From Lab to tail boom: the challenges to develop an SHM system in an industrial context

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Abstract

To prevent any accident, schedule-driven maintenance is mandatory to review the many critical parts of a helicopter. As a result, the ratio of maintenance man-hours to flight hours is often near 4. Despite the time of meticulous review, 14 % of the accidents in the aeronautical industry are linked to maintenance issues or clumsiness. The global cost of maintenance is high due to the wasted time of inactivity, the human resources involved and the risk of over-damaging during disassembly. The transition to condition-based maintenance requires a reliable monitoring system.

For many years, new monitoring techniques have been developed to estimate the health of the structures and shorten maintenance time. The structures are monitored in place without any disassembly to limit handling accidents. The rear transmission shafts of helicopters are critical and need to be monitored. A promising technique, the Gapped Smoothing Method (GSM), was developed by Ratcliffe and Bagaria in 1998 and allows to localize damages in beam-type structures.

This paper points out the potential of the GSM to monitor helicopter shafts without the need for a pristine shaft. The method is based on the modal response of a beam-like structure. The modal curvature, which is computed from the measured displacements, is compared to the expected theoretical curvature. This value is computed from the beam vibration theory and is approximated with a third-order polynomial.

Results from this work are in agreement with those presented by Ratcliffe and Bagaria. This method was applied to a more representative structure of a rear drive shaft, differing from the original rectangular section beam. Different tests highlighted the limitations of the GSM which could not be observed in the case presented in the original article. New perspectives of research will be proposed to consider the use of the GSM in an industrial context.

1 Introduction

Helicopter manufacturing is a very competitive sector of the transport industry. A key challenge for the manufacturers is the reduction of their fabrication costs and their clients' operation costs. For a helicopter, an important part of the operation cost is related to the maintenance. The main objective of the Recompose project is to address both challenges applied on the rear shaft of helicopters. The operability of the helicopter is ensured by scheduled inspections of its structure and machinery. This preventative maintenance implies an immobilization of the aircraft and requires human and material resources to disassemble and control many mechanical parts.

To reduce the immobilization time and the need for human and material resources, new monitoring techniques are being developed. The structures are monitored thanks to integrated sensors and surveillance algorithms. Those techniques are clustered under the name *Structural Health Monitoring* (SHM). Two classes of damage detection methods exist: local and global methods. In the case of the rear helicopter shaft monitoring, the position of the damage is not *a priori* known. Also, using local methods enforces the structure to be accessible openly and to be entirely inspected [1]. However, global damage detection methods can be applied to complex structures and can localize damage.

Most of those global damage detection methods are based on the change in vibration characteristics of the structure. Indeed, the damage causes a local change in the material properties which modifies the dynamic response of the structure. At first, modal parameters are considered to detect the change of response, for

example, modal frequencies [2, 3] or mode shapes [4]. For the mode shape study, Pandey and al. [5] used the second derivatives of mode shapes (curvature), which appeared to be highly sensitive for damage detection. Fan and al. [6] compared several methods in a comparative study based on Finite Element Model. His main weakness of the tested methods is the need for a pristine structure to compare extracted parameters between undamaged and damaged structures.
Ratcliffe and al. [7] developed a method based on the curvature mode shape to detect and localize damage called the *Gapped Smoothing Method* (GSM). To overcome the need for a pristine structure, they propose to replace the undamaged structure modal curvature with the expected theoretical curvature. This curvature can be estimated from the beam vibration theory with a third-order polynomial. They showed the potential of this method in two different situations. The method detected and localized a local change of thickness in a rectangular cross-section beam [7] and identified delamination in a composite cantilever beam [8]. In this paper, the theory of the GSM is first presented. Then, the GSM is used to detect and localize damage in a simplified rear drive shaft model. The structure considered and the boundary conditions differ from the original rectangular section beam. The numerical model and the simulation are briefly presented and the results are discussed. To conclude this paper, future studies are presented to determine the sensibility and the application domains of the GSM.

