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High-speed internal strain measurements in composite structures under dynamic load using embedded FBG sensors

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ABSTRACT

Internal strain measurements in cross-ply carbon-epoxy composite plates under dynamic loads are carried out using embedded FBG sensors. The principle of the FBG interrogation is based on intensity demodulation achieved via a Fabry-Pérot filter. To account for the non-linearity of the filter, the system is calibrated and the amplitude of the strain data is validated. Strains are acquired at a rate of 100 kHz with a noise level as low as 2 $\mu\varepsilon$ and used for modal analysis and strain monitoring in low energy impact. The experimental results under impact and modal analysis compare very well with pertinent numerical models and modal analysis obtained from laser vibrometer measurements.

1. Introduction

Characterization of the response of polymer composite structures to dynamic and impact loads is at the forefront of experimental mechanics. This is due to an ever increasing interest for long-term monitoring and control of aerospace, naval, and civic structures. A first step towards addressing the pertinent problems is the real time strain response of the structure due to the external loads and the associated damage, in particular due to impact [1]. The response of a structure to dynamic excitation is traditionally carried out using either local probes like accelerometers, laser vibrometers for velocity measurements, polyvinylidene fluoride sensors, piezoelectric sensors or strain gages.

Since the arrival of optical fibers technologies various types of sensors, like intensity-based or optical cavity based sensors have been investigated for their use in composite structures [2]. With the introduction in the early 90s, Fiber Bragg gratings (FBG) have proved to be promising for temperature- and strain-sensing applications and are since then extensively used in structural monitoring of fiber reinforced composite structures [3]. Beyond the advantage of being immune to electromagnetic fields, FBG sensors are particularly compatible to fiber reinforced materials because of their small size and low density. The optical fibers are shown to be minimally invasive [4] and are well suited for long time integration in structures and hence for structural health monitoring. The response of FBG sensors has been well understood under quasi-static loads [5,6] and many principles for FBG read-out, which are limited in speed to a few kHz, have been investigated [7]. In impact loads FBG sensors are used for strain measurements after the impact event [8,9]. Recent advances in high rate interrogation systems for short Bragg gratings permit the use of FBG sensors in structural health monitoring. Several interrogation systems based on intensity modulation have been proposed during the last years. The intensity demodulation is achieved by coupling the Bragg reflection peak through a filter which can be either a chirped and strongly apodized fiber grating having a linearly varying transmission spectrum [10], an arrayed waveguide grating [11], a standard Bragg grating [12] or a Fabry-Pérot (FP) filter [13]. A very sensitive intensity-based measurement principle uses a tunable laser light source initially set to a wavelength at full width half maximum (FWHM) of the Bragg grating reflection band [14–16]. A high speed swept light source is also studied for being used for fast interrogation of wavelength division multiplexed Bragg gratings [17]. Another fast interrogator for multiplexed FBG sensors is based on the conversion of wavelength to time measurement using a dispersion compensating module [18].

Fast FBG interrogation systems need to be further investigated in order to improve the signal-to-noise ratio and the accuracy in strain amplitude, to facilitate a good quality calibration procedure and last but not least to allow an easier handling and compatibility to different sensors. In this work, the MO si920® 'Alpha' Prototype FBG interrogator is used to acquire strains at high frequencies. In cooperation with Micron Optics, the instrument was modified to obtain a precise calibration of intensity–strain and an improved sensitivity and signal-to-noise ratio.

Finally the system is adapted to the test configuration for impact and modal analysis. The data obtained from the tests are validated using pertinent numerical models. The applicability of embedded FBG sensors as a tool for modal analysis or for in situ

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monitoring of local and dynamic strains is demonstrated and paves the way for new methods in structural health monitoring. The following sections are dedicated to the presentation of the fast FBG interrogation principle and the calibration of the system, the validation of the dynamic measurements, and finally the application of FBG sensors in experimental modal analysis and in situ strain monitoring under impact load.

2. Fast FBG interrogation

An FBG sensor is an optical interference pattern written by UV irradiation in the core of an optical fiber which usually has a cladding diameter of 125 μm. If broadband light is coupled into the fiber, a narrow wavelength band is reflected. The peak wavelength of this reflection band, called Bragg wavelength λ_B depends on the period Λ of the modulation of the refractive index along the fiber core and the effective refractive index n_{eff}:

$$\lambda_B = 2n_{eff}\Lambda$$

If the grating is submitted to strain, the Bragg wavelength λ_B shifts by an amount $\Delta\lambda_B$. Under the condition of a uniform longitudinal strain along the optical fiber axis and no temperature changes, the wavelength shift is related to the strain ε via the elastic–optical coefficient p_e:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon$$

The Bragg wavelength λ_B is commonly determined using optical spectrum analyzers which are limited in speed to a few hundred Hertz. However, fast interrogation of the Bragg wavelength (several kHz) would make FBG sensors suitable for monitoring internal strains in structures that are submitted to dynamic excitation like impact or vibration load.

