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# Damage Tolerant Active Control: Concept and State of Art

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**Abstract:** Damage tolerant active control is a new research area related to fault tolerant control design methods applied to mechanical structures. It encompasses several techniques commonly used to design active vibration controllers and to detect and diagnose faults, as well to monitor structural integrity. Brief reviews of the common intersections of these areas are presented, with the purpose to clarify their interrelations and also to justify the new controller design paradigm. Some examples help to better understand the role of the new area.

**Keywords:** Damage tolerant active control, fault tolerant control, structural health monitoring, active control, fault detection and diagnosis, vibration control.

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## 1. INTRODUCTION

Damage Tolerant Active Control (DTAC) system design is a new research area, that has intersections with Fault Tolerant Control (FTC) and active control of vibration methods, and relies also on Structural Health Monitoring (SHM) and Fault Detection and Diagnose (FDD) systems to provide feedback data which are used to achieve the performance goals established at the design phase of the controller development. Relations between all these areas, which have been intensively and independently investigated during the last decades, are examined in this work, and the objectives that specifically concern to DTAC systems are presented.

### 1.1. Objectives

This paper aims to introduce a new controller design concept, dealing with active control of mechanical vibrations when occurrence of structural damage compliance is considered as part of the design requirements. For this situation, the controller may be designed with different goals, considering the state of the structure where it will be applied: if the structure is in a known healthy state, the objective of the controller may be to restrain the vibration energy level, maintaining a satisfactory performance even if some future damage begins to degrade the structure; if there is a known damage, the objective may be to deflect the vibration energy flow from the damaged region, preventing the evolution or spread of the detected damage; or, for a new structure where the most probable points to occur damage are known, the objective must be just to avoid or to retard this occurrence. Therefore, in any case, sensors are necessary to produce vibration measurement data to be used by the feedback control loop, but also to feed specialized modules implementing structural integrity analysis techniques, in order to guarantee that the controller will present robustness if some damage is identified. Brief reviews of the several related domains involved in DTAC concepts are included, to clarify the interrelations between them, and how they may be placed at service to this new area.

### 1.2. Conceptual Motivations

International intense research activity brought to maturity several methods which were developed to attend the goals of the aforementioned related areas. These efforts represented the application of multidisciplinary monitoring and control methods to assess complex systems of modern engineering, seeking essentially safe operation and useful life extension for these systems, generally based on evaluation of their operational status, and eventually applying control methods to ensure the required performance.

SHM methods and techniques enable fault detection and diagnosis of the state of a mechanical structure. Such methods have been developed to various sectors of engineering, especially air or land vehicles and civil structures. However, despite more than two decades of research, the results are still largely academic, due to difficulties to transport results from laboratory to real systems. But it is undeniable that they are about to be widely adopted, following the evolution of instrumentation and signal processing methods, and becoming robust enough to cope with large disturbances caused by operational and environmental variations, as required by real systems. Some recent surveys have shown that even reluctant industry areas are now convinced that SHM is the key technology to enable the transition from traditional schedule-driven maintenance to condition-based maintenance (Chang, 2011).

The active control of vibrations in mechanical structures has evolved significantly in the last two decades, following the evolution of the control area. But it also has little application to the real world, of which the main example of success would be the response control of buildings to vibrations caused by winds or earthquakes. Several other problems have been treated, and an increasing number of applications may be expected in the next few years.

Fault detection in controlled systems has generally conducted to the development of the area, now, known as FTC, where two main methods may be identified, besides the case of a

robust lone controller designed to encompass some faults: the accommodation of the fault replacing the controller by choosing another one previously designed and made available as an option to the system; or the redesign or adjustment of controller parameters, in face of faulty conditions, in order to maintain adequate performance. Some variations or combinations of these two models exist, but generally these are the two basic architectures.

Thus, the association of these different research areas, directing its application to mechanical structures, is leading to the new area that may be called *Damage Tolerant Active Control* or DTAC for short. The joint methods aim basically to control the structural vibrations, but adopting three different strategies, as mentioned before, attaining performance in the presence of damage, controlling the power flow in damaged regions or actively isolating vibrations in parts of the structure. DTAC therefore makes use of a widely multidisciplinary context, which applies knowledge from different fields, such as mechanical structures modeling, signal processing, instrumentation, fracture mechanics, modal analysis and artificial intelligence, among others.

This set of disciplines is currently associated with the concept of smart structures, which includes embedded sensors, actuators and even processors, enabling the structure to diagnose and react to abnormal states, and thus minimizing the effects of a possible damage. Following the trend due to the evolution of microelectronics, and consequent increase in digital processing power, such smart structures must soon integrate high levels of embedded intelligence. It is necessary therefore to develop new methods and procedures adapted to real-time performance, enabling the automation of analysis, diagnosis and damage control processes. Thus, the set of techniques that will be embedded to the monitoring and control of mechanical structures now includes a large amount of transducers and routines for the detection of abnormal states, its diagnosis, its prognosis and also the reconfiguration of the active control algorithms responding to a damage, either in a permanent way or to face an emergency situation.

### 1.3. Paper outline

In Section 2, smart structures are described and damage is defined. Section 3 is dedicated to the presentation of a brief state of art of DTAC domains. Concepts, architecture and key issues of DTAC system are introduced and discussed in Section 4. Concluding remarks and future perspectives are drawn in the last section.

## 2. SMART STRUCTURES

To perform a DTAC system the structure has to be smart and controlled. A brief insight of the smart structure field is given in the sequel.

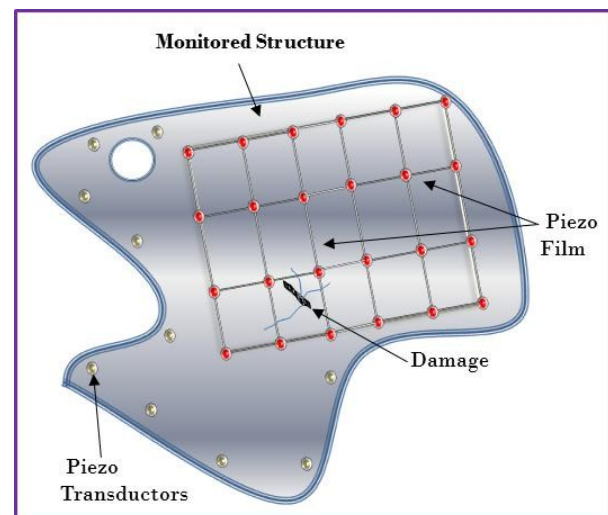
### 2.1. Monitoring and diagnosing layers

Advanced structures with improved self-capabilities have been intensively studied over the last four decades. A smart structure has the ability to respond to changes in its own and environmental conditions. It has built-in sensors and actuators, to monitor and diagnose these changes. We can use the analogy with biological systems to define smart structures.

