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REAL-TIME IMPACT LOAD IDENTIFICATION

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Abstract. *The objective of this paper is to analyze feasibility of the real-time impact load identification (using RIM- Real Time Impact Monitoring sensors) concept, applicable to so called Adaptive Impact Absorption (AIA). The structure equipped with the RIM monitoring sensors, a controller and controllable dissipaters can perform as an AIA system smoothing down structural dynamic response due to random impact loads. The RIM sensor operation can be based on local strain/acceleration measurements already in few, properly chosen locations of the structure. The motivation to undertake the above research problem is stimulated by the following challenge: "is it feasible to predict the impact load energy via monitoring of local dynamic response (in real time) fast enough to feed up the adaptive impact absorption system"? The positive answer would mean that fully automatic system detecting and identifying environmental impacts (and adapting to them in a pre-designed way) can operate in practice.*

1 INTRODUCTION

The demand for the systems able to absorb impact energy has been recently growing up. It is mainly caused by the rise of requirements to life, health and property protection, which touches the wide range of industrial, public and environmental applications.

The versatility of those impact absorbing systems (AIA systems) is characterized by possibilities to use them as the protective barriers against float, wind blast, hurricanes, snow slide or soil slip events. The adaptive shields in coal mines, wind turbines, car crash accidents, the protective monitoring systems of nuclear power plant containment structure as the safest technical installation or protective road barriers could be the next appropriate applications of the impact absorbing systems.

Mentioned events have to perform in time range of 20-200 milliseconds. During this short time period, the impact described in form of signal response of measuring sensors has to be recognized, described, evaluated and in form of proper signal should be sent to adaptive device, where it becomes an input signal of close loop control systems. The actively adaptive absorbing systems have to react immediately. The whole process should run online; therefore we propose to design a device called Real-Time Impact Monitoring sensor.

2 IMPACT CHARACTERISTICS

Let us consider structure shown in Fig.2, affected by dropping mass and the sensor RIM yielding much faster than the structure itself. The minimum required information determining impact load (in the location of the sensor) consists of two quantities: the initial impact velocity and the dropping mass (or kinetic energy). The truss cantilever, shown in Fig.1, demonstrates how differently the above characteristics affect dynamic response of the structure. The curve lines describe various combinations of dropping mass and its impact velocity resulting in the same impact energy. It means, that we can have *slow dynamics* (the area 2) corresponding to heavy mass dropping with slow velocity and *fast dynamics* (the area 1) corresponding to small mass dropping with high velocity. The structural response to each of these impacts (despite of identity of the impact energy) is different and requires different control strategy of adaptation. Finally, let us conclude that real-time identification (by means of RIM) of the impact velocity and the dropping mass allows us to feed up the AIA system protecting the main structure.

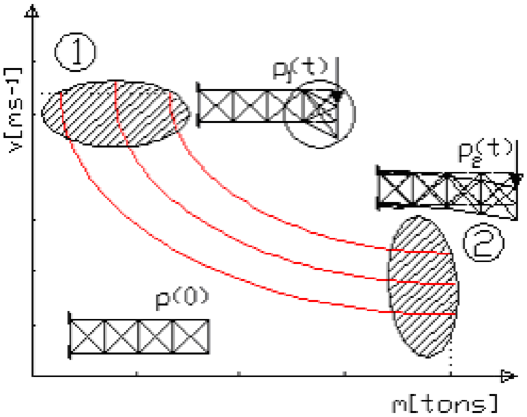

Figure 1. Influence of impact velocity and the mass of the dropping object on structural response

3 THE CONCEPT OF THE RIM SENSOR

Let us assume that the following measurements can be done with our RIM sensor: impact velocity, acceleration development under the dropping mass and the force development under the RIM sensor.

