INTEGRATION OF HEALTH MONITORING SYSTEM FOR COMPOSITE ROTORS

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1 Summary

A concept of a combined material-integrated structural health monitoring and active vibration damping system is proposed. Using a common set of sensor and actuator components integrated in a composite rotor, the system allows the control of the structural dynamic behaviour under relevant operating conditions as well as the detection of a progressing damage. A theoretical and experimental validation of this concept was conducted on the example of a complex shaped carbon fibre reinforced composite structure.

2 Introduction

Fibre reinforced composites offer, in comparison to classical materials, excellent material properties e.g. high specific strength and stiffness as well as adjustable damping properties. Thus, a growing interest in automotive, aerospace and other weight-relevant applications dealing with dynamically loaded structures is noticeable.

The performance of nearly all in-service composite structures is altered by the exposure to severe environmental and operational conditions as well as by damage caused by fatigue, impact, abrasion and overload or operator abuse. The aforementioned influences can have serious consequences on the reliability, the maintenance costs and the operational capability of the structure. Therefore the on-line monitoring of safety relevant structures concerning their material degradation and unexpected damage are of major concern in composite applications [1].

Numerous researchers [1, 2] identify the degradation of the structural stiffness as a good indicator of several different failure modes such as fibre failure or inter fibre failure. Cawley et al. [3] describes that not only the stiffness but also the material damping is dependent on the state of damage in the fibre reinforced composites. An important practical consequence is a correlation between the changes in structural dynamical behaviour represented e.g. by modal properties and the damage state of the composite structure. An appropriate interpretation of such changes and their patterns could be used for an assessment of the progressing damage in order to avoid critical operating conditions. The achievable assessment resolution is however limited through the frequency bandwidth, the number of sensors and the resulting number of observable natural frequencies [3].

According to Sohn [1] there are five levels of damage identification: existence, location, type, extent and prognosis of remaining lifecycle. The here proposed diagnostic model obtained the second level of damage identification based on the vibration signals from additional material-integrated functional elements. Such embedded sensors were used for the monitoring of the structural dynamic behaviour direct on the structure.

The proposed structural health monitoring system is structured as an inverse problem diagnostic model, where the damage parameters, e.g. damage presence or location, are calculated based on the modal properties.

3 Problem Definition

In the former activities of the research group, complex shaped carbon fibre reinforced rotor structures with integrated active vibration damping

(AVD) systems were developed [4, 5]. The presented investigation focuses on an extension of this system mainly by the implementation of additional vibration-based structural health monitoring (SHM) functions.

In order to allow an estimation of the structural integrity using the existing AVD hardware, the software of the existing controller block (Fig. 1) was extended. On the one hand, it was necessary to implement an instant calculation of modal properties and on the other hand, appropriate diagnostic models, consisting of inference rule-sets, had to be developed and implemented.

The goal of the proposed approach was to identify the discrete changes of vibration properties that could be correlated with the relevant changes of the structural properties. Additionally, the achievable resolution and the accuracy of the change identification were estimated.

4 Configuration of the Investigated Active Structure

A carbon fibre reinforced scaled blade of an aero engine fan (Fig. 2) with integrated AVD system was analyzed. The macro fibre composite patch and semiconductor strain gauge were used for the deflection actuation and for the vibration measurement, respectively.

The distribution of the integrated elements was optimized for the maximal damping performance of the first eigenmode, which was identified as the most critical during operation of the investigated structure. The integrated vibration measurement system was however sufficiently sensitive to record the structural dynamical response up to the first three natural frequencies (Fig. 3), which were subsequently used by the structural health monitoring function to assess the structural integrity.

The strain gauge, the piezoelectric actuator, the conducting paths and the external connectors were encapsulated between two thin polyimide films. The resulting self-contained active layer was subsequently integrated into the structure during the resin transfer moulding consolidation procedure.

5 Experimental Procedure and Vibration Signal Analysis

Due to the large number of possible combinations of failure modes, damage extents and their positions, the structural vibration behaviour was changed during the experimental procedure in a simplified way by attaching different small masses to the structure. Three different masses: 2 g, 5 g and 10 g were attached separately and independently in 110 uniformly distributed surface points on the investigated 400 g heavy blade (Fig. 2). For each mass and its position, the structure was excited with the integrated actuator in a broad frequency band using white noise signal for a specific period of time.

