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ON-LINE IMPACT LOAD IDENTIFICATION FOR ADAPTIVE IMPACT ABSORPTION

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Abstract. *The so-called Adaptive Impact Absorption (AIA) is a research area of safety engineering devoted to problems of shock absorption in various unpredictable scenarios of collisions. It makes use of smart technologies including systems equipped with sensors, controllable dissipaters and specialized tools for signal processing. One of the most challenging problems for AIA systems is on-line identification of impact loads, which is crucial for introducing optimum real-time strategy of adaptive impact absorption. This paper presents development of methodology which enables real-time impact load identification. In considered problem a dynamic excitation is generated by a mass M_1 impacting with initial velocity V_0. An analytical formulation of the problem, corresponding numerical simulations and experimental tests are presented. Two identification algorithms based on measured response of the impacted structure are proposed and thoroughly discussed. Finally, a concept of the AIA device utilizing the idea of detecting device (the so called "impactometer") is briefly described.*

1 INTRODUCTION

The objective of this paper is related to the concept of Adaptive Impact Absorption (AIA)[1,2]. An AIA system is a structure equipped with control devices which modify its local structural properties (e.g. local stiffness) in real-time in order to adapt the structure to the actual dynamic loading. In AIA applications development of the optimal adaptation strategy requires information about the characteristics of the impact loading and the value of the impact energy which has to be dissipated. Therefore, the initial step of the adaptive impact absorption should be identification of the impact loading.

Load identification constitutes an important type of engineering problems. It belongs to the category of inverse problems since its objective is to determine the reason (load) on the basis of the result (measured response). The above task is usually not trivial because in many cases inverse identification problems are ill posed[3] and solution can not be found unambiguously. Many techniques were developed in order to identify parameters of impact and dynamic excitations. Generally identification techniques can be divided into three main categories: deterministic, stochastic and based on artificial intelligence. The most frequent approach is identification of the impact force. In paper [4], a brief review of methods used in the case of indirect impact force identification is presented. The article compares various approaches for identification of the time history of an impact force, its direction and location. In turn, the authors of [5] give a detailed overview of the on-line load identification techniques and their basic evaluation.

This paper is focused on detection of impact parameters which is understood as impacting mass M_1 and its initial velocity V_0 identification. Taking into account the objective of this paper, the crucial issue is the operation time criterion i.e. the time required for impact load parameters detection. The identification techniques considered in this paper have to be performed in several milliseconds to allow the AIA control procedure to be triggered in real-time. Developed identification algorithms utilize sensors, which are not directly fixed to the impacting object. It is justified by the practical aspects and potential application of the impactometer for unidentified impacting objects parameter's estimation.

More detailed analysis for developed methodologies can be found in the authors' journal paper [6].

2 RESEARCH METODOLOGY

Impact tests have been performed using a free-fall drop test stand. The set-up allows to generate initial impact energy up to 1.5 kJ by a mass of 100 kg dropped from the height of 1.5 m. The object was impacted into a pneumatic absorber equipped with set of sensors (see Fig. 1 a). This absorber has been used as a prototype of the "impactometer" which is a detector dedicated for real-time identification of impact parameters.

The considered impact types were limited to the collinear central collision between two rigid bodies (i.e. falling mass and the piston rod of pneumatic absorber). A variety of impact scenarios of this kind have been tested. The impact scenarios were defined by three parameters: the impacting mass value, the velocity of the colliding object and the initial pressure inside the pneumatic absorber. The range of the impacting mass was 10 kg ÷ 55 kg, while the relative impact velocity was adjusted by the drop height, which was confined to the range of 0.05 m ÷ 0.5 m. Pressure inside pneumatic cylinder was modified in the range of 0 kPa ÷ 400 kPa where 0 is understood as the atmospheric pressure.

a. b.

