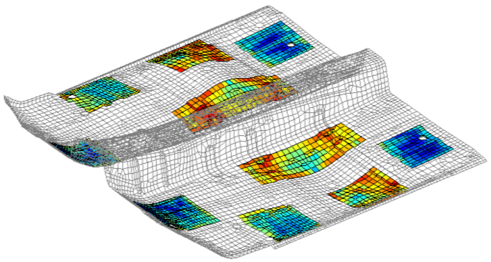
DAMAGE TOLERANT ACTIVE CONTROL:

CONCEPT AND APPLICATIONS



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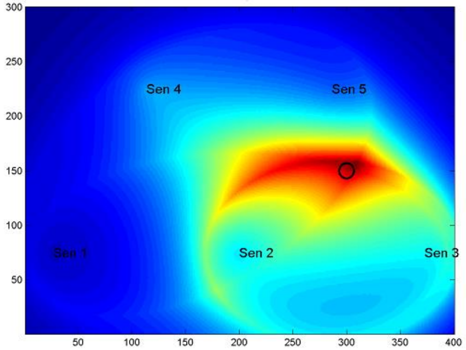
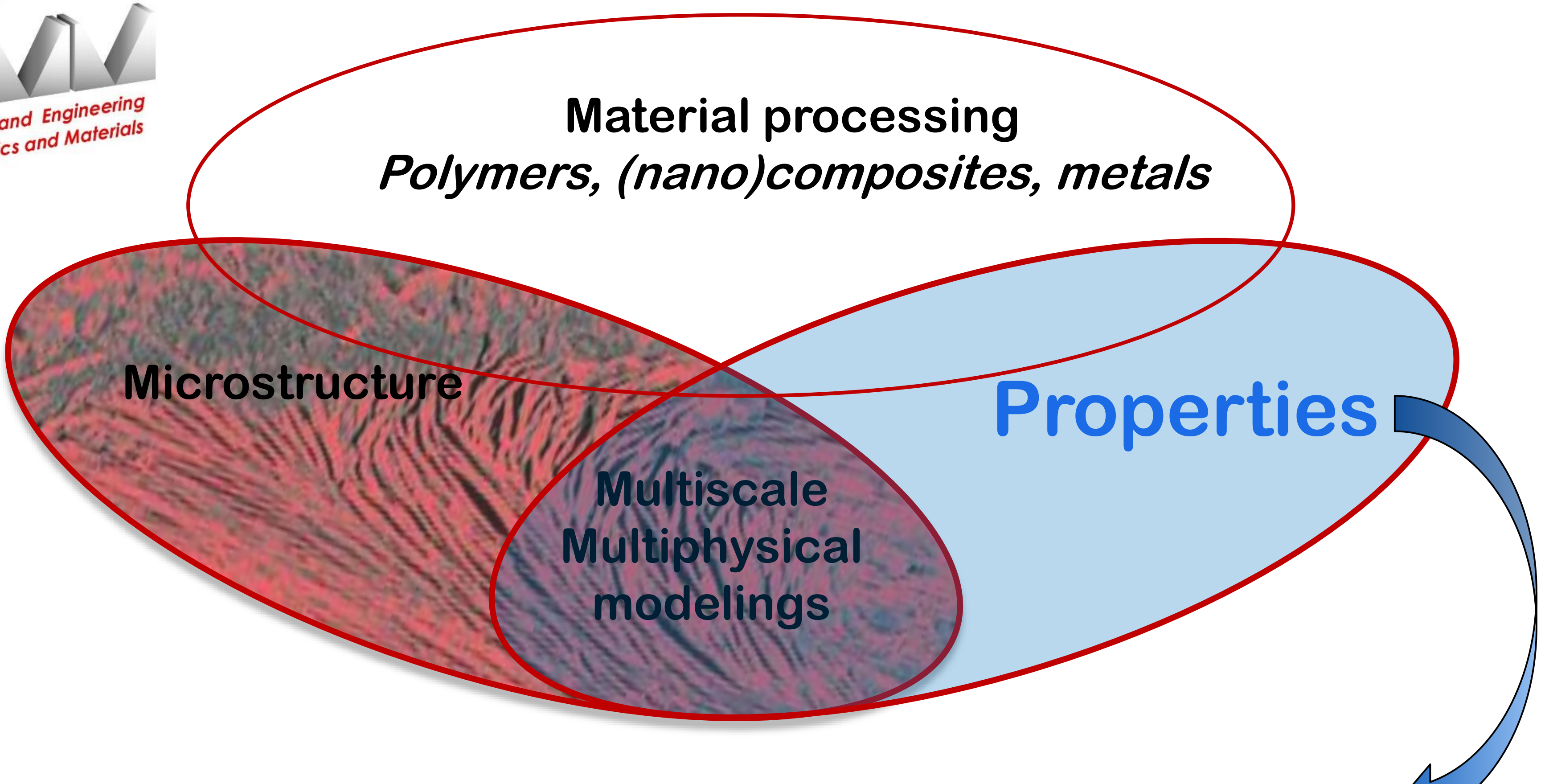


1ERE JOURNEE NATIONALE CONTROLE SANTE ET MONITORING DES STRUCTURES

15 Mars 2018



- **Mechanical,** electrical, thermal, optical, dimensional properties
- **Long-term properties**: durability of polymers, composite, gigacycle fatigue of steel

Multidisciplinary competences

From chemistry to mechanics and **control**, from experimental to numerical simulations

OUTLINE

- Introduction and Motivation
- Damage Tolerant Active Control (DTAC)
- DTAC Strategies & Examples
- Conclusion

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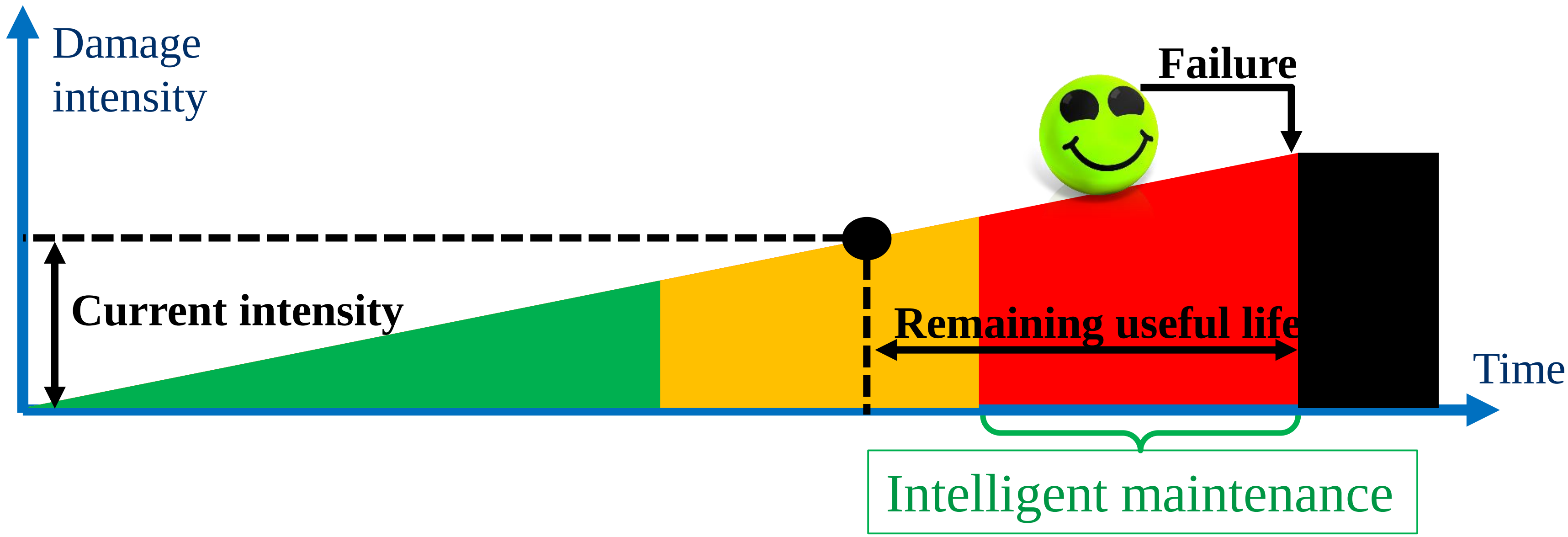
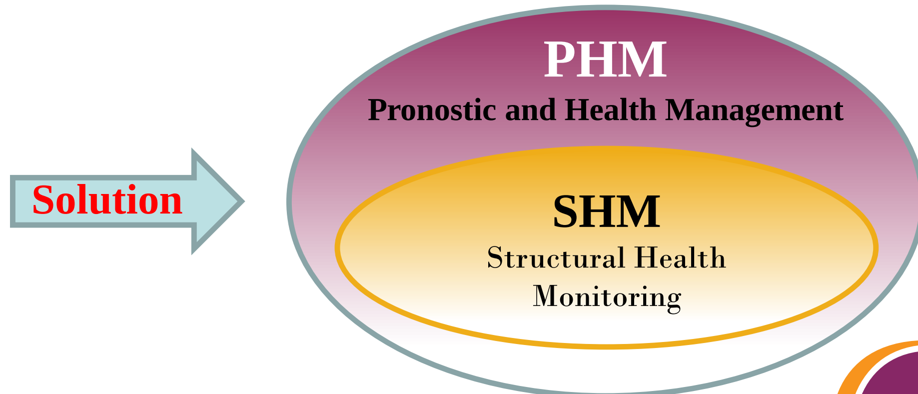
WHY DTAC ?

- **Increasing the availability: intelligent maintenance**



- **Need for a solution to:**
  - Assess the current damage intensity
  - Infer the remaining useful life (**RUL**)



Why DTAC ?

- **Vibrations …**
  - are recurring problems in means of land and air transport. …….

Cost reduction → Lightweight structures

Vibrations

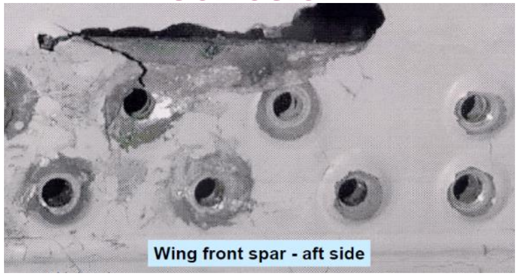
- **Damages …**

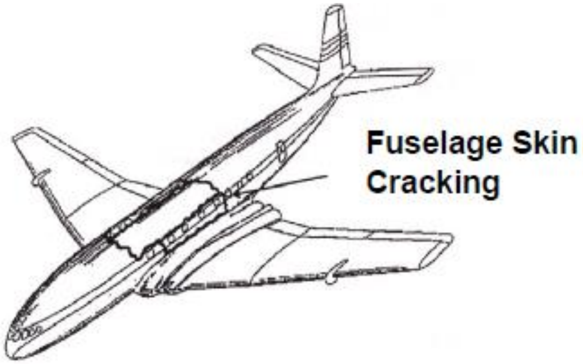
Accidental

Impacts

- **Aging and fatigue …**

Corrosion





1290 flight cycles

WHY DTAC ?

- **A question:**

Without compromising safety, could we make our structures:

- Better available?
- Lighter weight?
- More cost efficient?
- More reliable?
- More sustainable ?

DTAC

- **A response is : Smart structures …**
  - *which is the integration of sensing and possibly also actuation devices seeking to satisfy several characteristics of a biological system as sensing, actuation, adaptability and self-repair ...*
- **… with SHM (Structural Health Monitoring) ….**
  - *which is the integration of smart devices allowing the loading and damaging conditions of a structure to be recorded, analyzed, localized and predicted in a way that non-destructive testing becomes an integral part of the structure …*
- **… and Active Control capabilities**
  - *…. that will permit to reduce noises and to minimize mechanical vibrations of structures preventing from prejudicial damage provoked by excessive strain or by fatigue*

DTAC → **Damage Tolerant Active Control**
(Contrôle Actif Tolérant aux Dommages)

SOMMAIRE

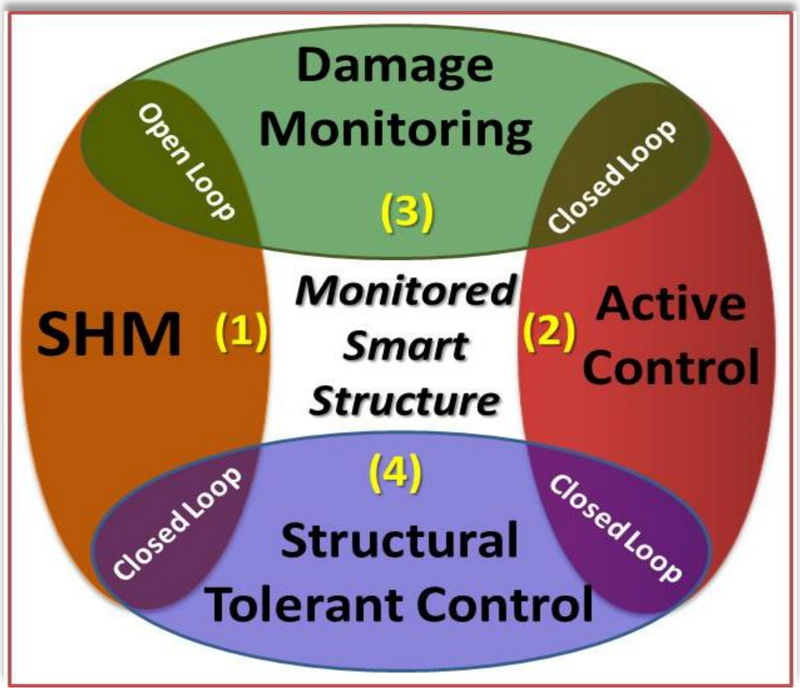
- Introduction and Motivation
- Damage Tolerant Active Control (DTAC)
- DTAC strategies: Examples
- Conclusion

DTAC

- **Damage Tolerant Active Control – DTAC**
  - A new paradigm that we have proposed (Mechbal and Nobrega, 2012) to design *fault tolerant controllers*, specifically dedicated to face **structural damages**.
  - DTAC makes use of a widely **multidisciplinary** context, which applies knowledge from different fields, such as *mechanical structures modeling*, *signal processing*, *control theory*, fracture mechanics, modal analysis and artificial intelligence, …

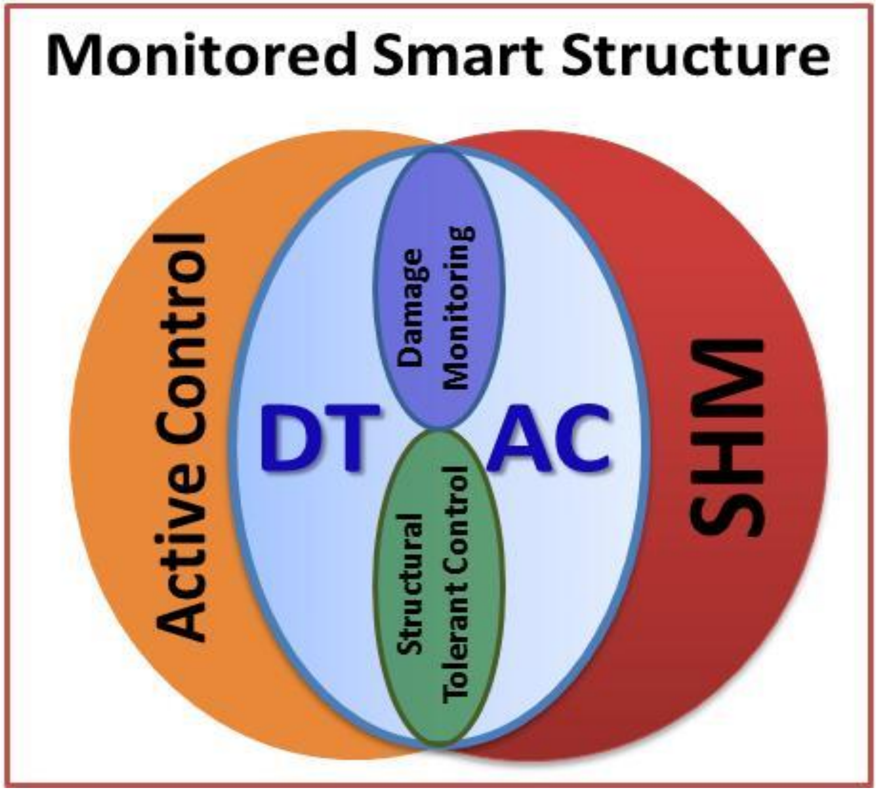
- **Four principal topics:**

1. *SHM*
2. *Active Control*
3. *Damage Monitoring*
4. *Structural Tolerant Control*