2 Description of Gapped Smoothing Method

The GSM was presented by Ratcliffe and Bagaria in 1998 [8]. This method was originally developed to detect delamination in a composite beam. It is based on the comparison between the real curvature of the flexural beam with the theoretical curvature (see Fig. 1). The main assumption is to consider that the theoretical curvature can be described with a cubic polynomial. A difference between both real and theoretical curvatures shows discontinuities in the material properties. In particular, it highlights the presence of a defect in the structure. In practice, the curvature is arduously measured. It is more convenient to deal with displacement, which can be derived twice to obtain the curvature.

Ratcliffe and Bagaria [8] defined a damage index δ_i at the point i as:

$$\delta_i = (\gamma_i^{th} - \gamma_i^{df})^2, \tag{1}$$

with, γ_i^{th}, the curvature computed with the cubic polynomial (see Eq. 3) and γ_i^{df}, the curvature computed by finite difference (see Eq. 2).

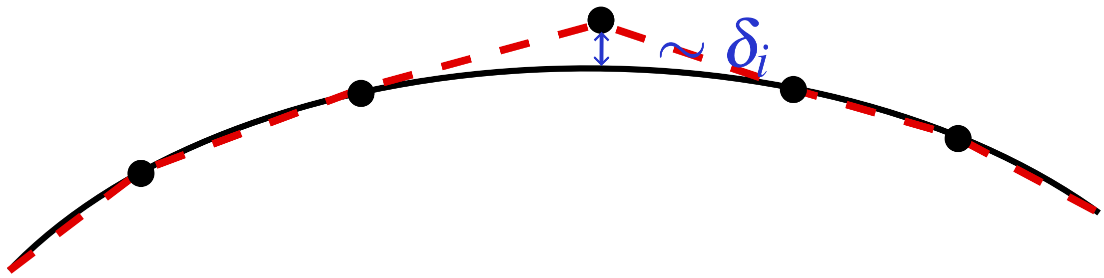

Figure 1: Representation of the damage index from theoretical curvatures (black curve) and real curvatures (dotted red curve).

The real curvature γ_i^{df} at the point i, being the second derivative of the displacement, can also be computed using the method of central finite difference from the bending displacement as:

$$\gamma_i^{df} = \frac{w_{i-1} - 2w_i + w_{i+1}}{h^2}, \tag{2}$$

with, w_{i-1}, w_i and w_{i+1} corresponding to the flexural displacements respectively at the point $i-1$, i and $i+1$ and h, the uniform spatial step.

The theoretical curvature γ_i^{th}, at the point i can be computed from the resolution of a cubic polynomial given by:

$$\gamma_i^{th} = p_0 + p_1 x_i + p_2 x_i^2 + p_3 x_i^3, \quad (3)$$

with, x_i, the position at the node i and p_0, p_1, p_2 and p_3 the coefficients of the cubic polynomial, which can be determined with the adjacent curvatures γ_{i-2}^{df}, γ_{i-1}^{df}, γ_{i+1}^{df} and γ_{i+2}^{df}.
At the extremities of the beam, a backward and forward difference is used to estimate the real curvature. The same decentering can be done for the cubic interpolation.
Once the damage index is computed for each point of the beam, a possible damage could be identified and located where the damage index increases. The damage index magnifies the discrepancy between the curvature derived from the modal displacements and the theoretical curvatures. Thus, the damage index, computed along the whole structure, is expected to increase for each point in the region of the damage. The bigger the damage, the larger the affected zone.
At the beginning, the GSM was only applied on bending modes of the beam [8]. Ratcliffe demonstrated an interest in applying GSM on a wide frequency range [9] and also obtaining a map where the damage index is a function of the spatial position and the frequency. Using a wide frequency range requires the damage indices to be normalized. Without any normalization, the damage indices near the natural frequencies dominate the damage indices map. Ratcliffe proposed the normalization of each frequency such that the mean value of each damage index is one.