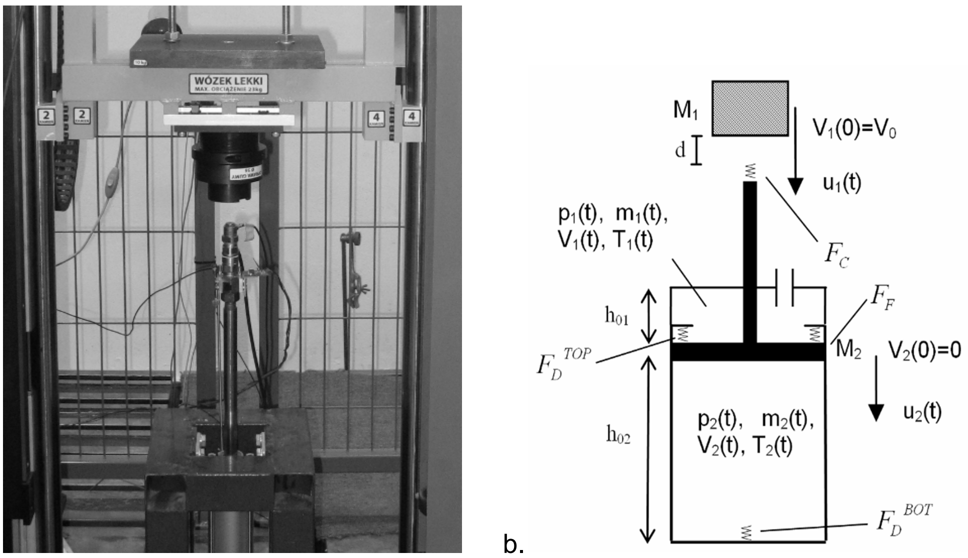

Figure 1: Considered mechanical system: a. experimental set-up, b. numerical model

2.2 Mathematical modeling

Mathematical model of described above pneumatic absorber (see Fig. 1b) was developed in order to simulate its response to various impact scenarios, i.e. impacts of a rigid object of various masses and initial velocities. The considered system consists of two rigid objects, the falling mass and the piston, which are represented by two mechanical degrees of freedom. Equations of motion take the form:

$$M_1 \frac{d^2 u_1}{dt^2} - M_1 g + F_C = 0 \tag{1}$$

$$M_2 \frac{d^2 u_2}{dt^2} - M_2 g - F_C + F_P + F_F - F_D^{\ TOP} + F_D^{\ BOT} = 0 \tag{2}$$

where: M_1, M_2 are the masses of the falling object and the piston, while u_1, u_2 denote their displacements and g is the gravitational acceleration. Equations (1) and (2) are coupled by the contact force F_c acting between the falling mass and the piston rod, which is modeled as a combination of springs and viscous dampers[7]. Coulomb friction - based model is used to simulate friction force F_F between the piston and cylinder walls. Pneumatic force F_p is defined as the difference of the pneumatic forces acting on both sides of the piston. Finally, in order to confine the piston movement to the range determined by the cylinder geometry, the top and bottom delimiting forces were introduced.

2.2 Numerical and experiment results

The experimental drop tests have been performed for a better understanding of the impact process and its dependency on particular parameters of impact. The collected measurements have been used for validation of the numerical model and to test the effectiveness of the impact identification algorithms. The developed methodologies make use of the force and acceleration sensor measurements only. Nevertheless, other sensors, as well as the high-speed camera, were utilized for the validation of the numerical model.

Selected cases of collision scenarios are presented in Fig. 2. The graphs illustrate both experimental measurements and simulation results of the contact force acting between the impacting mass and the piston rod. Characteristic change of contact force observed in the experiment allows to divide the impact process into two separate stages (i.e. A, B) which were marked in Fig.2:

- the first one i.e. stage (A) when the piston rod rebounds from the falling mass and large oscillations of the contact force occur,
- the second one i.e. stage (B) during which the falling mass is moving downwards together with the piston which results in a smooth change of the contact force.

