

Fiber Bragg Grating Sensors for Dynamic Machining Applications

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ABSTRACT

Fiber Bragg grating sensors have attracted considerable attention for measurement applications due to their greatly reduced size, low weight, and immunity to electromagnetic interference in comparison with traditional sensing methods. Dynamic measurement of industrial machine tools is useful for gauging surface accuracy, monitoring tool condition, and predicting process stability, but requires a robust sensing scheme. The small size and high natural frequencies of micro machining tools coupled with a harsh manufacturing environment can render traditional sensors ineffective. This work presents a new method for measuring tool motion with fiber Bragg grating strain sensors. The feasibility of the sensing scheme is first demonstrated with a simple bench-top cantilever beam experiment. Then, a method for potting the sensors in the through coolant holes of a 1/8" carbide end mill with a high-viscosity gap-filling cyanoacrylate is demonstrated. Comparative structural analysis tests demonstrate the effectiveness of the sensors. Measurements of tool motion during cutting are presented. Finally, methods of noise reduction and improving signal accuracy are discussed.

Keywords: Bragg gratings, sensors, dynamics, vibrations, micro, machining

1. INTRODUCTION

The competitive industrial market has forced manufacturers seek new methods to reduce costs and improve profit margins. Substantial financial benefits can be won if manufacturers are able to monitor and predict errors and improve process efficiency. In metal cutting, accurate measurement of tool displacement is desirable for monitoring tool condition and determining the accuracy of surface placement. Additionally, modal parameters measured during structural tests can be used for of process stability and accuracy. However, manufacturing environments are characterized by harsh conditions that render several common sensing techniques useless. These environmental handicaps coupled with the high frequency characteristics of small cutting tools require the selection of a durable and robust sensing scheme. Potential sensing problems include, mass loading of the tool with conventional accelerometers, inadequate target size for non-contact displacement sensors (capacitance probes or laser vibrometers), coolant flood and chip interference, and the high-frequency limitations of most standard excitation and sensing schemes.

Fiber Bragg gratings have attracted considerable attention in applications varying from monitoring traffic patterns in civil structures to the detection of fatigue cracking in reinforced carbon fiber composites for aerospace assembly¹⁻². This work introduces a novel method for measuring machine tool vibration using embedded fiber Bragg grating strain sensors. Fiber Bragg grating sensors have significant advantages over conventional sensing methods including greatly reduced size, reduced weight, flexibility, and immunity to electromagnetic interference (EMI). In comparison with other optical sensing elements, the principle advantage of the fiber Bragg grating system chosen for this study is that the measured signal is wavelength-encoded. Therefore the sensing mechanism operates independently from the source power and connector loss problems that plague other photonics based sensing systems with fluctuating light levels.

The fundamental principle of operation for Bragg grating sensors lies in constructive interference resulting from light interacting with a reflective grating inscribed in the fiber core. The Bragg grating reflects a sharp spectral peak at the characteristic wavelength (the Bragg wavelength) that corresponding to the grating pattern. Strain sensing is achieved by monitoring the shift in this reflected wavelength, which is modulated by deformation of the grating resulting from thermal or mechanical strain in the fiber. Subsequently, the wavelength shift is filtered and calibrated with a reference signal to calculate the change in strain.

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The following sections will discuss some of the pertinent issues addressed in applying fiber Bragg grating technology to the study of a machine tool vibration. First the proper selection of optical components for filtering and demodulation of a high-frequency signal is discussed. Then, techniques for mounting the fiber sensors on selected structures are presented. Next, the operation of the system is demonstrated on a simplified cantilever beam apparatus. A series of modal tests on a carbide micro end-mill provides the framework by which the Bragg sensors are compared to several traditional sensing methods. Finally, the Bragg sensors are used to monitor tool-tip motion of an instrumented tool during a cutting test.

2. METHODS

2.1 Component Selection

In selecting the components for the fiber based system, an appropriate optical source and detection mechanism had to be chosen. Optical fiber systems also must be designed to operate at specific wavelengths that minimize dispersion, thus optimizing bandwidth. A robust optical source must also allow for direct modulation of output power. Edge-emitting LEDs (ELEDs) have a narrow emission angle which permits good source-to-fiber coupling, which is important when using small core-diameter single mode fibers³. A 1300nm broad band ELED source was chosen for this study.

To address the bandwidth requirements of the metal cutting system the selection of a proper optical detector was essential to ensure acceptable system performance. The important detector characteristics that determine system performance criterion are, spectral response, sensitivity, frequency response, and dynamic range⁴. A semiconductor positive-intrinsic-negative (PIN) photodiode with a 2GHz bandwidth in the 1300nm range was selected for this study.

