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ON INFLUENCE OF DELAYED ADAPTATION OF INFLATABLE SCTRUCTURE FOR EVACUATION OF PEOPLE AT HEIGHTS

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Abstract. Our study presents the research on elaboration of a novel type of the rescue air cushion, which is an inflatable structure used by fire brigades for evacuation of people at heights. The goal of our work is to increase its injury prevention capabilities. We consider the system based on an airframe filled with a compressed gas and a double-chamber airbag, which exchanges the air with environment. Discussed research includes modelling of the system, numerical simulations of its dynamic behavior and description of the dedicated adaptive solution. Practical implementations of the original ideas are conducted using the rescue cushion in 1:2 scale and a full-scale demonstrator of semi-passive valves. According to the already obtained results it is experimentally proven that a significant improvement of the system's characteristics can be achieved by introducing valves of simple construction [1]. In this study the influence of a delayed start of the adaptation procedure is investigated in detail. Obtained conclusions are used in order to indicate directions of further system development, which will concern, among others, estimation of the impacting body trajectory and identification of the impact position.

Key words: Adaptive Impact Absorption, Airbag system, Dynamic characteristics optimization, Impact mitigation, Rescue cushion, Pneumatic shock-absorber.

1 INTRODUCTION

The inflatable structure being a subject of this paper is a type of an airbag system and is called rescue air cushion or safety cushion, what relates directly to its application. Rescue cushions are devices applied by fire brigades for evacuation of people at heights [1]. The airbag, which is a main part of the rescue cushion, utilizes the pneumatic effect of compressing the air and releasing the compressed gas in order to obtain favorable loading profile. As a result, hard contact of falling persons with the ground is avoided and replaced by relatively soft deceleration within the airbag stroke. In terms of system operation, design and modelling, rescue cushions can be treated as impact absorbing structures under dynamic excitation, similar to car airbags [2]. Indeed, there is more airbag systems which can be used as references for development of novel rescue cushions. They include, among others, advanced cargo airdrop systems [3],

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emergency landing devices for drones [4] or offshore protecting structures for wind turbines [5].

Depending on the type of shock-absorbers different approaches to adapt the system response can be applied. When pneumatic absorbers are considered, adaptation is realized using adjustable [6] or controllable release vents and valves [7]. In order to determine appropriate valve opening, which allows for minimizations of dynamic loading, the impact conditions should be predicted or identified, and the model of shock-absorbing structure should be known. Airbags are modelled using Fluid-Structure Interaction (FSI) approaches [8], which are typically realized by combining Finite Element Method (FEM) with Uniform Pressure Method (UPM) [9]. UPM relates to a simplified gas behavior modelling, assuming uniform distribution of its thermodynamical parameters within a control volume. This approach is commonly used in automotive industry for modelling of car airbags and it is also applied by the authors for rescue cushion's simulation.

The paper focuses on the implementation of adaptive, semi-passive valves [10], which were invented in the Institute of Fundamental Technological Research. In the following sections authors introduce their structure and explain their operation on the example of laboratory demonstrator. Then, numerical model of the rescue cushion with adaptive valves is presented and finally, a numerical study discussing the influence of a delayed valves operation on the performance of the rescue cushion is shown. The paper is ended with short conclusions, which include a requirement for the adaptive valves' system provided in order to obtain successful and efficient system adaptation.

2 PROBLEM DESCRIPTION

Fundamental aim of the pneumatic impact absorber, one of which is the presented rescue cushion, is mitigation of accelerations (or interchangeably forces) acting on the landing object, in particular a human. We have already presented this problem in the context of rescue cushions, and discussed our general approach for dealing with it utilizing a semi-passive approach [1]. Specifically, some especially designed valves are introduced into the structure of an airbag which allow for adjustment of the venting area according to the identified impact conditions – mass and velocity of the object hitting the rescue cushion.

