論 文 の 内 容 の 要 旨

論文題目　Development of High-sensitivity Optical Fiber Ultrasonic Sensing Systems for Structural Health Monitoring of CFRP Laminates
（CFRP積層板の構造ヘルスモニタリングのための高感度光ファイバ超音波センシングシステムの開発）

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In this dissertation, systematic theoretical and experimental studies of three ultrasonic optical fiber sensing systems for structural health monitoring (SHM) of carbon fiber reinforced plastic (CFRP) laminates with their practical applications are presented. These works aim to provide effective solutions to the practical existing problems, including the bandwidth, sensitivity, robustness and system cost, in the interdisciplinary research on optical fiber sensors, ultrasonics, composites, and SHM.

Composite materials, such as CFRP laminates, have many practical applications, including aerospace, automotive, civil engineering, etc. However, the microscopic damages in CFRP laminates are complex, leading to the requirement of SHM for guarantee of its safety. Acousto-ultrasonic method and acoustic emission (AE) method, which are active and passive methods respectively, are attracting and used in ultrasonic SHM. Although sensors based on piezoelectric ceramic materials (PZT sensors) are widely used, they have some disadvantages, such as bulk size, heavy weight and susceptibility to electromagnetic interference (EMI) that limit their application to SHM of composite structures. In order to solve these problems, researchers focus on optical fiber sensor, especially fiber Bragg grating (FBG), due to their advantages of small size, embedding ability, insusceptibility to EMI, etc.

Normal FBG sensors have limited ultrasonic bandwidth and sensitivity, derived from the conflict between grating length and spectrum slope. Thus, designing a novel FBG sensor suitable for ultrasonic detection is primary. We proposed the phase-shifted fiber Bragg grating (PS-FBG) for ultrasonic SHM. PS-FBG is manufactured by inserting a π phase shift in the middle of the grating. Due to this special structure, an ultra-narrow peak is generated from the middle of the structure. Then, we simulated several typical FBGs and PS-FBGs with different parameters. The spectra of PS-FBG include the steep peek in the middle, which has narrow optical bandwidth and no-side-lobes. Then, we simulated PS-FBG's response to ultrasonic wavelength and compared to normal FBGs. According to the simulation results, the ratio of grating length and ultrasonic waveform influences a lot to the responses of the gratings (effective Bragg wavelength shift). When the ultrasonic wavelength is over ten-times longer than the grating length, both FBG and PS-FBG have almost complete response to the ultrasonic strain, similar to the case of static strain. When the ultrasonic wavelength is comparable or smaller than the grating length, the responses from both FBG and PS-FBG become weak. However, the decrement is much gentle in PS-FBG, showing the broader bandwidth response to ultrasonic waves. Furthermore, increment of the index modulation can broaden the ultrasonic bandwidth further and also can increase the spectrum slope. The simulated sensitivity of PS-FBG with deep index modulation parameter will be much higher than that of FBG. Thus, PS-FBG with relative large index modulation is very suitable for ultrasonic detection.

Then, we considered two practical issues in PS-FBG's application. First issue is the sensitivity distribution properties of PS-FBG when surface attachment method is applied. Unlike PZT sensor which is omnidirectional sensitive, the sensitivity of PS-FBG shows large dependency on the angels and the distances. Moreover, the waveforms, initial phases, corresponding spectra are all influenced by the angels and the distances. Thus, the sensitivity distribution of PS-FBG can be roughly divided into three parts. For example, in area C, there exists an angle, which is slightly smaller than 90^o, where the detected wave shows the smallest amplitude due to the counteraction of ultrasonic strains from different angles. Moreover, we investigated the effects of attachment methods, including couplant, adhesive, cantilever fixing and so on. As a result, even though the amplitude of the detected signals change depending on the attachment method, the waveforms were kept the same. On the other hand, they will impact on the birefringence, removability and susceptibility to quasi-static strain. Thus, to the certain application, we should select the most suitable attachment method.

Based on the PS-FBG, we designed suitable demodulation techniques because the Bragg wavelength shift caused by ultrasonic wave is very small and fast. The first sensing system is called cascaded PS-FBGs sensing system. In this sensing system, a broadband amplified spontaneous emission (ASE) light source is used to illuminate the sensor. Two PS-FBGs are cascaded, used as sensor and filter, respectively. When the ultrasonic wave shifts the Bragg wavelength of the PS-FBG sensor, the overlapping area between the sensor and the filter will change, leading to the output power vibration. This sensing technique not only has relative high sensitivity and broad bandwidth due to the utilization of PS-FBG, but also has multiplexing ability due to the broadband light source. The performance evaluation of this sensing system shows that the detectable ultrasonic frequency is up to MHz level, and the sensitivity is high enough to detect ultrasonic signals from PZT actuators and simulated AE signals from pencil lead break. We also practically used the sensing system in acousto-ultrasonic detection and impact detection. It can detect the ultrasonic wave propagating in the CFRP laminate in real time (without averaging for noise reduction). Furthermore, the real-time detected signals can be used to analyze the mode change of Lamb wave, in order to evaluate the damages in the CFRP laminate. All the results show that this sensing system is suitable for acousto-ultrasonic detection. However, although very clear waveforms can be detected when this sensing system is applied to impact detection, large deformation is also observed due to the relative narrow dynamic range of the PS-FBG. Thus, extra attention should be needed.