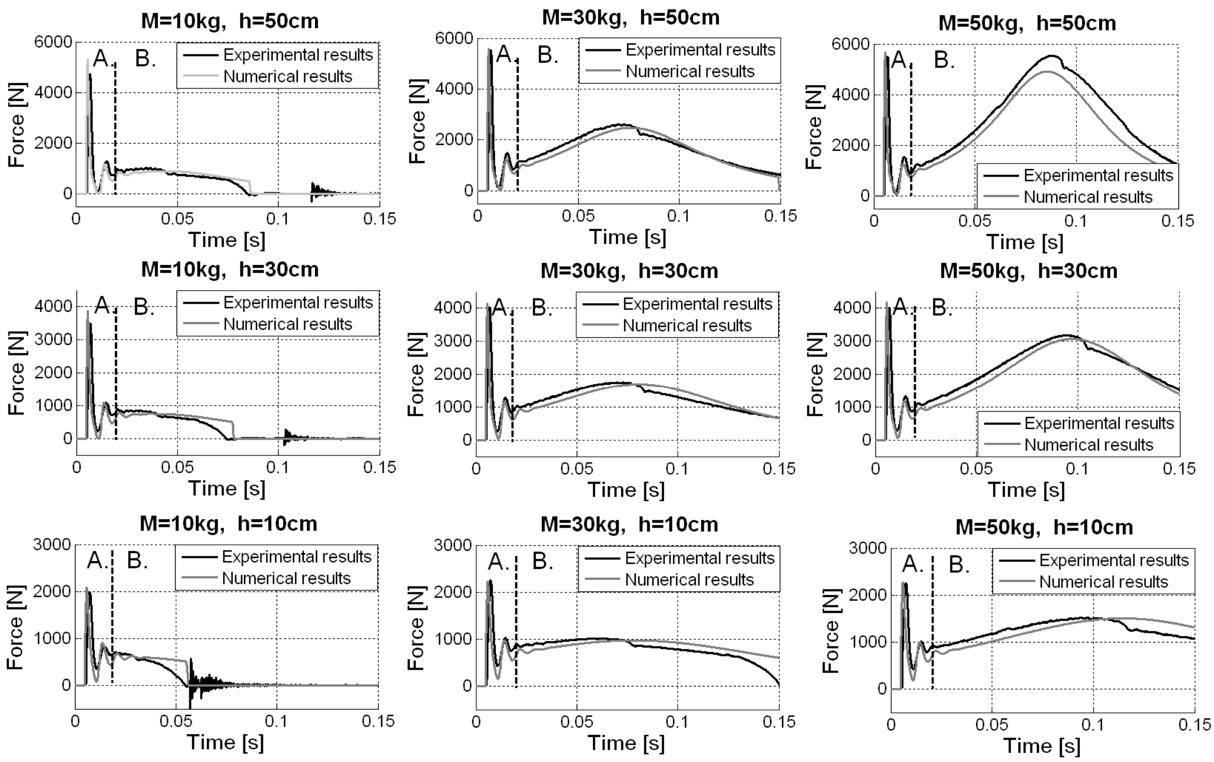

Figure 2: Numerical and experimental results of contact force in time domain

3 IDENTIFICATION TECHNIQUES

Two algorithms for real-time identification of impact parameters (i.e. impact mass and velocity) have been developed and verified experimentally and numerically: “peak-to-peak" approach and “response map” approach. Both methods operate in real-time and enable identification during the initial milliseconds of impact. It makes them useful for potential future applications in adaptive impact absorbing systems since non of them requires the sensors located in the impacting object.

4 IMPACT IDENTIFICATION BASED ON “PEAK-TO-PEAK” APPROACH

The first of the proposed approaches (the "peak-to-peak" method) uses two sensors (i.e. contact force and piston acceleration) for a very fast identification, which is possible due to the simplicity of the proposed procedure. The methodology is based on analytical formulation utilizing the well-known mechanical principles.

4.1 The idea

As it was observed in experimental tests the impact process begins with several rebounds of the piston and the falling mass (*stage A*). The rebounds are separated by short time periods during which both objects remain in contact with each other. During these periods certain instants of time occur, when the velocities of both colliding objects are equal.

Proposed method of impact identification is based on computing the time integral of the equation of the impacting mass motion in the range defined by the time instants when the relative velocity of colliding objects vanishes. Let us denote these characteristic time instants by t^{01} and t^{11}. In the equations presented in this section the upper indices represent the instant of time while the lower ones correspond to the colliding objects. Integration of the equation of motion of the falling mass yields:

$$M_1 \int_{t^{01}}^{t^{11}} \ddot{u}_1 dt - \int_{t^{01}}^{t^{11}} M_1 g dt + \int_{t^{01}}^{t^{11}} F_C(t) dt = 0 \tag{3}$$

Taking the advantage of the fact that in the considered time instants the velocities of both objects are equal, the velocities and accelerations of the falling mass can be replaced by the velocities and accelerations of the piston:

$$M_1 = -\frac{\int_{t^{01}}^{t^{11}} F_C dt}{\int_{t^{01}}^{t^{11}} (\ddot{u}_1 - g) dt} = -\frac{\int_{t^{01}}^{t^{11}} F_C dt}{\left(V_1^{11} - V_1^{01}\right) - g\Delta t} = -\frac{\int_{t^{01}}^{t^{11}} F_C(t) dt}{\left(V_2^{11} - V_2^{01}\right) - g\Delta t} = -\frac{\int_{t^{01}}^{t^{11}} F_C(t) dt}{\int_{t^{01}}^{t^{11}} (\ddot{u}_2 - g) dt} \tag{4}$$

The velocity of the impacting object at time instants t^{01} and t^{11} is determined basing on condition that both velocities are equal. Hence the following equations can be introduced:

$$V_1^{01} = V_2^{01} = \int_{t^{00}}^{t^{01}} \ddot{u}_2 dt \quad \text{and} \quad V_1^{11} = V_2^{11} = \int_{t^{00}}^{t^{11}} \ddot{u}_2 dt \tag{5}$$

The formulae (4) and (5) can be utilized directly, if both the contact force and the acceleration of the piston are measured.

4.2 Verification of the method

The proposed “peak-to-peak” identification method was verified experimentally and numerically. The experimental verification makes use of measurements from two sensors (i.e., force sensor and accelerometer attached to the piston rod). Both measurements enable to determine the time instants t^{01} and t^{11} and, further, to calculate mass of the impacting object and its velocity by using the equations (4) and (5), respectively.