The most popular type of the rescue cushion in Europe is the one with pneumatic airframe. These devices are designed according to the requirements stated in domestic standards or regulations, which in most cases specify the maximum height from which a person can jump on the cushion as 16 m. Free fall from 16 m lasts about 1.8 s and the typical impact duration is between 50 and 100 ms. Taking these values into account, as well as the limitations of the maximum speed of the actuators controlling the valves, adjustment of the valves is supposed to be conducted as soon as possible before the impact. Late identification of impact parameters entails a delayed start of the adaptation procedure. This, in turn, would definitely affect the operation of the adaptive rescue cushion, since the adaptation procedure can still continue during the impact.

In this study we examine the influence of the delayed start of the adaptation procedure. We consider two exemplary cases chosen arbitrarily – first case of the very late start of the adaptation procedure, namely the adjustment of the valves starts when the impact occurs, and second case when the procedure starts in a moment chosen so it could end near the moment of reaching the first peak of force acting on the landing object. This point is calculated for the reference case with the same impact parameters but passive behavior of the rescue cushion.

Juxtaposing the results of such impact cases with optimally adapted and passive ones will help answer the question of the minimum time advance with which the impact parameters should be determined.

3 ADAPTIVE RESCUE CUSHION

The development process of the adaptive rescue cushion comprised both experimental and numerical works. Experimental demonstrator was used for validation purposes of the numerical model. It is also essential to study all aspects of its ergonomics – folding, unfolding, preparing for the usage, etc. A numerical model was developed in order to provide an efficient way of testing the proposed new adaptive solutions as well as optimizing its dynamic behavior. In this study, it is used to evaluate the effect of the delay in the start of the adaptation procedure on the forces acting on the landing object.

3.1 Experimental demonstrator

The demonstrator, built for the purposes of conducting real-life tests of the adaptive rescue cushion, is a device of dimensions scaled by half comparing to typical rescue cushions used by fire brigades. It is a cuboid with a square base with side length equal to 1.75 m and height of 0.85 m. Its shape is maintained by an airframe consisting of pipes with a diameter equal to 0.1 m. The airbag is divided horizontally with a bulkhead into two chambers of equal dimensions. The airbag envelope is built of a special fabric designed for building the rescue cushions. It is a woven material with a polyester warp and a polyethylene matrix with a fireproof capability.

The most important part of the developed rescue cushion, in the context of the research conducted on its adaptivity, is the system of adaptive valves allowing for changing the venting area. The impact is alleviated by the rescue cushion thanks to its pneumatic behavior. Compressed gas generates a pneumatic force which depends on the pressure of the gas inside the airbag and the contact area. Adaptive valves influence this pressure by adjusting the venting area and making the rescue cushion more or less stiff, depending on the desired characteristics. Adaptation system consists of two main parts – the valves themselves and the drive train, both of which may have different layouts. The most straightforward implementation of the valves is utilizing a special tape with holes of a specific shape cut in it and placing it in a special pocket sewn to the side wall of the airbag. Such design creates a kind of a shutter. Drive train can be designed in many different ways – e.g., it may utilize pneumatic or hydraulic linear actuators, or electric rotational stepper motors. A demonstrator of the adaptive rescue cushion with pneumatic actuators used as a drive for the valves is presented in Figure 1.

Figure 1: Adaptive rescue cushion experimental demonstrator

Experimental tests are carried out on a specially constructed drop tower equipped with a measuring plate for evaluating reaction forces. Two fundamental impact parameters – mass and velocity of the object can be adjusted by changing the object itself and altering the drop height respectively. Mass of the object is measured directly while the impact velocity is estimated with computer vision methods.

3.2 Numerical model

We have developed a FEM model of the rescue cushion in Abaqus software. It is presented in Figure 2.