In fact, smart structure is an instrumented structure with embedded sensors (nerves) and actuators (muscles) with a central processor (brain) that try to mimic living beings systems (for example the nervous system) in the presence of internal or external forces. Hence, smart structures strive to satisfy several characteristics of a biological system as sensing, actuation, adaptability and self-repair. Development of smart structures is fuelled by the on-going technological progress and evolution of performance demands.

Two types of signal processing for smart structures can be distinguished: *closed-loop* and *open-loop*. Closed-loop smartness means that the structure senses and reacts to mitigate a detected problem. Open-loop smart structure enhances structural integrity only when needed and relapses to its normal state when there is no need for any monitoring.

Different materials can be used on smart structures to act and sense. For vibration control purposes, we can use actuators and sensors such as piezoelectric and shape memory alloys. For passive SHM, when we need only sensing, we can use optical fiber sensors (Fiber Bragg Grating, FBG) and MEMS.



**Fig. 1:** Monitoring smart structure layer

Among all smart materials, piezoelectric materials are those which are currently widely used, due to their adaptable properties. Because the piezoelectric effect may be used in both senses, from mechanical to electrical transduction and vice-versa, the respective elements offer in general the ability to be employed as sensors and/or actuators. This property makes it possible to integrate the structure and the sensing and acting mechanism. In fact, this mechanism becomes a part of the structure. The commonly used piezoelectric materials are semicrystalline polymer film PVDF (polyvinylidene fluoride), and piezoelectric ceramic PZT (lead zirconate titanate).

Nowadays, and specifically in aeronautic industry, composite materials are increasingly used due to their strength properties. Because of their multilayer structure, composite are inherently suitable to host smart materials. Indeed, embedded sensors and actuators could be incorporated permanently into the composite as a smart layer and hence to become part of the structure. This can be easily achieved during the manufacturing phase of the composite panels.

## 2.2. Damage definitions

Before going further in describing DTAC system we need to define damage in a smart structure. A monitoring system is supposed to be concerned for instrument faults as well as structural damages. In a structure, damages can be provoked by external and internal action and/or by normal aging due to usage. They also depend on the material constituting the structure. Moreover, the effect of damage can be classified as *linear or nonlinear*. In the most general terms, the damage can be defined as changes introduced into a system that adversely affects its current or future performance. Implicit in this definition is the concept that damage is not meaningful without a comparison between two different states of the system, one of which represents the initial state of the system, admittedly representing an intact or healthy state. For common structures, the definition of damage will be limited to changes in material properties and/or geometry of these systems, including changes in performance conditions and system connectivity. Taking as an example, a dent formed in a mechanical part is a change in geometry that changes the stiffness characteristics of this part. Depending on the size and location of the dent and the loads applied to the system, the adverse effects of damage can be immediate or may take some time before the system performance changes. For smart structures, this definition is extended to include sensors and actuators failures:

**Definition:** A damage in a smart structure concern any unexpected material or geometrical changes of the structure from their usual condition, including its smart materials part (actuators and sensors).

Referring to the definition of a fault in a technological system (Isermann, 2006), this damage definition could be somewhat confusing in terms of differentiation between fault and damage. Indeed, as sensors and actuators are now part of the whole structure, their failures will then be considered as damages. This implies that some FDD methods could also be used in the DTAC system.

Let us consider another example, which concerns the case of composite materials with fiber reinforcements (composite commonly used in aeronautical industry). There are three main types of damage that can evolve in number and size until the collapse of the structure: cracks within the plies, delamination and fiber breakage. The latter damage is said to be "*no-mechanical*" because of its thermal, electrical or other origin (e.g. short circuits or lightning strikes). For example, during an impact, which is the most commonly encountered source of damages, these three damages may appear in a sequential manner (starting with cracks) along with the solicitation of the structure. The availability of mathematical models to understand and predict changes at different scales of the structural state is required to make a reliable prognosis.

## 3. STATE OF THE ART OF DTAC DOMAINS

DTAC's areas of research include relevant engineering domains (Fig. 2) as material science, sensor technology, signal processing, control theory, wave propagation, fracture mechanics, fatigue life analysis, structural design assessment and more.

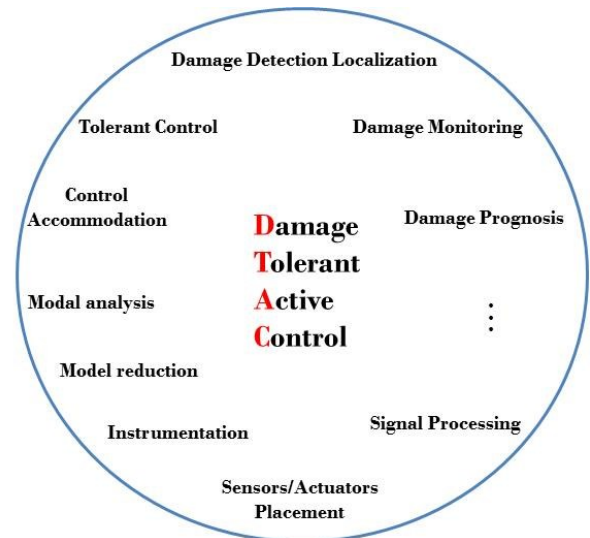


Fig. 2: Research areas of DTAC

Before introducing and reviewing the different domains involved in a DTAC system, we present a brief review of fault tolerant control systems. This will help the better understanding of links and interactions between DTAC and FTC that will be discussed in section 4.