The resulting vibration signals were measured with the integrated sensor, analogue filtered and cleansed in the signal conditioning unit by removing the trends in order to reduce the systematic errors. The obtained signals were used for the parameter estimation of autoregressive linear prediction models using the Burg method. These parametric models of the measured signals were subsequently applied for the determination of power spectral densities, which were used as an input to a semi-automatic algorithm of natural frequency detection. The obtained damage-sensitive features: natural frequencies and spectral densities were stored in one data set required for the machine learning procedure (Fig. 4) used during the identification of diagnostic models.

Two separate diagnostic models in form of rule-based classifiers were developed and implemented. The first classifier delivers the information about the existence of an additional mass and therefore could be associated with first level of damage identification. The distinguishable data clusters were named: ‘Change’ and ‘No Change’ in order to describe the presence or absence of the additional mass, respectively. The second classifier distinguishes between the mass in blades tip (‘Upper Change’) and root region (‘Lower Change’) and hence it is connected with the second stage of damage identification – the damage location.

The diagnostic models were inducted as deterministic decision trees (Fig. 5) using an inductive learning method similar to the C4.5 classification algorithm [6]. Respective learning data sets were formed from the experimental data using the described clustering patterns.

6 Validation

The achievable detection and location accuracy of the analysed structural changes was assessed based on the results of the standardised leave-one-out cross-validation performance testing. In the cross-validation procedure the dataset was iteratively partitioned into two complementary subsets. One subset was used for the inference of diagnostic trees, which performance was subsequently validated using the data from the remaining subset.

The results reveal that the reliable detection of the mass existence could be achieved with the overall performance of above 90 % and in the case of mass location of above 80 % (Table 1).

Figures 6 and 7 depict the distribution of prediction errors for the classifiers built from data collected during experiments with different positions of the 10 g mass. Left and right sides of the markers show the actual and the predicted class membership of each experimental configuration, respectively. From Figure 7 it is noticeable that the most of incorrect classified states in the location phase lay near the boundary between the clusters representing the state classes.

7 Conclusion and Outlook

An algorithm for detecting the discrete change of structural properties originating from simulated defects through a vibration-based model was proposed. The integrated sensor and actuator elements allowed the realisation of two different active functions. The ADV system controls the structural dynamic behaviour under relevant operating conditions. The on-line SHM system detects changes of the structural properties. Although the integrated elements (strain sensor and piezoelectric actuator) were distributed according to the characteristics of the undamaged structure, the system could adequately measure the changes of structural dynamic properties of the structure modified through attached masses. The demonstrated function integration of the active composite structure was achieved by a software extension without a change to the hardware part.

The estimated performance of the classifiers used for the detection of the structural changes confirmed a high sensitivity of the proposed method to the simulated defects. The achievable resolution of the structural change location, although limited due to the small number of the integrated sensors, was also high.

Further investigations could involve analyses of long-term changes of the dynamical behaviour in order to improve the quantification of a cumulated damage and prediction of the remaining lifetime of the component.

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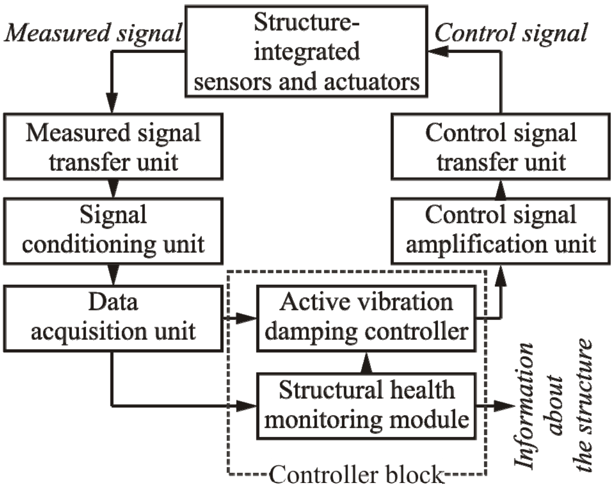

Fig.1. Block diagram of the combined active vibration damping and structural health monitoring system