The impact mass identification was tested for a vast variety of impact scenarios defined by impact mass, velocity and initial pressure. Exemplary results of identification in the case of the initial pressure of 100 [kPa] are shown in Fig. 3. The graph presents in each case the exact value of the mass and the identification error (i.e. the relative difference between the identified and actual values). The results presented in Fig. 3 show a large diversity of identification errors. It is a consequence of the strong sensitivity of the method to measurements inaccuracy which is especially apparent for small initial pressure and large mass of the impacting object.

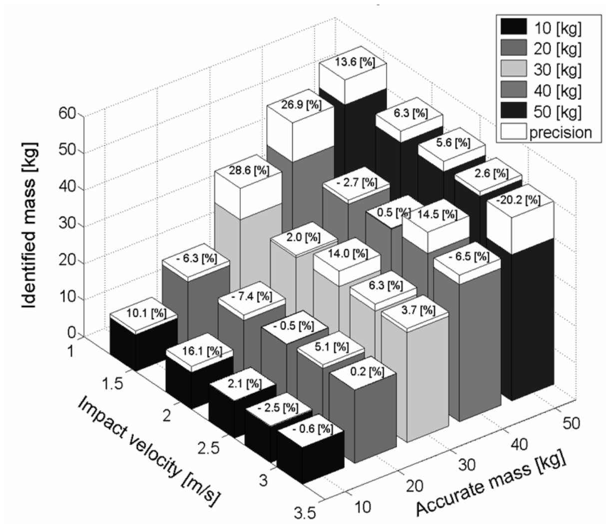

Figure 3: Mass identification precision (experimental results for initial pressure 100 kPa)

The identification of the velocity was tested experimentally by using integration of the piston rod acceleration (Eq. 5). The method uses the assumption of the equality of velocities of the colliding objects at time instants t^{01} and/or t^{11}. Although the velocity can be identified at time instant t^{01}, the time instant t^{11} was additionally used since then the impacting object mass can be identified and impact energy can be calculated. For the verification purposes the determination of the actual velocity was performed by an analysis of a movie taken by the high-speed camera. The identification results are shown in Fig. 4. The accuracy is consistently better than 2% and no significant influence of the initial condition was observed.

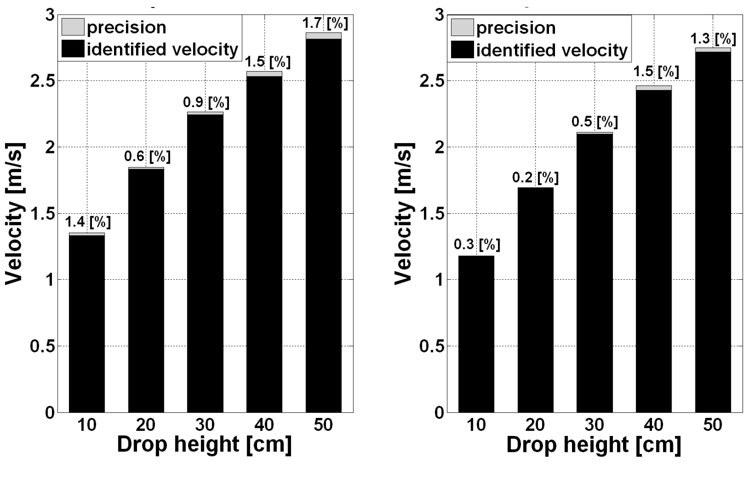

Figure 4: Velocity identification precision: (left) initial pressure 20 kPa,
(right) initial pressure 100 kPa

The numerical model presented before was used to perform a statistical analysis of mass identification error and to investigate the influence of selected parameters. The analyses were focused rather on qualitative than quantitative effects. In order to obtain more representative results, the average identification error for 125 impact cases (impact mass 10-50 [kg], impact velocity 1-3 [m/s], initial pressure 20-400 [kPa]) was calculated.

The proposed methodology turns out to be sensitive to impact conditions. Fig. 5 presents the influence of impact mass, velocity and initial pressure on the mean identification error. More accurate results were obtained for smaller masses of the impacting object, which can be explained by an analysis of the ratio of the falling mass to the piston rod mass. A smaller ratio leads to a larger change of velocity of the dropped mass in the first phase of the impact process. As a consequence, the identification procedure seems to be less sensitive to measurements noise in the case of small impacting masses. The second aspect noticed from the statistical analysis is that a higher initial pressure in the pneumatic absorber leads to more accurate results. Contrary to the mentioned parameters, the velocity effect was not significant, even if the precision slightly increased together with the impact velocity.