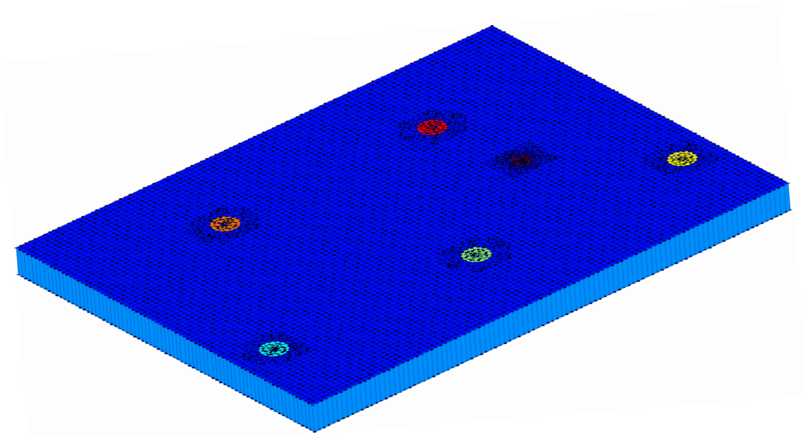
DTAC STRATEGIES

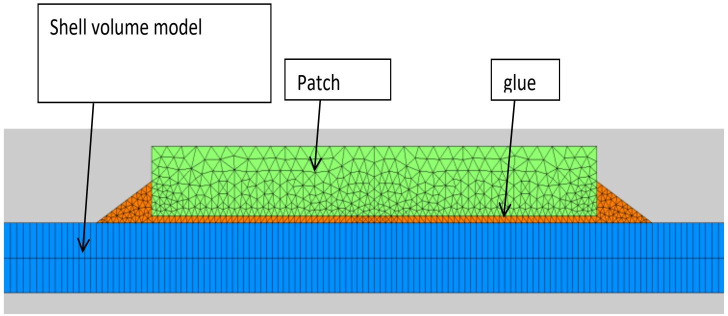
- **DTAC architectures:**
  - DTAC combines the functions of SHM and active control.
  - DTAC encompasses two main fields: damage monitoring and damage tolerant control



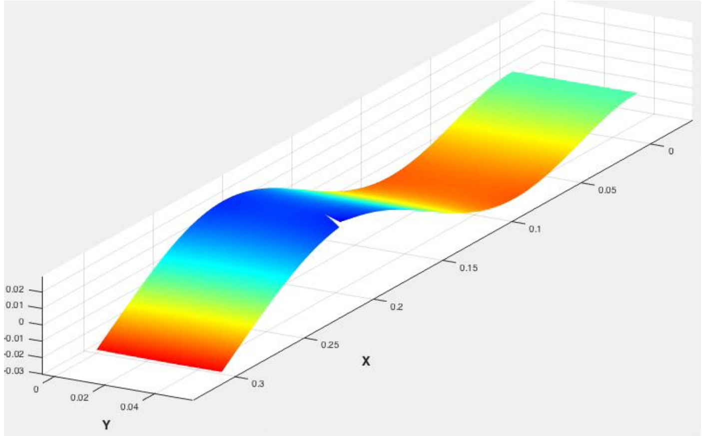
Numerical Simulations

- Smart Structures with PZT

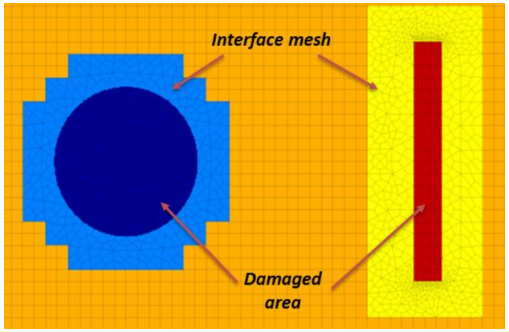


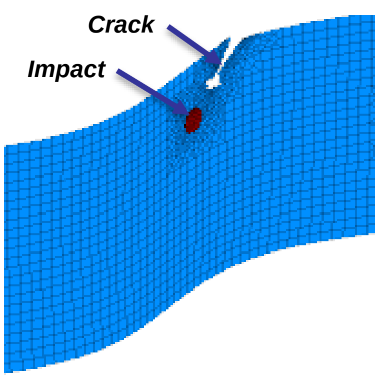


SDT software



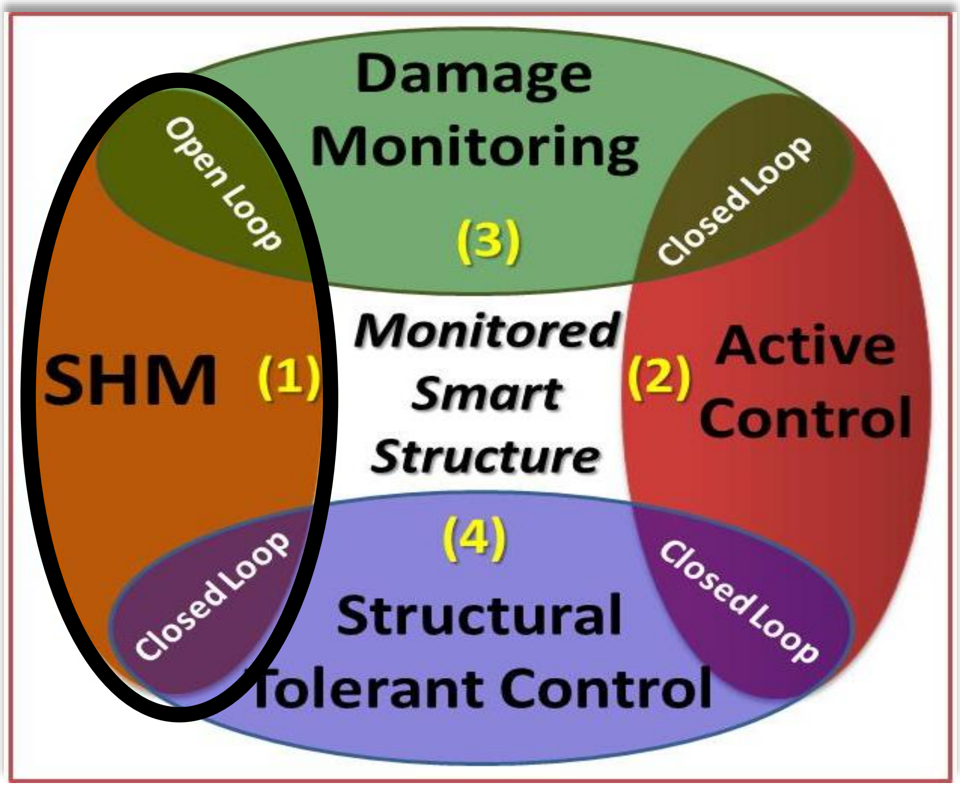
- and damages





Damage acts as a source in healthy-damaged signal

DTAC Topics - SHM



DTAC Topics - SHM

- ## SHM methods

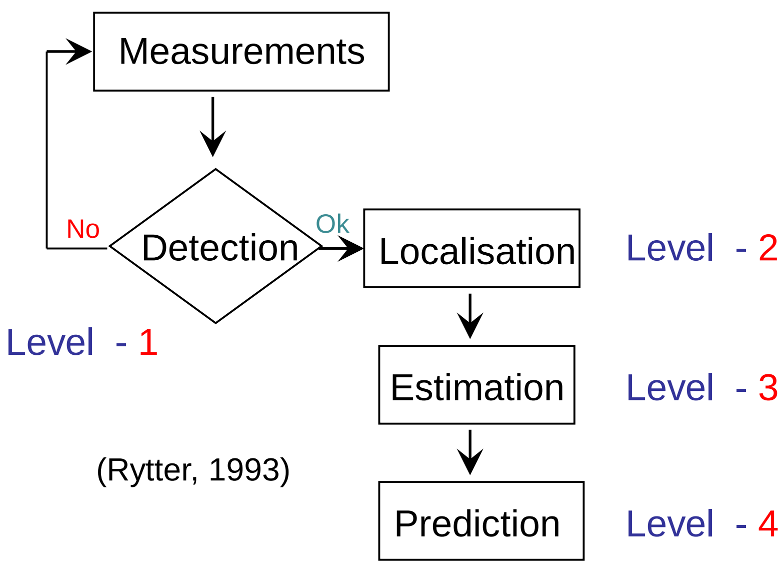
~ Passive Methods~

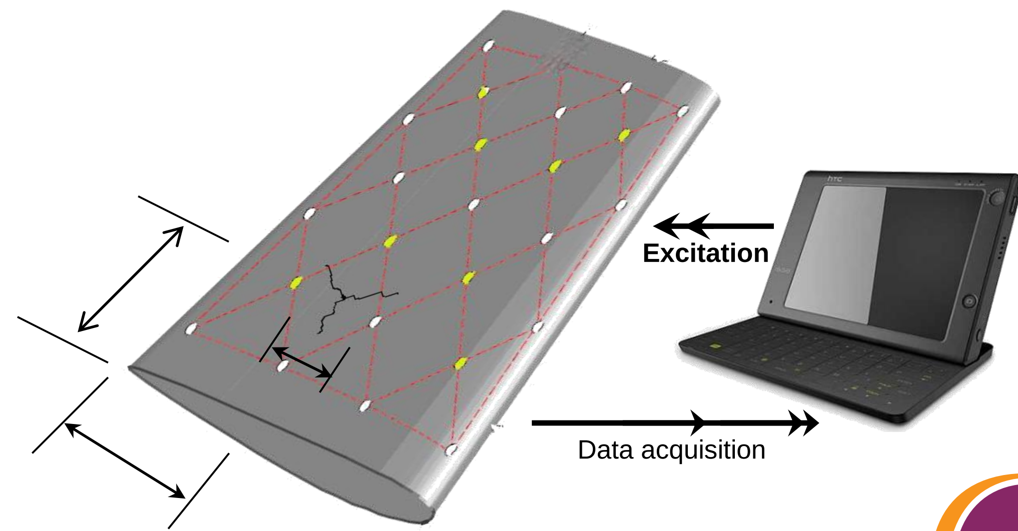
Use a large number of sensors
Ambient or damaging impacts excitations
Example: *acoustic emission in a loaded structure, output only vibration based approaches*

~ Active Methods~

Possibility to use actuators
Controlled excitations
Example: *acoustic emission emitters and detectors – Lamb waves, …*

- ## SHM sequential levels

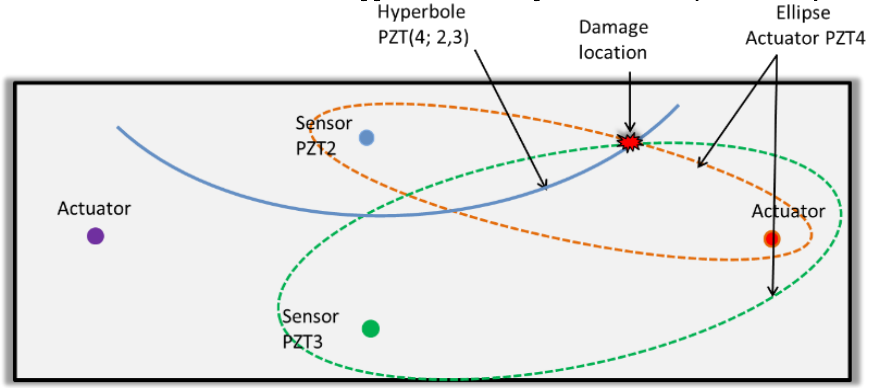




FOCUS: BAYESIAN FRAMEWORK FOR SHM

Lamb waves-based damage localization :

- *Time of flight (Tof) based principle*:
  - *Ellipse method: time of arrival (ToA) :*
  - *Hyperbola method: time difference of arrival (TDoAs)*



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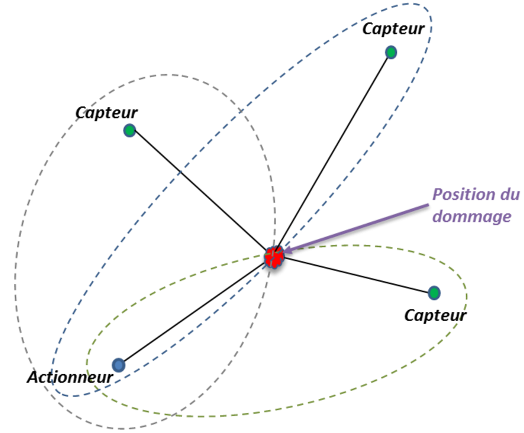
$$d_{a-D} + d_{D-C} = Vg \; ToF \; (scatt.signal)$$



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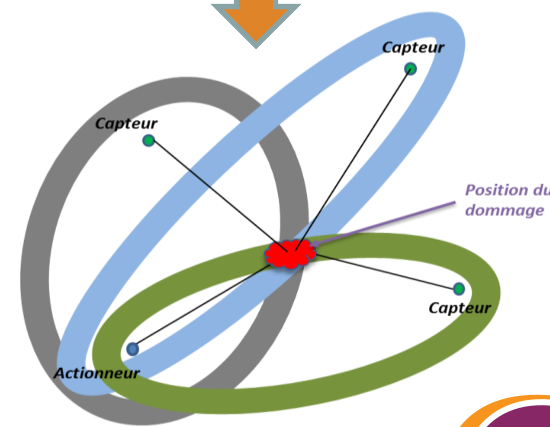

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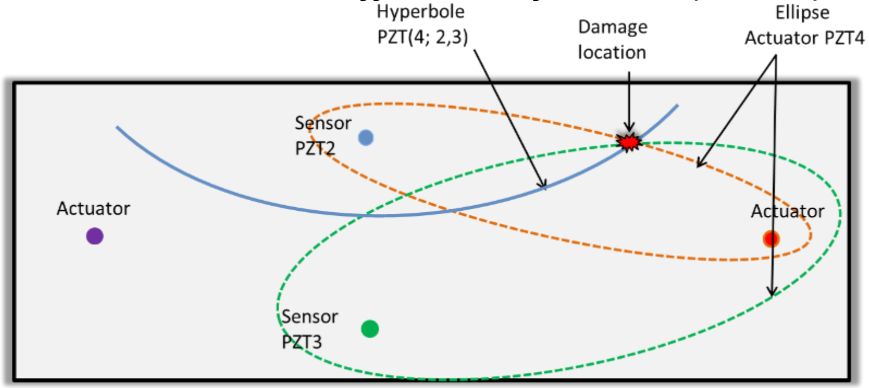

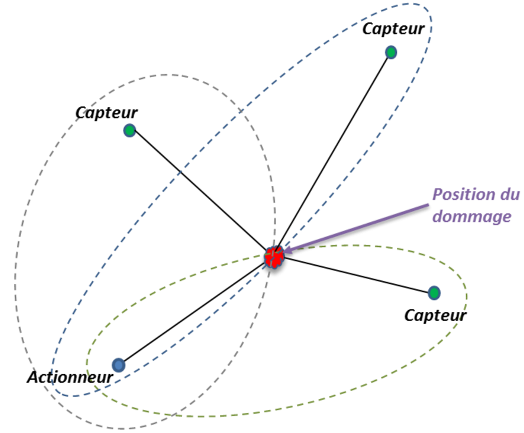

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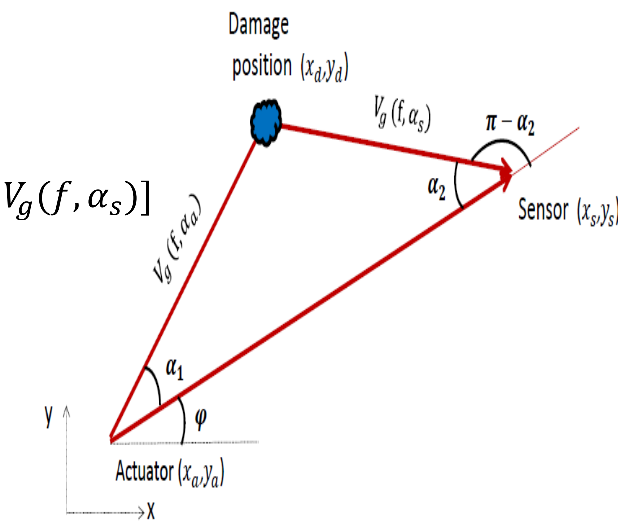


