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A NEW STRATEGY FOR ADAPTIVE IMPACT ABSORPTION (AIA)

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Summary: *This contribution presents and overviews a new class of strategies for Adaptive Impact Absorption (AIA) and illustrates a selected strategy in a numerical example. The proposed strategies are based on a challenging approach of a semi-active management and dissipation of structural kinetic and potential energy. The entire process of AIA is considered, including its two main phases: semi-actively controlled reception of an impact and semi-actively controlled damping of the resulting structural vibrations. Management and redistribution of impact energy seems to be one of the most promising and challenging problems in the field of AIA, which requires a substantial theoretical progress in semi-active control strategies and in structural optimization, besides a technological progress in semi-active actuators.*

1. INTRODUCTION

The main purpose of systems of Adaptive Impact Absorption (AIA) is effective mitigation of the destructive effects of significant dynamic loads occurring, for example, in transport collisions. The AIA constitutes a part of the field of safety engineering, which involves various techniques for monitoring of technical conditions and external excitations of engineering structures. Such techniques are based on a distributed sensor system, a certain numerical model of the monitored object and software tools used for interpretation of the measurements, which can include identification of possible structural damages and/or triggering the process of a real time control of the structure.

1.1 Impact absorption systems

The two extremes of absorption systems are *passive absorption systems* on one hand and *active absorption systems* on the other hand. In general, the traditional optimum passive design of a structure (such as a car structure [1]) for its best crashworthiness is equivalent to the maximization of its impact absorption capacity (or other related measures) for some predetermined collision scenarios only, while for other impact conditions, which for example can involve lower velocity or mass, different impact direction, etc., such a passive structure can respond suboptimally [2, 3]. For safety and/or legal reasons, the most dangerous loading scenario has often to be taken into account in structural optimization. Nevertheless, in practice such a scenario might occur very infrequently, and as a result, such a passively optimized structure behaves suboptimally for most of its operational lifetime. Such a clear pattern of suboptimality is particularly evident in the case of landing gears, which must be designed for the harshest landing condition, as specified by regulations, but whose typical usage involves much smaller vertical velocities and loads [4, 5]. The opposite extreme of absorption systems is constituted by active control systems, which, besides the sensing system, rely on dedicated actuators that introduce into the scene additional external significant control forces. Active control strategies are very effective, and at least for linear systems, researched very thoroughly [6–8]. In applications to impact absorption they have however important disadvantages, which include the necessity for applying high control forces and the related high-energy consumption of the actuators, as well as susceptibility to dangerous instabilities in case of a power loss or actuator failure.

1.2 Adaptive impact absorption (AIA)

The AIA systems, located in-between the two extremes of passive and active impact absorption, are based on semi-active control strategies [9, 10]. In general conceptual terms, the cornerstone concept of any AIA system is its *adaptivity*, which is clearly different from the concept of passive impact reception, as well as from the concept of active impact counteraction. Such an adaptive approach assumes that the structure exposed to impact-type loads is equipped with

- sensors that monitor its response and/or loading conditions and with
- semi-actively controlled actuators, which play the role of structural members that are able to modify their own local mechanical properties, such as their dissipative characteristics [11].

In comparison to actively controlled systems, in semi-active systems there is no need and no possibility for exerting additional significant control forces. As a result, the level of energy consumption of semi-active actuators and the probability of their failure is much lower. Similarly, the risk of instabilities in semi-active control is also greatly reduced. On the other hand, in comparison to passive absorption systems, semi-active solutions can offer a significantly enlarged impact absorption capacity, and consequently, much better protection against damage in critical loading conditions [12–14]. Research and development activities in the field of AIA systems included inflatable airbags equipped with fast valves for controllable release of pressure during the process of impact absorption [15], adaptive landing gears for air transport safety [4,5], adaptive pneumatic fenders for maritime safety [15], adaptive road barriers for road transport safety [16], adaptive front energy absorbers for vehicles [17–19] and adaptive vehicle airbags [20], arctic engineering and protection of off-shore installations against ice loading [21], adaptive wind turbines [22], adaptive supports in a vehicle-span/track system [23], adaptive damping of torsional vibrations in rotating systems [24, 25], etc.