### 3.1 Fault Tolerant control

An FTC system is a control system that possesses the ability to accommodate for system failures automatically. Hence the main task to be tackled in achieving fault-tolerance is the design of a controller with suitable structure to maintain overall system stability and acceptable performances. FTC may be called upon to improve system reliability, maintainability and survivability. FTC systems have appeared since the early 1980s (Chizeck & Willsky, 1978 ; Eterno et al., 1985). Nowadays, FTC has gained in popularity among industrial and academic researchers. Several survey paper and books have appeared (Stengel, 1991; Patton, 1997; Blanke et al., 2001; Staroswiecki & Gehin, 2001; Steffen, 2005; Isermann, 2006; Blanke et al., 2006; Zhang & Jiang, 2002)

Generally speaking, FTC systems can be classified in two types: *passive* (PFTCS) and *active* (AFTCS):

- The *passive* methods or *reliable control* aims at achieving insensitivity to some specific anticipated faults by means of making the system robust with respect to them. The controller is fixed and need neither FDD schemes nor controller reconfiguration. In this approach, often fault-tolerance is achieved by considering faults as uncertainties that the controller can deal with. Hence, we assume that the faults occur in a predefined subset and the controlled should be designed to optimize the worst fault performance (Jiang & Zhao, 2000; Yang et al., 2001; Hsieh, 2002; Liao et al., 2002).
- In the *active* approach to FTC, faults are detected and identified by a FDD scheme, and the controllers are reconfigured accordingly on-line and in real-time so that stability and acceptable performance of the entire system can be maintained (Steinberg, 2005; Cieslak et al., 2008). The AFTCS methods present the ability to deal with a large type of faults. The controller can be designed in several schemes:

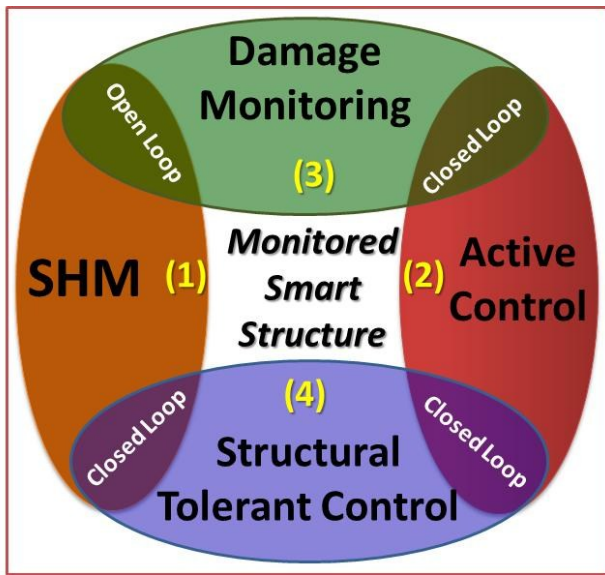


performing fault accommodation (Belcastro, 2001); selecting a pre-computed control law (Maybeck & Stevens, 1991) or synthesizing a new one on-line (Zhang & Jiang, 2002). In the case of hybrid systems several approaches have been investigated, see the book of (Yang et al., 2010) and references therein. Another approach that can be included in a FTC scheme is the integrate design of the control and the FDI systems (Stoustrup et al., 1997; Mechbal et al., 2006; Ding, 2009). A complete review of AFTC methods is given in (Zhang & Jiang, 2008).

To complete this condensate review, we include some collection (major reviews and books and some new papers) of references dealing with fault detection and diagnosis (Willsky, 1976; Basseville & Nikiforov, 1993; Chen & Patton, 1999; Patton et al., 2000; Venkatasubramanian et al., 2003a, 2003b, 2003c; Isermann, 2006; Ba et al., 2009a, 2009b)

### 3.2 DTAC principal topics

For a smart structure, and depending if the structure is controlled in an open or closed loop scheme, the principal domains involved in DTAC could be gathered in four different topics (Fig. 3): *SHM*, *Active Control*, *Damage Monitoring* and *Structural Tolerant Control*.



**Fig. 3:** Principal areas involved in DTAC research

#### Area 1: Structural health monitoring.

SHM is an emerging technology to automate the inspection process to assess and evaluate the health condition of structures in real-time or at specified time intervals. SHM systems for smart structures may automatically process data, assess structural condition, and signal the need for human intervention (Worden et al. 2007).

SHM technology involves multidisciplinary fields ranging from material, structure, signal processing, data mining, fracture mechanics, fatigue life analysis and more. It aims to detect, localize and evaluate the severity of damages. The improvement of the integrity assessment of in-service structures is the main challenge that motivates the use of SHM

systems. As structures age, or undergo fatigue loads, the possibility of failure increases, which may significantly jeopardize operation and safety without timely awareness. The SHM can be described as a 4-step process corresponding to the following questions (Rytter, 1993):

SHM Levels	Questions to answer
Level 1	Is there any damage in the structure ( <b>existence</b> )?
Levels 2	Where is the damage in the structure ( <b>location</b> )?
Levels 3	Which kind of damage ( <b>type</b> )?
	What is the severity of the damage ( <b>extent</b> )?
Level 4	What is the in "service" remaining lifetime ( <b>prognosis</b> )?

**Fig. 4:** SHM levels

SHM has been the focus of intense research for these last few years. The approach can be classified according to the answers to these questions, in the order presented, which represent the increasing knowledge of the state of damage.

The field of damage identification is very broad and encompasses different approaches which depend on structure materials, technology used for acting and sensing, position, size and nature of damage (Doebeling et al., 1998; Worden & Dulieu-Barton, 2004; Staszewski et al., 2004). They could be sorted in two main categories: *global* or *local*. Most of SHM methods are based on the interpretation of signals generated by the sensors of the smart structure. The greatest challenge is to ascertain what changes are sought in the signals after the presence of damage. Features extraction is therefore a key step in the processing of signal sensor for SHM. Feature extraction is the process of identifying damage-sensitive properties derived from the measured response of the structure and it serves as an indicator to describe damage. These extracted features are termed as damage index (DI).