A schematic of the system designed for the measurement using a single strain signal is shown in Fig. 1.

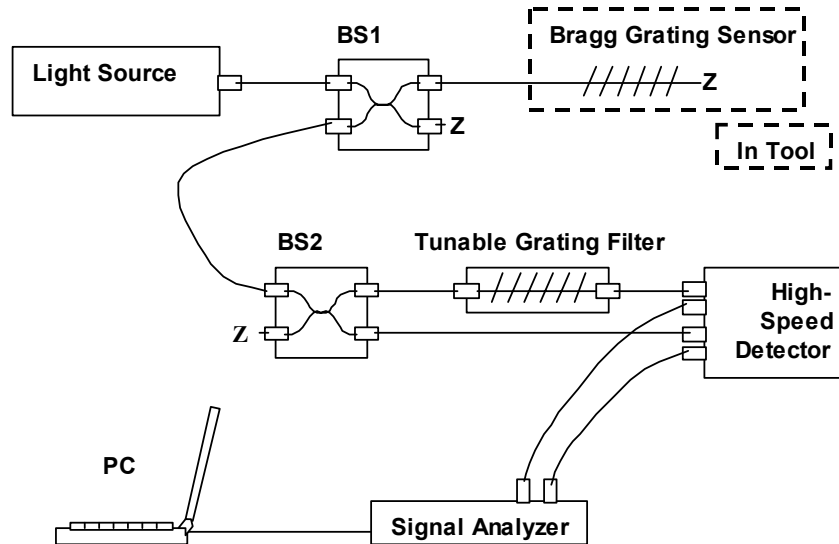


Figure 1: Schematic of a High-Speed single-channel fiber Bragg grating demodulation system with two 3dB beam splitters (BS), port terminators (Z), and a Tunable Grating Filter (TGF).

Tracing the path of an optical signal through the system, the output of the second beam splitter is sent through the Tunable Grating Filter (TGF), which acts as a notch filter, modulating the back-reflected spectral peak from the Bragg sensor. The second beam-splitter output is channeled directly into the detector and used as a reference signal. To calibrate the voltage outputs from the High Speed Detector (HSD), thermal strain effects are added to the Bragg

equation. Then, the overall dynamic change in strain is equated to the normalized ratio of the filtered signal and the reference channel.

Careful consideration must be taken in properly mounting the sensors. Mounting the sensor on the neutral axis of the structure (such as between lamina in a 2-ply composite beam) will obviously result in a signal that does not respond to simple bending vibrations. Additional care should be taken to account for the anticipated structural mode shapes, placing a displacement sensor at a node or a strain sensor at an inflection point will yield no quantifiable results. Finally, proper adhesion of the fiber to the structure under test is vital to the measurement process. If the fiber is improperly mounted, strain profiles and magnitudes can be misleading.

2.2 Fiber mounting

In this study Permabond 910, a general-purpose cyanoacrylate, was used in the surface mounting applications. The mounting surface and fiber were first brushed clean and wiped with alcohol. Then, the fiber was tacked to the surface with cellophane tape and the adhesive was rolled and pressed along the length of the grating with additional tape until the bond had set. Permabond 922, a high-temperature gap-filling adhesive, was used for embedding the fibers in the through-coolant holes of a straight-fluted 1/8" carbide end mill, which required a fiber mounting procedure. First, a custom suction device was designed to draw the high-viscosity cyanoacrylate into the tool from a prepared reservoir. The sensor was then located in the fiber with a laser fault-finder using visible light and marked with high-observability paint. After drawing the adhesive into the through-coolant holes, the suction device was quickly removed and the fiber was inserted into the tool, placing the sensor placed at the desired location. Then, a high-temperature cure was implemented to increase the operating range of the bond.

2.3 Cantilever beam tests

In the initial verification tests on a simplified structure, an instrumented cantilever beam was subjected to various loading conditions to determine its dynamic response characteristics. The performance of the Bragg grating sensor was compared to measurements made with a piezoelectric accelerometer. Excitation of the structure was provided by a simple finger-‘pluck,’ a modal hammer impact, and a surface mounted piezoceramic (PZT) actuator placed at the base of the beam and designed to impart bending moments on the beam proportional to an input voltage. Figure 2 shows the instrumented cantilever beam with the PZT actuator mounted near the base.