Approach: Bayesian estimation

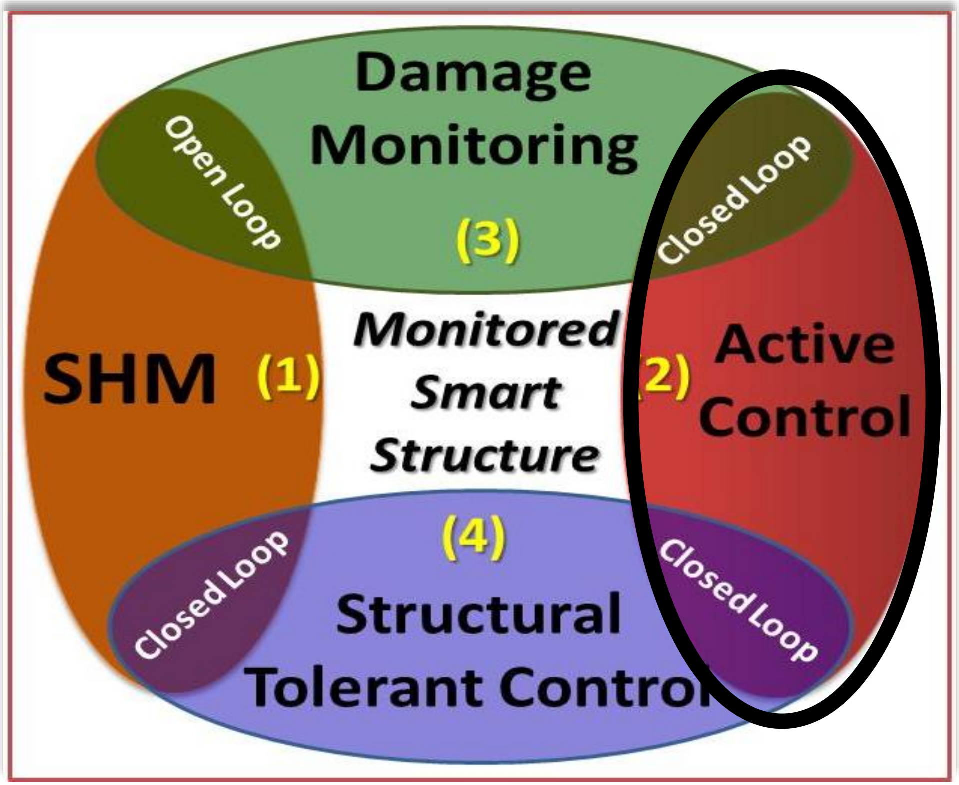
- Bayesian formulation of the Tof:

$$\boldsymbol{\theta} = [x_d, y_d, V_g(f,\alpha_a), V_g(f,\alpha_s)]$$

$$Tof_m = Tof_c(\boldsymbol{\theta}) + \varepsilon$$

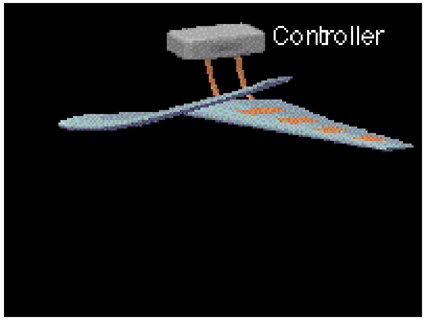
$$\varepsilon \sim \mathcal{N}(0,\sigma_\varepsilon^2) = \frac{1}{\sigma_\varepsilon\sqrt{2\pi}} \exp\left(\frac{(Tof_m - Tof_c(\boldsymbol{\theta}))^2}{2\sigma_\varepsilon^2}\right)$$

DTAC Topics - Damage monitoring



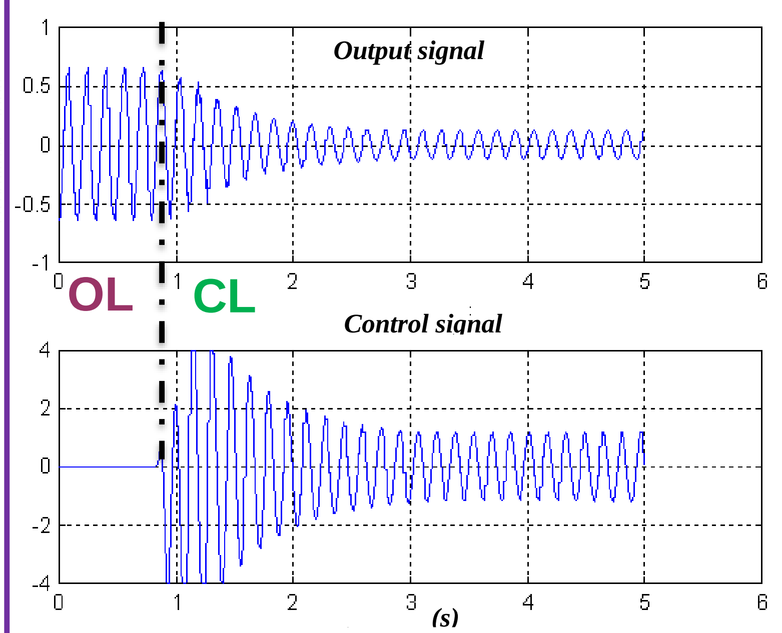
DTAC Topics - Active Control

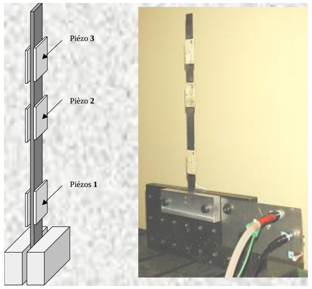
- ***Minimize mechanical vibrations* of structures preventing from prejudicial damage provoked by excessive strain or by fatigue.**
- **Control techniques: *feedback* and *feedforward***
  - Modal control avoiding spillover phenomena (Balas, 1978; Inman, 2006)
  - Conventional PID control (Sutton et al., 1999)
  - LQR (Petersen & Pota, 2003) and H_2/H_∞ (Anthonis et al., 1999),
  - Distributed controller (Bhattacharya et al., 2002);
  - Model predictive controller (Wills et al., 2008),
  - Nonlinear controller (Gaudiller et al., 2007);
  - Modal: H_∞ controller (Genari et al., 2014, 2017)
  - *A* Hybrid controller : H_∞ controller and an adaptive controller (*Vergé et al., 2001*)
  - *Modal H_∞* controller (*Genari et al., 2014, 2017*)



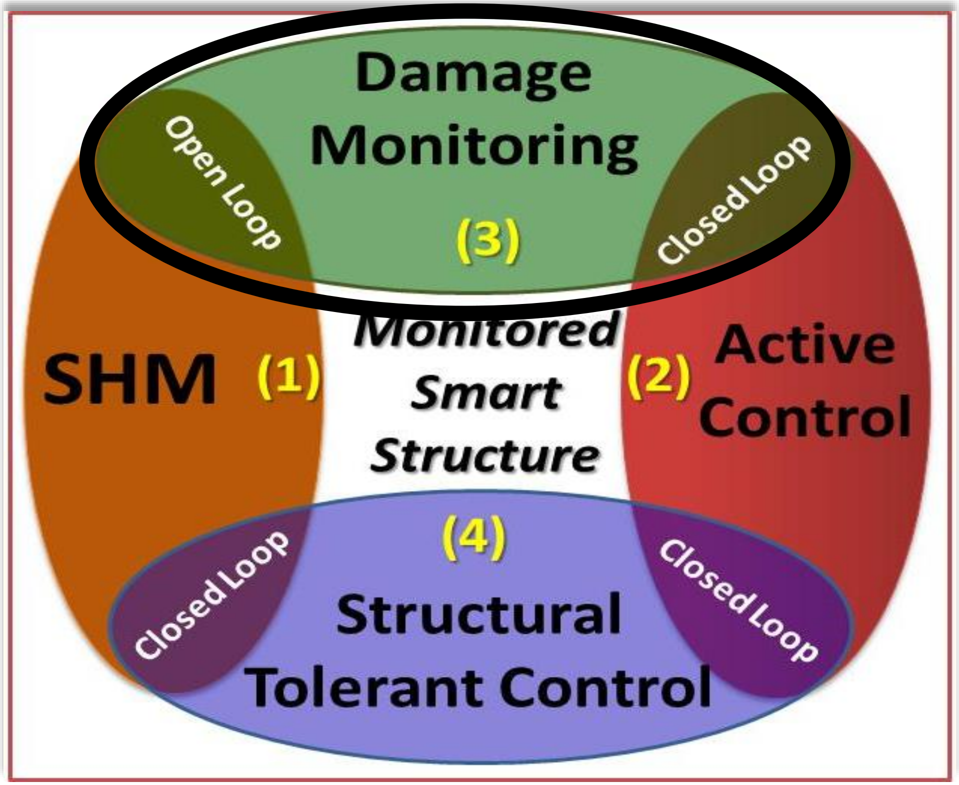
- **Robust approaches to disturbance rejection:**

Robust H_∞ approach





DTAC Topics - Damage monitoring

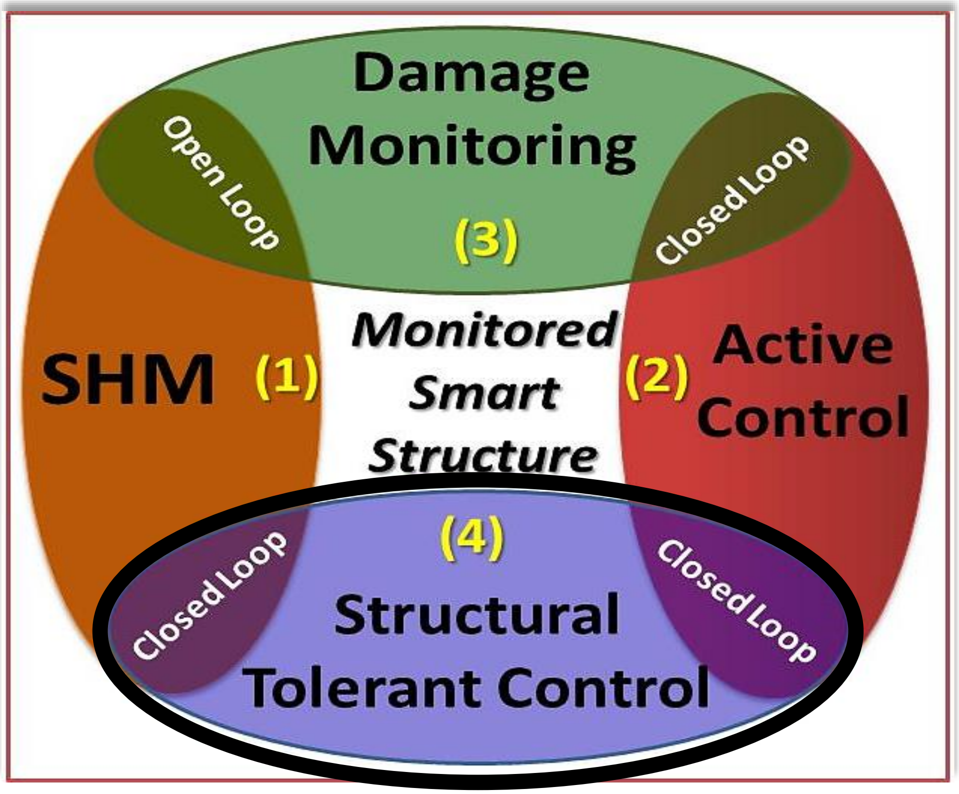


DTAC Topics - Damage monitoring

- **Damage monitoring**
  - *Monitoring of <u>already</u> 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.
  - Need to use models based on fracture mechanics, fatigue life analysis, or structural design assessment.
  - It's a <u>transversal area</u>:
    - *book on **prognosis** in SHM (Inman et al., 2005)*
    - *book on **durability** and aging of structures (Pochiraju et al., 2012).*

- ✓ **Durability of smart structures**
- ✓ **Aging Monitoring with PZT**
- ✓ **kinetics of damages.**

DTAC Topics - STC



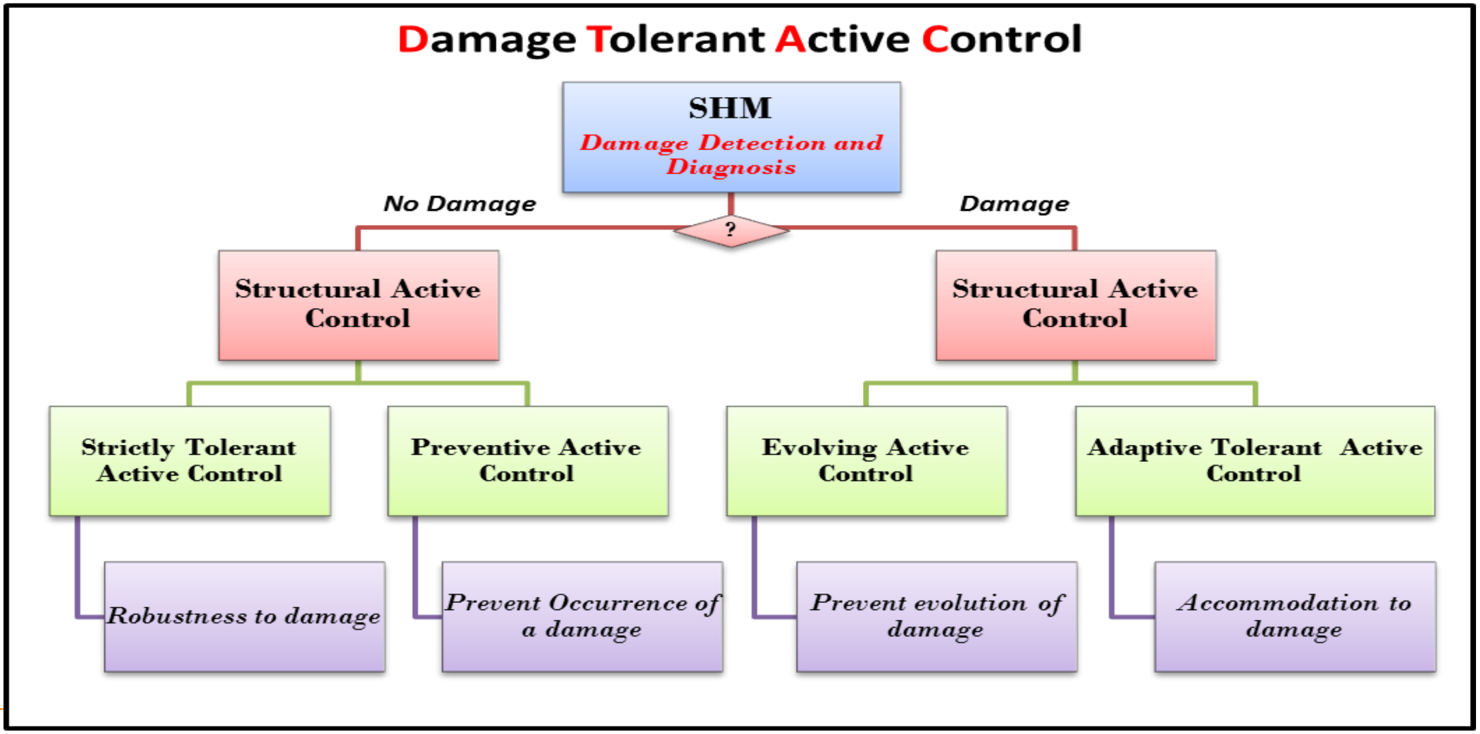
DTAC Topics - STC

- **Structural tolerant control (STC)**
  - *Deals with the **vibration suppression** control **problem** against potential damage.*
  - *Provides satisfactory performances in terms of vibration rejection under the **possible presence** of damages*
  - Simultaneously achieve high performance and structural durability.
  - **Approaches:** *robust control and reconfigurable control* (similar to FTC).
  - STC could also be used to monitor or to detain the evolving of damage
  - **However, this subject has seldom been discussed and in the literature, only few works are referred to it (sometimes unwittingly):**
    - The first addressed STC problem: Ahmad et al. (2000) - μ synthesis and H_∞ controllers
    - Caplin et al. (2001): simultaneously achieve high performance and structural durability.
    - **More recently**, a damage tolerant LQG modal controller has been applied to a printed circuit board (PCB) with PZT by (Chomette et al., 2008, 2010).