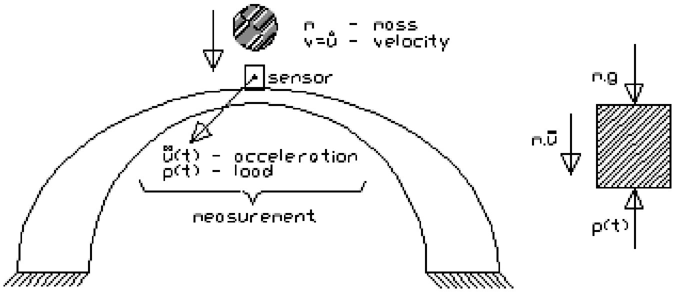

Figure 2. RIM sensor and adaptive structure

From equation of motion of the dropping mass it follows

$$F(t) = m \cdot g - p(t) = m \cdot \ddot{u}(t) \tag{1}$$

$$m(t) = \frac{p(t)}{g - \ddot{u}(t)} \tag{2}$$

where p(t) denotes measured force in kN, $\ddot{u}(t)$ expresses the acceleration under the dropping mass measured in ms^{-2}, and m(t) depicts mass to be identified in kg and g is the gravitation acceleration in ms^{-2}.

Having measured impact velocity, the impact kinetic energy (to be dissipated) can be now determined:

$$E_k(t) = \frac{1}{2} \cdot m \cdot \left(\dot{u}(t) \right)^2 \tag{3}$$

where E_k depicts the kinetic energy, m represents the mass of the system and $\dot{u}(t)$ denotes a velocity dependent on the impact development in time. The velocity can be obtained directly from measurement or indirectly by the integration of the acceleration signal in real time.

4. EXPERIMENTAL DEMONSTRATION

The proposed concept was verified experimentally by analyzing of the data obtained from the tests carried out at a small drop test stand. The mean feature of the experimental evaluation was a determination of the dropped mass magnitude, came out form the measured signal.

4.1 Mechanical layout

The drop test stand (made available by another project, Ref.3), shown on the figure 3, consists of the hydro-pneumatic damper mounted in vertical position, rubber element playing a role of bumper and dropping mass. The whole system is put into a steel frame, for a lifting purpose of the dropped mass. The experimental stand is fixed to the 800 kg foundation plate in order to avoid the unprofitable noise signals, which could affect an executed measurement. The lifting mechanism enables to set up the dropping height up to 700 mm. The weight of the dropped mass was during the measurement in the range from 12 kg to 17 kg. The mass is guided by the rail system embedded in the wood frame, to secure a stabilized horizontal movement.

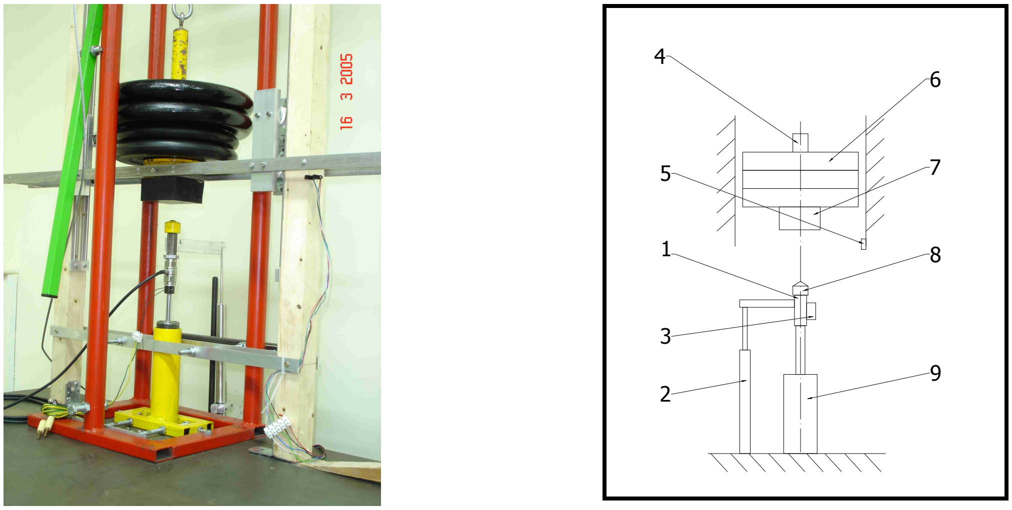

Figure 3. Dropping test stand

The buffer creates the impact interface segment between the piston rod and the rubber bumper in conical shape. The ordinary force displacement characteristic of the 5 cm thick rubber bumper should have been taken into account during measurement, due to specific behavior in contact with the steel element with specific geometrical shape. For that reason, a special set of the tests was carried out in order to obtain the force displacement compression characteristic of the rubber material compressed statically by the conical element used during the drop test. The dimensions of the rubber bumper and the collaborating conical steel element as well as the obtained static force displacement compression characteristic are given in Figure 4.