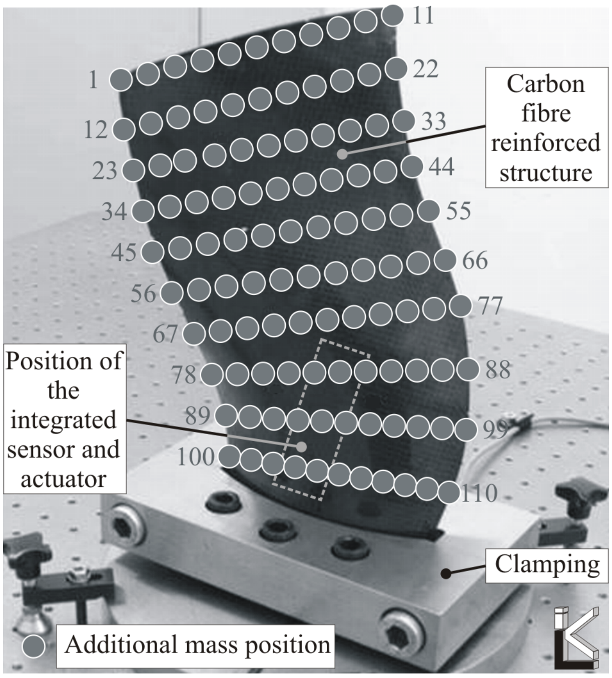

Fig.2. Investigated structure on the experimental test stand

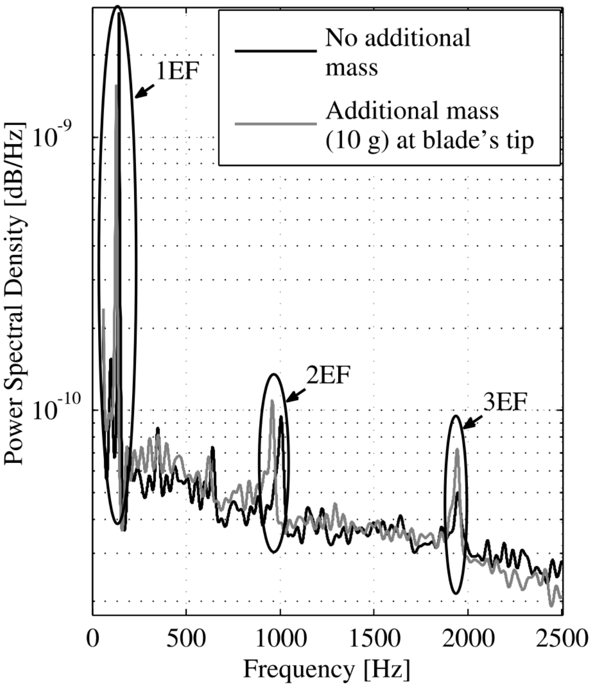

Fig.3. Example of the frequency response change due to attached mass of 10 g

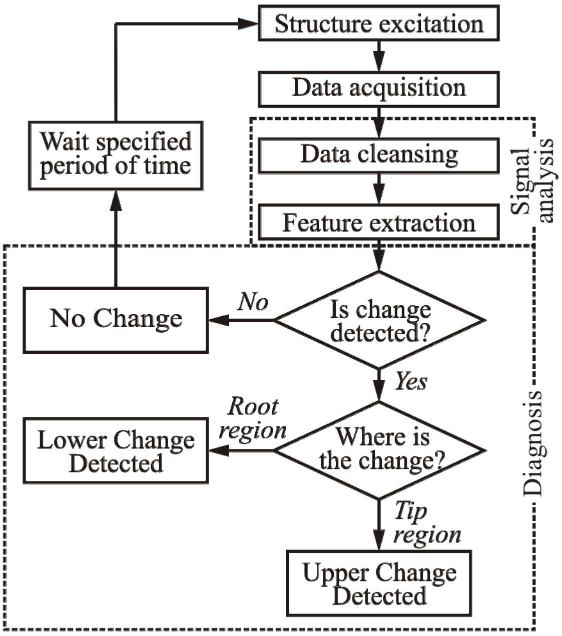

Fig.4. Repetitive diagnostic sequence implemented in the on-line structural health monitoring system

