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Vibration control of smart structures using an array of Fiber Bragg Grating sensors

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ABSTRACT

Optical strain gauges, such as Fiber Bragg Grating (FBG) sensors, are widely used to monitor the health of structures and their state of deformation. This paper proposes exploiting the measurements of these sensors as feedback for active vibration control applications. The advantages of this solution are the possibility of monitoring a large number of sensors (to approximate distributed measurements) and of embedding them in carbon fiber structures with negligible load effects. Experimental tests confirm that smart structures with embedded FBG sensors can be profitably designed to suppress vibrations.

1. Introduction

The widespread use of lightweight structures has emphasized the need to reduce undesired vibrations that can compromise the integrity of the system. Advances in materials technology have made available a new generation of structures regarded as smart. These systems can tune functionality to specific input, for example by changing their shape, stiffness or damping in response to a controllable input [1,2]. To achieve these results, smart structures are instrumented with sensors to evaluate system deformation and actuators to perform control actions [3].

Composite materials are interesting for the construction of smart structures thanks to their high mechanical properties and to the possibility of embedding sensors and actuators. Measurements relating to the structure deformation are used in a control algorithm that is generally based on robust control theory and structural dynamics [4–6]. Depending on the control algorithm, signals are sent to the actuators to generate the desired control forces, whose effect on the structure results in a change of shape, stiffness [7] or damping [8].

One of the most common applications of smart structures is vibration control. This field is interesting especially for lightweight structures, in which vibration phenomena may reduce the fatigue life of structural components [9], and also worsen the functioning of the system, causing discomfort and compromising the safety of people and objects [10].

In this field a sufficiently large number of measurements is preferred to check the state of vibration of the system [11–13]. Moreover, actuators and sensors must be easily integrated in the structure and must offer reduced loading effects [14].

Having a large number of sensors can be technically problematic, but Fiber Bragg Grating sensors (FBG) prove to be an interesting solution for inserting a large number of measuring points on a structure [14–16]. The great advantage of this technology is that a single optical fiber is able to provide a set of measurements of deformation at many points, providing distributed measurement along the structure. The small dimension of the optical fiber and the near absence of load effects make FBG sensors interesting for smart structures [17,18]. In literature, the most common applications of FBGs are structure health monitoring, damage detection and strain measurement in harsh environments[16,19].

One of the first applications of optical fiber sensors for vibration monitoring was presented by Houston in the early nineties [20]. In the following years, several research groups have focused their attention on achieving active control of vibration with FBG sensors. A single sensor was used by Chau and Chuang [21–23] to control the first vibration mode of a cantilever beam. Cheng et al. [24] use an FBG sensor to monitor the vibration of a flexible structure immersed in a fluid. Active vibration control has been implemented on a plate by Ambrosino et al. [25]. Gurses [26] presented an active control using measurements provided by a particular distributed sensor based on optical fiber technology that provides the state of deformation of a strip controlled by PZT actuators. More recently, a resonant inertial actuator with a single embedded FBG sensor was proposed by Cavallo et al. [27].

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In this context, the aims of this paper are:

– to extend the results obtained by previous research, exploiting the very high number of measurements made possible by FBG sensors. Thanks to the large number of sensors, a quasi-distributed measurement becomes available and the observation of the vibration phenomenon can be optimized [28–30]. Consequently, the control logics can be improved to achieve their best possible performance. Different control solutions can be introduced depending on the number of sensors and actuators involved in the control algorithm.
– to investigate the possibility of using commercial devices to perform active vibration control, in order to easily extend the results of the research to a large number of practical applications. As a matter of fact, much research in this field is carried out with ad hoc equipment that would be unthinkable in practical applications outside a research laboratory, thus limiting the effectiveness and the interest of the research. On the contrary, a commercial device is already a standard solution and can be profitably used in many practical applications.

The paper is structured as follows. Section 2 recalls the basics of optical fiber and FBG sensor technology, highlighting the advantages of their use in vibration control applications and their limits. Section 3 introduces some control algorithms, based on the increase of structural damping, implemented to demonstrate the effectiveness of FBG sensors in vibration suppression. Section 4 introduces the test bench designed to suppress vibrations using FBG sensors and PZT actuators. The experimental results are presented in Section 5. Tests have been carried out to evaluate the performance of the system with different controllers and different sets of sensors and actuators. Finally conclusions are drawn in Section 6.

2. Optical sensors in vibration control applications

Fiber Bragg Grating sensors, belonging to the optical strain gauges family, are a promising technology in active control applications. The working principle of these sensors is known and it is described in depth in [14], as are the different techniques available to measure the peak shift of the reflected light-wave.