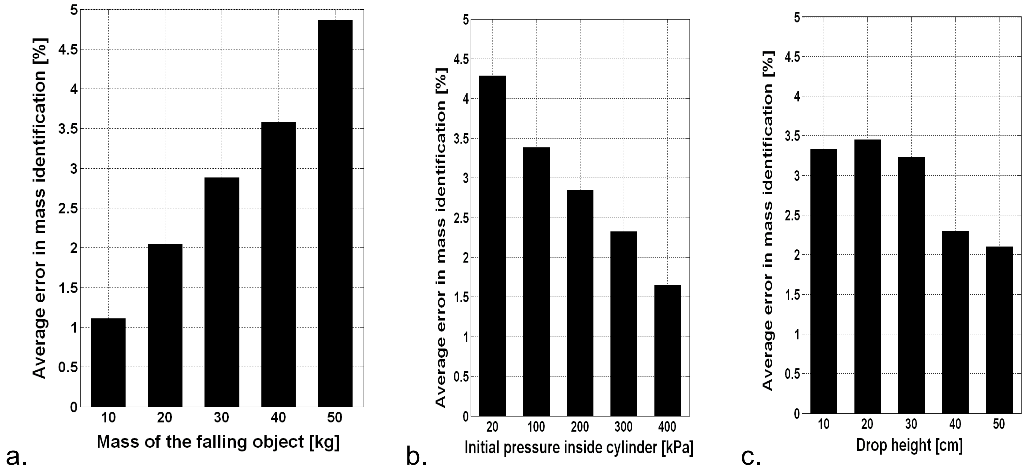

Figure 5: Average error of mass identification in dependence on: a. falling mass, b. initial pressure, c. impact velocity

Further, the sensitivity of the proposed methodology to these disturbances has been analyzed. In the numerical experiments, the noise-free simulation results were disturbed by random Gaussian noise in the range of 0-10 [%], which was defined as the root mean square value of the original signal. The results are presented in Fig. 6, where the force, acceleration and both quantities were disturbed. Each point in the graph presents the mean identification error for 125 impact cases (defined by various masses, velocities and pressures). Despite the large number of tests, apparently random values of identification errors were obtained. The noise in the force signal was found to have a larger influence on mass identification error than the noise in the acceleration signal. It was noticed that the crucial task is the proper determination of the instants t^{01} and t^{11}, which are obtained on the basis of the force signal. Hence, disturbances in the force signal lead to inaccurate determination of t^{01} and t^{11} and as a consequence, to errors in mass identification.

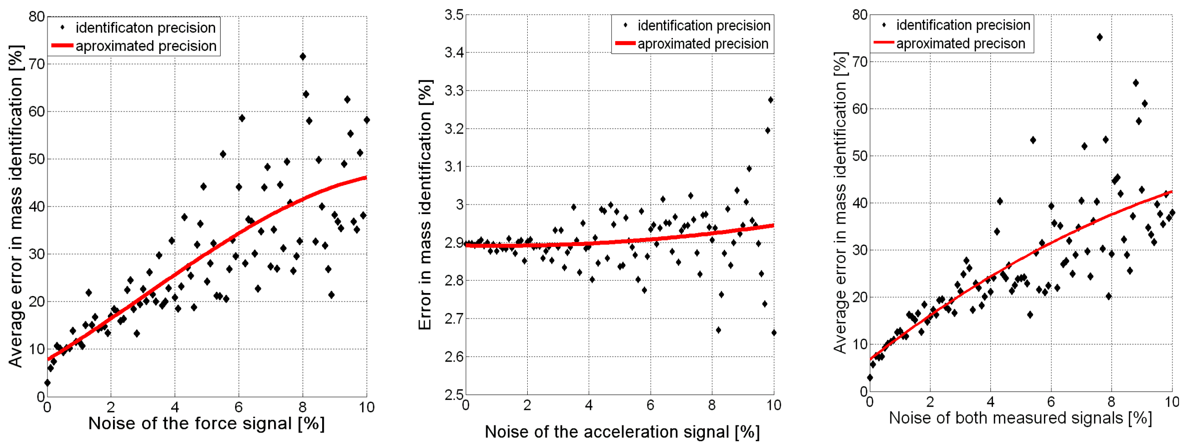

Figure 6: Error of mass identification as a function of signal noise: a. force signal noise, b. acceleration signal noise, c. both signals noise.

Finally, the influence of sampling frequency on the identification error has been analyzed. The results presented in Fig. 7 clearly reveal the importance of this parameter. As expected, higher sampling frequency enables to obtain more accurate results. Good results (i.e. mean error below 5%) are obtained for the sampling frequencies exceeding 30-40 kHz. Unfortunately, even in this case extreme outliers (i.e. approx. 20%) can be observed. A general conclusion might be drawn that the methodology requires a high sampling frequency of 50 kHz or more.