Different approaches have been developed to elaborate specific DIs. These methods are also categorized based on the type and nature of measured data used. Examples of proposed techniques include: model updating (Fritzen et al., 1998); statistical time series (Fassois & Sakellariou, 2009); vibration based processing (Carden & Fanning, 2004). In this last approach we seek to track changes in structural parameters (mass, stiffness, flexibility, damping) and modal parameters (modal frequencies, associated damping values and mode shapes), which induce changes in the dynamic behavior of a structure. Therefore, experimental identification of these dynamic properties gives insight on the structural damage conditions, see (Zou et al., 2000; Basseville et al., 2004; Inocente-Junior et al., 2009 and references therein). Detecting and localizing damage can be considered a classification problem. For example, Artificial Neural Networks (ANNs) have been applied successfully to solve this classification problem in different applications (Worden & Dulieu-Barton, 2004; Sohn et al., 2003; Roseiro et al., 2005). A coupled structural parameter identification and ANN have been proposed by (Saeed et al., 2009a, 2009b, 2010). Multivariate techniques have been also used in SHM: the POD (Proper Orthogonal Decomposition) (Hajrya et al., 2011a) and the ICA (Independent Components Analysis) (Hajrya et al., 2011b). To monitor sensor and actuator components of a smart structure (Mechbal & Vergé, 2006) have used a robust estimator. In the case of nonlinear damage, specific

approaches have been developed. An extensive overview of these methods can be found in (Farrar et al., 2007).

For local inspection, we can employ electro-mechanical impedance or displacement/strain as features indicating the presence of damage (Balageas et al., 2006). The sensibility of these techniques is strongly linked to the position of the sensors. We can also highlight acoustic emission or wave-based approaches that have the advantage to be sensitive to small damages and the capability of propagation over a significant distance. A large number of wave-based techniques exist for SHM. These techniques exploit surface acoustic waves (SAW) or guided waves in plates, shells, or tubes-like structures, to localize acoustic sources or flaws (Liu et al., 2011; Su & Ye, 2009; Zhongqing et al., 2006).

Concerning level 4 of the SHM scheme, detailed discussion and a collection of references, dealing with the various approaches used in damage prognosis, are given in the book of (Inman et al., 2005).

#### Area 2: Active control of vibration

*Active control* has emerged as a viable technology to minimize mechanical vibrations of structures. Vibrations have several effects on a structure and its environment. They can provoke damage by excessive strain or by fatigue and be prejudicial to machine precision and to human comfort.

Benefiting from the development in the control system theory, active control is now considered as a mature field, providing many powerful methods. In the literature, a large number of approaches have been proposed. However, there are only few cases that consider information concerning the effects of damage upon the active controller. These tolerant approaches are included in area 4 and will be presented later. The active control methods can be classified in two radically different categories (Preumont, 2002) *feedback* and *feedforward*.

Examples include, but are not limited to, early modal control avoiding spillover phenomena (Balas, 1978), recent modal control strategies were described and highlighted in (Inman, 2006; Singh et al., 2003), the conventional PID control (Sutton et al., 1999): input shaping (Singhose et al., 1997), minmax LQR (Petersen & Pota, 2003), modal control (Hurlebaus et al., 2008),  $H_2/H_\infty$  robust (Anthonis et al., 1999), distributed controller (Bhattacharya et al., 2002); time delay control (Jalili & Olgac, 1999) model predictive controller (Wills et al., 2008), nonlinear controller (Gaudiller & Matichard, 2007); and spatial  $H_2$  and  $H_\infty$  controllers (Halim, 2007; Halim et al., 2008; Barrault et al., 2008; Mazoni et al., 2011). This control approach allows achieving vibration control at spatial regions of interest, which may be, very useful in a DTAC system. For mechanical systems, a commonly applied method is Positive Position Feedback (PPF) control (Fanson & Caughey, 1990; Moheiman et al., 2006). Interested readers are encouraged to consult the following books (Preumont, 2002; Gawronski, 2004; Inman, 2006) and references therein.

#### Area 3: Damage monitoring

This area involves the monitoring of already detected and localized damage. The goal is to supervise the evolving of the damage and to provide prognosis about its in-service lifetime.

It is mainly based on methods described in the SHM area as for example, Lamb wave based approaches and mechanical/materials analysis. Indeed, to perform reliable prediction one need to use models based on fracture mechanics, fatigue life analysis, or structural design assessment. For more details on this transversal area, please refer to the book on prognosis in SHM (Inman et al., 2005) and the book on durability and aging of structures (Pochiraju et al., 2012).

#### Area 4: Structural tolerant control

Structural tolerant control (STC) deals with the vibration suppression control problem against potential damage. The goal is to design an active controller that provides satisfactory performances in terms of vibration rejection under the possible presence of damages. The approaches to perform STC are mainly based on approaches used in FTC systems: robust control and reconfigurable control. However, STC could also be used to monitor or to detain the evolving of damage as described in the previous area.

However, this subject has seldom been discussed and in the literature, only few works are referred to it (sometimes unwittingly). Based on  $\mu$  synthesis and  $H_\infty$  controllers, (Ahmad et al., 2000) proposed one of the first addressed problems on STC design. Using the same tools (Caplin et al., 2001) have proposed a robust damage-mitigating control of aircraft. The goal of this controller is to simultaneously achieve high performance and structural durability. More recently, a damage tolerant LQG modal controller has been applied to a printed circuit board (PCB) by (Chomette et al., 2008, 2010). They proposed a complete methodology, from finite-element simulations to experimentation on a real PCB. PZT ceramics were embedded on the PCB and the controller was designed to reduce the vibration damage in PCBs, which may be extended to the majority of on-board structures subjected to damage.

### 4. DTAC CONCEPTS AND GENERAL ARCHITECTURE

Damage tolerant active control combines the functions of SHM and active control (Fig. 5). DTAC encompasses two main fields: damage monitoring and damage tolerant control.

