Smart technologies for structural safety

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Abstract

This paper presents the concept of smart structures dedicated to improving structural safety in case of unpredictable impact loadings. The concept is developed by bringing together two different ideas: adaptive impact absorption (AIA) and structural health monitoring (SHM). The potential for safe energy dissipation is maximized by optimum structural adaptation to impact loading parameters, for which the AIA subsystem is responsible. The SHM subsystem is used for on-line identification of impact type loadings, which is necessary in order to trigger optimum adaptation, as well as for post-impact damage assessment. Both subsystems depend on smart material technologies: optimum adaptation can be implemented through a small number of optimally distributed *structural fuses*, that is elements with controllable yield stresses, which can be implemented using magneto-rheological fluids, while the health and loading monitoring require a reliable sensing system, e.g. based on piezo-materials. The paper presents the general concept, provides a literature review and discusses in detail the challenges related to the SHM part.

Keywords: adaptivity, crashworthiness, inverse problems, structural monitoring, smart materials

1. Introduction

This paper reviews and reports on the research on smart structures capable of preserving integrity in case of unpredictable impact-type loadings and of accurate post-accident self-assessment of damages. Such structures shall find applications as protective elements of crashworthy vehicles, road barriers, light thin-wall tanks offering high protection against impacts, etc. The *modus operandi* of such a protective structure consists of the following three main phases:

1. *Load identification.* A dedicated sensors system is used for continuous monitoring of structural response and real-time detection and identification of extreme impact-type loadings. Once such a loading occurs, its most important parameters are identified. These parameters depend on the application area and the time scale of the event. They may include the location and basic characteristics of the contact forces or mass and velocity of the impacting object. It is crucial that the identification is performed in real-time, just in the initial stage of the impact, ahead of its destructive effects.

2. *Adaptive impact absorption (AIA).* The identified impact parameters are used to trigger an embedded adaptive absorption system that uses semi-active actuators distributed in the structure. Such actuators can be implemented in different technologies, for instance, they can be based on magnetorheological fluids and simulate elastoplactic characteristic with a controllable yield stress. The adaptation amounts to such a distribution of the yield stresses that is optimum with respect to the identified impact parameters and the selected objective of the adaptation (preserving the integrity of the structure, minimization of decelerations, stresses, impact penetration, etc.). As impact evolves, load identification can be continued for online fine-tuning of the adaptive reception process.

3. *Post-accident diagnosis* is performed after the impact ceases. Its outcomes and the estimated loading scenario can be used (i) to perform an automated emergency service call, (ii) in a possible forensic analysis of the event and/or (iii) to asses the remaining life-time and restore the structure to its normal operation state.

Two high-level subsystems are necessary to implement these tasks: an adaptive impact absorption (AIA) subsystem, responsible for the optimum control of the process of adaptive reception of an impact, and a structural health monitoring (SHM) subsystem, responsible for both load identification and post-accident diagnosis.

The three following sections provide a review on the research challenges related to such an envisaged smart structure. Due to the broadness of the field, this paper is focused on load identification and post-accident diagnosis. The research on the AIA subsystem is only briefly reviewed, but reported in detail elsewhere, see e.g. [4–6, 12, 16].

2. Adaptive impact absorption and structural fuses

Typical solutions offered for impact protection are passive energy absorbing systems, which are characterized by a high ratio of specific energy absorption and often based on aluminum or steel honeycomb packages [13]. Although their energy absorption capacity is high and advanced optimization techniques are employed [1], such passive energy absorbers are designed to work effectively in pre-defined impact scenarios only [11]. For example, frontal absorbers are very effective during a symmetric axial crash of colliding objects but completely useless in other types of loadings. Therefore, distinct and sometimes completely independent systems have to be developed for different collision scenarios. In contrast to passive systems, adaptive systems for impact energy absorption can guarantee near-optimum dissipation for a whole range of recognizable loading scenarios [4, 12], which is a principle long recognized and implemented in vibration damping [3], but neglected in the research on structural crashworthiness.

Given the impact detection and identification system, two other issues are crucial for an effective AIA system: the technological issue of semi-active actuation and the computational issue of optimum structural adaptation. It seems that there is a range of technologies that are suitable, partly depending on the application area [19], for example:

- *Magnetorheological fluids (MR fluids, MRF)* are controllable smart materials sensitive to applied magnetic field. In the presence of magnetic field the fluid changes its behavior from viscous to semi-solid with yield stress, which is dependent on the field strength. Typically MRF are non-colloidal suspension of ferric particles in a carrier fluid. In recent years a growing interest in MR fluids has led to a number of applications [3], mostly in vibration control (suspension of vehicles, rotary brakes, clutches and engine mounts, etc.) and in civil engineering (mitigation of vibrations due to seismic loads or for reducing cable fluttering in cable-stayed bridges). An application of an MRF-based AIA system for aircraft landing gears was pursued in FP6 project ADLAND [6, 27, 28].