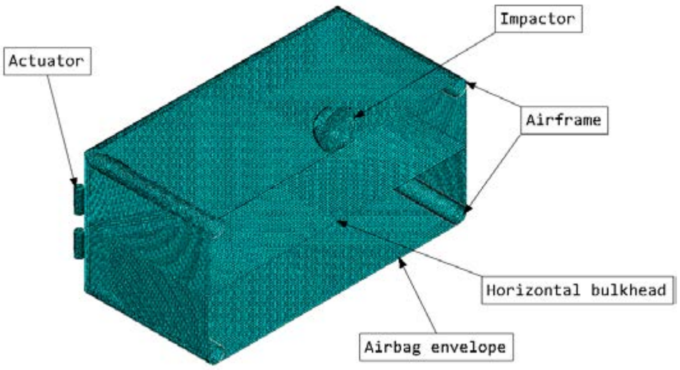

Figure 2: FEM model of the investigated adaptive rescue cushion

Its main elements are depicted and named in the figure. These are the airbag envelope (actual airbag), horizontal bulkhead dividing the airbag into two chambers, airframe maintaining the shape of the airbag, pneumatic actuators in the form of cylinders and the impacting body – here it is a ball. The model consists also of a ground plate, not presented here for the sake of clarity. Actuators, impacting body and ground are modeled as rigid bodies, while airframe, airbag envelope and a bulkhead are modeled with a special fabric material model used, among others, for automotive airbags modeling. Each part of the model is meshed with 4-node linear elements from the explicit library, either rigid or membrane ones.

Modeling of the pneumatic behavior of the structure requires utilizing one of the FSI methods. We have used one of the oldest and simplest ones – UPM, which is considered to be a good choice for simulating the interaction of objects impacting a fully inflated (or deployed) airbag[1]. It assumes the ideal gas law and adiabatic process [9]. As the name indicates, the pressure inside the control volume is assumed to be distributed uniformly. This approach allows for modeling the fluid exchange between the chambers of the airbag, as well as between the control volume and the environment. Abaqus provides a functionality for adjusting the exchange area during the simulation by the use of Fortran subroutines. The user needs to specify the so-called effective exchange area by including a predefined subroutine into a simulation, provided especially for this purpose. This subroutine is called on each iteration with a set of default arguments, such as the time point in the simulation, strains of the materials, pressure in the cavity, etc. The exchange area is defined by the user based on these arguments. Using the time passed in the simulation we could specify mathematically the adaptation procedure with a delayed start and answer the main question stated in this study.

4 NUMERICAL STUDY

We have conducted a series of numerical simulations in order to assess the influence of delaying the start of the adaptation procedure. The delay means that adjustment of the venting area is not conducted early enough to achieve the optimal venting area before the impact occurs. This means that the adaptation procedure will last during the impact. As pointed in Section 2, two delays were considered in the study – one when the adaptation procedure started with the beginning of the impact and one when the adaptation procedure started early enough to end at approximately the time when the first peak of force occurs. These two cases are presented graphically with the orange line on Figures 3 and 4 respectively. This line represents the time course of the venting area of the adaptive rescue cushion. In each case the venting area is changed from the default one, meaning the one defined for the passive rescue cushion, to the optimal one, determined during the optimization procedure described in [1]. Based on the already conducted experimental tests we assumed that it is possible to reach the speed of adjustment of the venting area equal to approximately 100,000 mm^2/s, and this value was used as a parameter in the Fortran subroutine included in the simulations.

Masses and impact velocities for each considered case were chosen taking into account the maximum height of the drop tower, as well as the strength of the experimental rescue cushion. Results presented in Figures 3-6 were obtained for the impact velocity equal to 5 m/s and the mass of the impacting body equal to 5 kg.

Figures 3 and 4 present the comparison of time courses of force acting on the landing body during the impact. Figure 3 presents the case when the adaptation procedure started at the beginning of the impact, while Figure 4 when the adaptation procedure started 1.3 s before the

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[1] In Abaqus it is called “Fluid cavity” or “Surface-based fluid cavity”.

impact occurred allowing for achieving the optimal venting area around 0.05 s after the impact began.

