Sensors and Actuators A 239 (2016) 185–195

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# Simultaneous precision measurement of high temperature and large strain based on twisted FBG considering nonlinearity and uncertainty

Yanhui Zhang, Wenyu Yang*

*State Key Lab of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China*

ARTICLE INFO

*Article history:*
Received 18 September 2015
Received in revised form
25 December 2015
Accepted 7 January 2016
Available online 12 January 2016

*Keywords:*
Fiber Bragg grating
Temperature
Strain
Bayesian

ABSTRACT

The measurement of temperature and strain during metal machining process has several challenges, such as high temperature, large strain, great gradient, and many interference factors, and so on. This paper uses the fiber Bragg grating (FBG) to achieve the simultaneous precision measurement of high temperature and large strain that occurred in the metal machining process. Considering the FBG nonlinear problem caused by the cross-sensitive item and high-order sensitivity due to the high temperature and large strain, and the uncertainty caused by the measurement error and modeling error, the Bayesian nonlinear model is proposed. The results of the proposed approach not only give the accurate values of temperature and strain, but also provide the corresponding uncertainty in the form of posterior probability density function. Then the indicators of measured accuracy and consistency are defined to evaluate the measurement performance of FBG. Finally, the experimental platform of controlled high temperature and large strain is constructed to verify the proposed method. Next we plan to use the proposed method in the real machining environment.



## 1. Introduction

With the Chinese economy to the deep ocean, more and more high-power (at least 3500 kW power) dynamic positioning systems are required to equip the large marine platform, submersible, aircraft carrier supply ship, and other large marine equipment. The controllable pitch propeller is one of the most important thrust components of the dynamic positioning system. In order to obtain the longer lifetime of the propeller in the harsh marine environment, many researchers have carried out the mechanism research of the anti-fatigue machining of the controllable pitch propeller. The machining process of the propeller is usually accompanied by the high temperature and large strain (even great strain rate) in a small area (the primary and secondary deformation zones) [1]. The high temperature and large strain (strain rate) could affect the microstructure formation of the metal surface [2], and further affect its anti-fatigue performance. Therefore, the simultaneous precision measurement of the temperature and strain in the metal machining process is important for the mechanism research of the anti-fatigue machining.

The measurement challenges of the temperature and strain during the metal cutting process have the following characteristics. (1) The temperature and strain field are the energy coupling field, and are transformed into each other during the cutting process, which requires the simultaneous measurement of the temperature and strain. (2) The gradient of the temperature/strain field is great: which requires the sensor as small as possible, and the measurement process can not destroy the measuring surface, otherwise it will lead to the redistribution of the temperature/strain field. (3) Change rate of temperature/strain field is high: which requires the sensor sampling rate is high. (4) Measurement environment is complicated, and is interfered by many factors, such as the cutting tool, chip, and so on. (5) Because of the several restrictions above, the measurement process is inevitably affected by many uncertainties including the measurement noise and modeling error. Assessing and reducing these uncertainties is essential to improve the measurement accuracy.

Most of the current literatures usually separately research the temperature and strain measurement. There are many methods to measure the cutting temperature measurement [3–5], such as the thermocouple methods, physically vapour deposited film method, infrared camera, thermographic phosphor thermometry, and so on. The strain measurement of the metal cutting is mainly based on the digital image correlation or particle image velocimetry method [6–8]. Uhlmann et al. [9] proposed a new method based

* Corresponding author. Tel.: +86 27 87548180.
*E-mail addresses:* yanhuizhang@hust.edu.cn (Y. Zhang), mewyang@hust.edu.cn (W. Yang).

http://dx.doi.org/10.1016/j.sna.2016.01.012

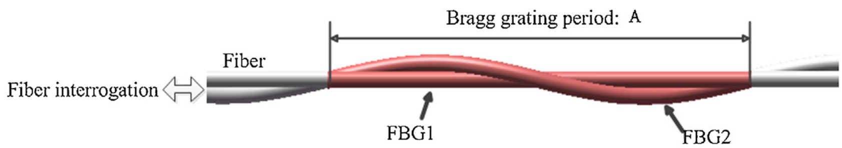


**Fig 1.** Twisted configuration of two FBGs.

on X-ray diffraction to measure the strain. Although the method could achieve the in situ strain field measurement, this method is limited to the quasi-static experiment. There are relatively few methods that could simultaneously measure the temperature and strain in the literatures. Potdar and Zehnder [10,11] have proposed a method, in which the temperature is measured using the InSb infrared detector and the deformation is obtained by the grid method. Actually, the precision measurement of the cutting temperature field only through the infrared detector above is difficult, because there are many uncertainty sources due to the complexity of the machining process [4,12,13].