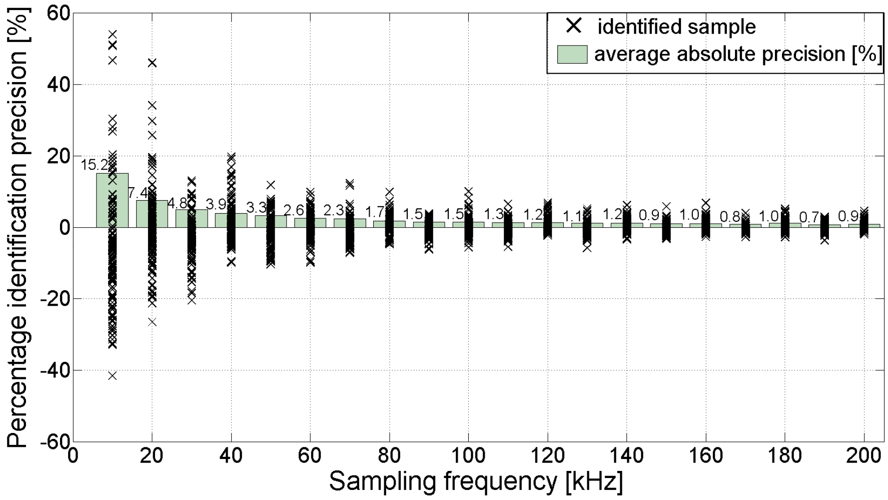

Figure 7: Error of mass identification as a function of sampling frequency

5 IMPACT IDENTIFICATION BASED ON "RESPONSE MAP" APPROACH

The methodology proposed in this section is focused on the maximum simplicity of the data acquisition set-up, i.e. application of an algorithm which utilizes measurements from one sensor only. Besides, the aim was to decrease the computational cost, which is crucial, as the device has to respond immediately in order to fulfill the deadline condition.

5.1 The idea

The proposed method can be classified into the group of pattern recognition techniques. The identification is performed based on a formerly prepared database of measured dynamic responses caused by various impact scenarios applied to the considered structure. The actually measured dynamic response is compared with the responses stored in the database. The methodology can be classified as model-free because the structural model is not required in the identification stage.

The objective of identification is to determine the impact parameters (mass and initial velocity of the impacting body) for which the structural response is the most similar to the actually measured response. The identification is based on a pre-fetched database (called the response map) which gathers selected characteristic parameters of the measured structural responses $Y_1, Y_2, \ldots, Y_m$ (e.g. signal amplitude, its period etc.) that correspond to various parameters of the applied loading $x_1, x_2, \ldots, x_n$ (e.g. mass, impact velocity, etc.).

The approach consists of two main steps. In the first step, the database is generated, which can be performed either via a calibrated numerical model of the structure or by experimental tests. The second step is real-time impact identification. Measurement of the actual response is performed and compared with the measurements stored in the database.

The proposed approach leads to an optimization problem in which the discrepancy between the actually measured response Y_i^M and the stored responses Y_i is minimized. With the normalized least squares discrepancy measure, the objective function to be minimized takes the following form:

$$L(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{m} \left[\frac{Y_i^M - Y_i(x_1, x_2, \ldots, x_n)}{Y_i^M} \right]^2 \tag{6}$$

and the corresponding optimization problem relies on minimization of the objective function over impact parameters $x_1, x_2, \ldots, x_n$. The number of parameters to be identified, denoted by n, is limited by the number m of the parameters used for identification: $n \le m$.

In the considered case two parameters (i.e. falling objects mass $M_1 \equiv x_1$ and its impact velocity $V_1 \equiv x_2$) had to be identified by using a single measurement from the force sensor. Therefore, in order to construct the response maps, at least two characteristic quantities had to be extracted from each single measurement. The selected quantities were either the amplitudes of the two first peaks of the force signal or, alternatively, maximum value of force and its time integral in the considered time interval. For the given response maps, the impact identification procedure utilizes the error function defined as:

$$f\langle M_1,V_1\rangle = \left[\frac{Y_1^M - Y_1(M_1,V_1)}{Y_1^M}\right]^2 + \left[\frac{Y_2^M - Y_2(M_1,V_1)}{Y_2^M}\right]^2 \qquad (7)$$

where: M_1 and V_1 are the impact parameters to be identified, Y_1 (M_1, V_1) and Y_2 (M_1, V_1) are obtained from the response maps for the specific values of M_1 and V_1, while Y_1^M and Y_2^M denote the actually measured values.

5.2 Verification of the response map approach

The verification of the method was focused on the sensitivity analysis and it was performed on the basis of numerical simulations. Two features of the proposed procedure were considered: identification error and computational cost.