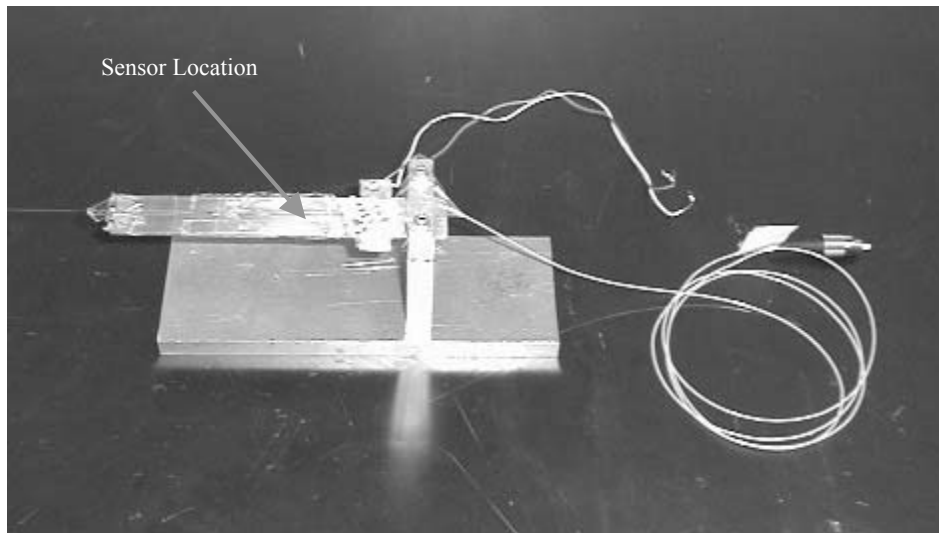


Figure 2: The instrumented cantilever beam with PZT patch and leads on top and above the beam respectively and the fiber optic cable (with Teflon strain relief coating) and connector coiled to the right of the structure.

2.4 Carbide tool tests

For the tool tests, the Bragg sensor was attached to the tool surface after heat-shrinking an aluminum collar to the tool tip; the collar left a gap behind each of the teeth where the sensor was inserted. The fiber Bragg sensor was positioned as closely as possible to the point where the tool diameter increased to the full shank diameter. This point was selected due to the anticipation of large bending strain magnitudes. The collar provided sufficient surface area for impact testing and displacement sensing with a non-contact capacitance probe. Figure 3 shows a sample drawing of a tool used in the study with the sensor mounting location indicated. To determine the modal behavior of the carbide tool, various methods were employed to effectively compare available sensing techniques with the response measured by the fiber Bragg sensor. Figure 4 depicts the tool holding apparatus and shows the bracket used to hold the non-contact sensor.

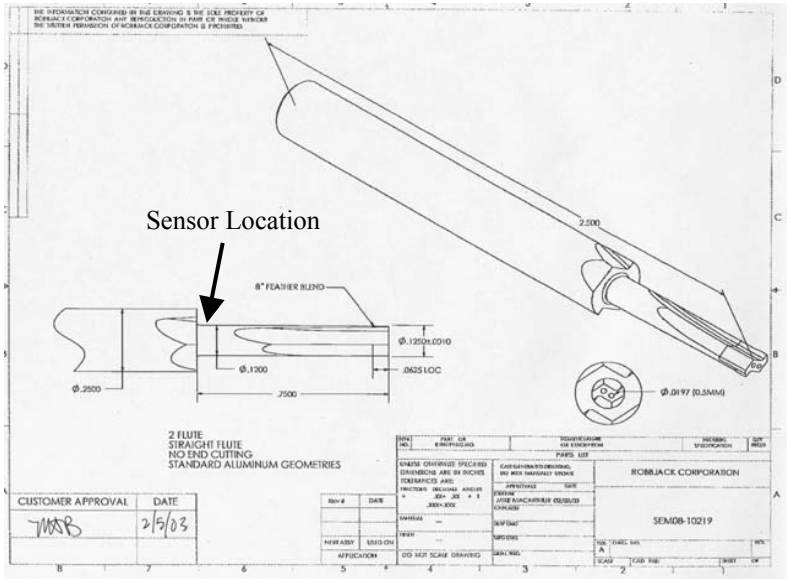


Figure 3: Tool dimensions, with approximate surface sensor location indicated.