- *Piezovalves* and piezoelectric devices provide a very high accuracy in a very wide frequency range. There are several available commercial and prototype flow-control devices based on the piezo-technology. The piezo-actuator usually operates indirectly and blocks the flow through an additional mechanical system. The application in AIA systems involves the problem of large forces and pressures, which requires large displacements and large blocking forces and thus dedicated actuators.

- *Micro-pyro-systems (MPS).* Besides military use and rocket propellant systems, applications of pyrotechnics in machine engineering involve mainly crushable bolts for detaching aircraft or spacecraft parts, structure cutting, valve control and actuation [20]. Pyrotechnically driven systems are also widely used in automotive airbags and safety belt pre-tensioners. Recently, micro-pyro devices are proposed with applications to micro mechanical systems (micro-pyro actuators and valves for medicine applications, space exploration and micro propulsion systems) [21]. A pyrotechnically pressurized impact absorbing structure has been recently proposed in [22], an impact energy absorber with crushing stiffness controlled by pyrotechnically detachable connectors has been discussed in [23, 24].

- *Adaptive airbags.* The load energy absorbing principle is to control the release of compressed gas from an impacted pressurized thin-walled structure. Due to the controlled pressurization, such structures can quickly and continuously adapt their stiffness level, which significantly increases their resistance to dynamic loads. Simulations [25, 26] reveal the improvement of at least one order of magnitude. For instantaneous gas intake fast reacting micro-pyro-systems should be developed, while piezovalves can be used for the release of pressure. Gas intake takes place immediately after the impact, the pressure level is adjusted to the estimated impact characteristics. As the impacting object immerses into the structure, the pressure is decreased according to a predefined control strategy. Possible applications are [22, 25, 26] road barriers, protective cushions for offshore structures (e.g. wind turbines), rescue air cushions for fire brigades etc. Another application area is the crashworthiness of aircraft structures, where adaptive airbags can be considered in the lower shell structure of helicopter fuselages.

The computational problem of optimum adaptation arises in all above-mentioned application areas. Depending on the technology, up to two adaptation phases can occur. The first phase is the initial adaptation, which takes place in the very initial stages of the impact and reduces, for example, to the determination of the optimum pressure level in an adaptive pressurized structure and gas intake, or to the determination (and implementation) of optimum distribution of yield stress levels in controllable MR elements. The second phase is the control strategy implemented during actual impact reception, for instance, controllable release of pressure in case of an adaptive airbag, controllable fluid-flow in case of an adaptive landing gear, or pyrotechnical detaching of additional stiffeners in automotive energy absorbers. It can be demonstrated that AIA systems that implement even the first phase only considerably outperform passive absorbing systems in a range of applications, see [6] for adaptive landing gears or [25, 26] for adaptive pressurized structures. Notice that the objective of adaptation can be based on different criteria, depending on the application area: minimization of deceleration of the impacting object, preserving the integrity of the impacted structure, minimization of its deformations, etc.

In case of skeletal adaptive structures with several embedded adaptive structural fuses [16, 29, 30], an additional computational problem is related to determination of the optimum number of the fuses and their placement in the structure with respect to contradicting criteria like costs and effectiveness of adaptation. Essentially, this is a challenging problem of combinatorial optimization.

3. Load identification

Optimum structural adaptation is impossible without a reliable identification of impact parameters, based on the measurements of a dedicated sensing system. In order to be able to mitigate the impact effects, the AIA subsystem has to be triggered as soon as possible: it is crucial that the initial identification is performed in real-time in the initial stage of the impact. Depending on the application area and the time scale of the event, which can range from milliseconds (vehicle crashes) to several seconds (seaborne collisions), the to-be-identified parameters of the impact can include contact forces [9] or selected parameters of the impacting object, such as mass and velocity [14, 31]. This choice is crucial for the characteristics of the resulting identification problem and for the effectiveness of the adaptive absorption process.

After the AIA system is triggered with the initial data, the evolution of the impact process can be further monitored online and the data used to fine-control the crash reception process.