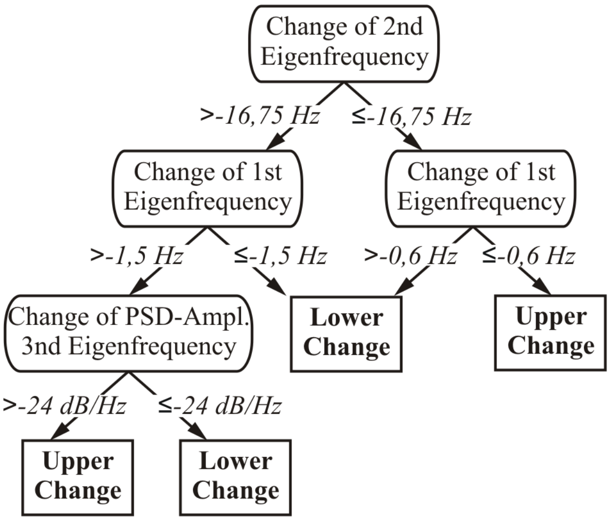

Fig.5. Example of the deterministic decision tree

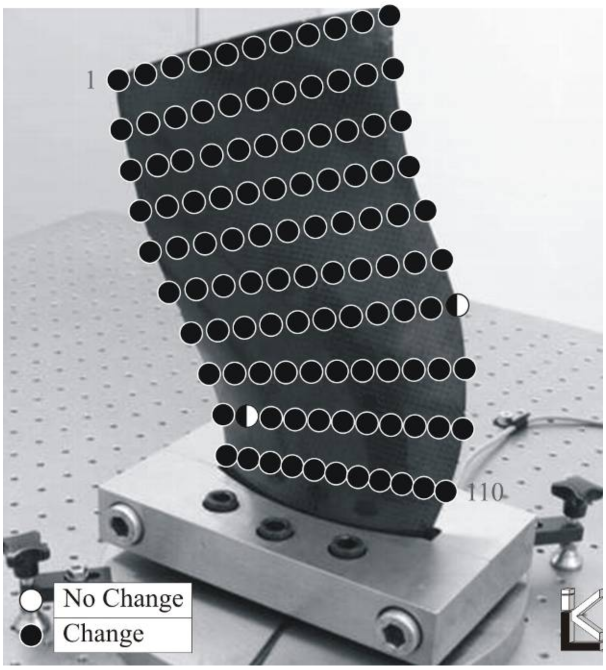

Fig.6. Classifier performance for 10 g mass detection

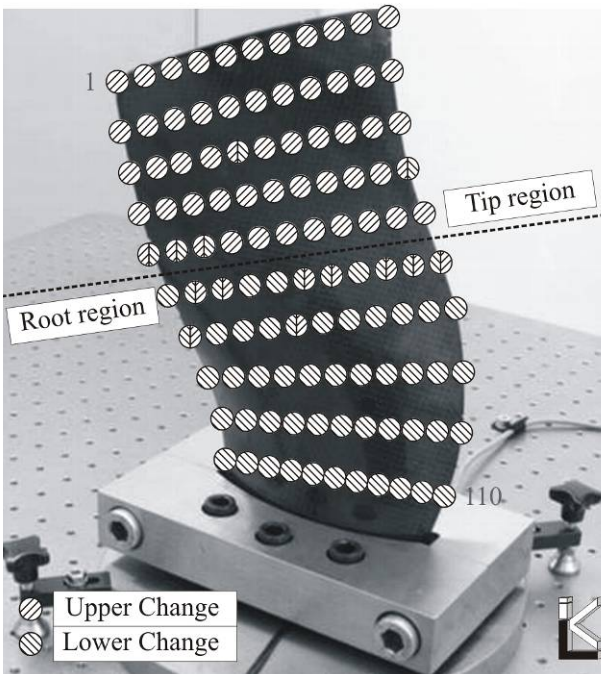

Fig.7. Classifier performance for 10 g mass location

Table 1. Estimated theoretical classifier performance of the diagnostic method for different masses

		Classifier	
		Detection	Location
Diagnosis performance [%]	Attached mass 10 g	97,3	89,1
	Attached mass 5 g	91,5	94,5
	Attached mass 2 g	90,8	81,9

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