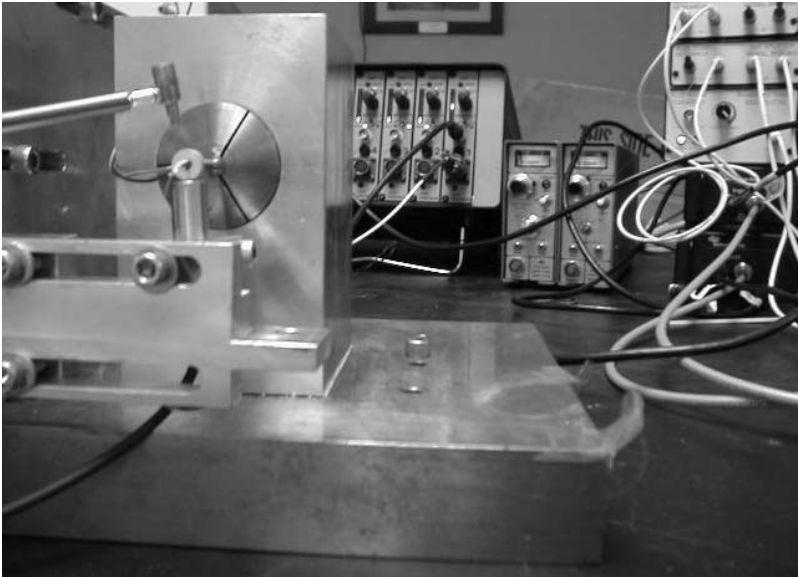


Figure 4: The carbide tool with the aluminum collar heat-shrunk onto the tool tip about to be struck with a calibrated impact hammer, the mounting bracket in the foreground held the capacitance probe; the fiber optic cable and strain relief Teflon tubing are barely visible at the tool tip.

First, a modal hammer was used to excite the system using the aluminum collar as an impact surface. Throughout the process a PZT patch (similar to the one used with the cantilever beam) mounted opposite to the Bragg sensor was also used for system excitation. The surface mounted Bragg sensor was used to measure the tool response. The progressive investigation compared the measurements from each of the methods with those recorded by the Bragg sensor, beginning with the accelerometer mounted on the aluminum collar with wax. After the accelerometer was removed, a capacitance probe was mounted to an adjustable bracket and focused on the collar surface. After removing the collar, the PZT patch provided excitation and the response was measured with the Bragg sensor.

An additional series of tests were performed on another straight-fluted 1/8" carbide end mill with the Bragg sensor mounted internally. The tool was mounted in a lathe collet held in an aluminum toolpost with a tightening nut that allowed the fiber to easily exit out the backside. Modal tests were performed using hammer impacts at the tool-tip to excite the system. Index matching gel was applied to the fiber tip to reduce Fresnel reflections. Numerical averaging techniques were applied to the recorded time series data to increase the signal to noise ratio in the measured data resulting from the difficulty in accurately impacting the tip of the miniature tool.

2.5 Lathe cutting tests

To test the Bragg sensors in an actual manufacturing environment, a series of lathe cutting tests were performed. For the initial proof-of-concept tests, an experimental environment in which the cutting tool remained free from rotation was necessary. To facilitate this requirement, the tool was held in the aluminum tool post, which was mounted on a steel plate affixed to the lathe carriage table. The custom toolpost allowed the fiber optic cable to exit from the rear of the collet clamp. Precision aluminum coupons, shown in Figure 5a, were prepared and held in the lathe spindle to create a simulated interrupted milling environment for the tools. The coupons were prepared such that the difference in diameter between the tool and the center hole of the coupon yielded the desired chip width and the lathe table feed and the spindle speed determined the depth of cut. Three channels of SigLab data acquisition were recorded to monitor the in-tool strain signal from the Bragg sensor during the test. A laser tachometer was focused on an optical barcode mounted on the spindle housing to mark the entry of a tooth into the cut and accurately monitor spindle speed. A schematic of the cutting test set-up is shown in Figure 5b.