The response map was built using the results obtained for 100 different impact scenarios (10 impacting masses 10-50 kg and 10 impact velocities determined by the drop height 5-50 cm), while the initial pressure was not altered. Hence, the database was originally of the size 10x10 and utilized two parameters. The approach was tested by using 10 randomly selected impacts. An important problem to be considered is the minimal size of the database which guarantees acceptable identification accuracy. The database size was numerically increased by interpolation. Nine databases (25x25, 50x50, 100x100, 250x250, 500x500, 1000x1000, 2000x2000, 2500x2500 and 3000x3000) were obtained.

The graphs shown in Fig. 8 present the average identification error and the computational cost of identification of impacting mass (Fig. 8a) and impact velocity (Fig. 8b) as functions of the database size. Here, amplitudes of the first two peaks of the contact force in the first stage of the impact process were used as characteristic parameters. In each case, the accuracy of velocity identification turns out to be much higher (about 5-10 times) than the accuracy of mass identification. It is the result of the different sensitivity of the measured contact force on both parameters. In general, the accuracy of the response map approach increases together with the database size. Nevertheless, the computation time increases significantly as well. Hence, the identification process for large databases became impractical with regard to the deadline condition. For databases larger than 3000x3000 ($9{\cdot}10^6$ of mass-velocity variants) the computational cost exceeded 350 ms for a modern PC. As a consequence, the 500x500 database has been used to guarantee an acceptable identification accuracy and to keep the computational cost low.

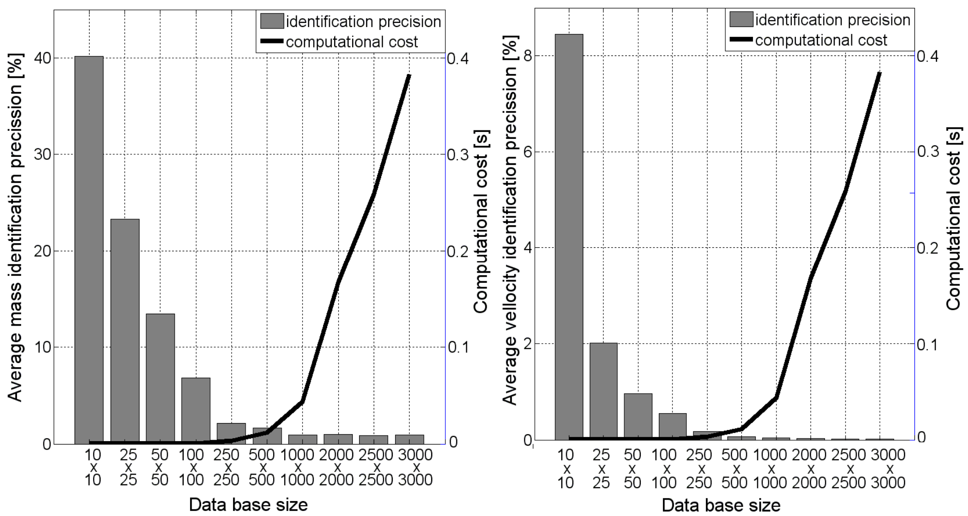

Figure 8: Identification error and time as functions of database size: mass identification (left), velocity identification (right)

Next, the maximum value of the contact force and its integral in a certain time interval were used as characteristic parameters to build the database. A significant influence of the integration interval length on the identification error was found. The results obtained for the database 50x50 are shown in Fig. 9. The accuracy increases together with the length of the time interval and this effect is the most significant for smaller databases. On a contrary, in the case of velocity identification, the obtained precision is insensitive to the length of the integration interval.

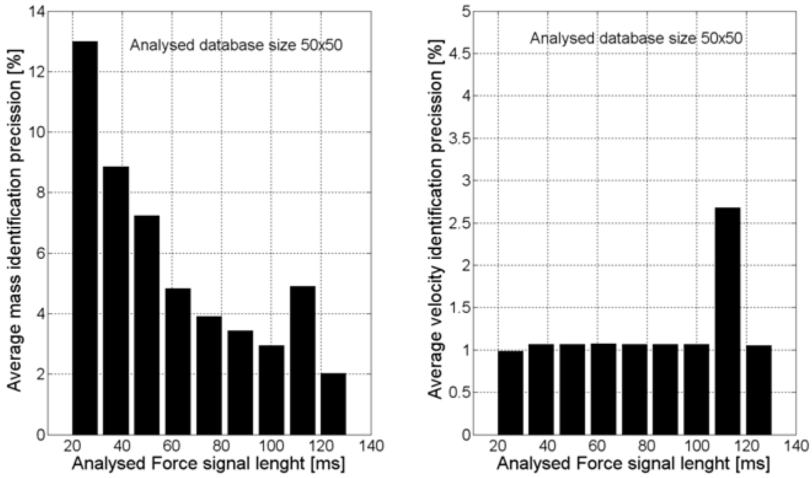

Figure 9: Identification error as a function of analyzed force signal length: mass identification (left), velocity identification (right).