1.3 Management of impact energy

This paper proposes and discusses a new class of strategies for Adaptive Impact Absorption (AIA) and illustrates a selected strategy in a numerical example. The process of AIA, as understood here, consists of two phases:

1. semi-actively controlled reception of an extreme impact load and
2. semi-actively controlled damping of the resulting structural vibrations.

In both phases, various measures of control optimality and constraints are possible. For example, in the first phase, they can be formulated based on minimum peak or rms accelerations, or on a weighted objective that involves also deformation, while in the second phase, the criteria can be based on minimum dissipation time, maximum dissipation rate or minimization of the mean square energy in a given time interval, etc.

The proposed strategy of absorption is based on *semi-active management and dissipation of structural kinetic and potential energy*. The *potential energy* is managed using the Prestress Accumulation–Release approach (PAR) [26, 27], which might employ two specific kinds of specialized, semi-actively controllable structural members:

- specialized nodes with a controllable moment-bearing ability that are capable of a quick transition between a truss-like state and a frame-like state or
- specialized bar members with a controllable axial stiffness of a bang-bang type, which are capable of a controllable transition between zero axial stiffness (which would effectively correspond to the lack of a connection) and an elastic state with a predefined level of axial stiffness (full connection).

As demonstrated in numerical examples [26, 27], such transitions, if triggered in a proper way, can be used to quickly transform a part of the locally stored potential energy into the energy of high-frequency local vibrations that are effectively damped by means of the standard mechanisms of material damping. In a more general approach, the energy transfer takes place between low-order modes and high-order, highly damped structural modes. In parallel, the *kinetic energy* can be managed by first storing it in specialized structural members involving worm-like gears and spinning discs with considerable rotational inertia and then, if deemed necessary, reusing the energy in a controlled manner [28]. All the control is performed semi-actively, that is only by affecting selected structural characteristics or configurations of selected structural members, that is without introducing any significant external forces into the system. Besides the determination of the optimum control strategy, an important point is the initial process of topological optimization of the underlying structure, as well as finding the optimum placement for the available controllable nodes and members [12, 13].

Such a semi-active approach to the process of adaptive impact absorption can be positioned in the wider context of structural control, and especially the bilinear [29, 30] and switched system control theory [31, 32] (elaboration of the optimum control functions for both phases), as well as in the context of structural optimization [33,34] (elaboration of the optimum structural design for a class of expected impact-type loads, including selection of the optimum number and placement of the semi-active actuators). A natural approach is to focus on one aspect, that is to consider these two contexts sequentially and separately from each other:

- to assume (intuitively) a given distribution of semi-active actuators in order to elaborate the optimum control functions, and then
- to assume the elaborated (feedback) control function in order to optimize the placement of the available semi-active actuators, and possibly, also the structural topology for an improved impact absorption and energy dissipation capacity.

The general, fully coupled problem of simultaneous topological optimization of an AIA structure and semi-active control of its selected controllable elements seems to be relatively original and not considered in its entirety in the scientific literature so far. Research on such a general methodology requires concurrent application of methods of topological optimization and control theory.

1.4 Structure of the paper

This paper is structured as follows. The two successive sections briefly discuss the semi-active management strategies of respectively potential and kinetic energy. The fourth and fifth sections deal with selected aspects of the optimum control strategy and the problems related to the optimum design of AIA systems. The sixth section cites an illustrative numerical example, while the seventh section concludes the paper.

2. SEMI-ACTIVE MANAGEMENT OF POTENTIAL ENERGY

Typical impact absorption systems, whether passive or semi-active, can be collectively called fender systems, as the impact energy is intended to be dissipated in applied shock absorbers. One of the classical examples here is provided by landing gears used in aviation for mitigation of touchdown loads: an ideal landing gear should effectively dissipate the entire impact energy and transfer to the fuselage as small peak loads as possible. In contrast to fender absorption systems, the strategies discussed in this paper rely on an essentially different mechanism for impact energy dissipation and for damping of the resulting vibrations. The main idea behind them is adaptive, switchable energy management, redistribution and dissipation. This section is focused on adaptive management and redistribution of potential strain energy.