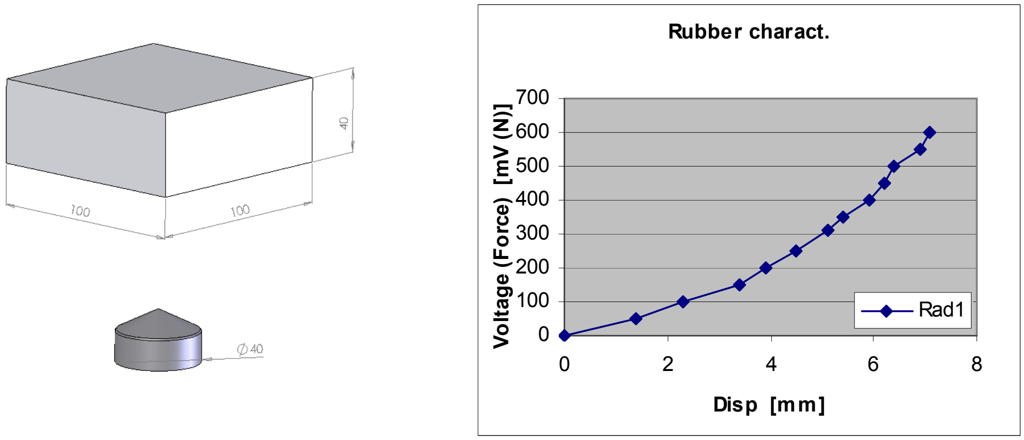

Figure 4. Rubber bumper, and its compression characteristic and the conical buffer

4.2 Sensors Configuration

The dropping stand, shown in the picture 3, was equipped with the following set of sensors:

- Piezo electric force sensor placed between rubber bumper and hydro-pneumatic damper
- Piezoelectric accelerometer fixed to the piston rod of the hydro-pneumatic damper
- Displacement sensor (LVDT) fixed to the piston rod of the hydro-pneumatic damper
- Piezoelectric accelerometer fixed on the dropped mass
- Photo optical logical switch

The force sensor (1) was mounted on the interface between dropping mass and supporting structure in order to measure the full history of the impact forces. The displacement sensor (2) and accelerometer (3) both measure the vibration of the same degree of freedom in the system. The configuration was chosen in order to get a possibility of validation of the data measured with the sensors. The accelerometer (4) was fixed on the dropped mass. The photo optical switch (5) enabled validation of the dropped mass vibration. The main purpose for the Photo optical switch was a determination of the initial impact velocity for the particular test. Additionally, the signal was used as a trigger for the data acquisition process.

The described drop-test stand enables us to simulate the wide variety of impact scenarios. The set up, due to crashed specimen, permits to gain the dissipation of the energy and to get an input either to mathematical model or to the real time impact simulation. This approach helps to define the material properties of specimens necessary for next proposed inverse methodology, which could speed up whole process of the impact recognition.

The dropped mass identification can be performed in two possible ways. First one is based on the force and acceleration measurement in time. The signal recorded by the sensors is adapted by the smoothing techniques and the value of the mass is evaluated by the equation no.2, mentioned in the previous section. The mass development in time is based, due to second approach, on the force and displacement measurement. The displacement chart is smoothed and twice differentiated to get an acceleration response. Thereafter, the transformed value is introduced into the same equation no. 2 and the mass value is calculated.

The analogous process establishes the velocity of the dropped mass. Either the measured acceleration is smoothed and once integrated to get the velocity development, or the displacement signal is also firstly smoothed and then differentiated to get the same response.

4.3 Mass identification

Two dropping tests have been performed and the measured signals are shown in Fig.5. One of them is with the mass of 12kg and the other with the mass of 17kg. Interpretation of the measured response is following:

- the impact occurs 10 ms after triggering the time measurement
- after further 20ms the dropping mass and the head of dissipater meet (point A on Fig.5) and start to move jointly,

