of the impacting mass just before the impact,
- the accelerometer attached to the drop-weight to determine deceleration of the falling mass (10)
- the magnetic linear sensor (11) to determine displacement of the drop-weight

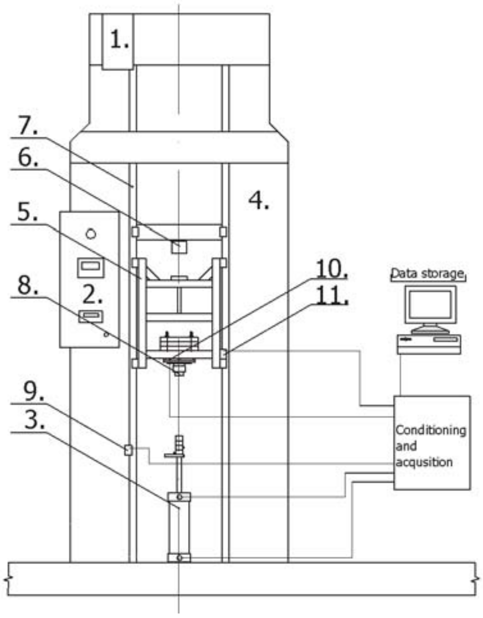

Figure 2 Experimental free-fall drop test stand: schema of the set-up

5 THE BENCHMARK PROCEDURE

In order to simplify the procedure and improve its comparability the benchmark test is proposed as follows: an stiff object with an invariable mass is dropped on the benchmarked device placed on a stiff base. The objective of the device would be absorption and dissipation of the energy possessed by the object. Versatility of the designs can be verified due to the test procedure containing four trials, in which drop-tests with masses of two values and two initial velocities of impact are going to be conducted. The magnitudes for the trials can be adjusted to the specific design of the device under assessment. The only requirement here is that energy ratio γ was:

$$\gamma = \frac{E_{\max}}{E_{\min}} \geq 3 .$$

The procedure may contain four cases e.g. with 10 kg and 15 kg masses and two heights: 0.2 m and 0.4 m, which would give the impact energy spread between 20 and 60 J.

6 EVALUATION

The benchmark devices shall be assessed on the basis of the criteria being a compilation of the introduced classical evaluation criteria for impact absorbers. The features that are crucial for evaluation of impact absorbers are: versatility, compactness, lightweight, force efficiency and stroke efficiency. The versatility will be confirmed by performing the multi-trial test with the energy ratio $\gamma \geq 3$. The rest of the criteria can be evaluated with the specific energy E_S, energy dissipation density E_d, force efficiency AE and stroke efficiency SE.

Each of the evaluated devices will be assessed with respect to all devices. The total evaluation result shall be calculated on the basis of the following formulae:

a) Average result of a device over the *n* trials (*n* = 4)

$$E_S = \frac{\sum_i E_{s(i)}}{n}, \quad E_d = \frac{\sum_i E_{d(i)}}{n}, \quad AE = \frac{\sum_i AE_{(i)}}{n}, \quad SE = \frac{\sum_i SE_{(i)}}{n}$$

b) Normalization of the results with respect to all tested devices.

$$n_{kj} = \frac{s_{kj} - \bar{s}_k}{\sigma_k},$$

s_{kj} - result of the k-th criterion (E_s, E_d, AE or SE) from the j-th device

$\bar{s}_k$ - arithmetic average of the k-th criterion value over all devices

σ_k - standard deviation of the k-th criterion over all devices

c) Total result for the j-th device:

$$t_j = \sum_k n_{kj},$$

After the conference presentation, the audience will be welcomed to discuss the proposed evaluation rules.

7 EXAMPLE SOLUTION

An impact energy dissipation with a pneumatic adaptive shock absorber (Mikułowski et al. 2009) is presented as an exemplary solution. In general the operation principle is based on smart management of gas migration between chambers of a cylindrical actuator in order to minimize the level of braking force acting on the impacting object. The adaptive functionality of the concept is realized by a fast actuated valve and a controller operated with signals from pressure sensors. The pneumatic absorber has been used as a prototype of the AIA device. Controllable valve installed into the piston allowed the device to act as a semi-actively controlled impact energy absorber whose characteristics can be modified in real-time.

The results acquired during the benchmark experiment are depicted in Fig. 3 and Fig. 4. On the basis of the measured data the following values in the particular criteria were calculated for the tested absorber:

Specific energy: E_s = 12.475 J/kg
Energy dissipation density: E_d = 170454.5 J/m^3
Force efficiency: AE = 0.55
Stroke efficiency: SE = 0.84

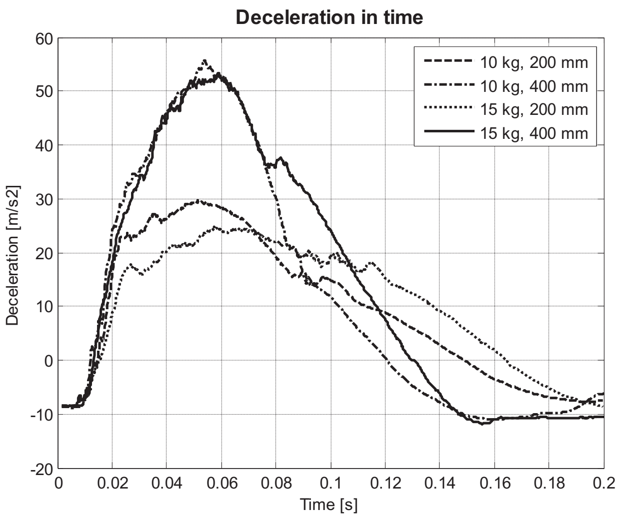

Figure 3 Deceleration of the drop-weight in the benchmark experiment

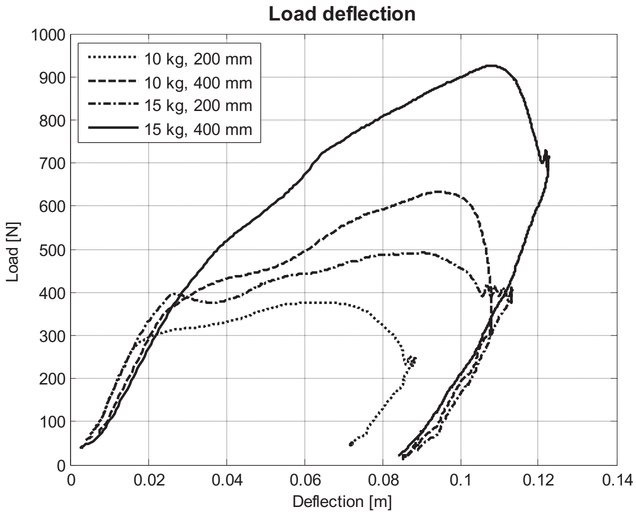

Figure 4 Load deflection curves acquired for the drop-weight in the benchmark experiment

8 CONCLUSSIONS

Proposed benchmark methodology can be used to evaluate devices dedicated to adaptive impact absorption. The procedure can be applied for various types of adaptive absorbers and arbitrary range of impact energies. Proposed methodology allows the designers to evaluate their own adaptive devices and compare them with existing solutions.

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