The approach of redistribution of potential strain energy accumulated in dynamically deforming structural members and substructures has been called the PAR strategy (Prestress

Accumulation-Release). Its dramatic effectiveness in damping of vibrations of a deployable space structure is demonstrated in [26], where a precise timing of switching instances between two structural configurations (a truss-like and a frame-like configuration) results in an almost immediate damping of vibrations, which occurs in less than a single cycle of the first natural vibration mode. Essentially, the strategy is based on a controlled conversion of vibration energy from lower-order structural modes to higher-order modes and/or local vibrations of structural elements, which are effectively damped by means of standard mechanisms of material damping.

In technical terms, the switching of structural configuration requires specialized sem-active actuators. Numerical and experimental investigations have been performed using a range of various technologies. In the case of a relatively simple structure of a cantilever beam, the technologies included:

1. Controllable delamination of a layered beam [27]. The connected state (no delamination) has been simulated by pressing two beam layers together with a piezoelectric actuator and a mechanical displacement amplifier [37].

2. Jammed granular material [35], where jamming of the granules occurred due to under-pressure.

3. Magnetorheological elastomer [36], where the elastomer filled a part of the middle layer of a three-layer sandwich beam.

In all the above examples, the purpose of the actuator was to control the shear stress level between the outer layers of the investigated beam. Rapid decrease of the shear stress at the instant of maximum beam tip displacement allowed a part of the strain energy of the layers to be transferred into longitudinal, high-frequency vibrations of the same layers. Similar actuators can be used in general framed structures. Nevertheless, for such general structures, two general solutions are also possible:

1. In [26,38], specialized, semi-active structural nodes are proposed. The nodes have a controllable moment-bearing ability, so that they are capable of a quick transition between a truss-like state and a frame-like state. A transition to the truss-like state of a series of such nodes can be used in order to release high-frequency vibrations of a part of the structure, such as in the examples described above. Moreover, it would also release a part of the local bending strain energy of frame members with the released rotational degree of freedom.

2. Specialized bar members with a controllable axial stiffness of a bang-bang type, which are capable of a controllable transition between (almost) zero axial stiffness (which would effectively correspond to the lack of a connection) and an elastic state with a predefined level of axial stiffness (full connection). For applications with up to certain stress level, the mechanism of control can be based on dry friction and piezoelectric clampers.

Furthermore, the strategy opens a promising perspective of designing small, properly tuned and located PAR dampers in the form of substructures that are easily excited by vibrations of the main structure. Such an approach might parallel the approach of smart, controllable tuned mass dampers [9], but it would utilize a different mechanism of energy dissipation.

3. SEMI-ACTIVE MANAGEMENT OF KINETIC ENERGY

The approach of accumulation of kinetic energy by means of dedicated rotating inertial discs develops on the concept of an element called “inerter”, which has been discussed in [39–41] and which utilizes a properly designed mechanism of a rack and a pinion. However, such mechanism lack the ability of adaptation. To introduce such an ability, in [28, 42] an adaptive inertial damper is proposed, which utilizes a system of worm-like gears and clutches placed in between threaded concentric cylinders. The impact energy, once stored in the involved rotating disc or cylinder, can be then either dissipated by a gradual braking or reused by means of switching the configuration of clutches in order to reverse the direction of the relative movement of the threaded cylinders. As the idea of an adaptive inertial damper is new, development of the formal models and experimental demonstrators of the element, as well as of the respective adaptation strategies, are currently in progress. An introductory example can be found in [42].

4. OPTIMUM CONTROL

For each of the particular general concepts of an AIA system, and irrespective of the specific technological challenges of its practical implementation, one of the crucial general challenges is the development of effective methodologies for optimum control of an AIA system.