3.1. Identification of initial contact forces

If impact identification amounts to identification of the contact forces, the problem reduces to a linear inversion involving a large number of unknowns, provided the structure in the undamaged state is linear. The linearity can be assumed, since only initial contact forces are considered, well before nonlinearities, either material or geometric appear. In general, in such a case load identification is equivalent to finding a solution to the following equation:

$$\mathbf{u}^{\mathrm{M}}(t) = \mathbf{G}\mathbf{f}(t) + \int_0^T \mathbf{B}(t-\tau)\mathbf{f}(\tau)\,\mathrm{d}\tau, \qquad t \in [0,T], \tag{1}$$

where the vector $\mathbf{u}^{\mathrm{M}}(t)$ collects measured responses of $N_{\mathbf{s}}$ sensors, the vector $\mathbf{f}(t)$ collects the unknown time histories of all the $N_{\mathbf{f}}$ contact forces and $\mathbf{B}(t)$ denotes the $N_{\mathbf{s}} \times N_{\mathbf{s}}$ matrix of structural impulse response. Each entry g_{ij} of the feed-through matrix $\mathbf{G}$ is non-vanishing only if the ith sensor measures acceleration and is collocated with the jth excitation point. In case of a finite element model, such an entry equals the corresponding entry of the inverse of the mass matrix. Equation 1 is a Volterra integral equation and can be formulated in the operator notation as

$$\mathbf{u}^{\mathrm{M}} = \mathbf{G}\mathbf{f} + \boldsymbol{\mathcal{B}}\mathbf{f}, \tag{2}$$

where $\boldsymbol{\mathcal{B}}$ is the respective matrix integral operator. Notice that the kind of Eq. 2 depends on the type of the used sensors: if all sensors are accelerometers and $\mathbf{G}$ is square and non-singular, Eq. 2 is of the second kind. If all the sensors measure displacement, strain or velocity, then Eq. 2 is of the first kind. Otherwise, it is neither of the first nor of the second kind.

In practice, the responses are discretized in the measurement process by sampling at equally spaced time instances $t_1, \ldots, t_{N_\mathrm{t}}$. Similarly, the impulse responses are usually also discrete, whether they are obtained from numerical simulations or from measurements. Equation 1 should be thus discretized with respect to time. Due to the discrete nature of measurements and impulse responses, only the quadrature discretization method [32] seems to be appropriate. The method yields N_t discrete linear systems that share the same unknowns $f_i(t_k)$,

$$\mathbf{a}^{\mathrm{M}}(t_k) = \mathbf{G}\mathbf{f}(t_k) + \sum_{l=1}^{k} \alpha_{k,l}\mathbf{B}(t_k - t_l)\mathbf{f}(t_l), \qquad k = 1, \ldots, N_\mathrm{t}, \tag{3}$$

where $\alpha_{k,l}$ are quadrature weights, N_t is the number of time steps and $\mathbf{B}(t_k)$ is the $N_\mathrm{s} \times N_\mathrm{f}$ matrix of discrete structural responses to impulse excitations of the magnitude Δt (the discretization time step). All systems from Eq. 3 can be merged together and stated in the form of a single large discrete linear equation:

$$\mathbf{a}^{\mathrm{M}} = \hat{\mathbf{G}}\mathbf{f} + \hat{\mathbf{B}}\mathbf{f}, \tag{4}$$

where the vectors $\mathbf{a}^{\mathrm{M}}$ and $\mathbf{f}$ collect for all time steps the discrete measurements of all sensors and the discrete excitations in all potential excitation points, respectively. With a proper ordering of these vectors, the matrix $\hat{\mathbf{B}}$ is a structured matrix: it takes the form of a large $N_\mathrm{s}N_\mathrm{t} \times N_\mathrm{f}N_\mathrm{t}$ block matrix with Toeplitz blocks (BwTB matrix), where each block is $N_\mathrm{t} \times N_\mathrm{t}$ and relates the discrete response of a single sensor to the discrete excitation in a single excitation point, see an example in Figure 1. The matrix $\hat{\mathbf{G}}$ denotes a block matrix of the same dimensions composed of diagonal matrices with g_{ij} on the diagonal of the (i, j)th block.