DTAC STRATEGIES

- **DTAC strategies:**
  - Depending on **the objectives and how "smart"** is the structure (number, position and type of sensors and actuators), we proposed different ways to perform DTAC:

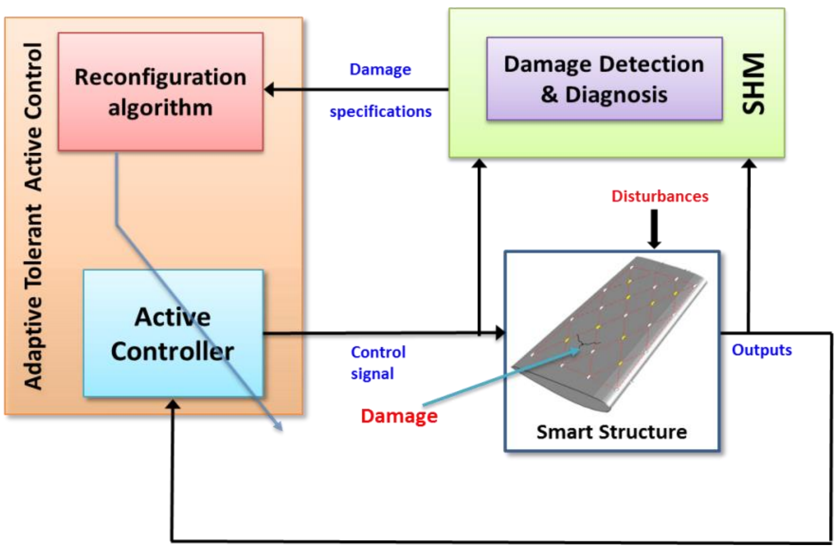
1. *Strictly Tolerant Active Controller* - ***STAC***
2. *Preventive Active Controller* - ***PAC***
3. *Evolving Active Controller* - ***EAC***
4. *Adaptive Tolerant Active Control* - ***ATAC***

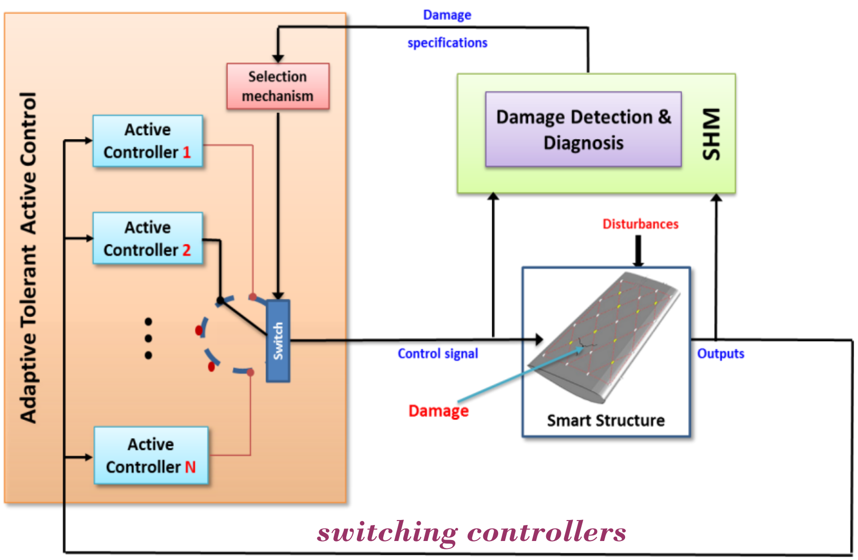


DTAC STRATEGIES

- **Strictly Tolerant Active Controller (STAC)**
  - **Fixed** and **robust** enough to guarantee a minimal acceptable performance to some future damage level.
  - *The compromise between robustness and performance may conduct to a **poor** controller behavior for **a not damaged** structure*
- **Preventive Active Controller (PAC)**
  - **Avoid** or delay **the occurrence** of damages
  - This is the aim of *several recent works*. (Chomette et al., 2010).
- **Evolving Active Controller (EAC)**
  - **Protect** the structure avoiding the evolution of the damage.
  - Achieve vibration reduction and perform damage prognosis
- **Adaptive Tolerant Active Control (ATAC)**
  - **Accommodate** a detected damage.
  - Include an **SHM module**
  - Different system configurations are possible:

DTAC STRATEGIES





- **Adaptive Tolerant Active Control (ATAC)**
  - **Accommodate** a detected damage.
  - Include an **SHM module**
  - Different system configurations are possible:

DTAC – Issues and Problems

- **The goals:**
  - To control the vibration in predefined **regions** of the structure,
  - To perform **self diagnosis** and to accommodate for damages
  - To adapt automatically the **control spatially** when a damage occurs
  - To pay attention to the number of active elements

- **Problems:**
  - The **spatial dimension**

    → *what's about vibration reduction over the entire structure* ?
  - The curse of dimensionality ! → Model **reduction** problems
  - The interaction between the **SHM** and the control systems is not straightforward

    → **Stability** issues
  - It's a ***Singular Perturbation*** control problem – two dynamics !
  - **Numerical** simulations and experimentations

DTAC – APPROACHES

- **To deal with such problems:**
  - Robust control
  - Adaptive control
  - Distributed and decentralized approach
  - FTC methods

- **Two approaches:**
  - Adaptive Modal H_∞ control & Subspace metric for damage monitoring (Genari, et al., 2015, 2017)
  - Spatial H_2/H_∞ control (Mechbal and Nobrega, 2014, 2015)

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Focus: Modal H_∞ controller - STAC

Modal H_∞ Control Problem

- According to the optimal controller design framework, a performance indicator is introduced as an output vector $\mathbf{z}(t)$, leading to the following state-space equations:

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}_1\mathbf{w}(t) + \mathbf{B}_2\mathbf{u}(t)\\ \mathbf{z}(t) &= \mathbf{C}_1\mathbf{x}(t) + \mathbf{D}_{11}\mathbf{w}(t) + \mathbf{D}_{12}\mathbf{u}(t)\\ \mathbf{y}(t) &= \mathbf{C}_2\mathbf{x}(t) + \mathbf{D}_{21}\mathbf{w}(t) + \mathbf{D}_{22}\mathbf{u}(t),\end{aligned} \tag{4}$$

  in which the matrices $\mathbf{C}_1$, $\mathbf{D}_{11}$, and $\mathbf{D}_{12}$ are chosen to define the desired performance vector.

- The H_∞ **control problem** is to find a controller $\mathbf{K_c}$ to the plant given by Eq. (4), if there is one, stated as:

$$\begin{aligned}\dot{\mathbf{x}}_c(t) &= \mathbf{A}_c\mathbf{x}_c(t) + \mathbf{B}_c\mathbf{y}(t)\\ \mathbf{u}(t) &= \mathbf{C}_c\mathbf{x}_c(t) + \mathbf{D}_c\mathbf{y}(t),\end{aligned} \tag{5}$$

  such that, for the closed-loop system and given a $\gamma > 0$,

$$\underbrace{\inf}_{\mathbf{K_c}\in V}\ \underbrace{\sup}_{\mathbf{w}\neq 0,\ \mathbf{w}\in\mathcal{L}_{2[0,\infty)}} \frac{\int_0^\infty \mathbf{z}^T(t)\mathbf{z}(t)dt}{\int_0^\infty \mathbf{w}^T(t)\mathbf{w}(t)dt} < \gamma^2,$$

  in which V represents the set of all controllers that stabilises the plant.

Modal H_∞ Control problem

Theorem (Modal H_∞ theorem)

Consider the H_∞ problem of designing a controller $\mathbf{K_c}$ given in Eq. (5) for a structure according to Eq. (4) with the modal state matrix according to Eq. (2) and the following performance output:

$$\mathbf{z_p}(t) = \Gamma\mathbf{x}(t) + \Theta\mathbf{w}(t) + \Lambda\mathbf{u}(t), \quad (6)$$

with

$$\Gamma = \begin{bmatrix} \mathbf{Q}_1^{\frac{1}{2}}\mathbf{C}_{1_1} & \mathbf{Q}_2^{\frac{1}{2}}\mathbf{C}_{1_2} & \cdots & \mathbf{Q}_m^{\frac{1}{2}}\mathbf{C}_{1_m} \end{bmatrix}, \Theta = (\mathbf{Q}_1^{\frac{1}{2}}\mathbf{D}_{11_1} + \cdots + \mathbf{Q}_m^{\frac{1}{2}}\mathbf{D}_{11_m}),$$

$$\Lambda = (\mathbf{Q}_1^{\frac{1}{2}}\mathbf{D}_{12_1} + \cdots + \mathbf{Q}_m^{\frac{1}{2}}\mathbf{D}_{12_m}),$$

where the diagonal matrix $\mathbf{Q}_i > 0$ weights mode i and $\mathbf{C}_{1_i}$, $\mathbf{D}_{11_i}$, and $\mathbf{D}_{12_i}$ correspond to the respective mode i submatrices in $\mathbf{C}_1$, $\mathbf{D}_{11}$, and $\mathbf{D}_{12}$.
Then, given a scalar $\gamma > 0$, a controller that solves the respective H_∞ problem:

$$\|\mathbf{T_{z_pw}}(s)\|_\infty < \gamma,$$

also guarantees that:

$$\|\mathbf{T_{zw}}(s)\|_{\infty,\mathbf{Q}} < \gamma,$$

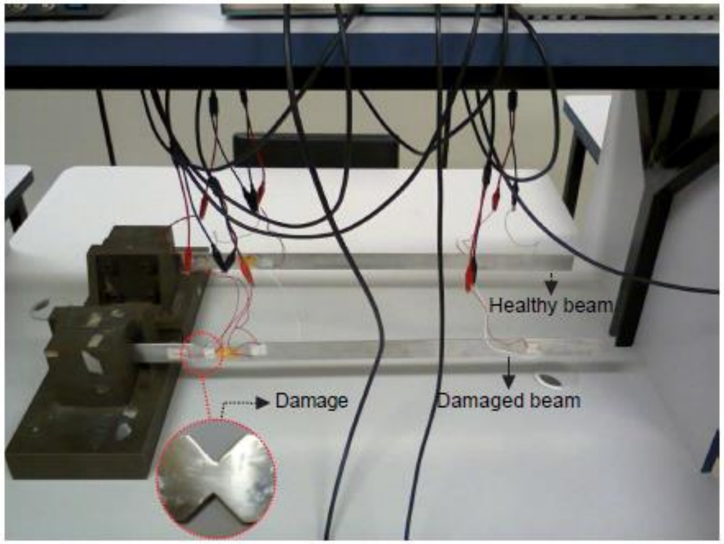
where $\mathbf{T_{z_pw}}(s)$ and $\mathbf{T_{zw}}(s)$ are the closed-loop transfer matrices using $\mathbf{K_c}$ for the modal performance vectors.

Focus: Modal H_∞ controller - STAC

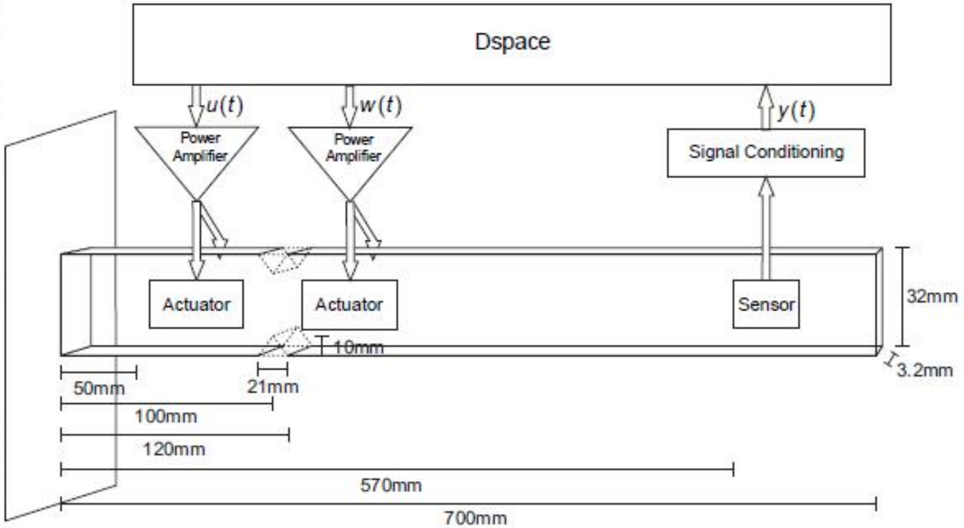
Experiment results

Objectives:

- Test the methodology for the **regular active vibration control**;
- Test the methodology for DTAC using the **STAC strategy**;



(a) Aluminium beams.

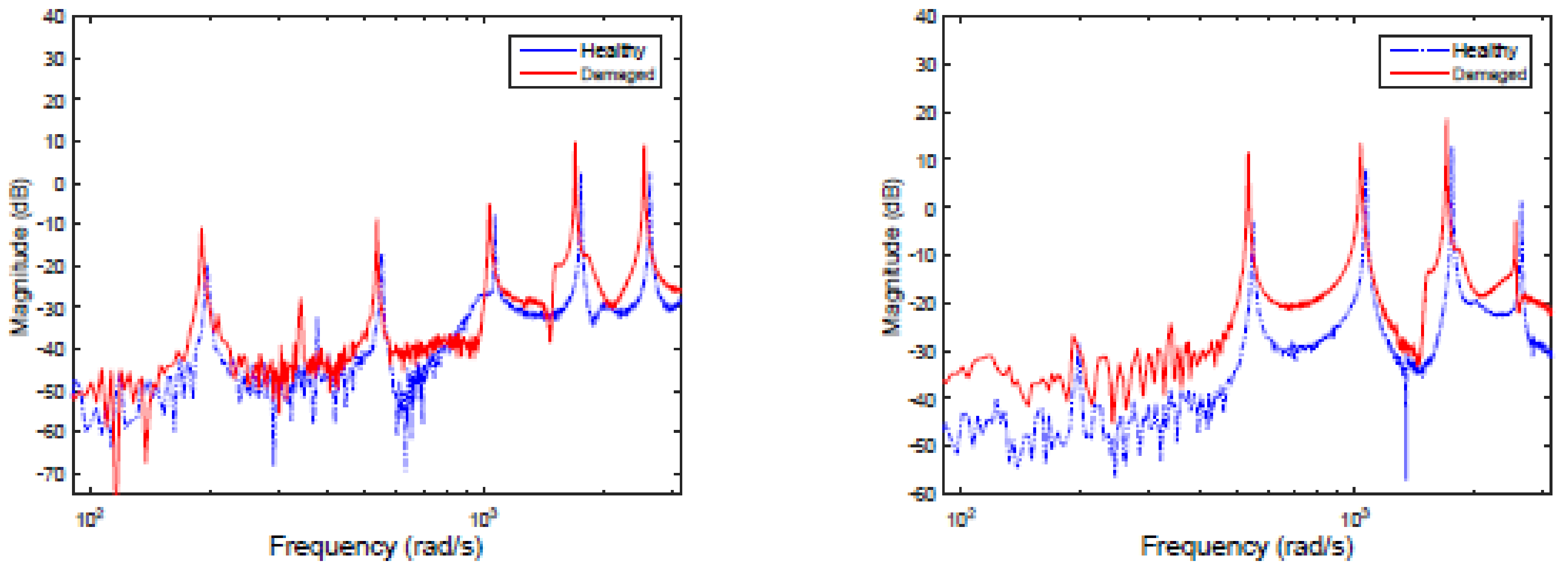


(b) Block diagram.

Focus: Modal H_∞ controller - STAC

Experiment results

- Application of the controller for the **healthy** and **damaged structure**;
- Frequency response comparison between the healthy and the damaged structures:

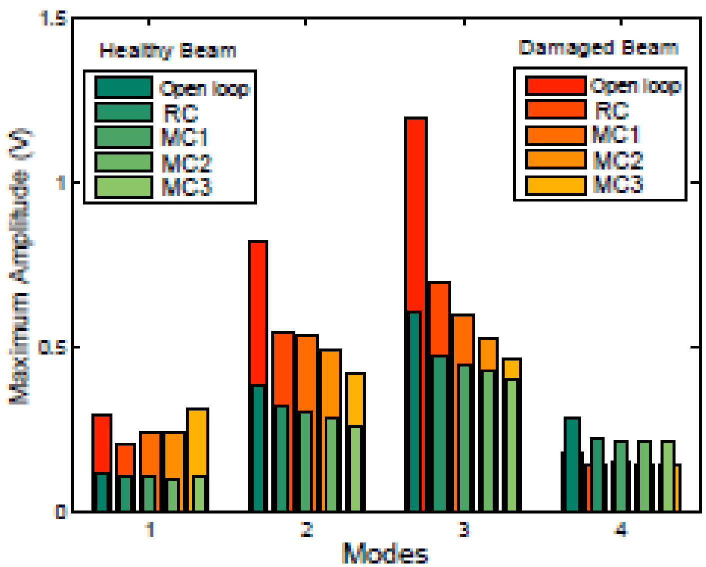


(a) P_{yu}. (b) P_{yw}.

