Damage detection and health monitoring of composite structure

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Introduction

Damage are a main cause of structural failure and often occurs on structures. In the past decades, special attention was given to avoid the sudden failure of structural components by detection damage in structures in the early state. More specifically, structural health monitoring based on the vibration of structures has been at the focus of attention of many researchers in order to obtain very efficient tools of great importance for the civil, aeronautical and mechanical engineering communities.

This is why, in recent years, various developments of non-destructive techniques based on changes in the structural vibrations have been extensively published not only to detect the presence of damage but also to identify the location and the severity of the damage. Moreover, the need to be able to detect in the early stage the presence of damage in complex mechanical structures has led to the increase of non destructive techniques and new developments. Not only extension of techniques that are based upon structural linear vibration analysis, but also the emergence of non-linear methodology and analysis have been
investigated. It is generally admitted that Rytter [1] gave the four principal damage stages of structural health monitoring:

1- the determination of the presence of damage in the structure,
2- the determination of the damage location in the structure,
3- the quantification of the severity of the damage,
4- the prognosis of the remaining service life of the damaged structure.

DEFINITION OF STRUCTURAL HEALTH MONITORING

- Structural Health Monitoring (SHM) aims to give, at every moment during the life
- of a structure, a diagnosis of the "state" of the constituent materials, of the different
- parts, and of the full assembly of these parts constituting the structure as a whole. The
- state of the structure must remain in the domain specified in the design, although this
- can be altered by normal aging due to usage, by the action of the environment, and by
- accidental events. Thanks to the time-dimension of monitoring, which makes it
- possible to consider the full history database of the structure, and with the help of
- Usage Monitoring, it can also provide a prognosis (evolution of damage, residual life,
- etc.).