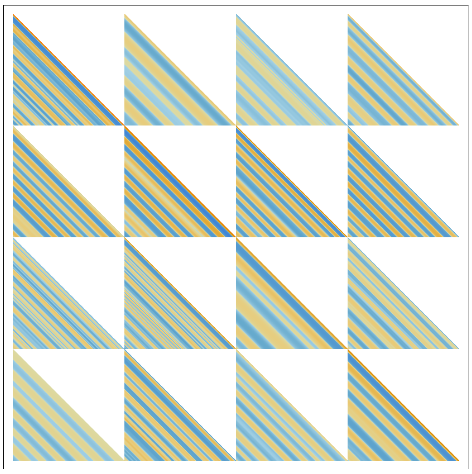

Figure 1: Structured impulse response matrix $\hat{\mathbf{B}}$, an example

Although the matrix integral equation Eq. 2, whether it is of the first kind or the second kind, is discretized into the same Eq. 3, the distinction does matter. In case of an equation of the first kind, load identification amounts to finding and applying an inverse of a compact integral operator. Since an inverse of such an operator cannot be bounded, see [32], the original identification problem in this case is ill-posed. Consequently, its discretized version has a seemingly contradictory property: the finer the time discretization Δt, the more ill-conditioned it is. On the other hand, the continuous problem of the second kind, is well-posed, even if ill-conditioned, and so it has always a unique solution in $(C[0,T])^{N_\mathrm{f}}$. In practice, the discrete system Eq. 4 is always significantly ill-conditioned, unless the considered structure is extremely simplistic. As a rule, a robust regularization technique, such as TSVD, Tikhonov or CGLS, is necessary, see [9, 33, 34].

Even with the regularization techniques, solution of Equation 4 is straightforward, provided the equation is overdetermined, which in practice requires the sensor to be not fewer in number than the considered excitation points and to be "reasonably distributed" (see below) with respect to these points. An overdetermined equation has always a unique least-squares solution, even if part of the information is masked by the measurement noise due to the high degree of ill-conditioning. However, in certain applications it might not be possible to designate a small number of points that are load-exposed. As a result, in such cases the number of sensors might be significantly smaller than the number of potential impact points, Equation 4 becomes underdetermined and has an infinite number of solutions. Basically, two approaches can be used to identify the initial contact forces in such a case:

1. It might be assumed that only a single point (degree of freedom) is excited, which indeed can be true at initial stages of many impact-type loadings. Load identification amounts that to the identification of a single point-wise force, which is an overdetermined problem, with the location identified in an additional nonlinear optimization, see e.g. [35]. In such a case, the feed-through and impulse response matrices in Eq. 4 depends on the location $\mathbf{x}$ of the impact force, and so does the solution $\mathbf{f}(\mathbf{x})$,

   $$\mathbf{a}^{\mathrm{M}} = \hat{\mathbf{G}}(\mathbf{x})\mathbf{f}(\mathbf{x}) + \hat{\mathbf{B}}(\mathbf{x})\mathbf{f}(\mathbf{x}). \tag{5}$$

   For each assumed location $\mathbf{x}$, Eq. 5 can be solved in the least-square sense to obtain the corresponding impact forces $\mathbf{f}(\mathbf{x})$, which, using the pseudo-inverse, can be stated as

   $$\mathbf{f}(\mathbf{x}) = \mathbf{H}^{\star}(\mathbf{x})\mathbf{a}^{\mathrm{M}}, \tag{6}$$

   where the superscript $\star$ denotes the (regularized) pseudo-inverse of a matrix and, for notational simplicity,

   $$\mathbf{H}(\mathbf{x}) = \hat{\mathbf{G}}(\mathbf{x}) + \hat{\mathbf{B}}(\mathbf{x}). \tag{7}$$

   The identified forces are then used to compute the corresponding theoretical response of the sensors, which is compared to the measured response. The location of the impact $\mathbf{x}_{\text{impact}}$ is identified by minimizing the discrepancy, that is

   $$\mathbf{x}_{\text{impact}} = \arg\min_{\mathbf{x}} \left\|\mathbf{a}^{\mathrm{M}} - \mathbf{H}(\mathbf{x})\mathbf{H}^{\star}(\mathbf{x})\mathbf{f}(\mathbf{x})\right\|^2. \tag{8}$$

2. Equation 8 is a nonlinear, non-convex optimization problem. It might not be possible to solve such a problem in real time. Therefore, another approach has been proposed in [36], where the singular value decomposition of the impulse response matrix $\hat{\mathbf{B}}$ is used to decompose the space $\mathbb{R}^{N_\mathrm{f}}$ of all possible impact forces $\mathbf{f}$ into a sum of two complementary linear subspaces of reconstructible and unreconstructible loads. Consequently, the actual contact force $\mathbf{f}$ is a sum of two independent components. One belongs to the reconstructible subspace and can be quickly identified using a simple, relatively low-dimensional linear inversion. However, all the information about the other component

is completely lost in the measurement process due to ill-conditioning (masking by measurement noise) and the insufficient number of sensors. Since the information is not retained in the measured data $\mathbf{a}^{\mathrm{M}}$, the corresponding component of the force is unreconstructible: it can be assumed using purely heuristic criteria, but there is no way to identify it directly from the measurement.