In specific, well-defined applications, the optimum control strategy for an AIA system can be derived in an intuitive, ad hoc way. For example, in the case of an adaptive landing gear of an airplane, based on the known or identified vertical touchdown velocity and the equivalent mass, the optimum characteristics of the strut can be determined, to be followed by their real-time control to keep the strut force at the constant level to assure the dissipation of all remaining impact energy on the full admissible dissipater stroke [4, 5]. Another intuitive example is the PAR-based control of a simple layered cantilever beam considered in [26, 27, 35, 36], where a precise timing of the control function allows the energy of vibrations to be converted from the basic low-frequency flexural mode into higher-order, highly damped longitudinal vibration modes. However, despite the specific applications described above, in the case of a complex general AIA system that is exposed to a variety of impact-type loads, there is a need for a general methodology of deriving the optimum control functions. A general approach to the problem of derivation of the optimum control can be based on the following steps:

1. Determination of general characteristics of the optimum open loop control. For example, in many bilinear control problems with a bounded control function, the optimum control is of the bang-bang type, that is the optimum control function assumes only its extreme values, so that the task of the controller is to switch between these values in properly selected time instants.

2. Determination of the centralized, globally optimal open loop control.
3. Determination of a centralized, globally optimal closed loop optimum control.
4. Determination of a decentralized, locally optimal optimum control.

4.1 Objective function

The crucial prerequisite for the development of the optimum control strategy for structural adaptation is the determination of the control objective. In general, two significantly different absorption phases need to be considered:

1. emergency absorption of a critical impact and
2. damping and mitigation of vibrations resulting from an impact or from repetitive operational loads.

In qualitative terms, in the first phase (absorption of a critical impact), the ultimate objective must be the preservation of structural integrity and safety of passengers or of the protected structure. In the second case (mitigation of vibrations), the ultimate adaptation aim will be usually related to certain measures of structural fatigue and/or comfort of passengers.

However, in order to determine the optimum control strategy, quantitative criteria are required. For example, in the first phase, they can be formulated based on quantities like the peak or rms acceleration (for occupant safety reasons), maximum deformations or displacements (for safety reasons or to satisfy the maximum stroke limitation for semi-active actuators), the rate of energy dissipation, etc. In the second phase, quantitative criteria will usually involve quantities like the dissipation time (minimization), the rate of energy dissipation (maximization), the mean square energy in a given time interval (minimization), etc.

It should be noted that many desired criteria are obviously contradictory (e.g., minimization of peak accelerations vs. minimization of deformations), which can lead to multicriteria optimization [1, 43, 44]. In applications to critical impact absorption, an objective of an intentional localized structural degradation (such as local perforation) can be also useful, as such a local degradation might contribute to the preservation of the global integrity of the structure. Such an approach might be called the absorb/avoid strategy and it is related to the general patterns of structural response for impacts of the same energy, but with different mass/velocity ratios of the impacting object, see an example in Figure 1.

4.2 Control functions and bang-bang control

Determined the control objective, a control strategy can be developed to achieve it [45, 46]. As described above, possible control strategies range from a globally optimal, centralized open loop control to globally optimal, centralized closed loop control, to locally optimal, decentralized control. In the last case, an important problem is the relation between local and global optimality of the strategy.

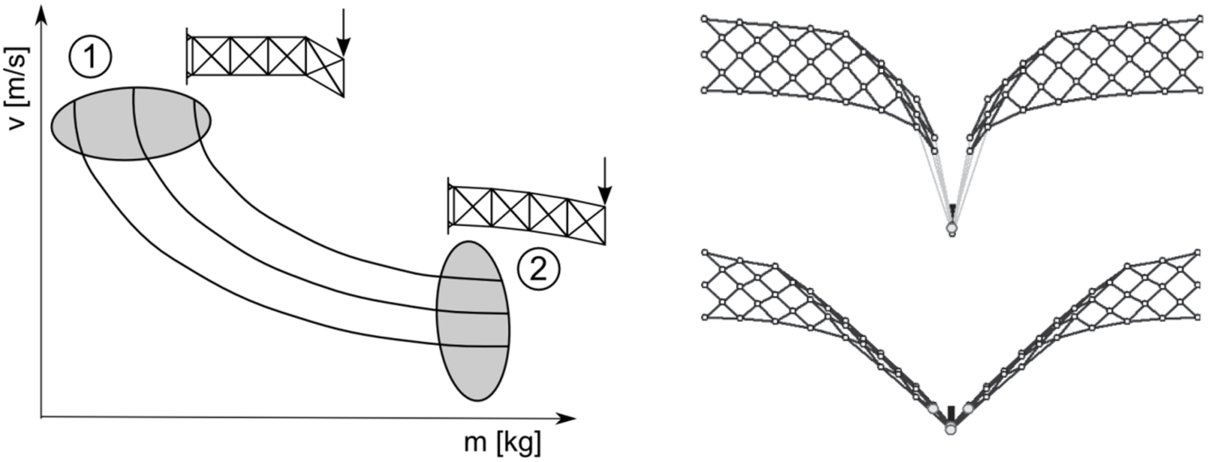

Figure 1. Influence of the impacting mass and the impact velocity on structural response: local structural degradation vs. global absorption.