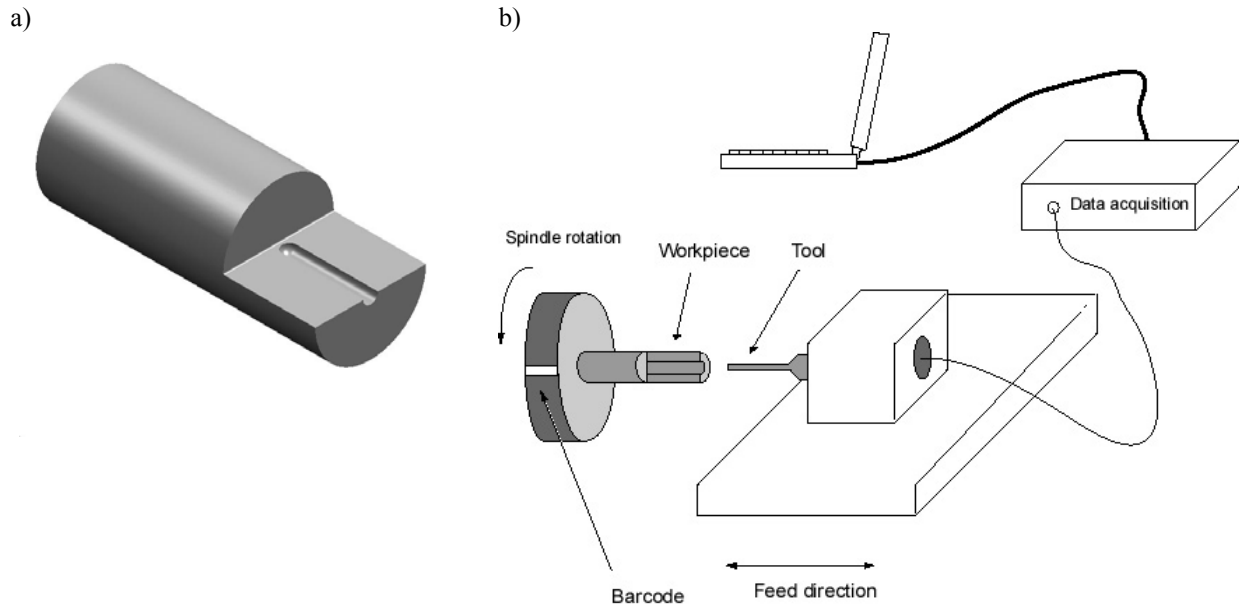


Figure 5: a) Detail of test coupon (workpiece) and b) Cutting test schematic showing test coupon mounted in the lathe spindle and optically instrumented tool mounted to the carriage table; the laser tachometer was focused on the barcode mounted on the spindle housing to mark tooth entry and monitor spindle speed.

3. RESULTS

3.1 Beam measurements

By placing the Bragg sensors on the aluminum beam we were able to compare the measured dynamics with data obtained by analytical predictions and conventional measurement techniques. First, the Bragg sensor was used to monitor the surface strain near the base of the beam during transient motion. Assuming the beam response to be dominated by the first bending mode, Euler-Bernoulli beam theory was used to predict the transverse (up and down) displacement of the tip⁵. Then, the magnitude of the predicted displacement was validated by comparison with an integrated accelerometer signal. A sample transient response is shown in Figure 6a. A digital Fourier Transform (FFT) performed on the transient signal yielded response peaks corresponding to bending natural frequencies that matched those analytically determined within 5%. The magnitude of the FFT is plotted in Figure 6b. The first two normalized bending mode shapes, predicted from the magnitude of the imaginary peak of the frequency response function (FRF) for the beam excited by roving modal hammer impacts at 15 locations along the beam, are shown in Figure 7. The plots show good agreement between predictions from an accelerometer and the Bragg sensor.

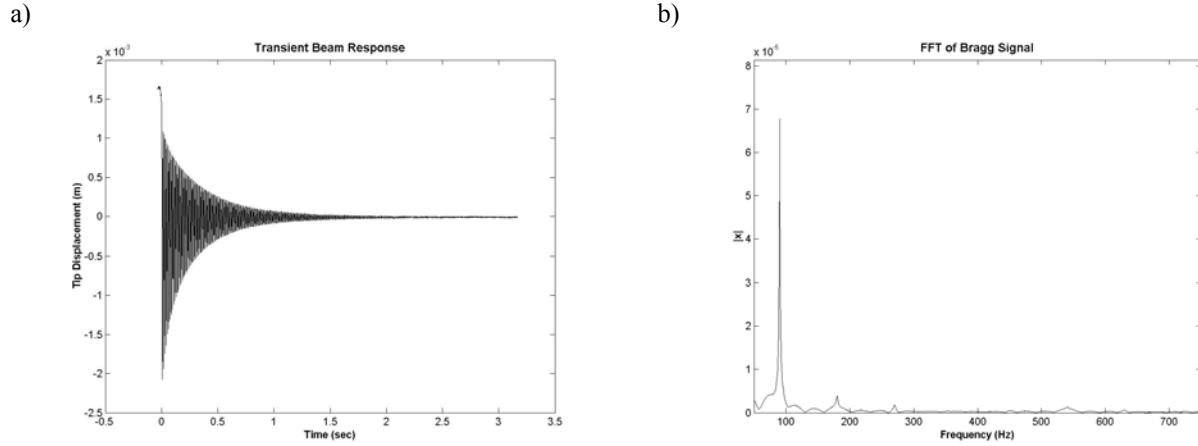


Figure 6: a) Transient response to “pluck” excitation measured by the Bragg grating strain sensor and calibrated for tip displacement and b) the FFT of the transient signal with resonant peaks indicating the bending natural frequencies.

Further demonstrating the necessity of the non-obtrusive measurement capability given by the Bragg sensor, the natural frequencies of the beam were distorted by more than 5% when the beam was instrumented with accelerometer. Table 1 summarizes the results of the experimental beam tests, comparing the results with a simple analytic prediction.