Although the first sensing system can detect ultrasonic wave, its sensitivity is still limited due to the inherent noise from ASE light source. Therefore, we improved the demodulation technique further in order to achieve higher sensitivity for detection of AE signals in CFRP laminate, which always have very low energy and high frequency. The second sensing system is called PS-FBG balanced sensing system. An external cavity laser is turned to 3-dB position of the spectrum of PS-FBG precisely. Then, the transmitted and reflected light from the PS-FBG enter the two ports of balanced photo-detector (BPD) simultaneously. This sensing technique can eliminate the DC signal, double the AC signal and eliminate the laser intensity noise which is main noise source, thus frequency-noise-limitation sensitivity can be achieved. We then evaluated the performance of this PS-FBG balanced sensing system. The sensitivity of this sensing system is about 28 dB higher than that of normal FBG.

Then, we used the PS-FBG balanced sensing system in AE detection of CFRP laminate. The first experiment is based on tensile test. The PS-FBG is attached on a CFRP laminate via cantilever method. Also, PZT sensor and strain gages are used for providing references. Thousands AE hits were detected. After simple data process method, the EMI noise in the PZT sensor and the low vibration noise in the optical sensor were removed. Then, the cumulative AE hits clearly shows Kaiser Effect, i.e., the AE only occurs when the strain exceeds the previous maximal value. Moreover, according to the different slopes shown in cumulative AE hits, we can separated different damage types in CFRP laminate which are transverse cracks and fiber breakings. These two main results are also demonstrated by different analysis on the AE parameters, such as amplitude analysis and energy distribution analysis, as well as proved by observation via microscope. Then, we compared two experimental results based on different CFRPs, which are angle-ply and cross ply laminates. From different CFRP laminates, we collected different signal waveforms. Considering the waveform properties, signal appearance in the strain level and different CFRPs, we can relate the AE signal to different damage types observed under a microscope. Although the waveforms from tensile test show many interesting phenomena, we did three point bending test in order to analysis the properties of optical AE detection further. In this case, three PZT sensors and one PS-FBG sensor were aligned on both surfaces of a CFRP laminate. This structure can judge the arrival time of the ultrasonic wave and discriminate the components of the Lamb wave. 19 AE signals were detected in this experiment and show same initial phase, meaning they were all from transverse cracks because of the dominant S modes. The CWT analysis of the detected waveforms shows the PS-FBG sensor has more sensitivity to low frequency components, opposite to the PZT sensor. Furthermore, based on arrival time of the detected wave and after data process methods (Fourier filter and Wiener filter), the AE position identification of the PS-FBG balanced sensing system is demonstrated with high accuracy. This part of the research is the first report on AE detection by optical fiber sensing technique.

Although, the above sensing systems show large potential in practical applications, the problem is the robustness because of the small optical spectral bandwidth of the PS-FBG. Thus, we design sensing system with self-adjustment ability. This system is based on erbium doped fiber ring laser with inbuilt PS-FBG sensor (laser-sensor system). Ultrasonic wave detection is achieved by the laser output modulation when the Bragg wavelength shift caused by ultrasonic wave changes the loss condition in the laser cavity. However, when the temperature or quasi-static strain largely shifts the Bragg wavelength of the PS-FBG, the emitting wavelength automatically shifts to the new oscillation position. Then, in the emitting wavelength, the ultrasonic detection is also achieved. A laser dynamic model based on two-level mode of erbium doped fiber amplifier is established for investigation of the property of the laser-sensor system. The simulation results reveal that the detected waveforms are influenced by the relaxation oscillation in the fiber laser. Thus, the detection system is suitable for detection of very small dynamic signals with very high frequency, which is the case of ultrasonic detection. However, mode hopping and instability of the detected signals are also shown in the numerical model, which will of course damage the performance of the sensing system. Then, we evaluate the performance of the sensing system. Firstly, the sensitivity of the laser-sensor system is about 20 dB better than traditional PZT sensors when no preamplifier is connected after PZT. Secondly, up to 7-MHz ultrasonic signal can be seen in electrical spectrum analyzer. Thirdly, the curve of frequency response of the laser-sensor system shows flat property and non-blind areas, unlike the traditional PZT sensor with resonant property and blind areas. Then, we applied this sensing system in acousto-ultrasonic method for evaluation of the damage from impacts on CFRP laminate. Due to the ultra-high sensitivity and broad bandwidth, this sensing technique can real-time detect ultrasonic wave with input peak-to-peak voltage of 5 V and frequency around 1 MHz. Due to its unique ability, the impact damage can be evaluated easier and more obvious.

Finally, in the summary of this dissertation, these systems are compared, especially, about their applications. These novel sensing techniques have potentials to improve not only the safety of composites, but also the safety of people's lives.