A number of approaches can be used to derive the control function, including classical methods of control theory (such as the feedback control with proportional-integral-derivative controllers) and applications of the modern control theory (such as Bellman's dynamic programming or Pontryagin's minimum principle). One should also attempt to generalize these methodologies for an application to dissipative structures subjected to large deformations. Analysis of the sensitivity of the control functions with respect to structural topology and placement of the adaptive devices might be treated as a prerequisite for the solution of the optimum design problem of an AIA system discussed in the next section.

Given the nonlinearity of semi-active structures, one might find useful the recently flourishing research on optimum control in bilinear [29, 30] and switched systems [31, 32]. Classical results in minimum time and minimum energy control, based on Pontryagin's minimum principle, state that the optimum bounded control function, in the absence of control costs, is usually (that is in common nonsingular cases) of the bang-bang type [45, 46]. In other words, the optimum control function assumes only its extreme values, and the task of the controller is to switch between these values in properly selected time instants. Formal derivation of these instants, even in simple cases of a single degree of freedom system and open loop control, is a nontrivial and challenging problem. Nevertheless, the knowledge of the general characteristics of the control function can be exploited in heuristic numerical search for a good-enough suboptimal control [47].

5. OPTIMUM DESIGN

From the theoretical point of view, the problem of development of algorithms and a general methodology for optimal design of adaptive dissipative structures is a general, high-level problem, which includes the combined problem of topological optimization of an AIA structure and of semi-active control of its selected controllable elements. Such a problem seems to be relatively original and requires concurrent application of methods of topological optimization and control theory. A good starting point for the research might be provided by the methods of topology design optimization [33, 34], which should include optimization of the damping topology [48], as well as optimization of placement of sensors and semi-active actuators, where the criteria of the largest sensitivity of structural response and the maximal effectiveness of dissipation can be utilized. Thereupon, the ultimate general coupled problem of topological optimization and optimum control should be addressed. In many applications, the impact scenario, including its location and direction, is unknown a priori, so that the AIA system should be designed for random impact multi-loads, which requires new probabilistic criteria for optimality of structural geometry, locations of sensors and actuators, and the control function.

In general, there exist commercially available, very advanced numerical tools, which are capable of reliable simulation of structural response of complex structures to a determined impact scenario. The majority of these tools is devoted to analysis in vehicle crashworthiness. However, they are not very efficient when searching for the best design in the case of an a priori unknown impact scenario. The trial and error approach seems to be the usual option in such a case. Currently, the design process of complex structures, is iterative due to safety aspects: a new set of design changes is introduced, and then the structure undergoes a full set of simulations once more time, etc. The duration of a single analysis of the whole scenario can amount to several hours, and an evaluation of influence of each modification requires a renewed analysis of the system. Manual change of parameters and application of a precise model makes such a simulation process tedious, ineffective, numerically expensive and time consuming. Therefore, in the early stages of design and redesign, it is recommended to use simplified models, which are numerically less expensive and which allow the remodelling and sensitivity analysis processes to be automatized.

For linear systems, the technique of simplified processes has been developed and applied for many years, while for nonlinear systems, especially systems subjected to a dynamic loading, there are only few researches published until now [34, 49–52]; a general survey of the related methods can be found in [53]. The models with concentrated masses have already been used in automobile industry for safety improvements in crash tests for a few decades [54, 55]. In such models, nonstructural elements are modelled with concentrated masses, whereas structural elements, which are subjected to deformation, are modelled as nonlinear elements with the load-displacement characteristics being usually the same as the characteristic generated in laboratory tests for crashed tubes [56]. For example, this is the main idea behind the V-CRASH method, which is a fast method of simulation and design of automobile structure frames [57].