2.1. FBG interrogation principle

The prototype device si920® from Micron Optics served as a platform for the improved operating principle presented in this paper. Simultaneous acquisition of four FBG sensors at a rate of up to 220 kHz per channel is feasible. The present device comprises two channels with a maximum range of 2000 με and two channels with a maximum range of 10,000 με. Apart from a common light source, the channels are independent and built in a similar configuration.

The basic principle used for the presented FBG interrogation system is the modulation of a wavelength shift $\Delta\lambda_B$ of the Bragg reflection band into an intensity variation which can then be acquired at high rates. This modulation is achieved by coupling the Bragg reflection spectrum through a tunable Fabry-Pérot (FP) filter as it is shown in Fig. 1. When the Bragg wavelength λ_B is located and varies on one edge of the FP filter function, the relation between the integral intensity of the filtered reflection peak and the Bragg wavelength λ_B is unique.

A simultaneous reference measurement of the integral intensity of the unfiltered Bragg reflection allows for taking into account intensity fluctuations of the light source and for losses in the light guides. The recorded signal is a ratio between the intensity of the filtered and unfiltered Bragg reflection peak. In order to obtain a strain signal, a discrete calibration curve expressing the relation between intensity ratio and strain has been established over the whole measurement range of each optical channel. Then, the data points of the strain signal are calculated from the intensity ratio signal via the calibration curve using a spline interpolation function.

The use of a tunable FP filter allows for initially setting the FP filter wavelength λ_F to a given wavelength offset to the Bragg wavelength λ_B of the FBG sensor and hence to an initial intensity ratio. This tuning step provides compatibility to different FBG sensors, permits to compensate for wavelength drifts due to slow temperature changes and sets the zero strain reference. The FP filter is tuned in a closed loop to the target intensity ratio prior to a measurement. Then the driving voltage of the FP filter is kept constant during a measurement. In our setup the driving voltage for the tunable filter is given by the analog output of a NI 6229 DAQ-card and is directly controlled by the acquisition software. In order to take into account the non-linearity between the tuning voltage of the FP filter and the actual intensity ratio, an exponential differential controlling loop is used. The parameters of the controller are based on the experimentally determined variation of the measured intensity ratio with the driving voltage of the FP filters.

2.2. Calibration of FBG interrogator

A basic requirement for a correct and scientific use of FBG sensors for monitoring dynamic strains is an accurate and reliable calibration. Throughout the present study FBG sensors of 3 mm gage length are used. The grating is written in an SMF-28 optical fiber with polyimide coating that has been removed along the FBG length and beyond by a few mm on each side. The described measurement principle and its calibration can be used for different gratings. The following specifications of the FBG however have to be met in order to guarantee for correct results: the reference Bragg wavelength of the grating should be around 1550 nm, its reflectivity 90% and the Bragg reflection bandwidth 500 pm which in general has to be smaller than the free spectral range (FSR) of the FP filter. The finesse and the FSR of the FP filter define the strain range and the sensibility of a channel.

The non-linear relation of the measured intensity ratio to the wavelength shift $\Delta\lambda_B$ and hence the longitudinal strain ε depends mainly on the shape of the FP filter function and slightly on the characteristics of the Bragg grating reflection spectrum. Due to the non-linearity it is not sufficient to determine a constant calibration factor. In this case a calibration curve is determined throughout a traction test on an unembedded FBG. In order to guaranty for correct results the calibration is carried out with respect to the longitudinal strain ε on the fiber and the corresponding Bragg wavelength shift $\Delta\lambda_B$.

Using a specially prepared cardboard frame the optical fiber with the FBG is clamped with a span of l_0 = 100 mm on an electro-mechanical traction test machine Bose ElectroForce® 3200 which is equipped with a force transducer (at 220 N max load) and an LVDT for displacement measurements (Fig. 2). The fiber is prestressed by 1 N and loaded with a sinusoidal force. Since the relation of the intensity ratio to the wavelength shift is independent of the frequency of the signal, the test could be carried out at a low frequency of 0.5 Hz. For each channel, a first calibration test is carried out, where the excitation force F, the displacement Δl, and the intensity ratio is measured (Fig. 2). The combined measurement of force and displacement allows to determine the apparent Young's modulus E of the optical fiber. The apparent Young's modulus of an uncoated fiber is 71.3 GPa for a glass fiber with a cross-section diameter of 125 μm. Traction tests on polyimide coated fibers have shown a negligible difference in apparent stiffness of 1.2%. Furthermore eventual slipping of the fiber at the grips can be easily detected in the load–displacement curve.

By plotting the strain signal as a function of the intensity ratio, it is shown that the calibration curve is reproduced reliably over multiple loading cycles. The calibration curve of each channel is then reduced to 100 data points. This number of data points is a reasonable compromise between required computational power for signal treatment and accurate conversion of intensity ratio to strain when a spline interpolation function is used.