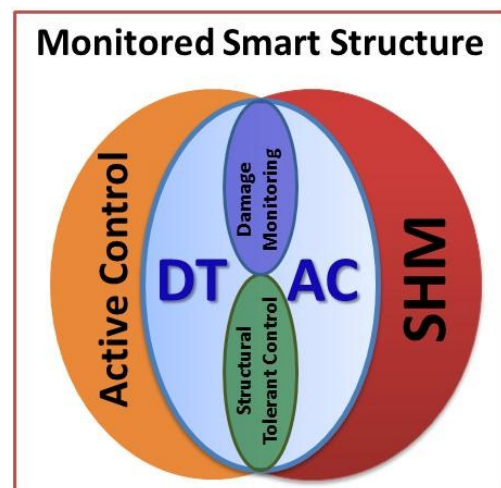


Fig. 5: DTAC domain

#### 4.1. DTAC strategies for Damage Control

Depending on the objectives and how "smart" is the structure (number, position and type of sensors and actuators), we define three different ways to perform structural active control under possible damage (Fig. 6):

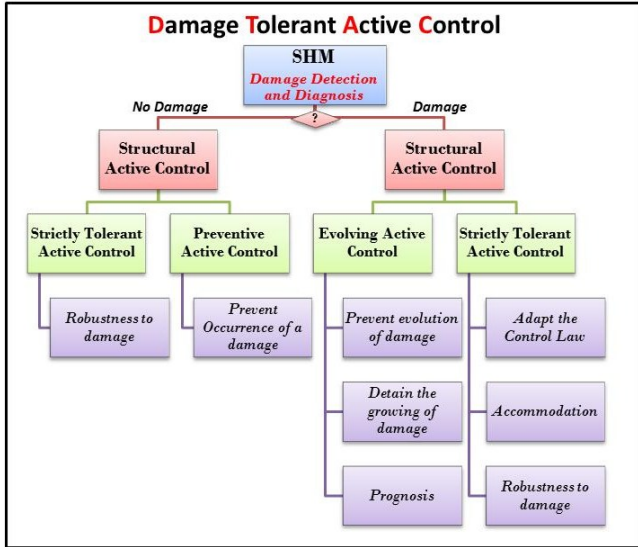


Fig. 6: Structural Active Controllers under possible damage

**Strictly Tolerant Active Controller (STAC)** – The damage has been detected, and then two designs can be carried out:

- A controller that is *robust* to the damage.
- A controller that is *adaptive* to the presence of damage (Fig. 7).

In the first case, the controller is designed to simultaneously achieve high performance and structural durability under a presence of a possible damage. It is also used to prevent the occurrence of damage.

The second design is based on reconfigurable or adaptive control theory. The design relies heavily on a real-time SHM scheme to provide as precisely as possible information about damage and then to design or to select a new active controller (Fig. 7). This controller will try to maintain acceptable rejection vibration performances by compensating damage-induced changes in the structure. As in reconfigurable FTC scheme, parameters and the controller structure might be changed.

**Preventive Active Controller (PAC)** – The controller is designed to avoid the occurrence of damage. This design procedure supposes a detailed preliminary study on critical damages (kind, localization and effect). This is the aim of several recent works. See for example on-board damage reduction of a printed circuit board (Chomette et al., 2010).

**Evolving Active Controller (EAC)** – The controller is designed to protect the structure avoiding the evolution of the damage. EAC will achieve vibration reduction or isolation. It can also be used to perform damage prognosis.

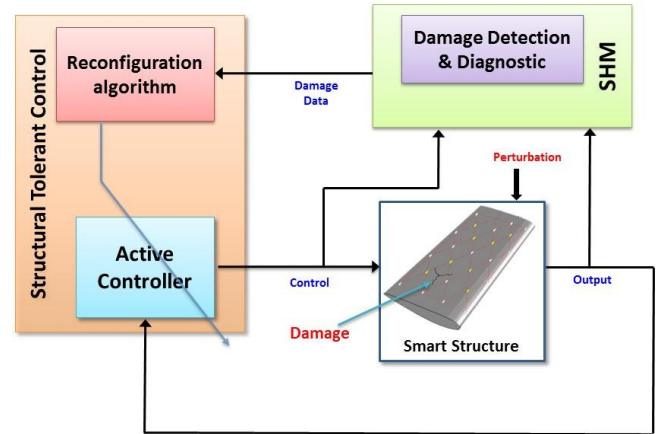


Fig. 7: DTAC scheme in a reconfigurable design

#### 4.2. DTAC strategies for Damage Monitoring

Besides the description of damage monitoring presented before, we also include *smart repair patches* in DTAC. Regular patches are commonly used to maintain the mechanical strength and behavior of the structure when small damages are detected by maintenance people. In general, the patch is made of composite materials, and it is pasted on the structure according to the assessment of the damage. If now we use a *smart patch* by embedding into it sensors and actuators (Fig. 8), one can perform monitoring of the in-service bounding of the patch (Chapuis, 2010) or to assess the evolving of the damage. We can also use this smart patch to perform vibration reduction or isolation, aiming detaining or mitigating detrimental evolution of damage, due to operating conditions, which will enhance structural durability. Investigations on these subjects are part of DTAC domains.

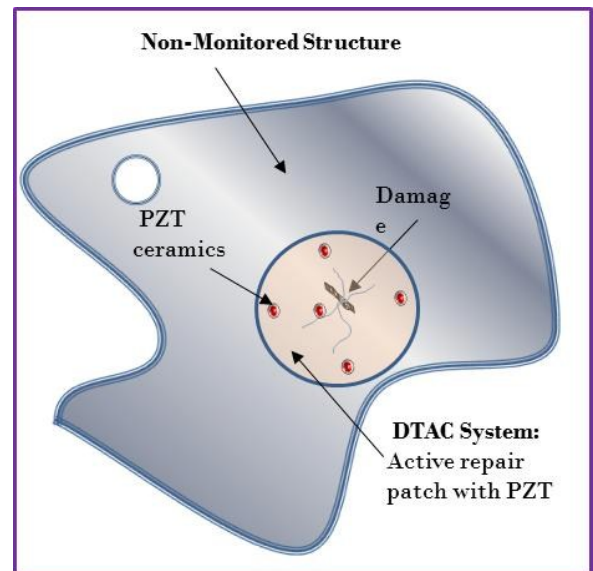


Fig. 8: DTAC system: Smart repair patch

#### 4.3. DTAC and FTC interactions

In the light of what we have presented until this point, DTAC may be seen as the extension of FTC methods to structures. It is partially the case, because as we are dealing with smart structures, DTAC stands up as a new area because it presents



several functions that FTC cannot generally perform. Moreover, even if the two concepts use the same control tools the objectives are somewhat different or even complementary.

For a better understanding of the role of each one and their interactions, we shall illustrate the two concepts through an example, which may help to better understand the differences between the several areas involved in this analysis.