6. NUMERICAL EXAMPLE

6.1 The structure

The example considers a frame-like structure shown in Figure 2 [26]. The control is exerted by means of semi-active nodes marked in green, which are essentially frictional joints with adjustable moment-bearing capability that allowed the structure to respond in a frame-like (maximum friction) and a truss-like (minimum friction) mode. For demonstrative purposes, the assumed frame ends with a hinge and an attached panel, which opens according to a prescribed angular velocity profile. Opening of the panel is initiated with a micro blast at the end of the main structure. Both the micro blast force and the step changes in the panel opening angular velocity result in free vibrations of the structure which are then mitigated using the semi-active nodes and PAR technique.

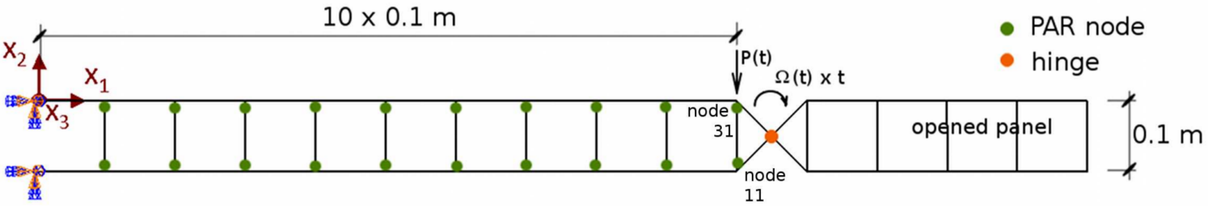

Figure 2. The structure simulated in the numerical example. Semi-active PAR nodes marked green.

The physical model simulated in computations was a one meter long cantilever beam comprised of two layers 0.1 m apart and connected elements spaced every 0.1 m. All members were modelled as steel, prismatic, rectangular bars with the cross-section of 20 mm × 6 mm. The two semi-active frictional joints at both ends of each connecting element (marked green in Figure 2) governed the rotation in the node about the X3 axis. The fundamental flexural mode of vibration of the model with an opened panel was 19.6 Hz in the frame-like mode and 3.96 Hz in the truss-like mode. The first longitudinal eigenfrequency was respectively 1213.4 Hz and 1186.8 Hz. The physical sources of energy dissipation in the assumed model were the proportional damping (the coefficients of 1.e-6 and 1.e-5 for the environmental and material damping were respectively used) and the friction between surfaces inside the semi-active nodes.

6.2 Control strategy

The main idea behind the control strategy was the transfer of vibration energy from the basic flexural mode into the high-frequency, highly damped longitudinal mode. The strategy can be summarized in the following way (see [26] for a detailed description and specification of the respective algorithm):

1. Phase 1. Start with the frame mode. Upon detection of the maximum displacement of the beam tip trigger the transition of the semi-active nodes to the truss mode (to release the longitudinal stress in the beam layers), and after a very short period of time (upon detecting the maximum longitudinal displacement of the released layers), back to the frame mode.

2. Phase 2. Gradually and slowly decrease the moment-bearing ability of the semi-active nodes and monitor the return of the structure to the initial configuration.

3. Phase 3. Restore the frame mode and go back to Phase 1, if needed.

6.3 Structural response

Response of the structure before and after activation of the above control strategy is plotted in Figure 3 (vertical displacement of node 11) and in Figure 4 (horizontal displacement of node 31). The qualitative change of the structural response is evident. Switching to the truss-like mode triggers longitudinal high-frequency vibrations of the beam layers, which are quickly damped by means of material damping, see Figure 4.