Table 1: Summary of beam bending natural frequency measurements

| Excitation-Response | ω_n 1 (Hz) | ΔF (Hz) | % Difference |
|---------------------|-------------------|-----------------|--------------|
| Analytic Prediction | 102.0 | – | - |
| PZT-Bragg | 95.9 | 0.31 | 5.9% |
| Hammer-Accel | 90.0 | 3.13 | 11.8% |
| PZT-Accel | 89.4 | 1.25 | 12.4% |

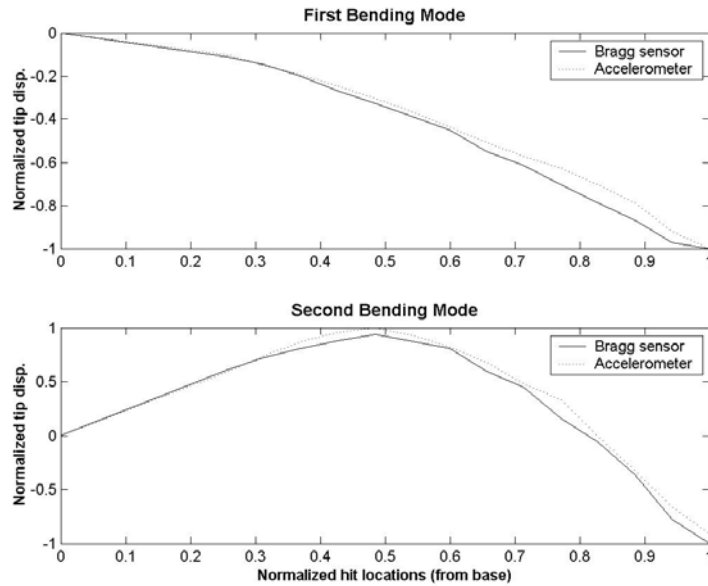


Figure 7: Bending mode shapes predicted by the Bragg sensor compared with those predicted by the accelerometer.

3.2 Carbide tool measurements

A series of tests were performed to qualitatively and quantitatively characterize the miniature carbide end-mills. In the initial tests, the Bragg sensor mounted on the tool surface, near the step down point where the tool diameter decreased from the 1/4" shank to the 1/8" cutter. This location was chosen due to the anticipated high strain magnitude, and to avoid any nodal points (zero strain) of the low-frequency bending modes.

A series of tests were then performed; first hammer and PZT excitations were measured with an accelerometer (mounted on the collar with wax) and the Bragg sensor. Upon removal of the accelerometer, the capacitance probe was used to validate the response measured by the Bragg sensor. The FRFs generated in these tests are pictured in Figure 8. It is important to note that the accelerometer picked up a lower frequency mode (albeit of smaller amplitude) due to vibration of the tool holding structure while the Bragg sensor isolated the tool response. The majority of the system compliance is readily visible in the dominant bending mode. Upon removing the accelerometer, the tool was once again excited with the Hammer and PZT and the response was measured with the non-contact capacitance probe (focused on the larger diameter collar surface to ensure an adequate target size) and the Bragg sensor. Subsequently, the collar was removed and an FRF, shown in Figure 9 was generated from the PZT to the Bragg sensor. A summary of the predicted values for the first bending natural frequencies from all the tests is given in Table 2. Also included are the predicted natural frequencies from a simplified finite element model of the tool, without teeth but including the coolant holes, values from and analytic model of a cantilever column.

Table 2: Summary of Experimental measurements for the first bending natural frequency of the carbide tool

| Excitation-Response | Collar(y/n) | w_n (Hz) | ΔF (Hz) | % Difference |
|---------------------|-------------|------------|-----------------|--------------|
| PZT-Bragg | n | 4592 | 0.125 | - |
| Simplified Analytic | n | 4409 | - | 3.99% |
| Simplified FE Model | n | 4373 | - | 4.78% |
| Hammer-Cap | y | 3723 | 1.563 | 18.92% |
| PZT-Cap | y | 3722 | 3.125 | 18.96% |
| Hammer-Bragg | y | 3722 | 1.563 | 18.96% |
| PZT-Bragg | y | 3719 | 3.125 | 19.02% |
| Hammer-Accel | y | 2725 | 6.25 | 40.66% |
| PZT-Accel | y | 2691 | 3.125 | 41.41% |