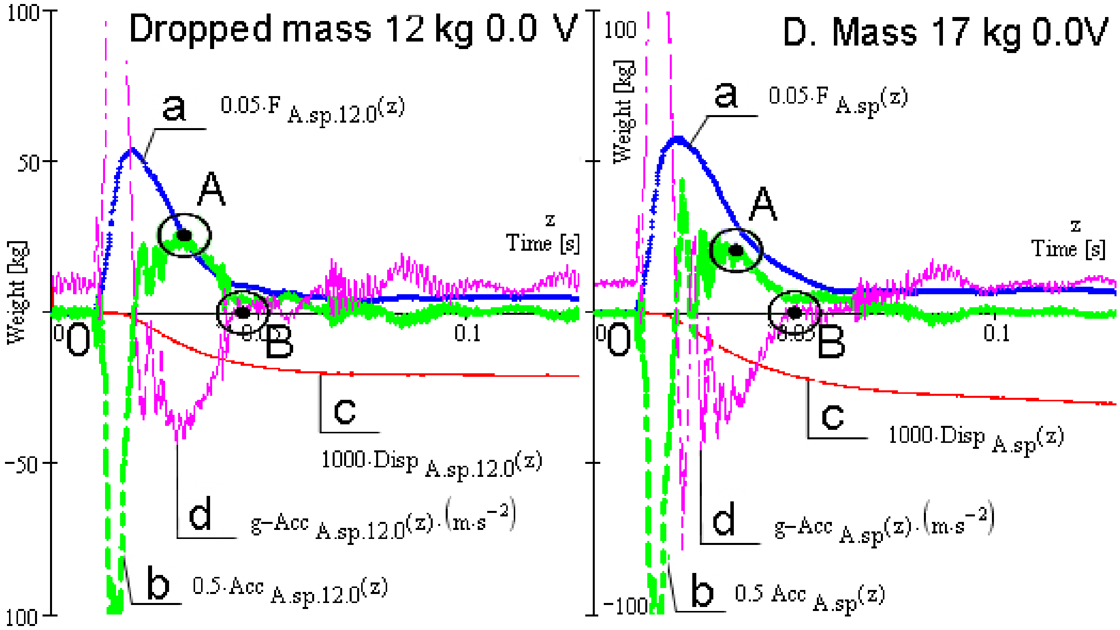

Figure 5. Measured signals for two dropped masses (12kg and 17 kg): a) force under the dissipater, b) acceleration measured on the top of dissipater, c) deflection under the dropped mass, d) function g-d2u/dt^2

- after further 12 ms the curve g-d2u/dt^2 crosses the value zero (point B) what causes jump to infinity of the value of expression (2) (cf. Fig.6).

- the mass *m* identification should be performed on the base of signal analysis in the time interval <t_A, t_B> where t_A and t_B correspond to points A, B marked in Fig.5.

As we can see, the mass identification (curve (e) in Fig.6) in the time interval <t_A, t_B> is close to the exact value (12 kg) in the first case and it keeps its maximal values close to the exact value (17 kg) in the second case.