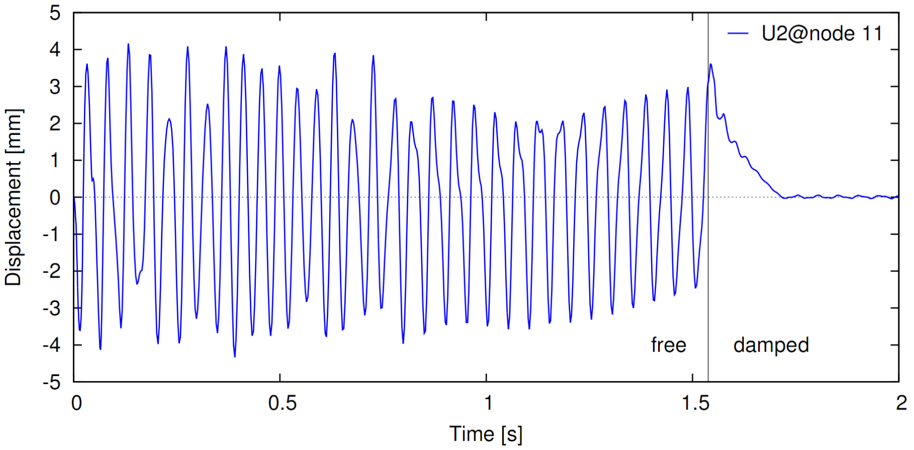

Figure 3. Vertical displacement of node 11; all nodes controlled.

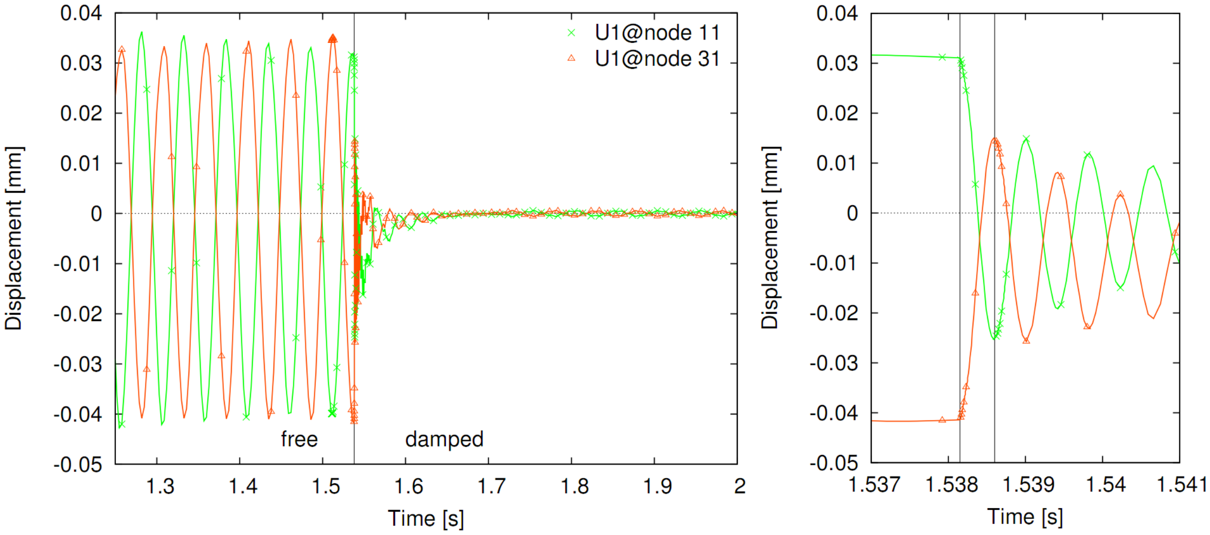

Figure 4. Horizontal displacement of node 31; all nodes controlled.

As such a high efficiency of vibration damping might be attributed to the high number of semi-active nodes, the simulations were repeated in the cases of a fewer number of controlled nodes. The cases of 10 pairs (all), 7 pairs, 3 pairs and 1 pair of semi-active nodes were tested;

Figure 5 shows the location of the controlled nodes in each case. The corresponding results (vertical displacement of node 11) are shown in Figure 6. In all considered cases, except the case with one pair of semi-active nodes, more then 90% decrease in vibration amplitude was obtained after just five periods of the first natural vibration of the reference structure. In the case of a single pair of controlled nodes, the reduction of more that 55% was achieved.