6 THE CONCEPT OF THE AIA DEVICE

The conducted research enables to propose a concept of the device which utilizes the developed on-line identification methods. Such a device contains a gas spring, which can be switched to a pneumatic absorber (via controlled opening of pressure release valve), and thus is capable of dissipating impact energy in controlled manner. A simplified scheme of the impactometer together with the pneumatic adaptive impact absorption device is shown in Fig. 10. The force sensor F and the accelerometer A are used for the identification of impact parameters and together with the gas spring and the control system CS, are the main part of the impactometer. The pressure sensors P1 and P2 are used for the measurement of the pressure in the chambers V1 and V2 and together with the control system CS and controllable valve Z are the main parts of the AIA system.

The theoretical effectiveness of an AIA system which utilizes impactometer-based impact identification is shown in Fig. 10 b. Three force histories are presented: i) the case when the valve remains closed during the impact process, ii) the case with constant optimum valve opening and finally iii) the case of real-time control of the gas flow. Both considered adaptation strategies enable to reduce the contact force observed in the second stage of collision and so to decrease the deceleration acting on the colliding object. The second of the applied strategies (real-time control of the gas flow) allows to obtain optimal, constant level of the deceleration during the entire second stage of impact.

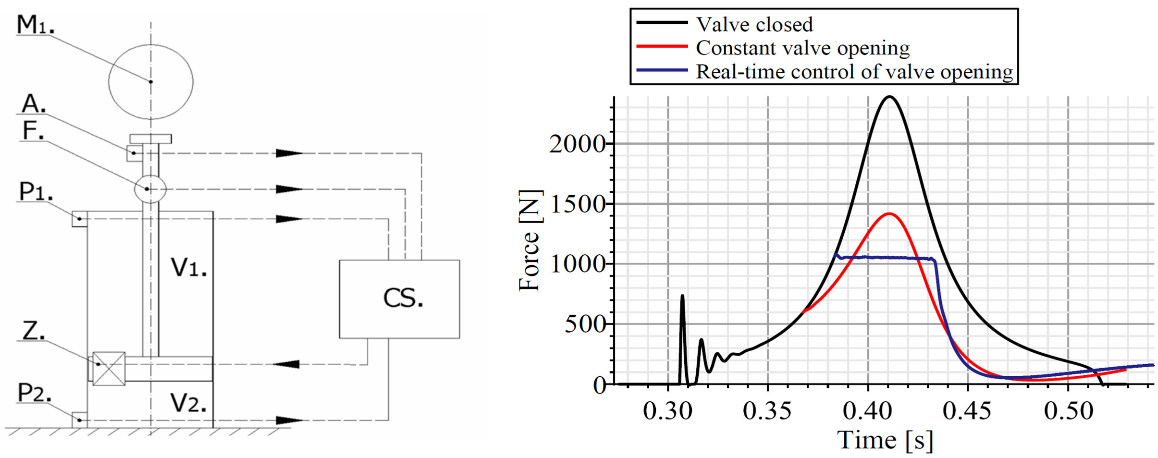

Figure 10: Adaptive impact absorption system equipped with the *Impactometer* device: a. scheme of the proposed system, b. numerical example of an impact scenario

8 SUMMARY

The paper presents an analysis of the process of a rigid body impact into a pneumatic cylinder. The impact drop tests were performed experimentally and a numerical model of the impact process was developed. A wide variety of impact scenarios have been tested and its range has been numerically extrapolated. Various properties of contact element in collision region were investigated. Two algorithms for real-time impact load (i.e. impact mass, velocity) identification have been demonstrated (in Sections 4 and 5). Both algorithms operate in real-time and enable identification of impact during its initial milliseconds. It makes them useful for potential future applications in adaptive impact absorbing systems.

The first of the proposed approaches (the “peak-to-peak” method) uses two sensors (contact force and piston acceleration) for a very fast identification). On the other hand, the method requires high sampling frequency and almost noise-free measurement data. Precision of the identification was found to be sensitive to the internal parameters of the impactometer. An acceptable precision was obtained when the mass of the impacting object was comparable to the mass of the piston rod (within the range of one order of magnitude) and for high pressures inside the cylinder.

The second of the proposed methods (the "response-map" approach) is based on single measurement only (contact force), however it requires initial preparation of the database. It can be obtained either by multiple experimental tests or by numerical simulations. The "response-map" approach requires longer identification time than the "peak-to-peak" approach, but the results are more precise. The mean value of identification errors as well as their deviations decrease for larger databases, however at the cost of the identification time. Independently on the identification method, accurate velocity identification is much easier to perform than accurate mass identification.

8 ACKNOWLEDGEMENT

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