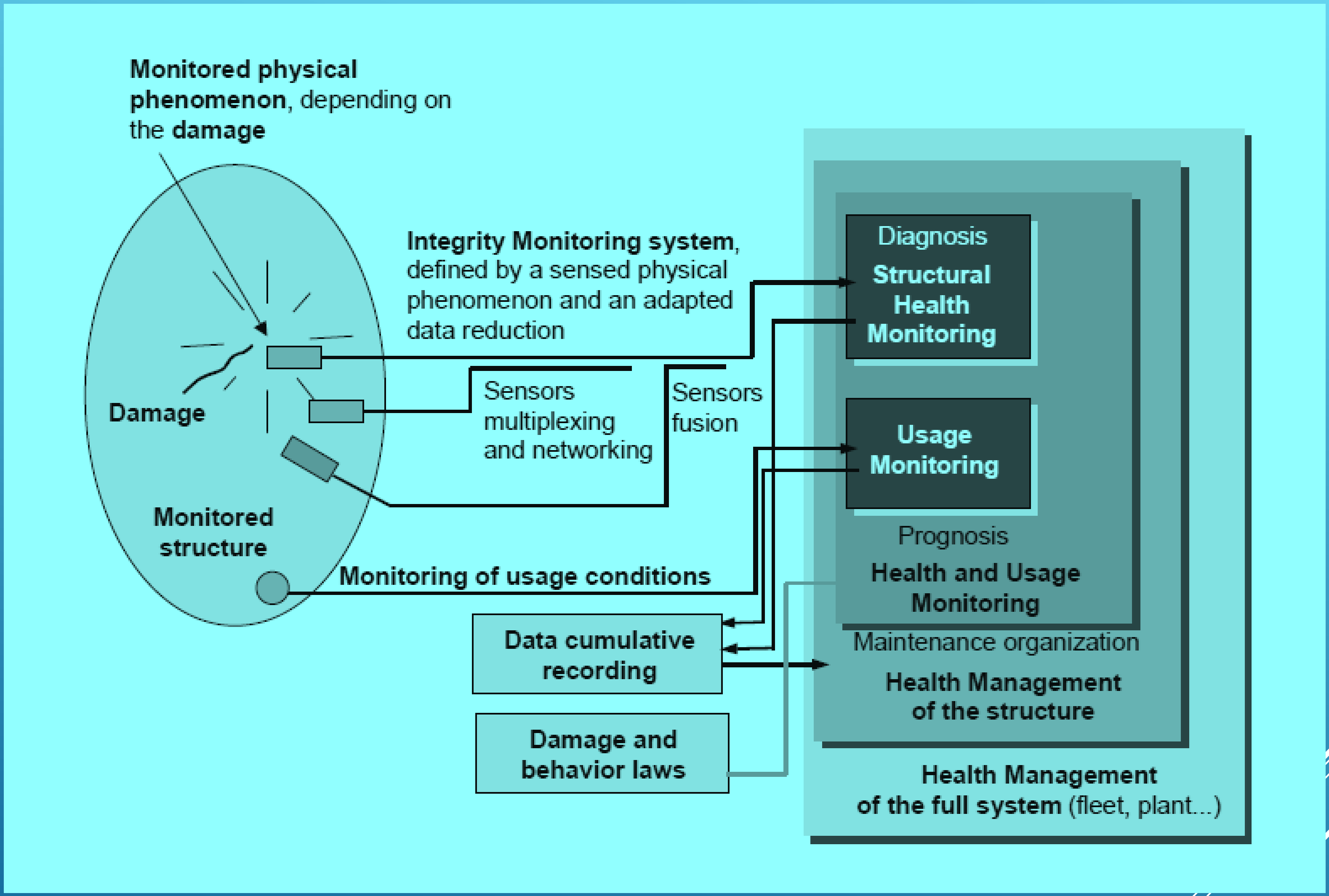

Figure 1. *Principle and organization of a SHM system*

Motivation for Structural Health Monitorin

Knowing the integrity of in-service structures on a continuous real-time basis is a very important objective for manufacturers, end-users and maintenance teams. In effect, SHM:

– allows an optimal use of the structure, a minimized downtime, and the avoidance of catastrophic failures,

– gives the constructor an improvement in his products,

– drastically changes the work organization of maintenance services: i) by aiming to replace scheduled and periodic maintenance inspection with performance-based (or condition-based) maintenance (long term) or at least (short term) by reducing the present maintenance labor, in particular by avoiding dismounting parts where there is no hidden defect; ii) by drastically minimizing the human involvement, and consequently reducing labor, downtime and human errors, and thus improving safety and reliability.