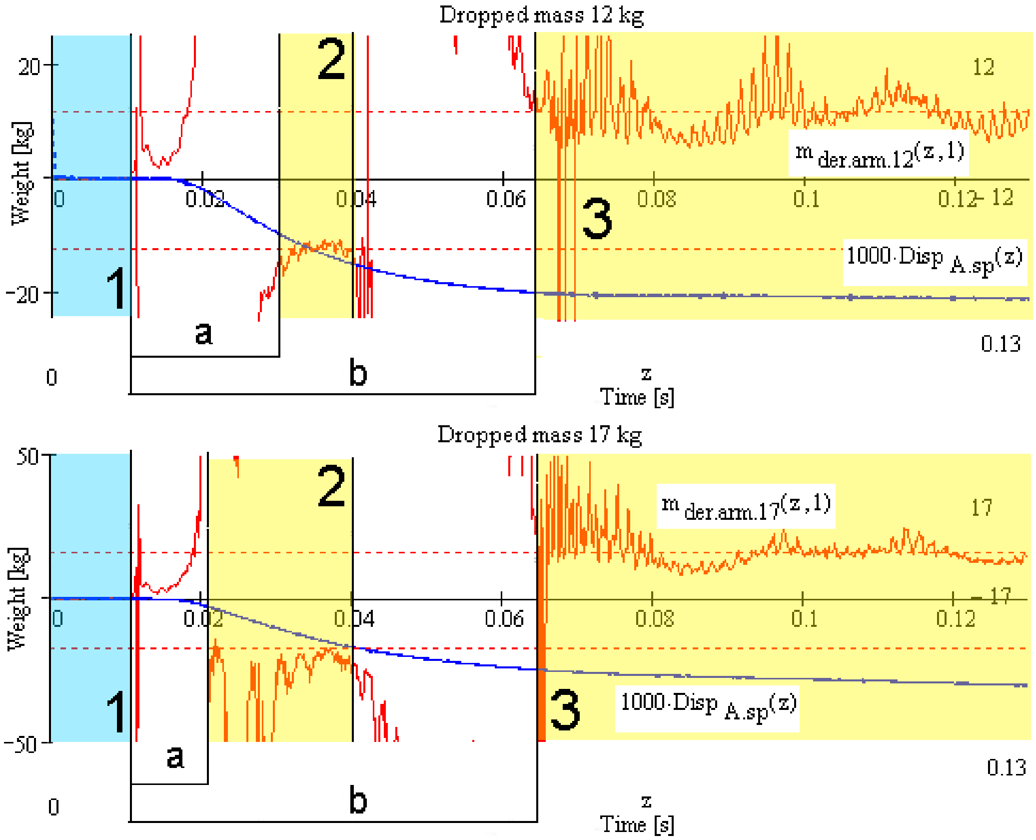

Figure 6. Mass identification curve (e)

The second test (Figs.7 and 8) has been performed with stiffer damper. Applying voltage 0.01 V .the activated MRF fluid causes increase of the overall stiffness of the dissipater what can be observed in development of measured signals.Comparing results from the two above discussed cases (Figs 5,6 vs. Figs.7,8), we can see that by the increasing compliance of the dissipater, the time interval <t_A, t_B>, necessary to perform the mass estimation, can be reduced In the case of 12 kg weight of the mass, the time instance t_A has been shifted from 0.02003 s to 0.02644 s after applying voltage.

The presented initial study shows that the crucial issue of the on-line impact identification is: i) proper tuning of the RIM sensor stiffness (to the stiffness of the main structure itself and to the range of expected impact energies) and ii) the measured signal conditioning allowing its interpretation through the proposed below identification algorithm. Moreover, the above discussion leads to the main conclusion that real-time identification of the impact can be feasible, feeding up AIA system (e.g. lasting 200 ms, like in landing gears) with the delay of 20, 15 or even 10 ms (depend on the RIM tuning). Properly tuned (to the dropped mass 12 kg) stiffness of the RIM sensor will get rid of the line *b* fluctuation (Fig.5) and its crossing zero. The main character of the desired response will be close to the line *c*.