3 Numerical application on a simplified tail boom

The helicopter shaft is modeled as a cylindrical hollow beam with a constant diameter and thickness. The geometric properties are presented in table 1. The shaft is made out of steel and the material properties are presented in table 2.

Geometric parameter	Value	Unit
Length	1000	mm
External diameter	60	mm
Thickness	1	mm

Table 1: Geometric beam parameters.

Material parameter	Value	Unit
Young's Modulus	210	GPa
Density	7800	kg.m^{-3}
Poisson's ratio	0.3	-
Structural damping	1	%

Table 2: Material beam parameters.

The failure of the shaft is represented by a decreasing of the Young's Modulus for a section of 40 mm, located between $x = 730$ mm and $x = 770$ mm, as shown Figure 2. For the proof-of-concept, this Young's Modulus has a value of 50 % of the one of the steel (*i.e.* 105 GPa). In this simplified shaft model, damage is introduced by locally scaling down the mechanical properties of the mesh. The boundary conditions are clamped-clamped.
The Finite Element Method is used to perform a frequency analysis of the shaft between 0 and 10 kHz. The structure is excited by a point force, the table 3 gives the details of this one. A line of sensors is artificially created, by extracting all the displacements at the top of the structure along the x-axis (points in black in Figure 2). The mean Frequency Response Function is presented in Figure 3.

Excitation parameter	Value	Unit
Position in x	550	mm
Position in y	0	mm
Position in z	30	mm
amplitude	1	N
Frequency range	[0, 10]	kHz

Table 3: Excitation parameters.

The curvatures and damage indices are computed from the displacements of the frequency analysis. After the normalization step, results are presented in map format in Figure 4, the abscissa is the position along the beam and the ordinate is the frequency. The color map depicts the value of the damage index at each node for each

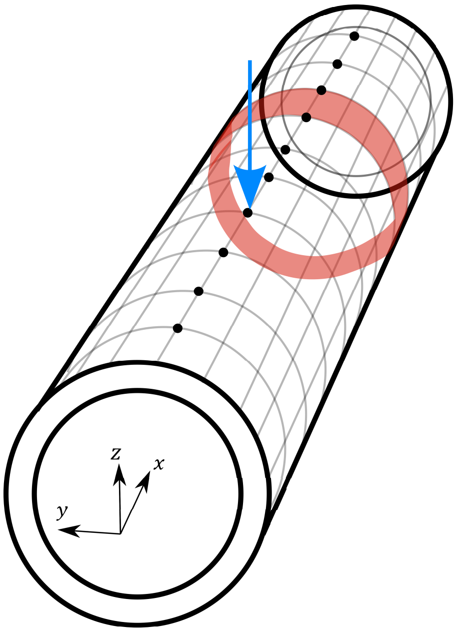

Figure 2: Scheme of the damaged cylinder hollow beam. The damaged section is in red, the excitation force is represented by the blue arrow and the measurement nodes are aligned on the top of the shaft.