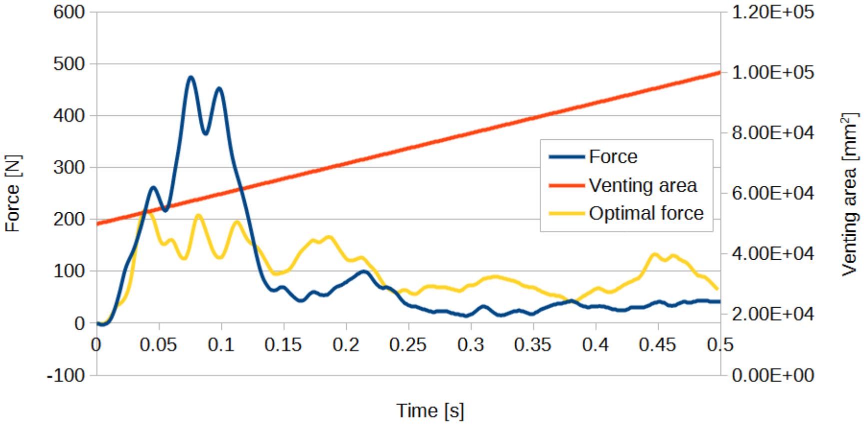

Figure 3: Time courses of force acting on the landing object – adaptation procedure started at the beginning of the impact

Examination of Figure 3 leads to the conclusion that the optimum venting area was not achieved during the simulation (orange line). Comparing the case of optimal venting area (yellow line) with the case when the delay of the adjustment is significant (blue line), we can notice that the peak force has more than doubled.

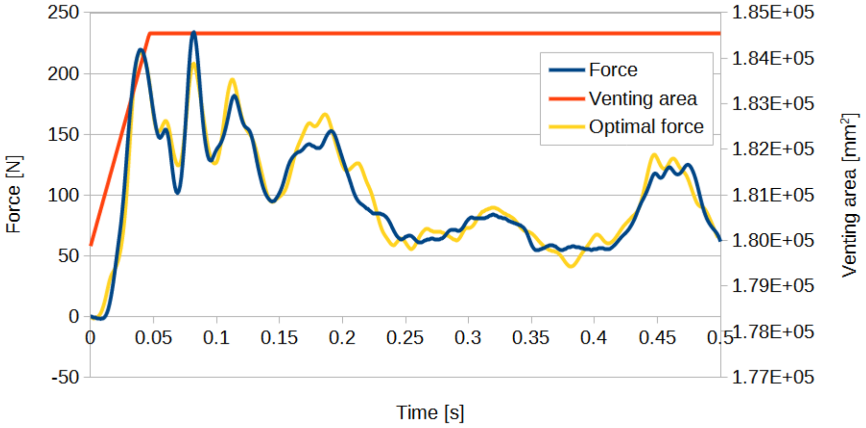

Figure 4: Time courses of force acting on the landing object – adaptation procedure started at 1.3 s before the beginning of the impact

Analyzing Figure 4 we can state that a slight lag in the start of the adaptation procedure does not have a great impact on the results achieved. Maximum force acting on the landing object during the impact increased by a very small amount.

Figures 5 and 6 present the same results as in Figures 3 and 4, but in addition to the cases of a large delay in the start of the adaptation procedure (blue line) and a small delay in the procedure (orange line), a comparison of the case of a passive rescue cushion with the venting area determined at the design and manufacturing stage (green line) and the case of an adaptive rescue cushion with the venting area determined for specific impact conditions in the optimization procedure (yellow line) are also shown. Figure 5 presents the results in the force-time space, while Figure 6 in the force-displacement space.