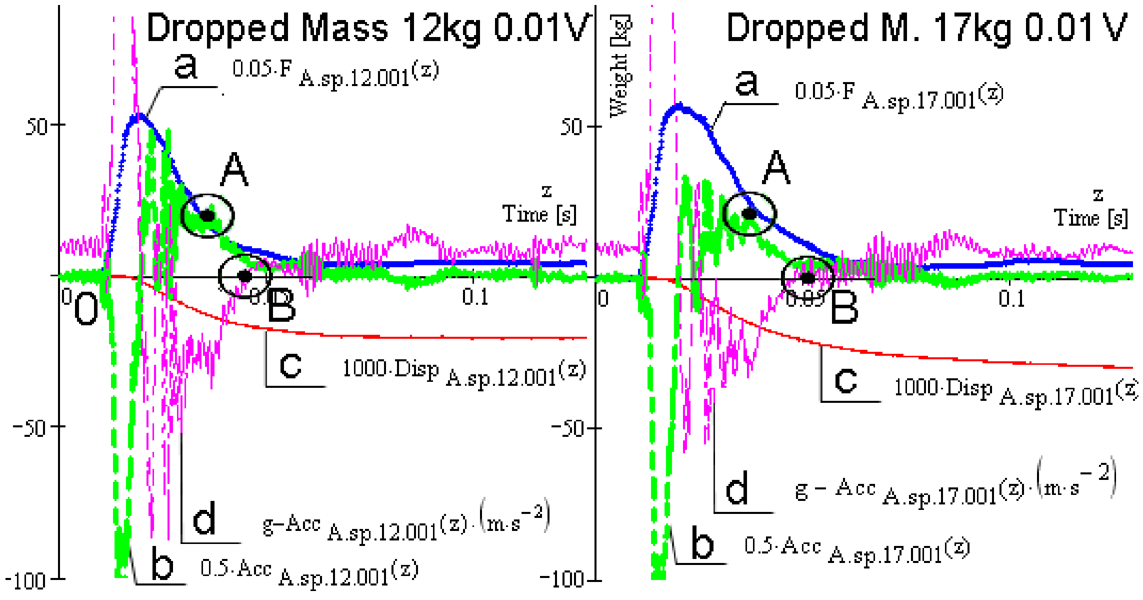

Figure 7. Measured signals for two dropped masses (12kg and 17 kg) with stiffened dissipater: a) force under the dissipater, b) acceleration measured on the top of dissipater, c) deflection under the dropped mass, d) function g-d2u/dt^2

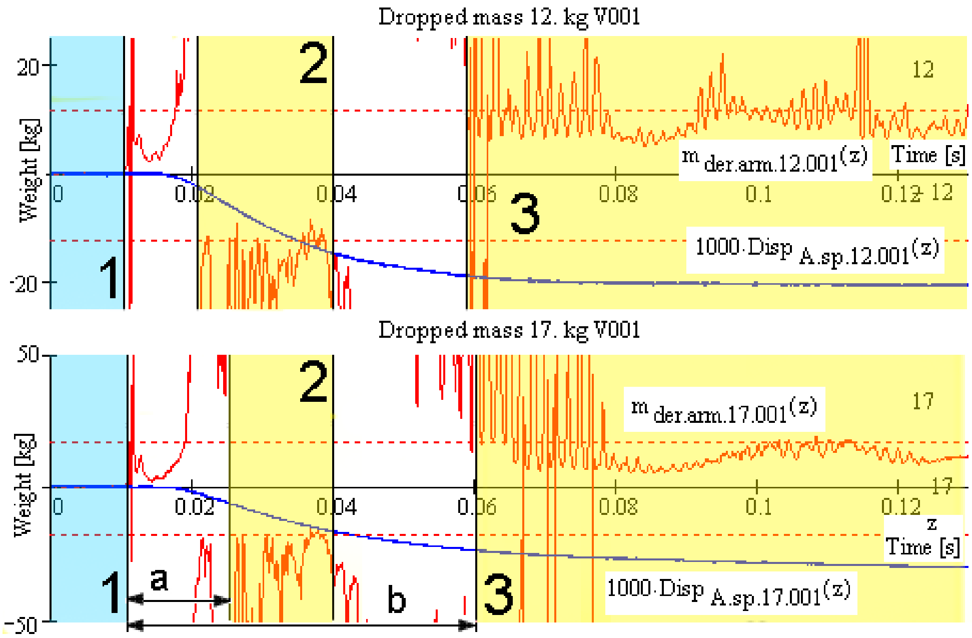

Figure 8. Mass identification curve (e) with stiffened dissipater

4.4 Measurement problems

The in-time smoothing techniques of the recorded signal are the necessary condition for performing of the real time impact recognition. The smoothing could be performed in two basic ways. First approach is based on the hardware level data processing, whereas the programmed software tool performs the second way.

The data acquisition process was performed by means of 8-channel, 16-bit, multifunction NI board PCI 6052E configured as a real time device in LabView environment. The signals measured with piezoelectric sensors (force and accelerations) were preamplified and preconditioned with low pass filters before feeding into the Data acquisition system. The sampling frequency for the tests was defined as 40 kHz. The scheme of the data acquisition setup is presented in figure 9

On the level of smoothing techniques were checked methodology of the least square fitting with different order of magnitude of the polynomials and the sp-line fitting. The methodology based on the least square polynomial fitting for lower order of magnitude seems to be quick enough to process the data in time, however the square error obtained during the evaluation is significant and it distort the results. On another hand the higher polynomials guarantee the adequate accuracy however the process of the performed calculation is time-consuming. During the experimental development we found out that the signal can by sufficiently described by the SP-line fitting, what doesn't distort the results significantly.