**Flight control system example:** Consider a fighter jet plane with two wing turbines, which, during a mission, it is shot in one of the turbines. As soon as the turbine was hit, an FTC system should recognize the critical situation and modify the controller to comply with the damage, considering the better achievable performance, because something has to be immediately done to prevent higher losses. Then, passed the critical initial moment, an FDD system, presenting a slower response time, would assess the damage to decide how the aircraft should operate in order to return safely to its base station. For this analysis, the same signals used by the FTC system would be used, maybe complemented by some other data. As a result of the FDD system prognosis, the controller of the FTC system could be modified again. For all these activities, no DTAC system is involved, only the FDD and FTC systems, integrated somehow. Nevertheless, suppose that the plane was shot only at the wing, and as a result it lost some lift capacity. Then the FTC and FDD systems are again involved in the same fashion. However, if the consequences are a great increase of the vibration due to the wing damage, an active control is necessary to attenuate the vibration, and, because there is a structural damage, then a DTAC system would be required, and it should promptly respond to the abnormal condition. Also, analog to the relation between FDD and FTC, after the initial reaction of the DTAC system, now it is necessary an SHM system to assess the damage and make some prognosis, and eventually cause some change to the DTAC parameters. Data used by the SHM is coming from the smart structure of the wing, and possibly also from the transducers specifically connected to the DTAC system. Here, we can see that all these systems have different functions and may be independently attached to the aircraft general flight system, in order to achieve the main goal of flying safely and to perform the better possible way according to the specific objectives of each situation.

Clearly, active structural control applications may be separated in two cases, when the possibility of damage is considered in the respective design of the controller, and when there is no concern about the possibility of damage. In the first case, it is indeed a DTAC system.

## 5. CONCLUSIONS AND PERSPECTIVES

A new paradigm to design fault tolerant controllers, specifically dedicated to face structural damages, was here examined, and called damage tolerant active control, or DTAC.

A brief review of some of the main methods concerning to FTC, SHM and active control of vibrations were presented, considering their interfaces with the introduced area of DTAC, and some examples were described in order to clarify

their relations and justify this new concept of vibration controller design.

Several techniques used in these areas are possible to be used to DTAC purpose, and main objectives and architectures to be adopted were discussed.

For the near future, examples of applications of the concepts and controller configurations are expected to be thoroughly studied to confirm the raised expectations.

## REFERENCES

### **Structural Health Monitoring, SHM:**

- Balageas, D., Fritzen, C.P. & Güemes, A., 2006. *Structural Health Monitoring*. ed. ISTE, London.
- Basseville, M., Mevel, L. & Goursat, M., 2004. Statistical model-based damage detection and localization: subspace-based residuals and damage-to-noise sensitivity ratios. *Journal of Sound and Vibration*, 275, pp.769-94.
- Carden, E.P. & Fanning, P., 2004. Vibration based Condition Monitoring: A Review. *Structural Health Monitoring Journal*.
- Chang, F.-K., 2011. Structural Health Monitoring: Condition-based Maintenance. In *8th International Workshop on Structural Health Monitoring (IWSHM)*. Stanford, 2011.
- Doebling, S.W., Farrar, C.R. & Prime, M.B., 1998. A summary review of vibration-based damage identification methods. *The Shock and Vibration Digest*, 30(2), p.91-105.
- Farrar, C.R. et al., 2007. *LA-14353 Nonlinear System Identification for Damage Detection*. Los Alamos National Laboratory. Los Alamos.
- Fassois, S.D. & Sakellariou, J.S., 2009. *Statistical Time Series Methods for SHM*. Chichester, UK: John Wiley and Sons Ltd.
- Fritzen, C.P., Jennewein, D. & Kiefer, T., 1998. Damage detection based on model updating methods. *Mechanical Systems and Signal Processing*, 12(1), p.163-186.
- Fritzen, C.P. & Kraemer, P., 2009. Self-diagnosis of smart structures based on dynamical properties. *Mechanical Systems and Signal Processing*, 23, pp.1830-45.
- Hajrya, R., Mechbal, N. & Vergé, M., 2011a. Damage Detection of Composite Structure Using Independent Component Analysis. In *International Workshop on Structural Health Monitoring, IWSHM*. Stanford, 2011.
- Hajrya, R., Mechbal, N. & Vergé, M., 2011b. Proper Orthogonal Decomposition Applied to Structural Health Monitoring. In *IEEE International Conference on Communications Computing and Control Applications*. Hammamet, 2011.
- Inman, D.J., Farrar, C.R. & Lopes Junior, V., 2005. *Damage Prognosis: For Aerospace, Civil and Mechanical Systems*. Wiley ed.
- Inocente-Junior, N.R., Nóbrega, E.G.O. & Mechbal, N., 2009. Real-time structural health monitoring using parity residue analysis. In *International Congress of Mechanical Engineering*. Brasil, 2009.
- Liu, Y., Mechbal, N. & Vergé, M., 2011. Damage monitoring based on wave illumination of structures. In *International Workshop on Structural Health Monitoring (IWSHM)*. Stanford, USA, 2011.