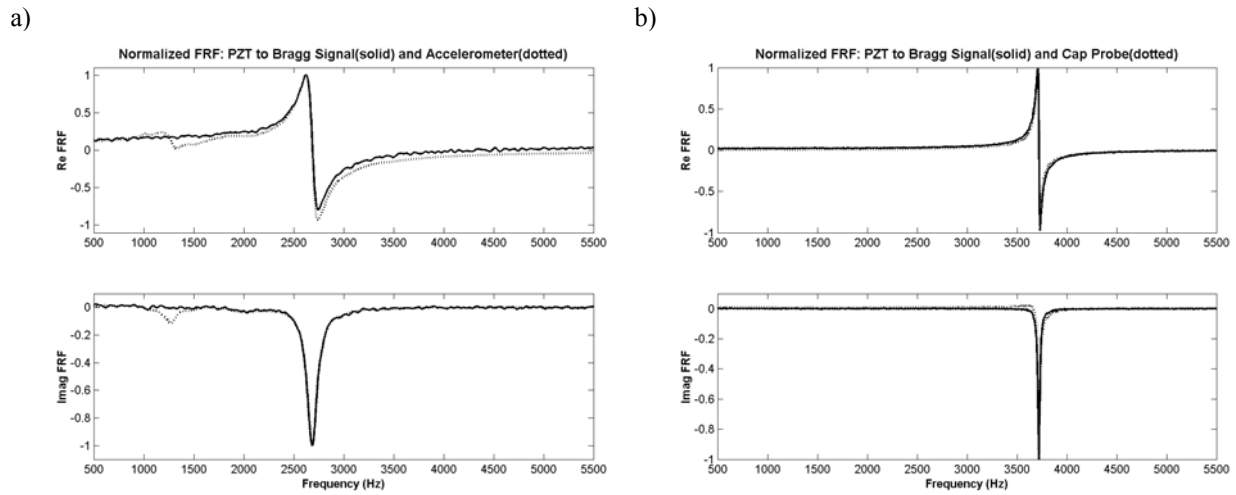


Figure 8: Comparison of real and imaginary parts of a) the normalized PZT-to-bragg sensor FRF (solid) and PZT-to-accelerometer FRF (dotted) for the 1/8" tool and b) the PZT-to Bragg sensor (solid) and PZT-to-capacitance probe (dotted) FRFs.

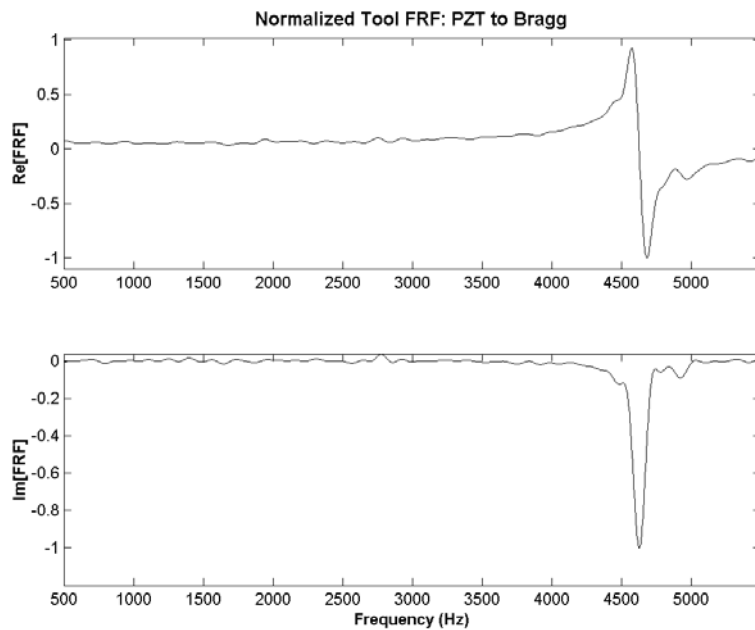


Figure 8: The tool FRF: PZT to Bragg sensor

3.3 Lathe cutting tests

The cutting-tests on the lathe demonstrated the ability to measure tool-tip motion with a fiber Bragg sensor during a metal cutting operation. Tests were performed a several lathe feeds and spindle speeds. Figure 9 shows the calibrated tip motion measured during a test with a chip width of 0.005" (0.13mm), a spindle speed of 2000 rpm, and table feed of 0.008" (0.20mm) per revolution. The dotted line square wave indicates the entry of the first tooth into the cut.