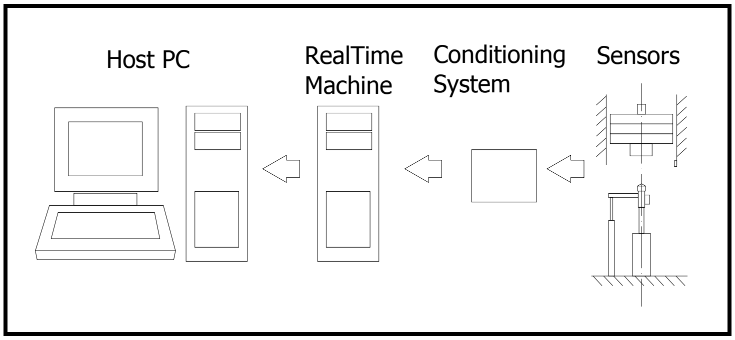

Figure 9. Mass identification example

4.5 Proposition for the on line mass identification algorithm

Let us propose the following algorithm of the real-time executable (via the "conditioning system", cf. Fig.9) mass identification (addressed to the case: 12 kg, 0.01V):

- If $\ddot{u}(t) < 0$ and $\| \ddot{u}(t) \| \geq \bar{\ddot{u}}$, the mass identification process is triggered (is denotes as 0-point in the pictures 5 and 6),

- If $\ddot{u}(t) \geq 0$, then the process of searching for the maximal value ($\ddot{u}_{\max}$) and the corresponding time instance t' is triggered. The search is confined to the range between the points A and B, which are determined in the following way: The point B corresponds to the time instance in which the measured acceleration ($\ddot{u}(t)$) falls for the first time below the acceleration of gravity (g). Next the point A is identified as the last time instance before the point B in which the measured acceleration attains a local maximum (i.e. in which $\Delta \ddot{u}(t)$ changes sign). The maximum acceleration ($\ddot{u}_{\max}$) occurs in the point A.

- The mass identification is performed according to (Eq.2), right after the determination of the range A-B, based on the stored values of $\ddot{u}_{\max}$ and p(t').

- the initial velocity can be estimated on the base of measurements u(t) stored in the time interval $<t_A, t_B>$.

In real applications the number of needed measurements can be reduced to simplify operation of the RIM sensor. For example, measurement of u(t) can be sufficient to deliver $\dot{u}(t), \ddot{u}(t)$ via the hardware based calculation of derivatives of the signal.

5. GENERALIZED IMPACT MONITORING CONCEPT

Very often, the impact load is generated by energy type of excitation, eg. in coal mining, where a seismic type of released energy affects supporting structure. It is proposed to apply the following two parameters identifying the impact process in this case of: velocity and pseudo mass, both of them time dependent.

Let us generalize formulation used in the Section 3 assuming analogous data acquisition collecting measurements of $\dot{u}(t)$, $\ddot{u}(t)$, p(t). (cf. Fig.10). However, the mass m(t) determined by Eq.2 is now time dependent, while it was expected to be constant in the previous case. This time dependent pseudo mass determine an auxiliary mass generating pressure on the structure. Also impact velocity has to be measured in time in order to estimate increments of impact energy. The energy (Eq.3) estimated in each time step shows up the amount to be dissipated in the impact absorption process.

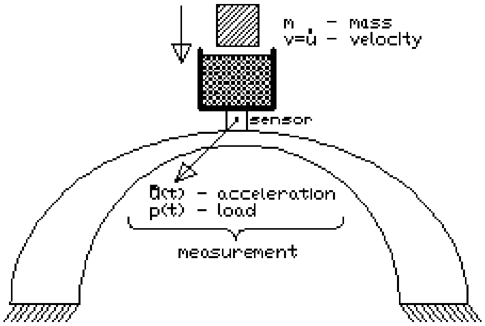

Fig.10. RIM sensor and adaptive structure. Energy type of the excitation case.

6. CONCLUSIONS

It has been demonstrated that real-time impact load identification is feasible and requires the following procedure:

- proper tuning of the RIM sensor stiffness in relation to the stiffness of the monitored structure and the expected impact intensity,
- proper data acquisition (cf. Chapter 4.4)
- real-time data processing, eg. following the algorithm presented in Chapter 4.5.

In the cased of dropping mass, the mass itself and its impact velocity have to be determined prior to the impact energy estimation. On the other hand, in the case of energy type of impact, time dependent so called "pseudo mass" and its (also time dependent) velocity identified on-line allow to determine the development of kinetic energy of the impact to be absorbed.

7. ACKNOWLEDGEMENT

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