- Mechbal, N. & Vergé, M., 2006. Active Robust Fault Estimation on a Composite Beam with Integrated Piezoceramics. In *SAFEPROCESS'06*. Beijing, 2006.
- Roseiro, L., Ramos, U. & Leal, R., 2005. Neural networks in damage detection of composite laminated. *WSEAS Transactions on Systems*, 4(4), p.430–434.
- Rytter, A., 1993. *Vibration based inspection of civil engineering structures*. PhD thesis. Aalborg University.
- Saeed, K., Mechbal, N., Coffignal, G. & Vergé, M., 2009a. Artificial Neural Network Based Structural Damage Diagnosis Using Nonparametric Subspace Residual. In *7th International Workshop on Structural Health Monitoring, IWSHM*. Stanford (USA), 2009.
- Saeed, K., Mechbal, N., Coffignal, G. & Vergé, M., 2009b. Structural Damage Diagnosis Using Subspace Based Residual and Artificial Neural Networks. In *7th IFAC, SAFEPROCESS*. Barcelona (Spain), 2009.
- Saeed, K., Mechbal, N., Coffignal, G. & Vergé, M., 2010. Subspace-based damage localization using Artificial Neural Network. In *18th Mediterranean Conference on Control & Automation (MED'10)*. Marrackech (Morocco), June 2010.
- Sohn, H. et al., 2003. *Review of Structural Health Monitoring Literature, 1996–2001*. Los Alamos National Laboratory Report. LA-13976-MS, Los Alamos.
- Staszewski, W.J., Boller, C. & Tomlinson, G.R., 2004. *Health monitoring of aerospace structures: smart sensor technologies and signal processing*. John Wiley and Sons.
- Su, Z.Q. & Ye, L., 2009. *Identification of Damage Using Lamb Waves*. Springer.
- Worden, K. & Dulieu-Barton, J.M., 2004. An Overview of Intelligent Fault Detection in Systems and Structures. *Structural Health Monitoring an international Journal*, 3(1), pp.85–98.
- Worden, K., Farrar, C.R., Manson, G. & Park, G., 2007. The fundamental axioms of structural health monitoring. *Proceeding of the Royal Society*, pp.1639–64.
- Zou, Y., Tong, L. & Steven, G.P., 2000. Vibration-based modeldependent damage (delamination) identification and health monitoring for composite structures - a review. *Journal of Sound and Vibration*, 230(2), pp.357–378.
- Zhongqing, S., Lin, Y. & Ye, L., 2006. Guided Lamb waves for identification of damage in composite structures: A review. *Journal of Sound and Vibration*, 295, p.753–780.
- Active Control of Vibration:**
- Ahmad, S., Lew, J.S. & Keel, L.H., 2000. Robust control of flexible structures against structural damage. *IEEE Transactions on Control Systems Technology*, p.170–182.
- Anthonis, J., Swevers, J., Moshou, D. & Ramon, H., 1999. H $\infty$  controller design for a vibrations isolating platform. *Control Engineering Practice*, p.1333–1341.
- Balas, M.J., 1978. Feedback control of flexible systems. *IEEE Transaction on Automatic Control*, pp.673 – 679.
- Barraut, G., Halim, D., Hansen, C. & Lenzi, A., 2008. High frequency spatial vibration control for complex structures. *Applied Acoustics*, p.933 – 944.
- Bhattacharya, P., Suhail, H. & Sinha, P.K., 2002. Finite element analysis and distributed control of laminated composite shells using lqr/imsc approach. *Aerospace Science and Technology*, p.273 – 281.
- Caplin, J., Asok, R. & Suresh, M.J., 2001. Damage-Mitigating Control of Aircraft for Enhanced Structural Durability. *IEEE transaction on Aero. Elec. Syst.*
- Chapuis, B., 2010. *Contrôle Santé Intégré par méthode ultrasonore des réparations composites collées sur des structures métalliques*. PhD Thesis. Paris: Univ. of Paris 7-ONERA.
- Chomette, B., Chesné, S., Remond, D. & Gaudiller, L., 2010. Damage reduction of on-board structures using piezoelectric components and active modal control – Application to a printed circuit board. *Mechanical Systems and Signal Processing*, 24(2), pp.352–54.
- Chomette, B., Remond, D., Chesné, S. & Gaudiller, L., 2008. Semi-adaptive modal control of on-board electronic boards using an identification method. *Smart Material and Structures*, 17, pp.1–8.
- Fanson, L. & Caughey, T.K., 1990. Positive position feedback-control for large space structures. *AIAA Journal*, 28(4), p.717–724.
- Gaudiller, L. & Matichard, F., 2007. A nonlinear method for improving the active control efficiency of smart structures subjected to rigid body motions. *IEEE/ ASME Transaction of Mechatronics*, p.542–548.
- Gawronski, W., 2004. *Advanced Structural Dynamics and Active Control of Structures*. Springer-Verlag.
- Halim, D., 2007. Structural vibration control with spatially varied disturbance input using a spatial method. *Mechanical Systems and Signal Processing*, 21(6), p.2496 – 2514.
- Halim, D., Barraut, G. & Cazzolato, B.S., 2008. Active control experiments on a panel structure using a spatially weighted objective method with multiple sensors. *Journal of Sound and Vibration*, 315(1), p.1 – 21.
- Hurlebaus, S., Stöbener, U. & Gaul, L., 2008. Vibration reduction of curved panels by active modal control. *Computers & Structures*, p.251–257.
- Inman, D., 2006. *Vibration with control*. ed. John Wiley & Sons.
- Jalili, N. & Olgac, N., 1999. Multiple delayed resonator vibration absorbers for multi-degree-of-freedom mechanical structures. *Journal of Sound and Vibration*, 223, p.567–585.
- Mazoni, A.F., Serpa, A.L. & Nóbrega, E.G.O., 2011. A decentralized and spatial approach to the robust vibration control of structures. *Challenges and Paradigms in Applied Robust Control*, pp.149–70.
- Mechbal, N., M., V., Coffignal, G. & Ganapathi, 2006. Application of a Combined Active Control and Fault Detection Scheme to an Active Composite Flexible Structure. *International Journal of Mechatronics*.
- Moheiman, i.R.S.O., Vautier, B.J.G. & Bhikkaji, B., 2006. Experimental implementation of extended multivariable PPF control on an active structure. *IEEE Transaction on Control System Technology*, May. p.443–445.
- Petersen, I.R. & Pota, H.R., 2003. Minimax LQG optimal control of a flexible beam. *Control Engineering Practice*, November. p.1273–1287.
- Pochiraju, K.V., Tandon, G.P. & Schoeppner, G.A., 2012. *Long-Term Durability of Polymeric Matrix Composites*. Springer.