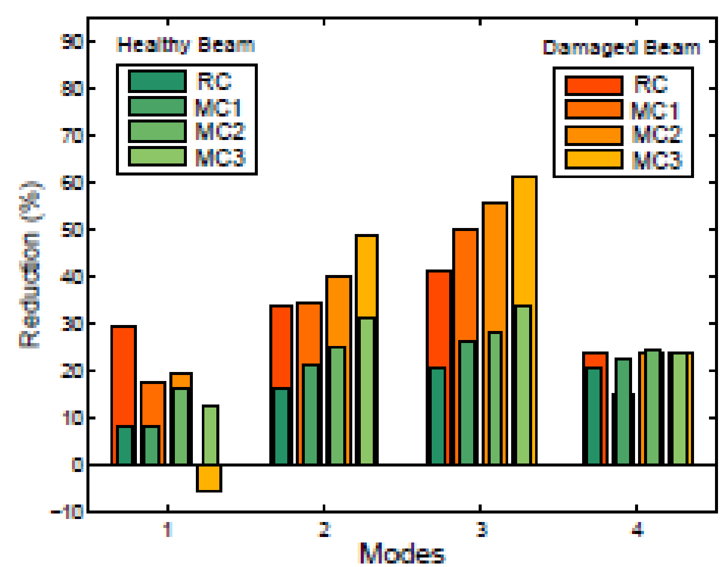
FOCUS: MODAL H_∞ CONTROLLER - STAC

Experiment results

- Application of the controller for the **healthy** and **damaged structure**;
- The **weighing** increase leads to **vibration reduction** for the healthy and the damaged structures;



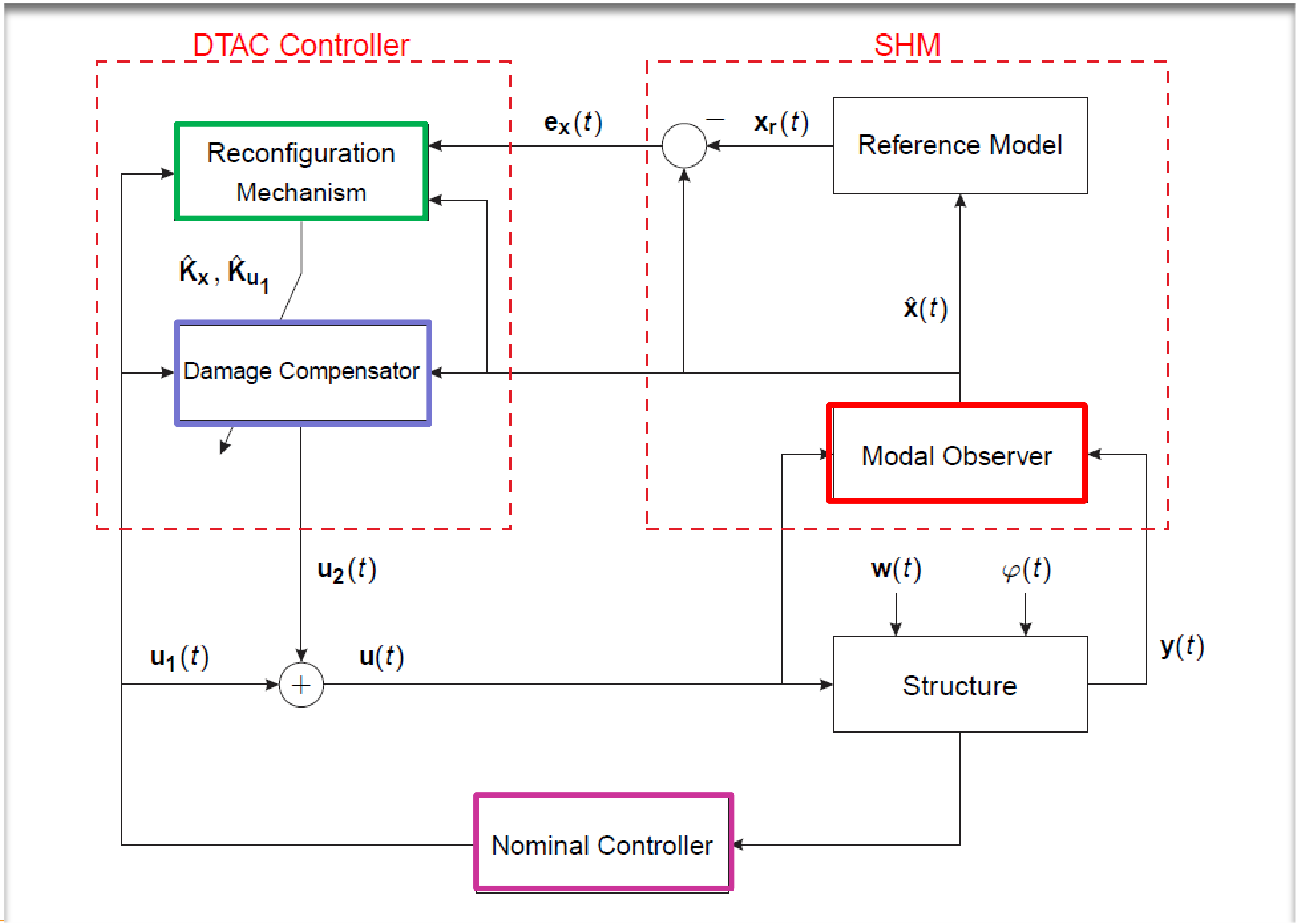
(a) Peak vibration of each mode.



(b) Percentage reduction.

Focus: Modal double-loop - PAC

- **Modal Double-Loop Framework**



Focus: Modal double-loop - PAC

- **Reconfiguration mechanism**

Theorem

The state-tracking error dynamics given in Eq. (10) are stable for the following adaptive gain laws:

$$\dot{\hat{\mathbf{K}}}_{\mathbf{x}}(t) = -\mathbf{T}_{\mathbf{x}}\hat{\mathbf{x}}(t)\mathbf{e}_{\mathbf{x}}^{T}(t)\mathbf{P}\mathbf{B}_{2}, \quad (12)$$

$$\dot{\hat{\mathbf{K}}}_{\mathbf{u}_1}(t) = -\mathbf{T}_{\mathbf{u}_1}\mathbf{u}_1(t)\mathbf{e}_{\mathbf{x}}^{T}(t)\mathbf{P}\mathbf{B}_{2}, \quad (13)$$

in which for $\mathbf{R} = \mathbf{R}^T > 0$, $\mathbf{P} = \mathbf{P}^T > 0$ *satisfies the following algebraic Lyapunov equation:*

$$\mathbf{P}\mathbf{A}_{\mathbf{r}} + \mathbf{A}_{\mathbf{r}}^{T}\mathbf{P} = -\mathbf{R}. \quad (14)$$

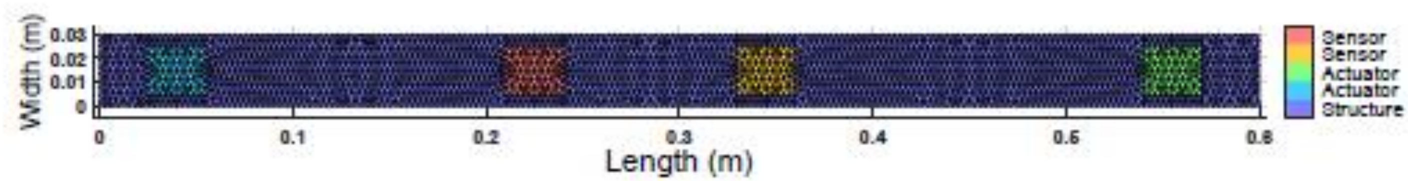
Moreover, $\mathbf{T}_{\mathbf{x}} > 0$ *and* $\mathbf{T}_{\mathbf{u}_1} > 0$ *are diagonal matrices that determine adaptation rates. Matrix* $\mathbf{T}_{\mathbf{x}}$ *is a function of the modal adaptation-rate submatrices:*

$$\mathbf{T}_{\mathbf{x}} = \begin{bmatrix} \mathbf{T}_1 & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{T}_2 & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{T}_m \end{bmatrix}, \quad (15)$$

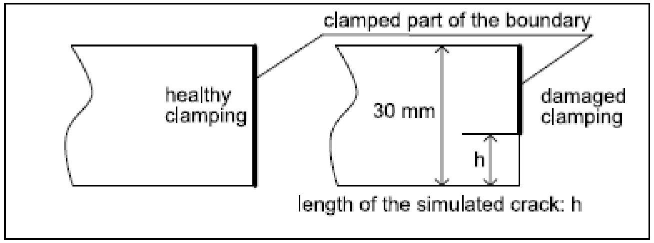
where the 2×2 *matrix* $\mathbf{T}_i$ *determines the adaptation rate of mode* i.

FOCUS: MODAL DOUBLE-LOOP - PAC

- **FE Simulations:**



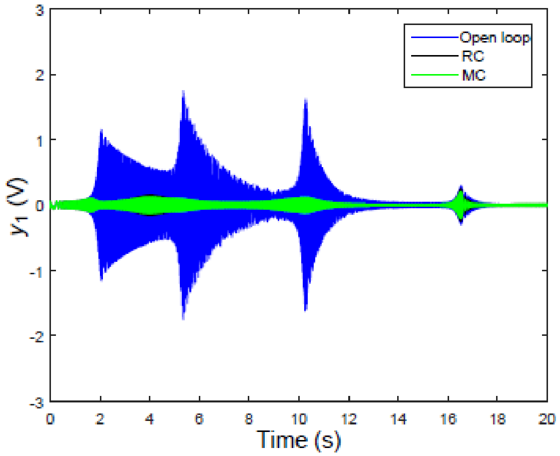
- Damage 2: $h = 15$ mm;
- Damage 3: $h = 20$ mm.

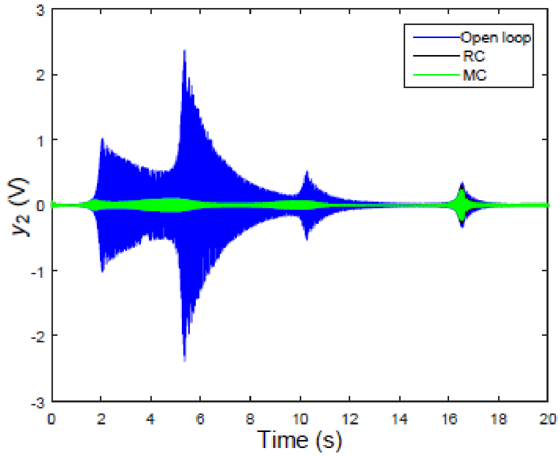


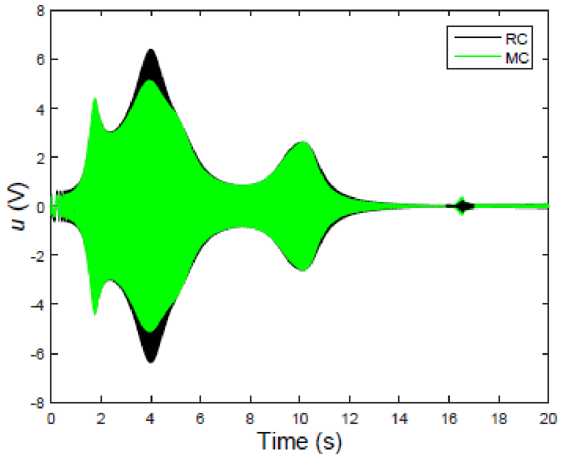
- The **chirp** signal of the previous examples is used as **disturbance**, considering **three cycles** of **12 repetitions**;

- **For each cycle**, there is **one condition** of the structure: healthy or damage 2, or damage 3;

- **Results: Healthy structure**

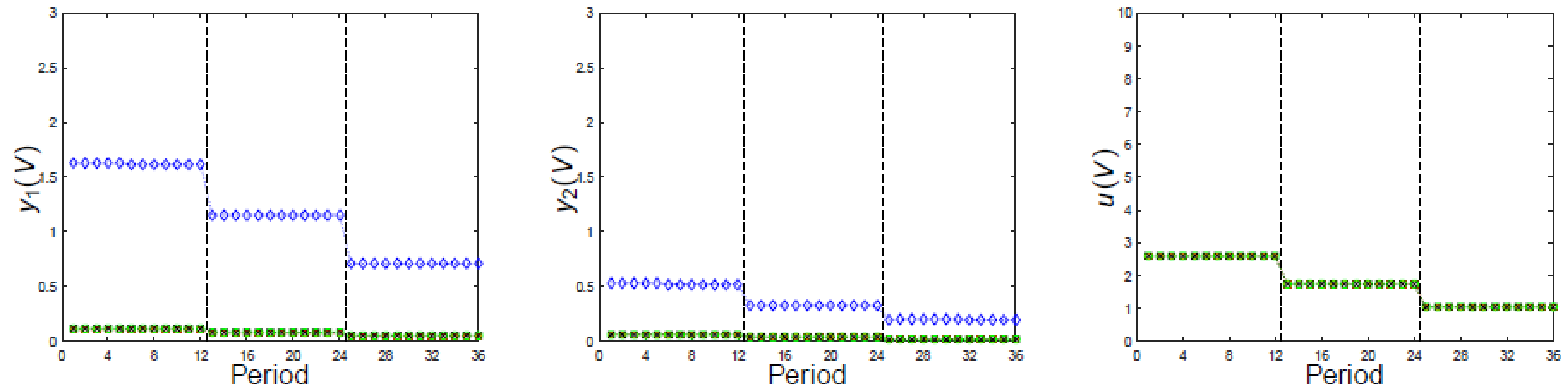




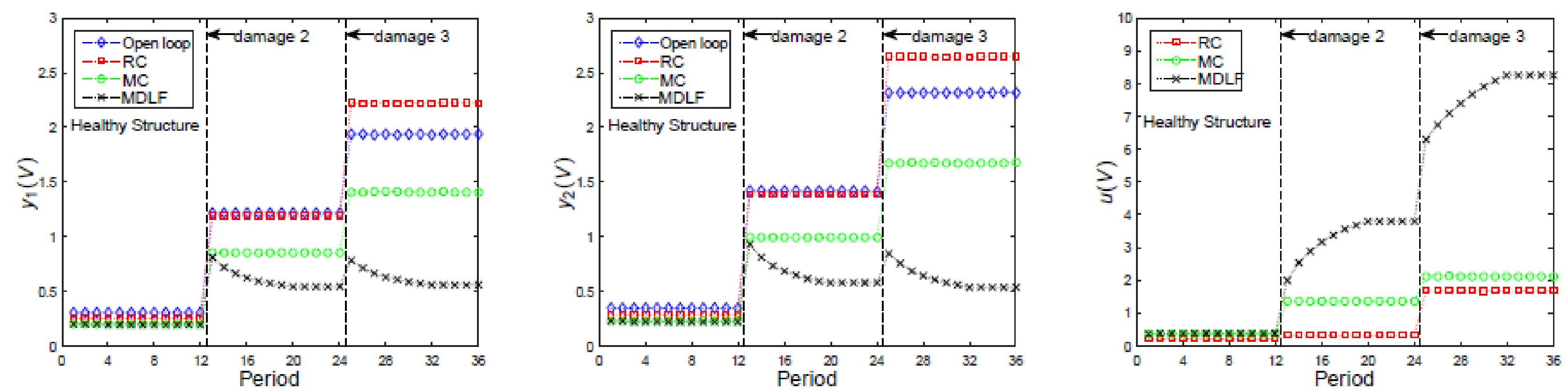


Focus: Modal double-loop - PAC

- **Results: Damage Controller**



(a) Mode 3.