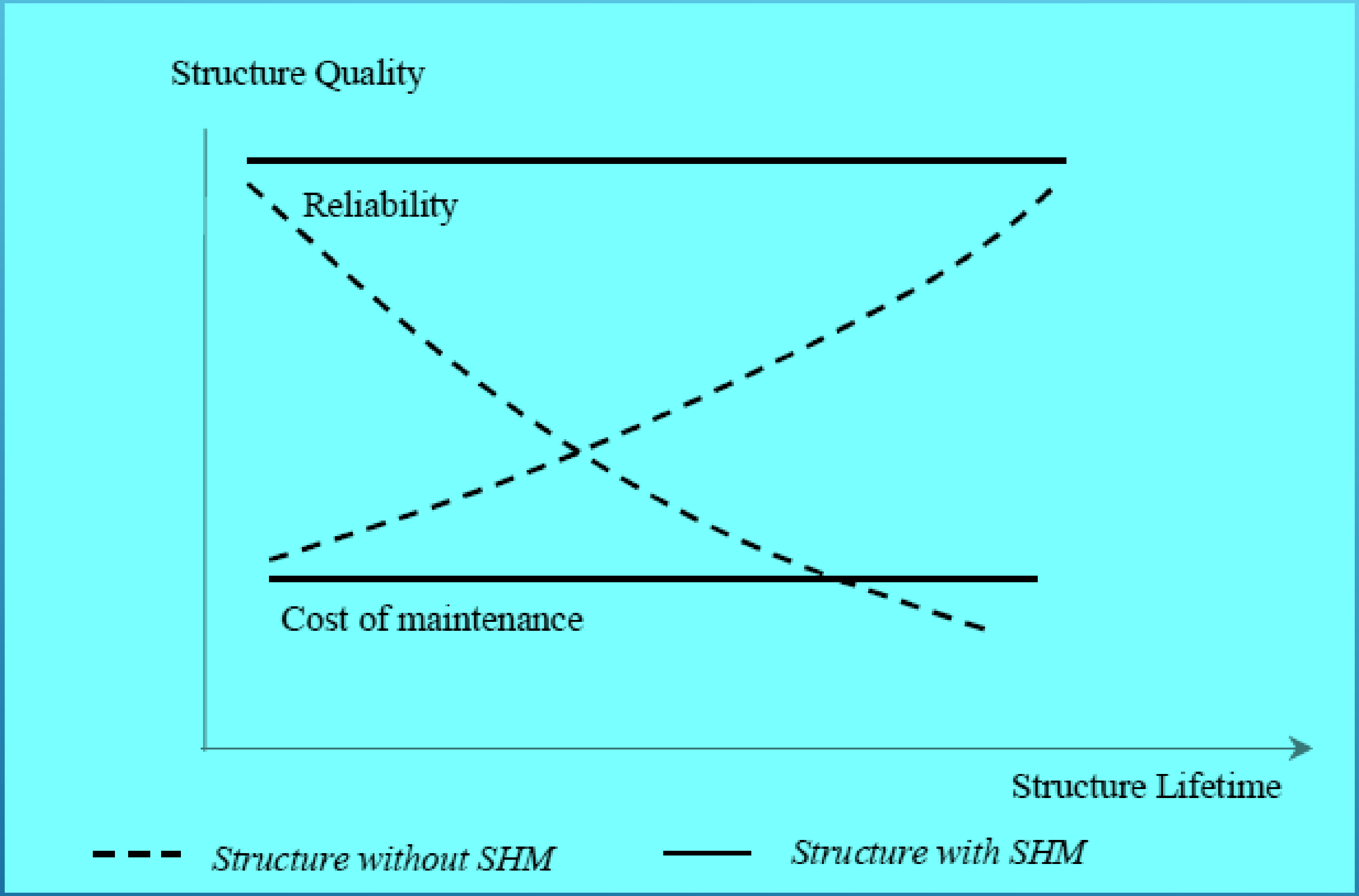

Figure 2. *Benefit of SHM for end-users [CHA 02]*

Changes in dynamic flexibility

The dynamic flexibility matrix can be used as a damage detection method in the static behavior of the structure

The dynamic flexibility matrix G is defined as the inverse of the static stiffness matrix

$$\mathbf{u} = \mathbf{G}\mathbf{f}$$

where f is the applied static force and u corresponds to the resulting structural displacement. By only keeping the first few modes of the structure, the expression of the flexibility matrix can be approximating by

$$\mathbf{G} = \Phi\Omega^{-1}\Phi^T = \sum_{i=1}^{n} \frac{1}{\omega_i^2}\Phi_i\Phi_i^T$$

where ω_i is the i^{th} resonant frequency of the structure. Ω is the diagonal matrix of rigidity given by

$$\Omega = diag\left(\omega_1, \omega_2, \cdots, \omega_n\right)$$

Φ_i defines the i^{th} mode shape and Φ is the mode shapes matrix given by

$$\Phi = [\Phi_1 \quad \Phi_2 \cdots \Phi_n]$$

The changes in the flexibility matrices before and after damage in structures can be obtained by considering the variation matrix

$$\Delta\mathbf{G} = \mathbf{G} - \mathbf{G}_{undamaged}$$

Dynamic flexibility curvature method

Zhang and Aktan [82] proposed to combine the mode shape curvature technique (see section 2.1.) and the change in dynamic flexibility matrix (see section 2.1.). They used the change in curvature obtained by considering the flexibility instead of the mode shapes as described for the mode shape curvature method.

The Dynamic Flexibility Curvature Change is defined by

$$\mathbf{DFCC} = \sum_{i=1}^{n} \left| \left(\Phi\Omega^{-1}\Phi^{T}\right)'' - \left(\Phi_{undamaged}\Omega_{undamaged}^{-1}\Phi_{undamaged}^{T}\right)'' \right|$$

where Ω and $\Omega_{undamaged}$ are the diagonal matrix of rigidity for the damaged and undamaged structures, respectively. Φ and $\Phi_{undamaged}$ correspond to the mode shapes matrix for the damaged and undamaged systems. n defines the number of modes shapes. So a localized increase curvature change in **DFCC** indicates a loss of stiffness at the same location indicating the presence of damage.

Sensitivity-based approach

The sensibility-based approach uses the mode shapes of the damaged and undamaged structures and the natural frequencies of the undamaged modes. The damage assessment technique localizes the damage by means of the mode shape sensitivities to changes in stiffness between adjacent structural degree of freedom or/and changes in mass in structural degree of freedom [83, 84].

The sensitivity of the i^{th} degree of freedom for the j^{th} mode shape in stiffness between the p^{th} and q^{th} degrees of freedom is defined by

$$\frac{\partial \Phi_{ij}}{\partial k_{pq}} = (\Phi_{pj} - \Phi_{qj}) \sum_{r=1, r \neq j}^{n} \frac{1}{\lambda_r - \lambda_j} \frac{\Phi_{pr}\Phi_{qr}}{a_r} \Phi_{ir}$$

where λ_r are the poles of the system and a_r the modal scaling factors.

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