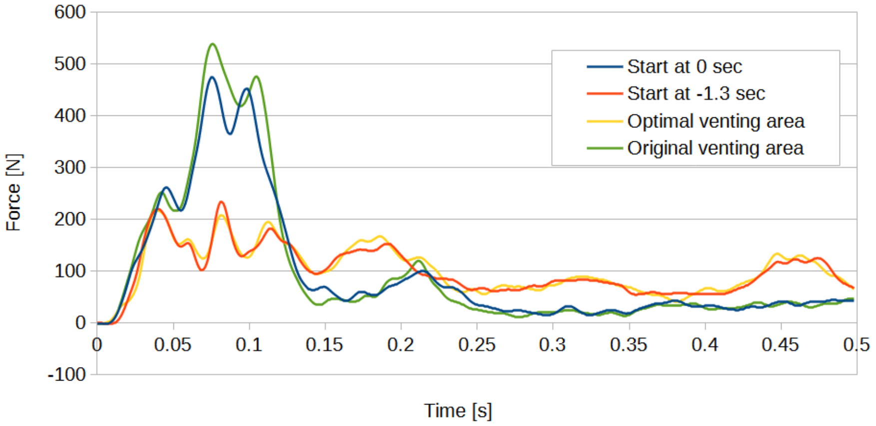

Figure 5: Time courses comparison of a reaction force between the original, optimal and two delayed start of adaptation procedure cases

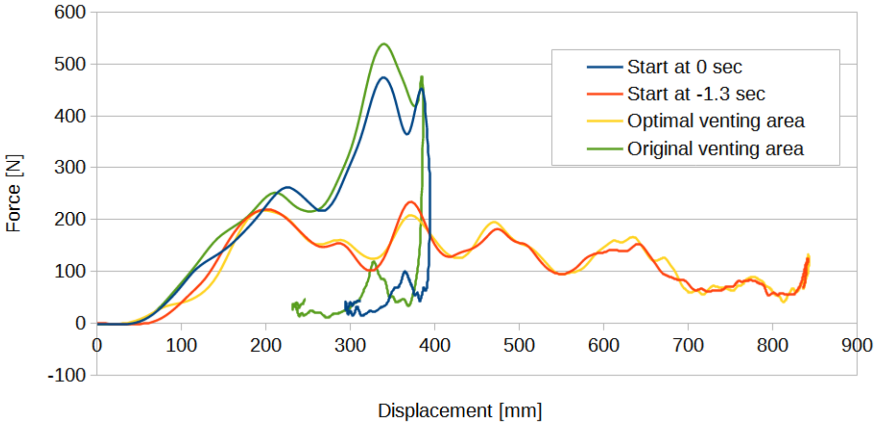

Figure 6: Comparison of a reaction force course between the original, optimal and two delayed start of adaptation procedure cases in force-displacement space

The comparisons shown in Figures 5 and 6 clearly demonstrate the importance of both accurately identifying impact conditions and doing so as early as possible. Identification of the impact parameters and adjusting the behavior of the rescue cushion according to them made it possible to reduce the maximum reaction force acting on the landing object by more than twofold (compare green and yellow lines). However, the identification of impact parameters alone is not sufficient. This must be done well in advance of the impact so that the adaptation system can adjust the venting area. Comparison of the blue and orange lines in Figures 5 and 6 shows this very clearly. Consequently, the importance of developing an identification system is very clear. Possible techniques suitable for this task are computer vision methods, LIDAR, radar or ultrasonic measurements.

5 CONCLUSIONS

Within the presented research a rescue device applied for evacuation of people at heights was considered. Paper includes introduction of adaptive rescue cushion system, discussion of its modelling, which took into account the possibility of delayed valves adaptation, and analysis of numerical results obtained for selected impact conditions. Simulations used for assessment of the influence of valves' delayed operation were conducted using experimentally validated model of rescue cushion equipped with shutter-type valves controlled by system of linear actuators. Presented results revealed the fact that small delays at the level of tens of milliseconds are acceptable, whereas higher delays result in performance not much better than for a passive system. According to this fact the authors could draw a conclusion that prior prediction or identification of impact parameters are necessary to successfully adapt the system to actual excitation conditions. Therefore, further research of the authors will be focused on elaboration of reliable impact identification system aimed at determination of impacting body velocity and predicted position of landing on the rescue cushion airbag. The exploration domain will include methods based on computer vision, LIDAR, radar and ultrasounds.

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