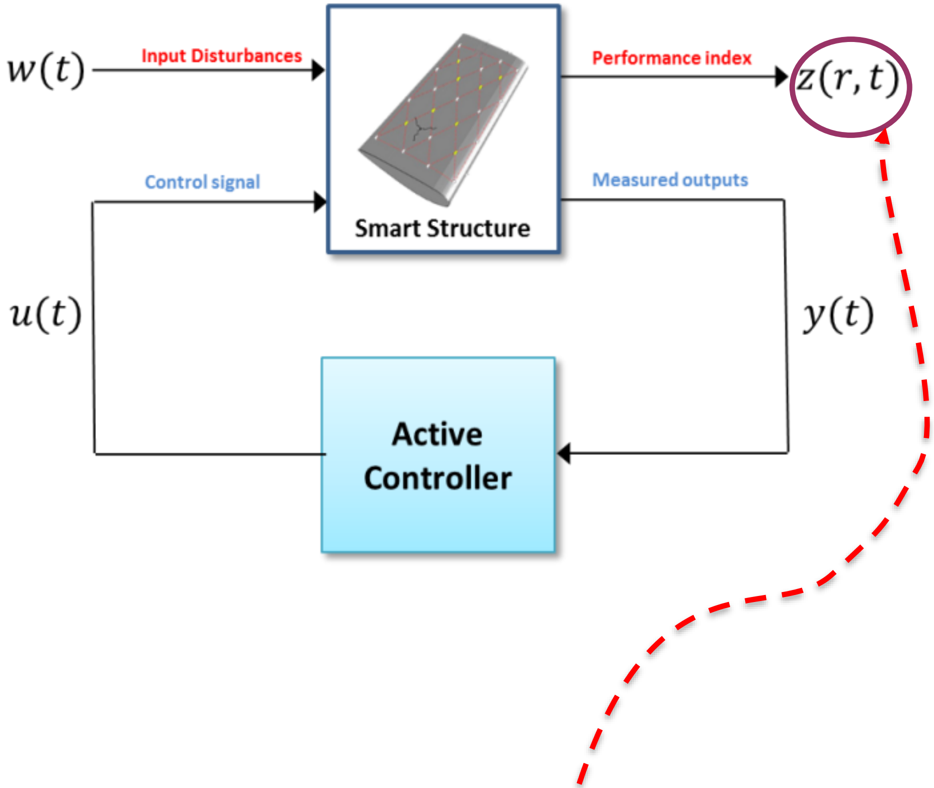


(b) Mode 4.

FOCUS: A SPATIAL H_∞ CONTROL APPROACH

- **H_∞ controller**
  - Time dependence formulation:

$$\dot{x}_p(t) = A_p x_p(t) + B_w w(t) + B_u u(t)$$
$$z(t) = C_z x_p(t) + D_{zw} w(t) + D_{zu} u(t)$$
$$y(t) = C_y x_p(t) + D_{yw} w(t)$$



  - Controller K,

$$\dot{x}_k(t) = A_k x_k(t) + B_k y(t)$$
$$u(t) = C_k x_k(t) + D_k y(t)$$

  - Criterion

$$\underbrace{sup}_{w \in L_{2[0,\infty)}} \; J_\infty < \gamma^2$$

$$\|G(s)\|_\infty = sup_\omega \sigma_{max}(G(j\omega))$$

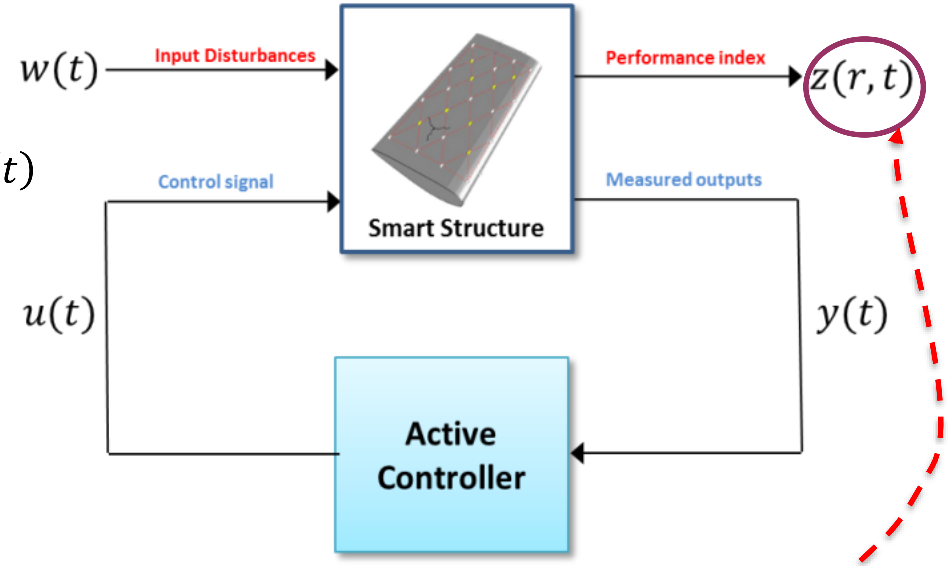
$$J_\infty = \frac{\|z(t)\|_2^2}{\|w(t)\|_2^2} = \frac{\int_0^\infty z(t)^T z(t)dt}{\int_0^\infty w(t)^T w(t)dt}$$

Problem: *How to conveniently incorporate the spatial information of the of structure ?*

Focus: A Spatial H_∞ Control approach

- **H_∞ controller**
  - Time dependence formulation:

$$\begin{cases} \dot{x}_p(t) = A_p x_p(t) + B_w w(t) + B_u u(t) \\ z(t,\mathbf{r}) = C_z(\mathbf{r}) x_p(t) + D_{zw}(\mathbf{r}) w(t) + D_{zu}(\mathbf{r}) u(t) \\ y(t) = C_y x_p(t) + D_{yw} w(t) \end{cases}$$



  - Controller K,

$$\dot{x}_k(t) = A_k x_k(t) + B_k y(t)$$
$$u(t) = C_k x_k(t) + D_k y(t)$$

  - Criterion

$$\underbrace{sup}_{w \in L_{2[0,\infty)}} \quad J_\infty < \gamma^2$$

$$\|G(s)\|_\infty = sup_\omega \sigma_{max}(G(j\omega))$$

$$J_\infty = \frac{\|z(t)\|_2^2}{\|w(t)\|_2^2} = \frac{\int_0^\infty z(t)^T z(t) dt}{\int_0^\infty w(t)^T w(t) dt}$$

Problem: *How to conveniently incorporate the spatial information of the of structure ?*

FOCUS: A SPATIAL H_∞ CONTROL APPROACH

- **Spatial H_∞ controller:**
  - Use spatial norms:

$$\ll G(s,r) \gg_\infty^2 = \sup \lambda_{max}\left(\int_\Omega G^*(jw,r)G(jw,r)dr\right)$$

  - which guarantees average reduction of vibration throughout the entire structure
  - **For specific region Ω** where we want to minimize the H_∞ spatial norm, a space dependent weighing matrix $\boldsymbol{Q(r)}$, where $\boldsymbol{r}$ is the spatial vector, is introduced:

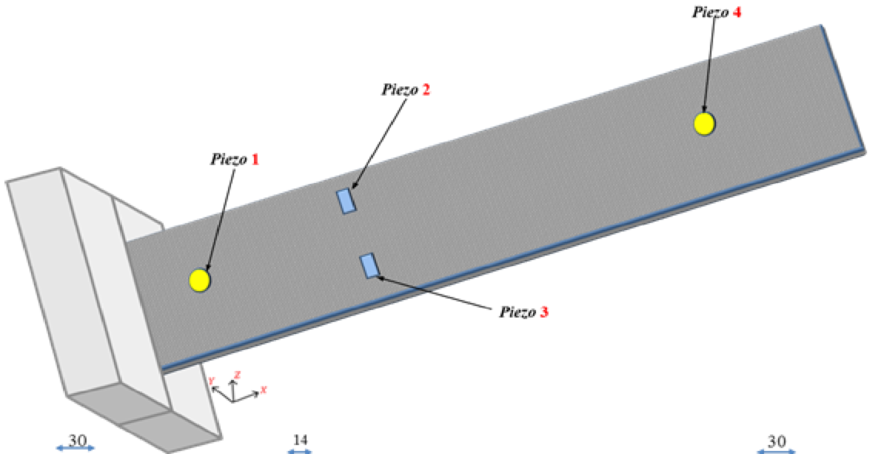
$$J_\infty = \frac{\int_0^\infty \int_\Omega z(t,r)^T \boldsymbol{Q}(\boldsymbol{r}) z(t,r)dr\,dt}{\int_0^\infty w(t)^T w(t)dt}$$

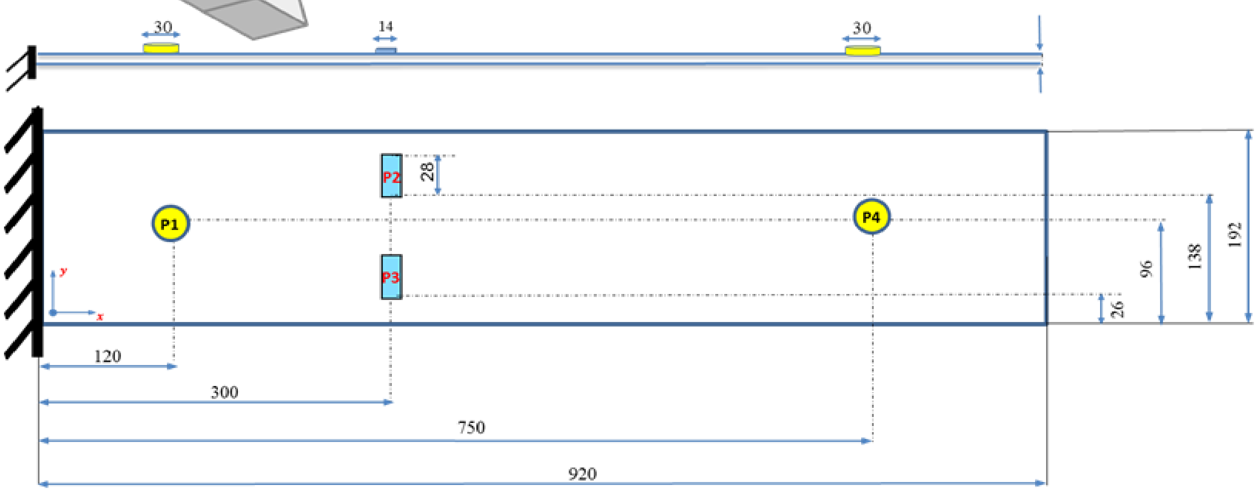
  - New performance index output vector with space dependence is driven:

$$z(t,\boldsymbol{r}) = C_z(\boldsymbol{r})x_p(t) + D_{zw}(\boldsymbol{r})w(t) + D_{zu}(\boldsymbol{r})u(t)$$

An example: Cantilevered active composite structure

Plate like-beam: 4 epoxy/carbon layers with orientation [0°/−45°/+45°/0°].



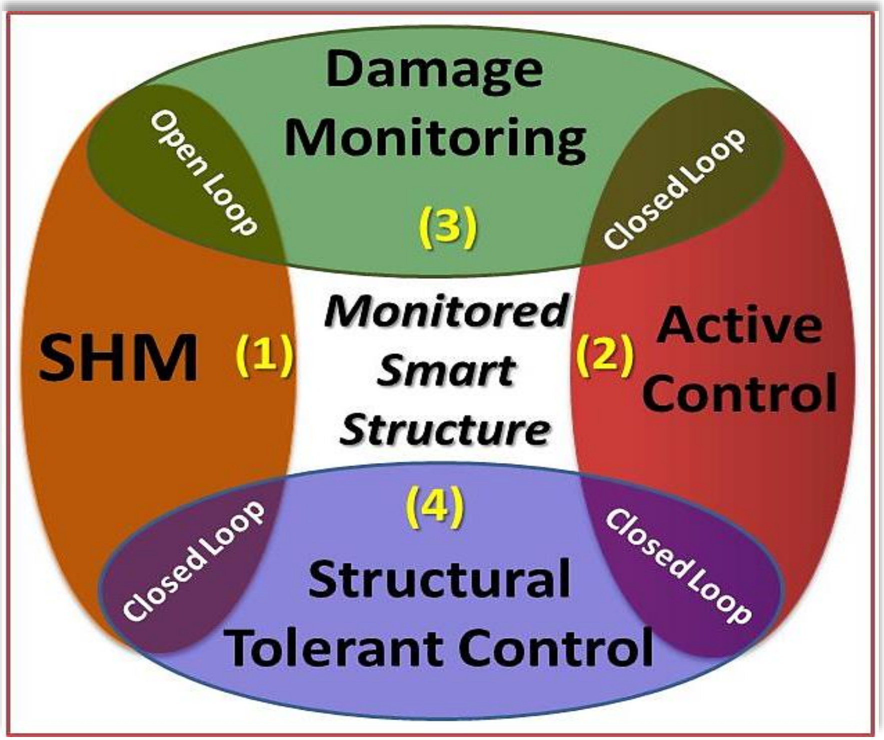


PZT disc from NOLIAC

MFC patch from SMART-MATERIALS

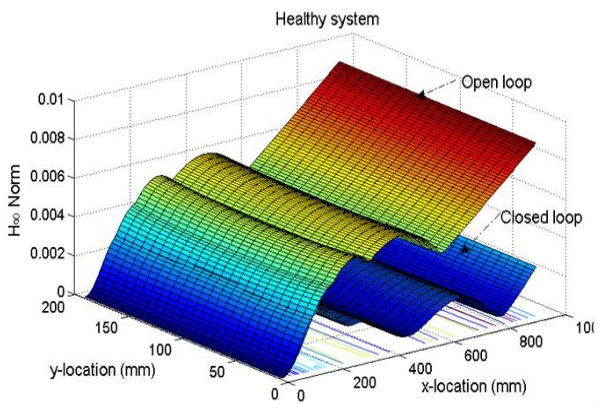
DTAC – AN EXAMPLE

- **An example: Cantilevered active composite structure**
  - Robust controller
  - Reconfigurable controller
  - Evolving controller

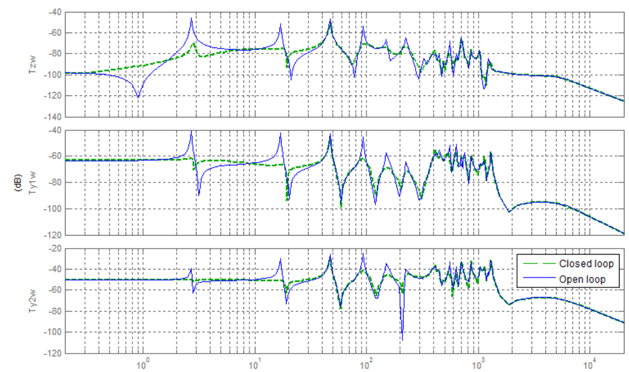


DTAC: A SPATIAL H_∞ CONTROL APPROACH

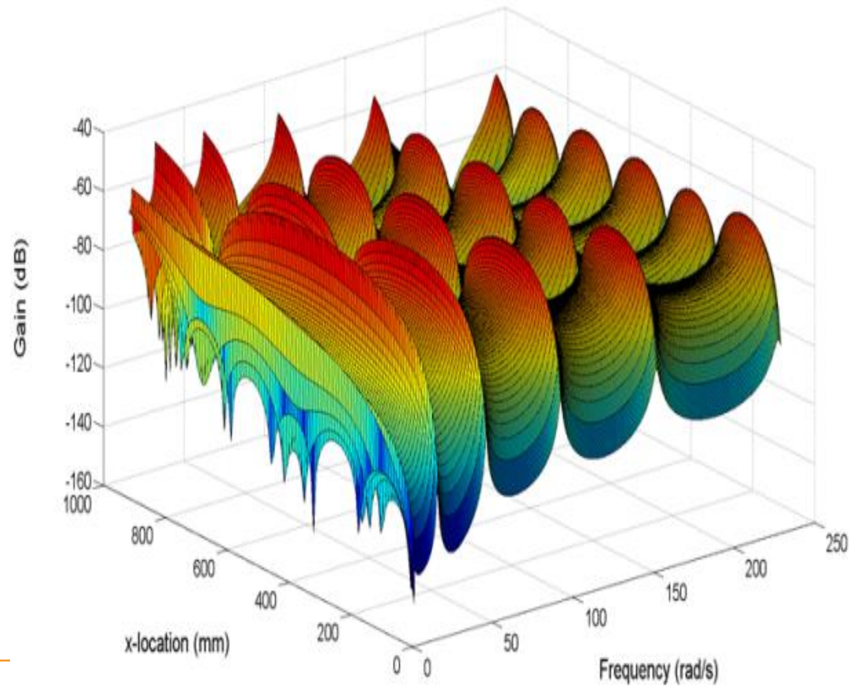
- The spatial H_∞ control of the **healthy** structure