The use of Fiber Bragg Grating sensors in active control of vibrations can be advantageous thanks to the small cross-section that allows them to be embedded in carbon fiber structures with negligible load effects and to the possibility of embedding tens of sensors on the same optical fiber, thus having a large number of measurements without increasing the number and complexity of cables and wiring. Both of these aspects are interesting in vibration control applications, since they provide an insight into the state of deformation of the structure using a non-invasive measurement system. Though the advantages of this technology are evident, there are a number of limitations to its use in applications of vibration suppression that can undermine the effectiveness of control. The main negative factors are related to the delay in the feedback signal due to the processing and the transmission of the signal by the optical interrogator, the discretization of the measurement signal and the resolution of the sensors. In this paper, the effects of these limitations are analyzed and some solutions are presented for exploiting this technology in vibration suppression applications. In the paper, in order to allow the use of technology-based FBG sensors in a large number of potential applications, the intention of the authors is to use only commercial instrumentation. As discussed in the introduction, this allows the results obtained in this work to be extended to a large number of practical applications and sensor configurations. In detail, the signals coming from FBG sensors are acquired using an interrogator based on the *Swept laser* interrogation technique. This interrogator technology, compared with other ones, allows a larger number of sensors (even larger than the number of sensors considered in this paper) to be managed and provides higher flexibility in sensors characteristics (e.g. the wavelength). This means that the number of sensors could be further increased if the structure to be controlled requires an greater number of measurements.

The interrogator adopted is the *MicronOptics SM130-500*. It has a resolution of 1*pm* (corresponding to a strain resolution of 0.84 μm/m) and a sampling frequency of 1 kHz, it has 4 optical channels and manages a maximum number of 80 FBG sensors on each channel. The output is provided through a digital *TCP/IP* Ethernet transmission. The resolution is due to the peak detection and cannot be improved with dynamic interrogators. A better resolution could be obtained only by using static interrogators, but these cannot be used for control applications. As previously mentioned, the main concern with this digital output is the time delay between physical light input and digital data transmission through the Ethernet board. This effect is related to how the peak is measured from the optical spectrum and to the non-deterministic digital Ethernet transmission. To evaluate the acquisition system time delay, tests were done comparing the measurements obtained with both electrical and optical strain gauges applied to the same section of a cantilever beam (Fig. 1a).

The system was excited by a shaker using a sinusoidal input. The mechanical strain is measured simultaneously by the electrical and optical strain gauges. The optical fiber signal is acquired by the interrogator, sent to a PC through the *TCP/IP* connection, acquired through a simple software and outputted to an electrical analog signal by a *DAC* board. The electrical signal is then re-acquired by an acquisition board together with the signal coming from the electrical strain gauges (Fig. 1b). This board, set to 51.2 kHz sampling frequency, is able to guarantee the synchronization of the acquired signals, so that a time delay analysis is possible. To acquire the electrical strain gauges a conditioning module was used. The delay is measured by means of a cross-correlation analysis between the two signals. The results show a delay of (1.7 ± 0.6) ms (Fig. 1c and d). The measured delay includes the interrogator, the *TCP-IP* connection, the software and the *DAC* delay, and represents the total delay due to the use of a digital interrogator. This limitation is difficult to be overcome. Indeed, the use of an interrogator based on different technologies (e.g. linear filter interrogators[25,26]) allows to reduce this delay. Unfortunately this kind of device cannot manage high number of measurements and its use in different applications is limited owing to the high customization of the instrumentation.

A significant contribution, in addition to this delay, is due to the need of low-pass filtering the feedback signal, to avoid high frequency contributions in the control force due to the quantization of the feedback signal. Indeed, the 1 kHz limitation to the feedback loop (due to the sampling frequency of the interrogator) is much lower than the bandwidth of most smart actuators (piezoelectric, magnetostrictive, etc.). For this application, a 4th order 200 Hz Butterworth filter was considered. Since the Butterworth filter phase is almost linear at low frequencies, its behavior can be approximated with a time delay. As a consequence, the average total feedback loop delay in control applications can be calculated as δ = 3.6 ms. Time delay results in a control action phase shift that increases linearly with frequency. As control applications are very sensitive to delays between system vibrations and the corresponding control action (which results in a phase margin reduction), there is a limit to the maximum frequency to be controlled. Considering as acceptable a maximum delay of *0.5* rad, the maximum control frequency can be computed as

$$f_{max} = \frac{1}{2\pi}\frac{0.5}{\delta} \approx 20\ \text{Hz}. \quad (1)$$