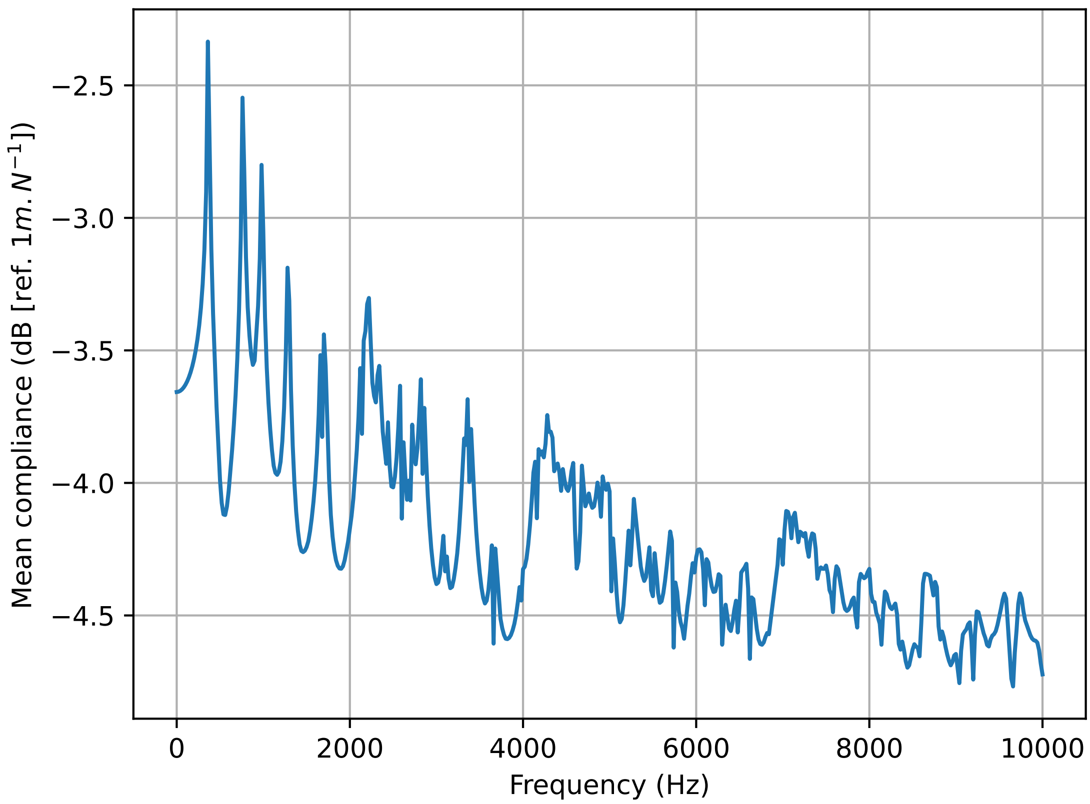

Figure 3: Mean compliance of the shaft response calculated by FEM.