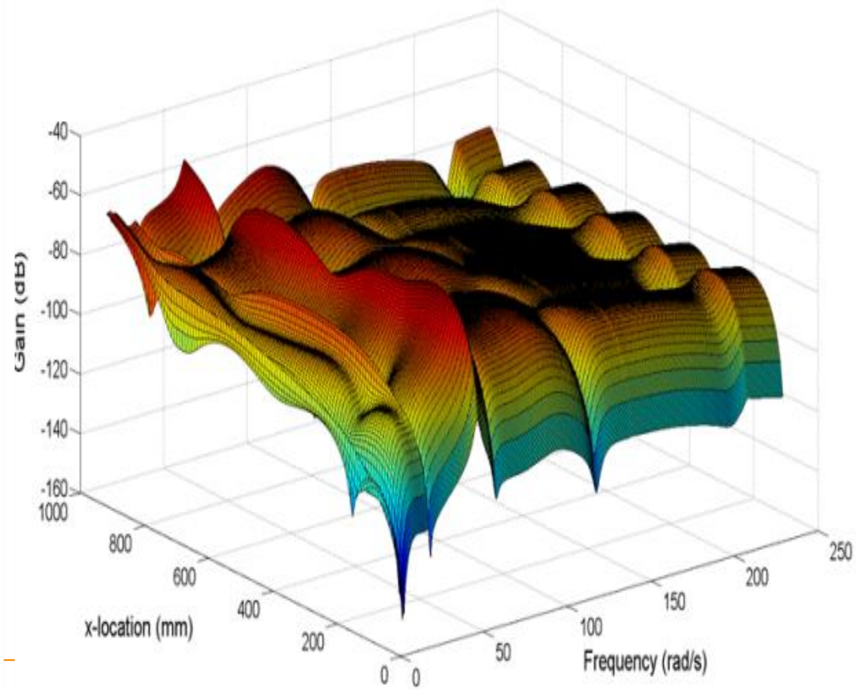


Open loop



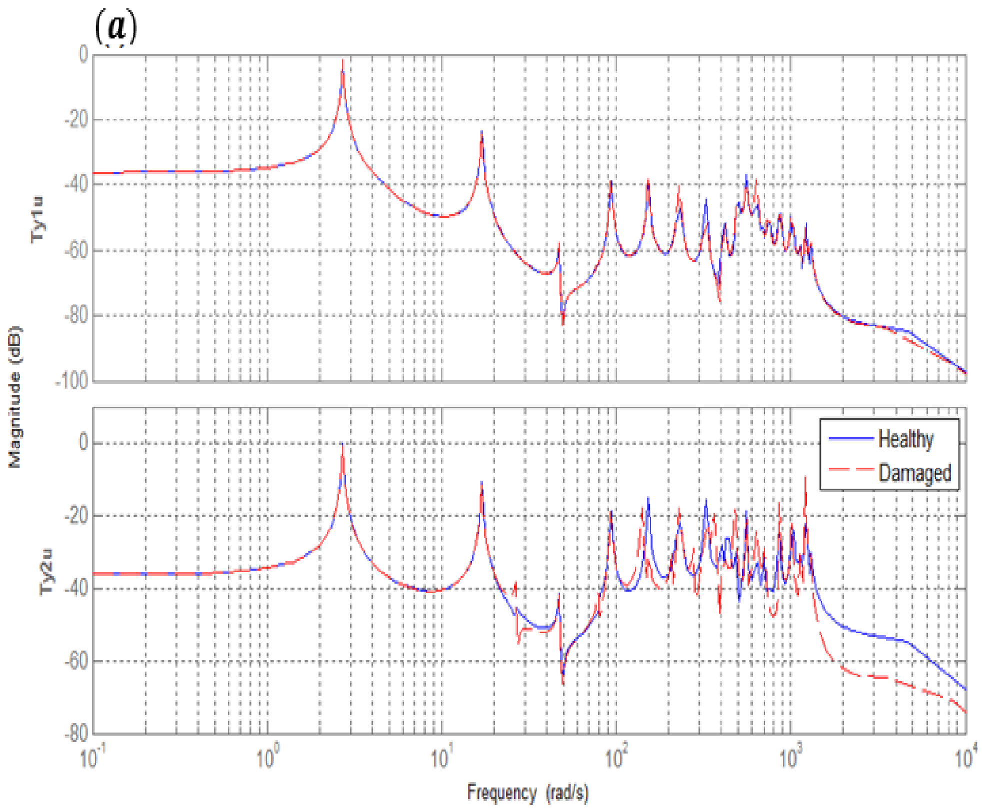
Closed loop

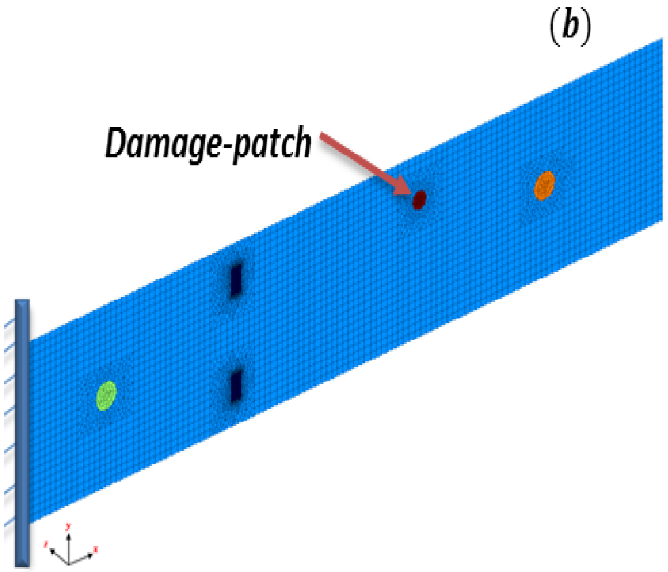




DTAC: A SPATIAL H_∞ CONTROL APPROACH

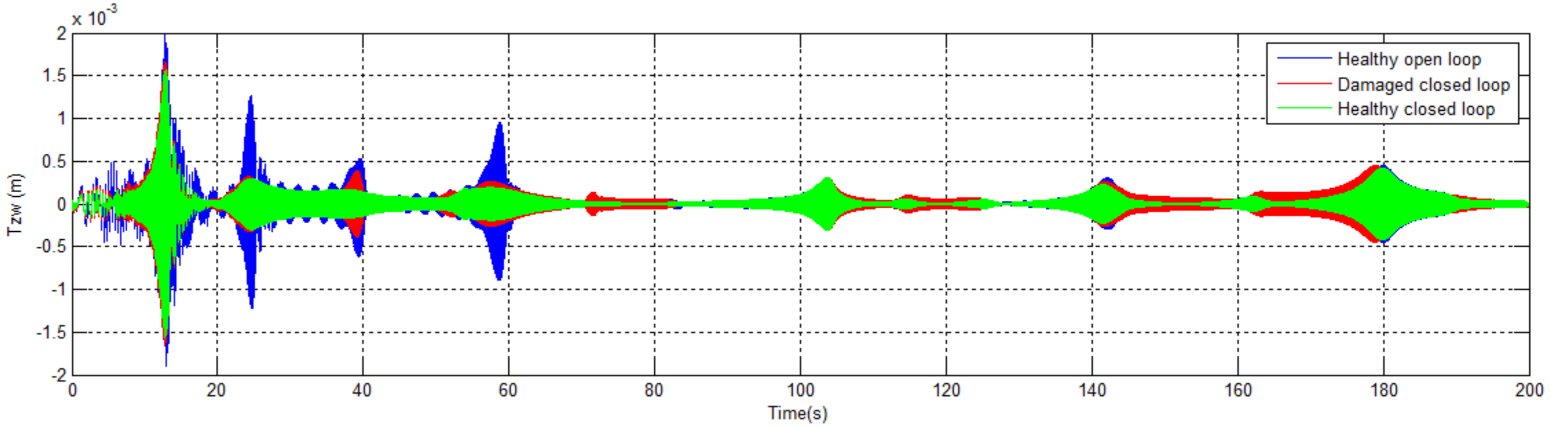
- **Robust controller:** **Small damage (Barely Visible Impact Damage - BVID)**

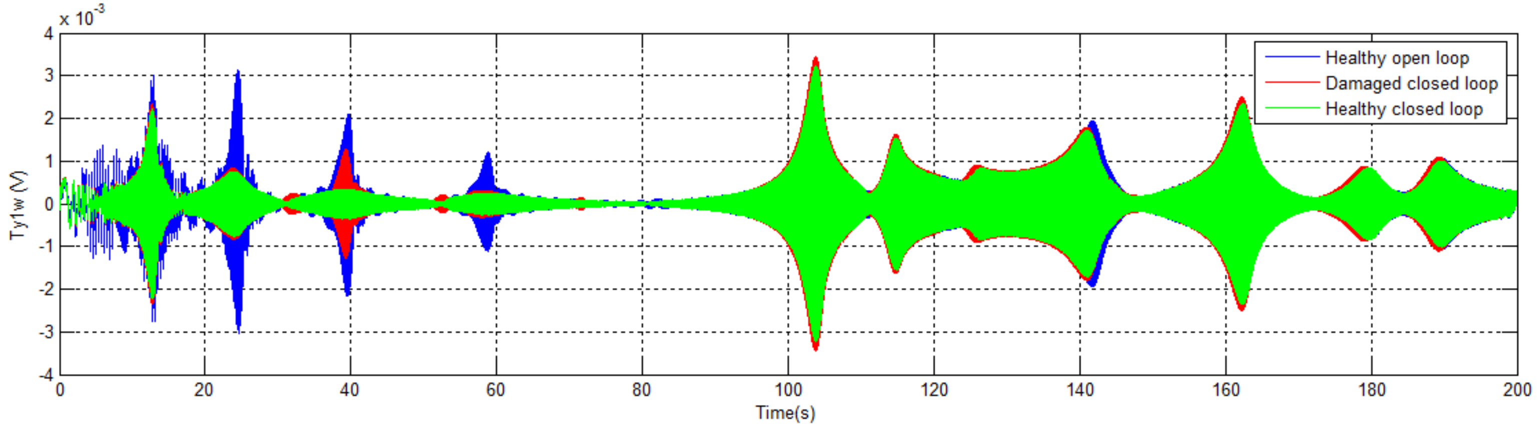




DTAC: A Spatial H_∞ Control approach

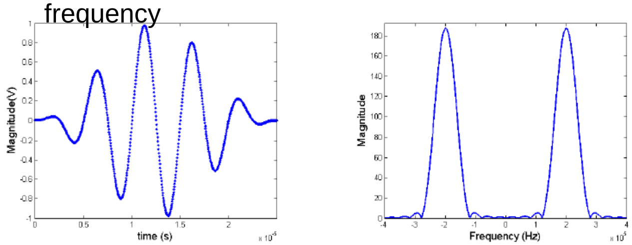
- **Robust controller - small damage (BVID)**



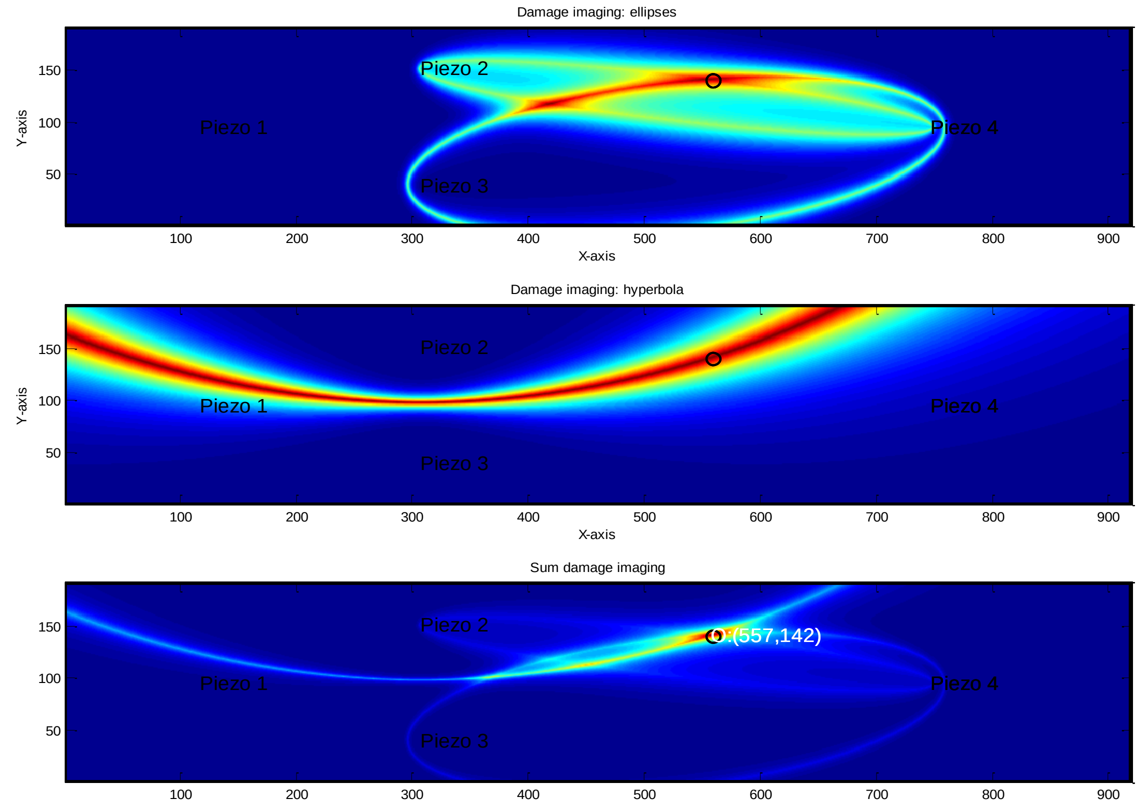


- **Reconfigurable controller – Severe damage**
  - **Damage localization** approach: Lamb waves-based damage localization

Burst signal and its spectrum at central frequency

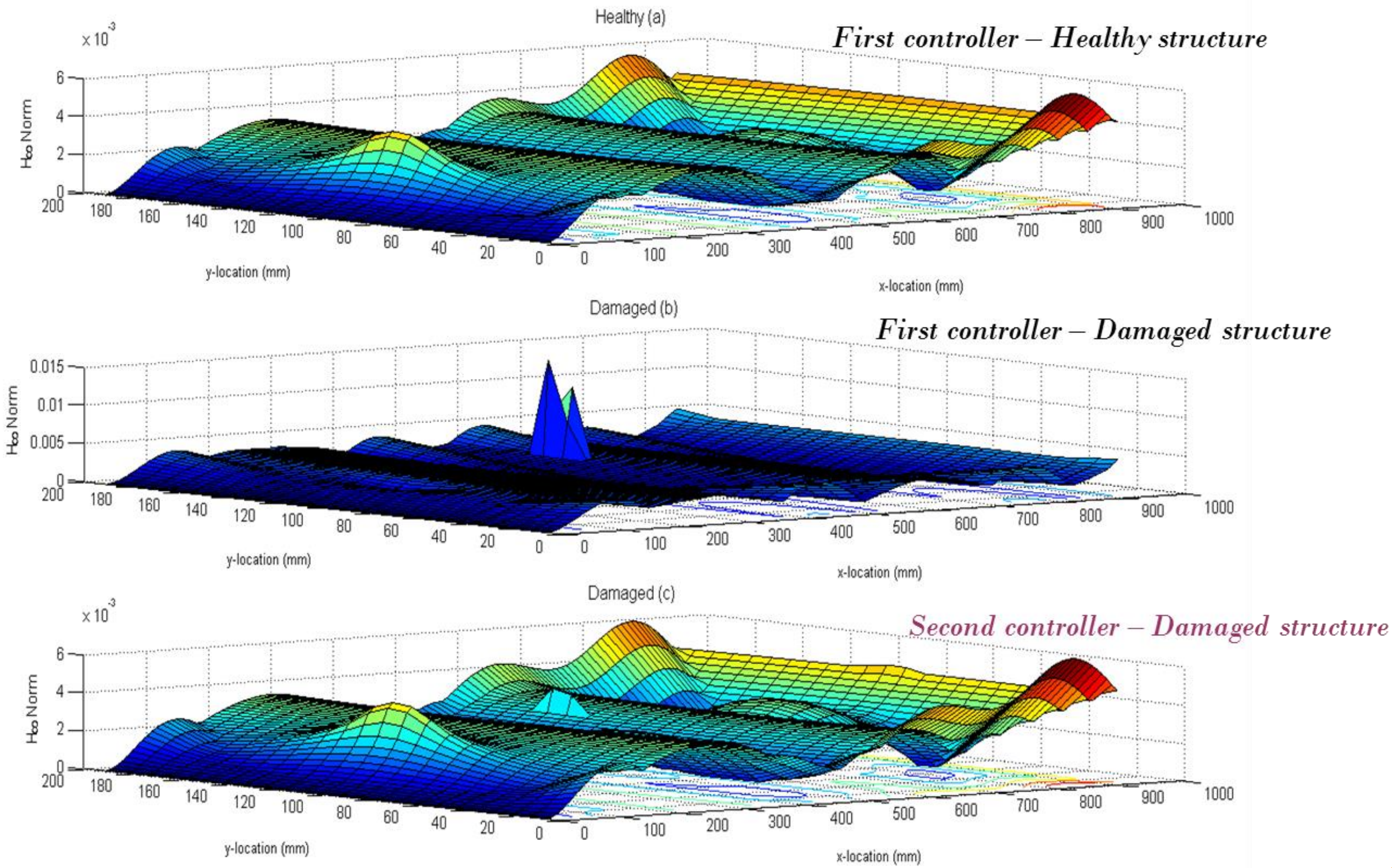


(a) (b)