- Preumont, A., 2002. *Vibration Control of Active Structures, An Introduction*. Kluwer, second edition.
- Singh, S.P., Pruthi, I. H.S. & Agarwal, V.P., 2003. Efficient modal control strategies for active control of vibration. *Journal of Sound and Vibration*, 262, p.563–575.
- Singhose, W.E., Porter, L.J., Tuttle, T.D. & Singer, N.C., 1997. Vibration reduction using multi-hump input shapers. *J. Dyn. Syst. Meas. and Control*, 119, p.320–326.
- Sutton, R.P., Halikias, G.D., R., P.A. & Wilson, D.A., 1999. Modeling and  $H_\infty$  control of a single link flexible manipulator. In *Proc. Inst. Mech. Eng.*, 1999.
- Wills, A.G. et al., 2008. Model Predictive Control Applied to Constraint Handling in Active Noise and Vibration Control. *IEEE Trans. on Contr. Syst. Tech.*
- Fault Detection and Diagnosis, FDD & Fault Tolerant Control, FTC:**
- Ba, A., Hbaieb, S., Mechbal, N. & Vergé, M., 2009a. Fault detection by marginalized particle filters: Application to a drilling process. In *7th IFAC Symposium SAFEPROCESS*. Barcelona (Spain), 2009.
- Ba, A., Pons, R., Hbaieb, S., Mechbal, N. & Vergé, M., 2009b. Particle filters for linear regression and fault diagnosis: An approach for on-line oilfield drilling processes monitoring. In *48th IEEE Conference on Decision and Control*, CDC'09. Shanghai (China), 2009.
- Basseville, M. & Nikiforov, I., 1993. *Detection of abrupt changes: Theory and application*. ed. Prentice Hall
- Belcastro, C.M., 2001. Application of fault detection, identification and accommodation methods for improved aircraft safety. In *American control conference, ACC*, 2001.
- Blanke, M., Kinnaert, M., Lunze, J. & Staroswiecki, M., 2006. *Diagnosis and fault-tolerant control*. ed. Springer, Berlin (Germany).
- Blanke, M., Staroswiecki, M. & Wu, N.E., 2001. Concepts and methods in fault-tolerant control. In *American control conference, ACC*, 2001.
- Chen, J. & Patton, R.J., 1999. *Robust model-based fault diagnosis for dynamic systems*. Kluwer Academic Publishers.
- Chizeck, H.J. & Willsky, A.S., 1978. Towards fault-tolerant optimal control. In *IEEE Conference on Decision and Control*, 1978.
- Cieslak, J., Henry, D. & Zolghadri, A., 2008. Development of an Active Fault Tolerant Flight Control Strategy. *Journal of Guidance, Control, and Dynamics*.
- Ding, S.X., 2009. Integrated Design of Control Structures and Embedded Diagnosis. Semi-Plenary Talk In *7th IFAC Symposium SAFEPROCESS Barcelona*, 2009..
- Eterno, J.S., Weiss, J.L., Looze, D.P. & Willsky, A.S., 1985. Design issues for fault tolerant-restructurable aircraft control. In *IEEE Conference on Decision and Control*, 1985.
- Hsieh, C.-S., 2002. Performance gain margins of the two-stage LQ reliable control. *Automatica*, p.1985–1990.
- Isermann, R., 2005. Model-based fault-detection and diagnosis—Status and applications. *Annual Reviews in Control*, p.71–85.
- Isermann, R., 2006. *Fault-diagnosis systems: An introduction from fault detection to fault tolerance*. Springer ed. Berlin , Germany.
- Jiang, J. & Zhao, Q., 2000. Design of reliable control systems possessing actuator redundancies. *Journal of Guidance Control and Dynamics*, 23(4), p.709–718.
- Liao, F., Wang, J.L. & Yang, G.-H., 2002. Reliable robust flight tracking control: An LMI approach. *IEEE Transactions on Control Systems Technology*, p.76–89.
- Maybeck, P.S. & Stevens, R.D., 1991. Reconfigurable flight control via multiple model adaptive control methods. *IEEE Transactions on Aerospace and Electronic Systems*, p.470–479.
- Patton, R., 1997. Fault tolerant control: the 1997 situation. In *IFAC Symposium SAFEPROCESS*, Hull, 1997.
- Patton, R.J., Frank, P.M. & Clark, R.N., 2000. *Issues of fault diagnosis for dynamic systems*. Springer ed. London, UK.
- Rauch, H.E., 1994. Intelligent fault diagnosis and control reconfiguration. *IEEE Cont. Systems Magazine*, 14(3), p.6–12.
- Staroswiecki, M. & Gehin, A.-L., 2001. From control to supervision. *Annual Reviews in Control*, p.1–11.
- Steffen, T., 2005. *Control reconfiguration of dynamic systems: Linear approaches and structural tests*. Lecture notes in control and information sciences, ed. Springer Verlag.
- Steinberg, M., 2005. Historical overview of research in reconfigurable flight control. *Journal of Aerospace Engineering*, 219, p.263–275.
- Stengel, R.F., 1991. Intelligent failure-tolerant control. *IEEE Control Systems Magazine*, p.14–23.
- Stoustrup, J., Grimble, M.J. & Niemann, H., 1997. Design of integrated systems for the control and detection of actuator and sensor faults. *Sensor Review*, p.138–149.
- Venkatasubramanian, V., Rengaswamy, R., Yin, K. & Kavuri, S.N., 2003a. A review of process fault detection and diagnosis. Part I.- Quantitative model based methods. *Computers and Chemical Engineering*, p.293–311.
- Venkatasubramanian, V., Rengaswamy, R. & Kavuri, S.N., 2003b. A review of process fault detection and diagnosis. Part II - Qualitative models and search strategies. *Computers and Chemical Engineering*, p.313–326.
- Venkatasubramanian, V., Rengaswamy, R., Kavuri, S.N. & Yin, K., 2003c. A review of process fault detection and diagnosis. Part III - Process history based methods. *Computers and Chemical Engineering*, p.327–346.
- Willsky, A.S., 1976. A survey of design methods for failure detection in dynamic systems. *Automatica*, p.601–611.
- Yang, H., Jlang, B. & Cocquenpot, V., 2010. *Fault tolerant control design for hybrid systems*. Lecture Notes in Control and Information Sciences, ed. Springer Verlag.
- Yang, Y., Yang, G.-H. & Soh, Y.C., 2001. Reliable control of discrete-time systems with actuator failure. *IEE Proceedings—Control Theory and Applications*, p.428–432.
- Zhang, Y. & Jiang, J., 2002. Design of restructurable active fault tolerant control systems. In *15th IFAC World Congress*, 2002.
- Zhang, Y. & Jiang, J., 2008. Bibliographical review on reconfigurable fault-tolerant control systems. *Annual Reviews in Control*, p.229–252.