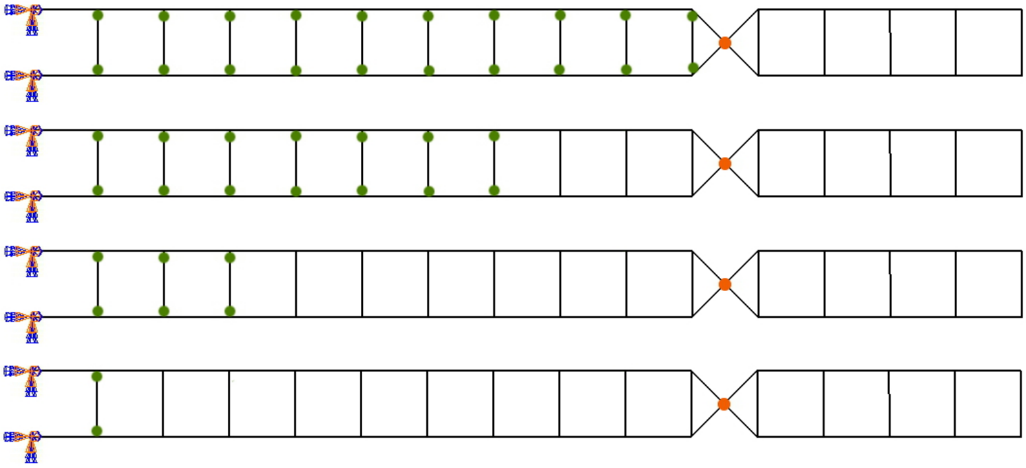

Figure 5. Various numbers of semi-active nodes used in simulations: locations of 10 pairs, 7 pairs, 3 pairs and 1 pair of nodes.

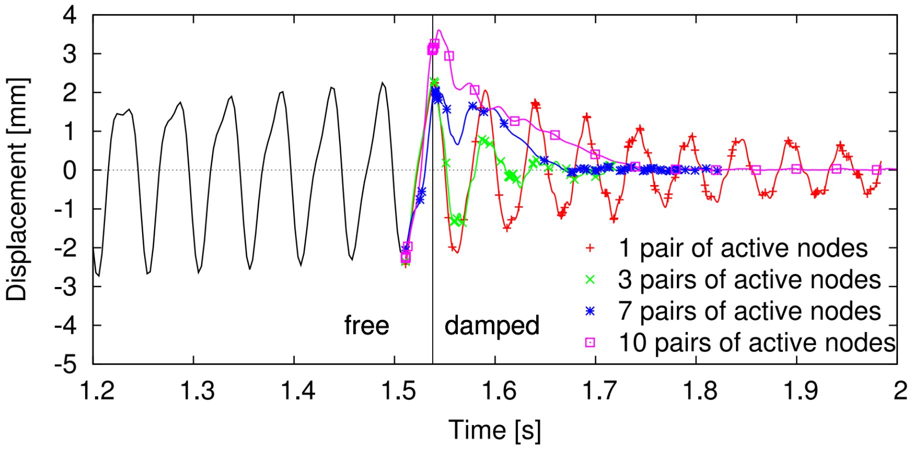

Figure 6. Various numbers of semi-active nodes used in simulations: vertical displacement of node 11.

Finally, it should be noted that the assumed control strategy was derived intuitively. It is well possible that a formally derived optimum strategy might result in even more effective mitigation of vibrations.

7. CONCLUSIONS

This paper presented an overview of a class of new strategies for Adaptive Impact Absorption (AIA). The strategies develop on the concept of a semi-active management, redistribution and dissipation of structural kinetic and potential energy, which seems to be one of the most promising and challenging problems in the field of AIA. Irrespective of the necessary technological progress in semi-active actuators, achieving formal development of the strategies (derivation of strictly optimum control functions and structural designs) requires a substantial theoretical progress in semi-active control strategies and in structural optimization. High effectiveness of a selected strategy of was illustrated in a numerical example. Potential energy management was made possible by means of frictional joints, which allowed the structure to respond in a truss-like and a frame-like mode, with a quick transition between both modes. Such transitions, if triggered in properly selected time instances, transform a part of the vibration energy (strain energy) from low-order structural modes into high-order modes, which are effectively damped by means of the standard mechanisms of material damping. It should be noted that the assumed control strategy was derived purely intuitively, and it is thus well possible that a formally derived optimum strategy might result in even more effective mitigation of vibrations.

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