The conditioning and determinacy of Eq. 4 depends on the number and placement of available sensors with respect to the points (degrees of freedom), which are potentially exposed to the unknown impact. Astonishingly, although there is a large bulk of research on optimum placement of sensors with respect to the objectives of optimum structural control and/or optimum characterization of structural dynamic response [], it seems that the objective of optimum identification of excitation forces is relatively unexplored. Actually, the authors are aware of only two such researches:

1. Reference [37] studies a single sensor single force reconstruction problem using a continuous structure and observe a relation between conditioning of the identification problem and certain characteristics of the frequency response function (alternate succession of resonances and antiresonances). This interesting, but as yet phenomenological and qualitative relation, can be potentially used also in multi-sensor and multi-force cases in order to designate a discrete set of limited size with candidate sensor locations to choose from based on other more specific optimality criteria.

2. Reference [36] notices that for underdetermined systems there are no specific non-heuristic *a posteriori* accuracy measures. However, the inaccuracy seems to be associated with the above-mentioned unreconstructible load subspace, which depends on sensor placement. Thus, the inaccuracy can be *a priori* minimized by a proper distribution of available sensors, which would assure that the reconstructible subspace is possibly large and informative with respect to given optimality criteria. Two such criteria are proposed, based either on the dimensionality of the unreconstructible load subspace (via the correlated feature of conditioning) or on the informative content of this subspace, which is quantified by the coincidence with a given set of expected or typical loads. These criteria are found in numerical examples to be negatively correlated, hence they are combined in a compound criterion, which can be seen as a single a priori measure of the accuracy of identification.

3.2. *Identification of impacting object*

in case contact forces are used, the initial identification problem reduces to a linear inversion involving a large number of unknowns, otherwise the identification problem features very few unknowns but becomes highly non-linear. Moreover, the effectiveness of the AIA may also vary: identification of the impacting object is usually less accurate, but can provide significantly more information on the future evolution of the crash process.

3.3. *Online identification of impact forces*

After the AIA system is triggered with the initial data, the evolution of the impact process can be further monitored and the data used to fine-control the crash reception process. However, the identification algorithm must then take into account the plastic response of the structural fuses and the effects of possible damages, which renders the problem much more difficult.

4. Post-accident diagnosis

After the impact loading ceases, an automated off-line post-accident damage diagnosis and accurate reconstruction of the impact scenario is performed. A range of approaches of Structural Health Monitoring (SHM) is potentially applicable. The damage identification task is typically formulated as an inverse problem of minimization of a certain function of the discrepancy between the actually measured and the modeled characteristics of structural response. The unknowns represent selected structural parameters that are assumed to model the expected damages. The compared characteristics can be either actually measured in response to additional testing excitations or the stored responses to the absorbed impact loading can be utilized. In the former case, a dedicated excitation system is required, but more information about the structure is provided. Impact reconstruction is a non-standard optimization problem, as unknowns of two types have to be identified (excitations and damages). A literature review reveals three possible approaches:

1. the difference in the type of the unknowns is retained in a two-step optimization procedure [18]

and/or a more or less general optimization scheme is applied to a set of unified unknowns obtained by

2. expressing the damages in terms of the equivalent pseudo-loads, which converts the problem into an inverse problem of input identification [17] (the number of unknowns is increased, but damages of arbitrary types can be identified),

3. or a parametrization of the loading with a limited number of unknowns of various types [10] (Fourier coefficients, load shape functions, loading masses, half sines, etc.).

Damage identification, as an inverse problem, is usually significantly ill-conditioned, especially in case of many unknowns or input identification. In literature, successful applications of direct as well as iterative regularization techniques can be found. Besides, typical damage identification methods often require a well-tuned parametric numerical model of the global structure. As such a model is often difficult to update, two solutions are sometimes applied: (i) measurements can be directly used in data-driven approaches [15] that range from pure pattern-recognition (with no immediate physical interpretation) to fully physical (based on non-parametric structural models) or (ii) parametric identification can performed locally at the substructural level [8].

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