According to the measurement requirements, this paper uses the fiber Bragg grating (FBG) to simultaneously measure the temperature and strain. FBG is sensitive to temperature and strain at the same time. The diameter of FBG is smaller than 0.2 mm, which can be attached directly to the measurement object surface, without disrupting the distribution of temperature and strain fields. The sampling rate of FBG can be up to MHz, which can satisfy the fast response of dynamic temperature and strain measurement. And also FBG can easily achieve the distribution measurement of temperature and strain at the different positions.

Recently, major development trends of FBG are the application in the extreme environments [14]. such as high temperature [15,16], large strain [17], high pressure [18] or shock [19] or detonation [20], and the development of the ultra-high-speed (100 MHz) fiber interrogation [21], and so on. In the multi-parameter measurement application based on FBG sensors, lots of methods have been proposed by many researchers, which could be classified into five categories [22]. The twisted fiber is a famous concept [23] that could simultaneously measure the temperature and strain [24–26]. In the twisted configuration, two FBGs are usually used, from which one FBG is straight and another FBG is twisted. Recently, Lee et al. [27] research the nonlinear polarization in twisted birefringent microfibers. Yang et al. [28] proposed the orthogonal polarization mode coupling of the pure twisted polarization maintaining FBGs. This paper selects the twisted FBGs method as the sensor configuration, the main reasons are that: (1) the existing FBG interrogation system fulfils the requirements, and other new instruments are not required; (2) the sensing principle of the temperature and strain is simple and clear.

Due to the high temperature (>150 °C) and large strain (>200 $\mu\varepsilon$) during the machining process, the FBG nonlinear problem caused by the cross-sensitive item and high-order sensitivity cannot be ignored. By using the Taylor series expansion, the traditional nonlinear method considered the first order cross-sensitive item and the second order sensitivity. Then the corresponding uncertainty can be generally calculated though the error propagation principle. Jin et al. [29] theoretically analyzed the systematic errors influence on the simultaneous measurement of the strain and temperature using the optical fiber sensors. Tang and Wang [30] theoretically and experimentally research the error analysis for the simultaneous strain–temperature measurement using a reference and a dual-wavelength FBG. Based on the International Standard Organization's Guide to the Expression of Uncertainty in Measurement, Possetti et al. [31] proposed a systematic approach that could identify, quantify, and express the uncertainties in the optical fiber grating sensor measurements.

For the traditional nonlinear method, the higher order cross-sensitive item and the higher order sensitivity are usually ignored, which are referred the modeling error. Furthermore, the measurement error caused by the uncertainty of the FBG sensor arrangement is inevitable. Assuming the modeling error and measurement error are the Gaussian random field, Bayesian statistical modeling framework has been the current popular method to model the uncertainty [32–35]. Bayesian approach could make the robust parameter identification based on Bayesian formula, in which the priori probability reflects the priori information of the unknown parameters, and the likelihood function combines the information of the mathematical model and the measured data. The identified results of the parameters are expressed through the posterior probability density function (PDF), rather than only pinpointing a single solution in the traditional deterministic approach. The posterior PDF quantifies the confidence level of the identified results, which usually provides an important reference for measured accuracy [36].

Using the twisted FBGs configuration, the purpose of the paper is to develop the suitable sensor that could achieve the simultaneous precision measurement of the high temperature and large strain during the machining process. There are two main problems: the FBG nonlinear problem caused by the cross-sensitive item and high-order sensitivity due to the high temperature and large strain, and the uncertainty problem caused by the measurement error and modeling error. Considering theses nonlinear and uncertainty problems, the Bayesian nonlinear model is proposed. The results of the proposed approach not only give the accurate values of the temperature and strain, but also provide the corresponding uncertainty in the form of the posterior PDF. In order to assess the measurement performance of FBG, the indicators of the measured accuracy and consistency are defined. Finally, the experimental platform of the controlled high temperature and large strain is constructed to verify the proposed method.

## 2. Measuring principle of twisted FBG considering nonlinear and uncertainty

### 2.1. Basic measuring principle of twisted FBG

The twisted configuration of two FBGs proposed by Frazão et al. [24–26] is shown in Fig. 1, from which the first FBG1 is straight and the second FBG2 is twisted onto FBG1. The twisted curvature should be large enough to prevent the introduction of the fiber bending power loss.

The thermal sensitivity of FBG is related with the fiber thermal-expansion and thermal-optical coefficient, and the strain sensitivity of FBG is related with the fiber Poisson's ratio, photo-elastic coefficient, effective refractive index of the core and fiber grating period. Because the twisted configuration changes the fiber grating period; therefore, these two FBGs have the similar thermal sensitivity, and different strain sensitivity.

The basic measuring principle of the twisted FBGs is based on the following dual wavelength matrix method:

$$\begin{bmatrix}\Delta\lambda_{B1} & \Delta\lambda_{B2}\end{bmatrix} = \begin{bmatrix}\Delta T & \Delta\varepsilon\end{bmatrix}\begin{bmatrix}K_{T1} & K_{T2} \\ K_{\varepsilon 1} & K_{\varepsilon 2}\end{bmatrix} \tag{1}$$