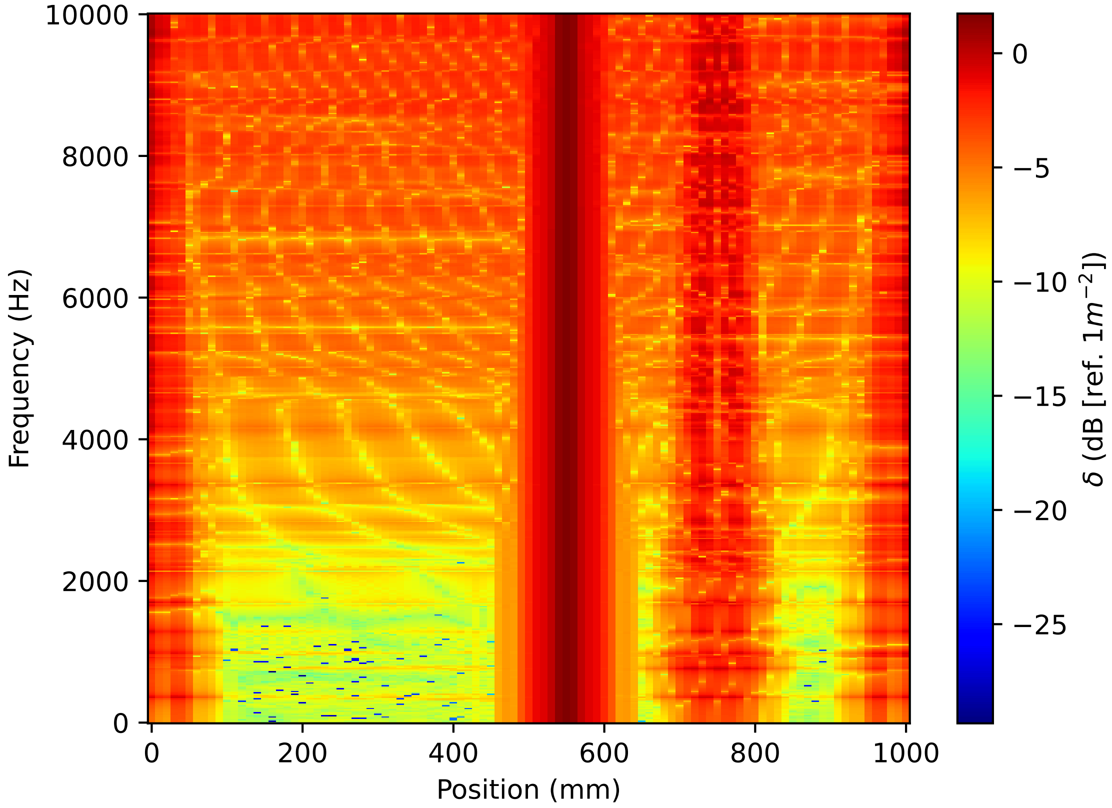

Figure 4: Map of the damage indices at each node for a wide-range frequency.

frequency. Four areas, where the damage indices are high, are visible on the map: at both ends of the beam ($x = 0$ mm and $x = 1000$ mm), near the point where the beam is excited ($x = 550$ mm) and near the position of the damage (between $x = 730$ mm and $x = 770$ mm). Outside of these four areas, the damage index is significantly lower. Moreover, it can be observed that outside of these areas, the damage index varies with the frequency according to the natural frequencies of the shaft.
These first results validate the proof-of-concept to use the GSM to detect and localize damage as long as the damage is not too close to the boundary conditions or to the excitation point. The boundary conditions and the influence of the load on the damage indices are the first limitations to overcome. The presentation of the results in a map format confirms that a wide-frequency range is an advantage to have better detection. More studies to determine the potential of this method are discussed in the next section.

4 Studies of the limitation of the GSM

The first results of the GSM validate the possibility of the detection of damage. The configuration of the structure was ideal and shows the good implementation of the method as described by Ratcliffe and Bagaria [8]. To implement this method on an industrial structure (in this case a driven shaft) and determine its sensibility, several parameters have to be studied. Those parameters are divided into two main categories: physical parameters and measurement parameters. Physical parameters are :

- position of excitation and distance from the damage,
- amplitude of the excitation,
- position of the damage,
- size of the damage (length and angular size of the section),

- decreasing of Young's modulus of the damage,
- frequency range,
- damping of the structure,
- boundary conditions.

Measurement parameters are :

- density of sensors,
- position of sensors in regards to the damage,
- measurement noise.

A Python program was created to automatize studies for each of those parameters. It means automation of the FE simulations and the post-processing. Those studies are in progress.

5 Conclusion

In this paper, a methodology for damage detection in a shaft has been described. This method was adapted from the GSM to be applied to a different structure. The structure considered was a hollow cylindrical beam, with both ends clamped. A frequency analysis was performed to extract the modal response of the beam for a wide range of frequencies. The GSM processes numerical displacements to determine complex curvature as a function of the frequency and theoretical curvature from a cubic polynomial interpolation. The comparison of both curvatures is used to compute a frequency-dependent damage index. This formulation of the damage index does not need any curvature extracted from a pristine structure. The location of the damage can also be revealed on a color map with an increase in the value of the damage index. The result of the simplified tail boom displays three locations of an increasing damage index: at the boundary, at the excitation position and the damaged area.

This work contributes to presenting the GSM as a promising method to detect and localize damages in structures. However, the method does not seem suitable if the damages are close to the boundary or the excitation point. To overcome the excitation issue, two different positions of excitation, working alternatively, could be considered. Thus, damages can be detected all along the beam. Furthermore, to use the GSM, more studies have to be conducted to determine the sensitivity and the application domain of this method. Then, an implementation on a rear shaft will be realized to test the GSM experimentally.

Acknowledgements - additional information

This study is part of the RECOMPOSE project funded by DGAC (Direction Générale de l'Aviation Civile), by France Relance and by NextGeneration EU, managed by NEXTEAM Group and in collaboration with AMVALOR and CT Ingénierie.

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