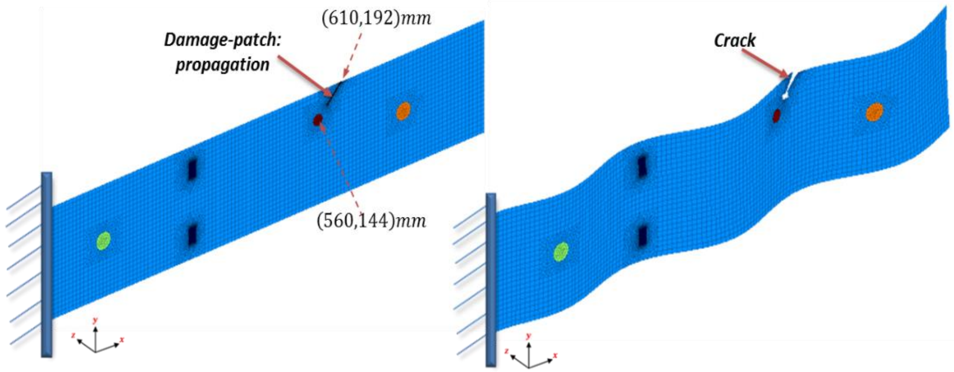
- **Reconfigurable controller – Severe damage**

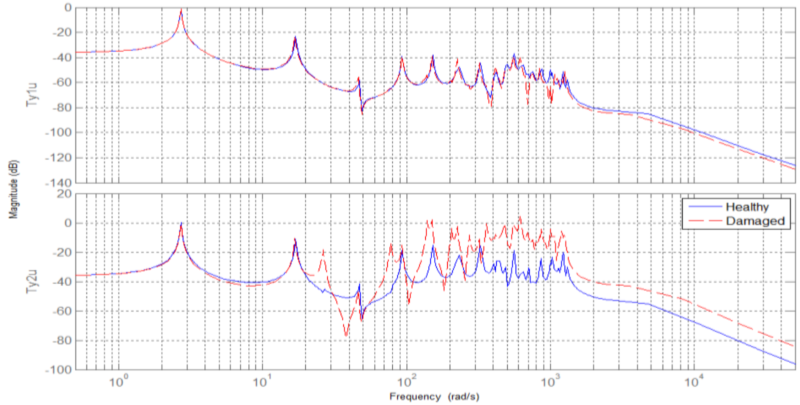
Burst s
freque

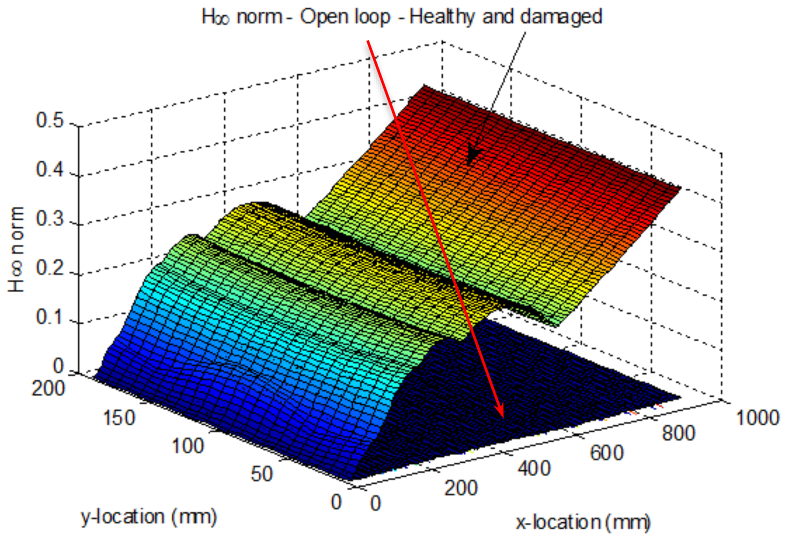


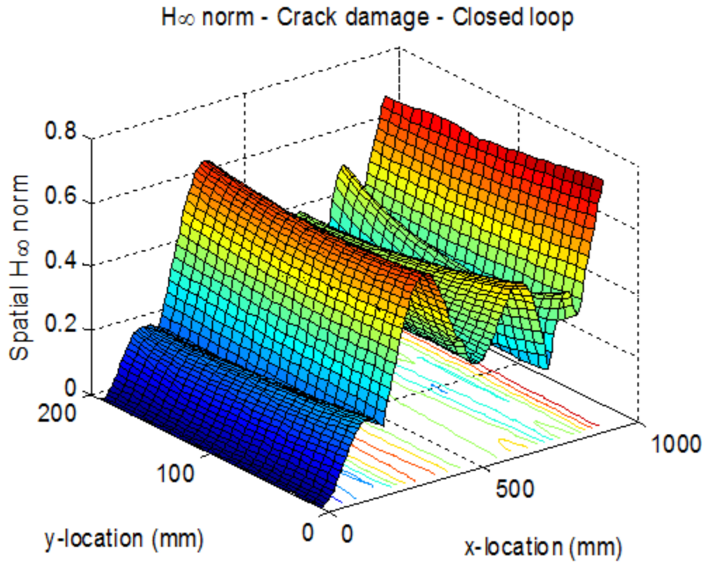
DTAC: A SPATIAL H_∞ CONTROL APPROACH

- **Evolving controller – Crack damage**



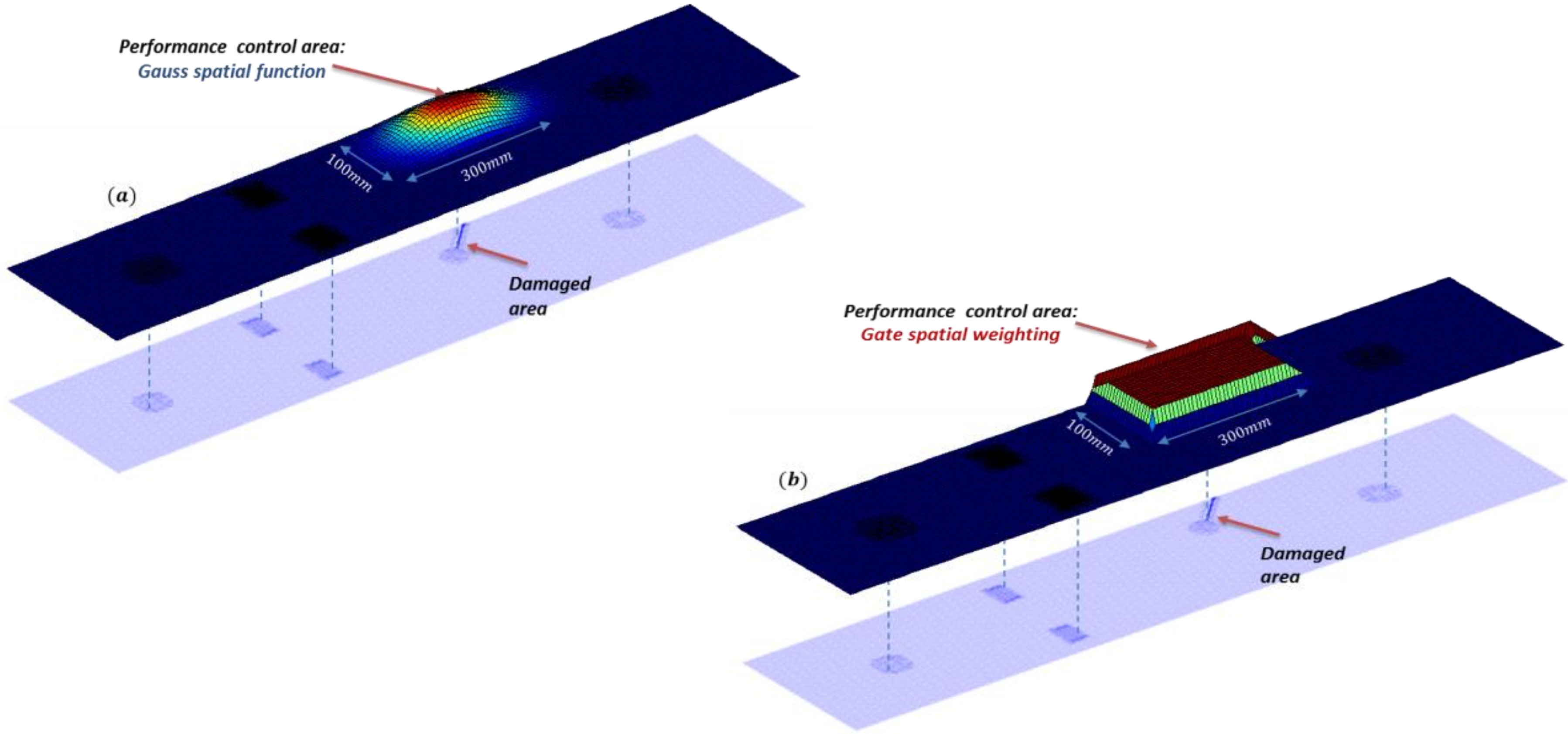






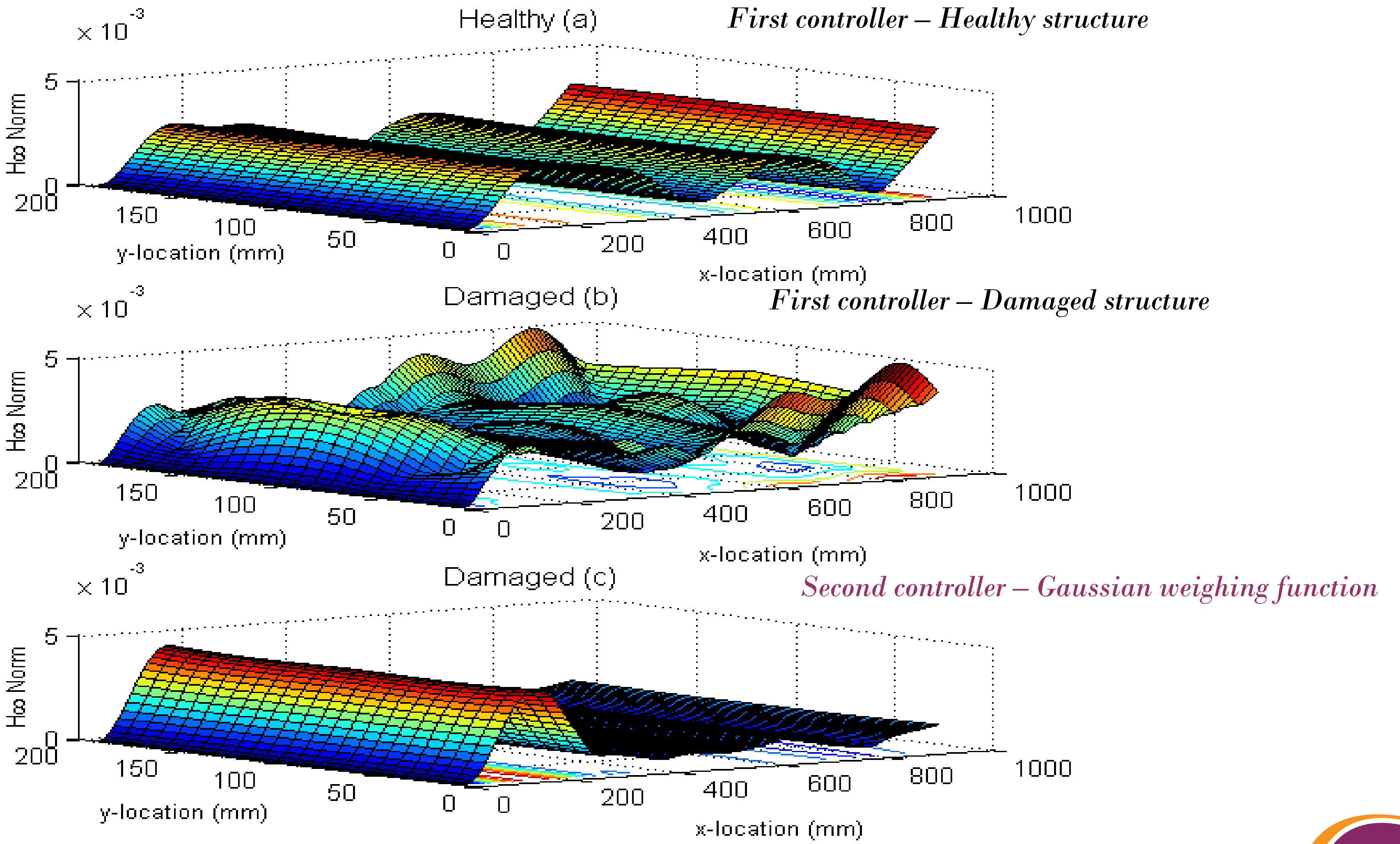
DTAC: A SPATIAL H_∞ CONTROL APPROACH

- **Evolving controller – Spatial weighting functions**



DTAC: A SPATIAL H_∞ CONTROL APPROACH

- **Evolving controller – Spatial weighting functions**



OUTLINE

- Introduction and Motivation
- Damage Tolerant Active Control (DTAC)
- DTAC strategies: Examples
- Conclusion

Conclusion

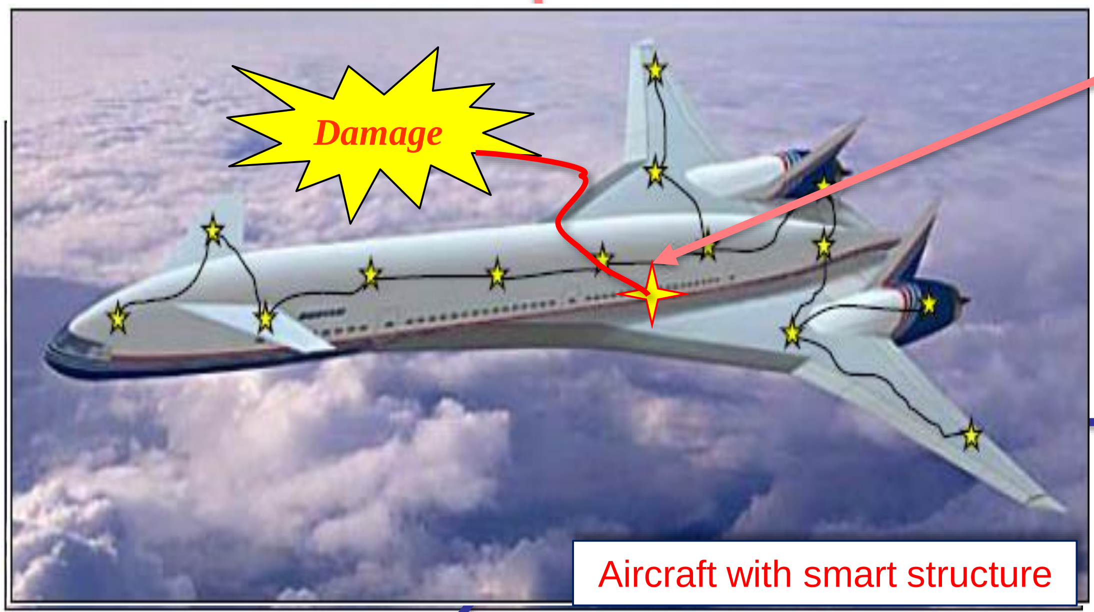
- A new paradigm to design fault tolerant controllers, specifically dedicated to face structural damages, was here examined, and called damage tolerant active control, or DTAC.
- Calls for FTC, SHM and active control of vibrations considering their interfaces with the introduced area of DTAC.
- Several techniques used in these areas are possible to be used to DTAC purpose, and main objectives and architectures to be adopted were discussed.
- On going works: theoretical investigation and experimental applications of the concepts and controller configurations are expected to be thoroughly studied to confirm the raised expectations
- New improvements: *fatigue and stress mitigation controllers* ….

DTAC NEW CONCEPT ?

- DTAC and FTC interactions

SHM
Detect and diagnosis damage

DTAC
reduce vibration and monitor the damage



FDD
Detect and diagnosis faults

FTC
Reconfiguration of the control

FIN