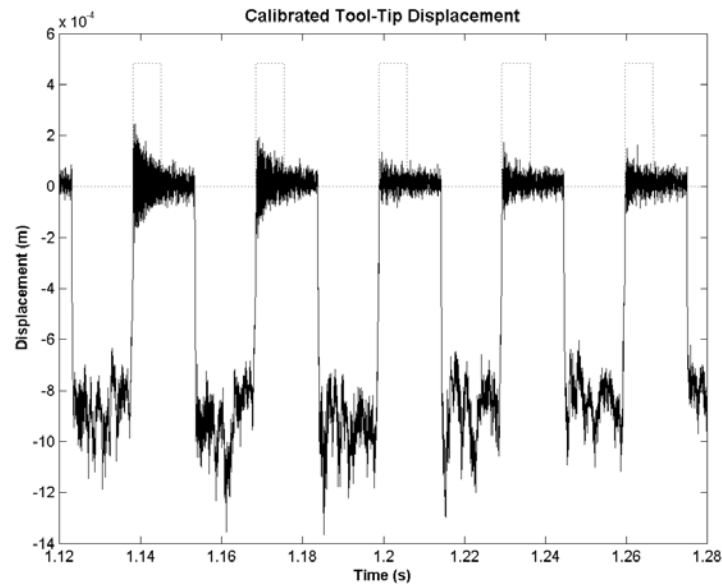


Figure 6: Measured tool-tip motion during a cutting test, square wave indicates exit of tool #2 from the cut

Figure 10a displays the magnitude of the power spectral density (PSD) of the Bragg signal measured during the cut, peaks are readily visible at the spindle turning frequency indicating tool runout resulting from misalignment between the tool and workpiece. Figure 10b plots the log-magnitude of the PSD over the entire measured frequency range, a subsequent peak is evident near the tool bending natural frequency predicted by the modal tests.

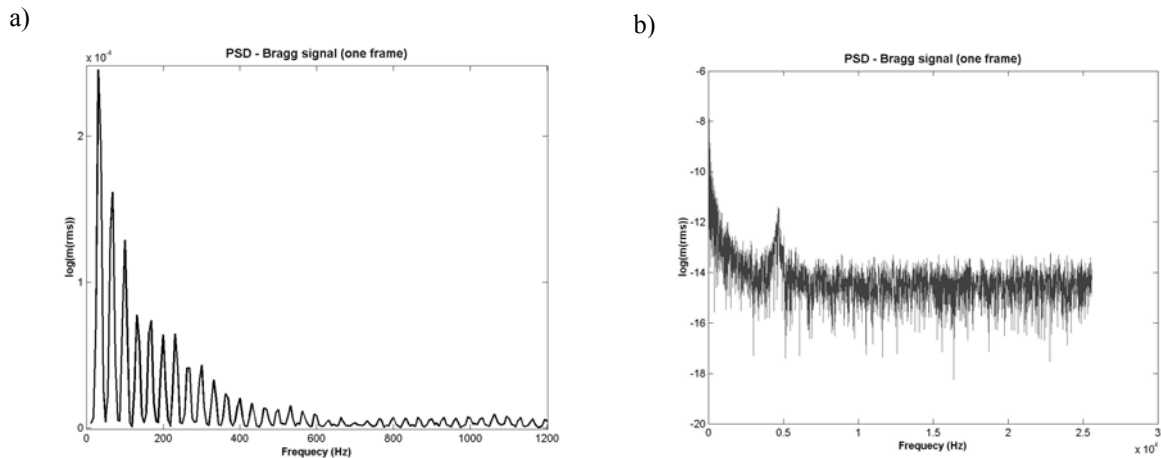


Figure 10: a) linear and b) log Power Spectral Density (PSD) of the Bragg signal measured during a cutting test

4. DISCUSSION

4.1 Sensors in manufacturing

The work presented here introduces a new application of fiber Bragg grating strain sensors to the manufacturing industry. The particular application addressed in this work is measuring the vibration of micro machining tools, in particular two-fluted end mills. The photonics based sensing system addresses a number of the problems encountered in

applying sensing principles to the manufacturing environment. First, the sensor must be resistant to electromagnetic interference, large manufacturing machines draw heavily upon power supplies and fiber Bragg gratings are immune to such interference. Additional interference issues may be encountered with structural excitation methods; large electromagnetic shakers can be a distinct source of measurement noise.

Non-contact displacement sensors, such as capacitance probes, eddy-current probes, and laser vibration sensors, require a “clean” operating environment. Coolant floods or flying chips that are common to metal cutting operations can render these sensors useless. Additionally, each of the aforementioned sensors requires a finite target on which the field or light can be focused. However, many cutting tools are characterized by complex geometries and small sizes that lead directly to nonlinear sensor measurement or insufficient signal reflection.

The biggest hurdle that must be addressed, however, is encountered in applying different sensing methods to micro tools. As mentioned before, small tool sizes limits the application of many sensors due to inadequate targets. But, in attempting to measure the motion of small tools, the engineer must also address inadvertent distortion of the motion resulting from the sensor application. For example, in attaching an accelerometer to a micro-machining tool the tool dynamics may be significantly altered as we saw with the 1/8" carbide tool. A further consideration is the bandwidth limitations of the sensors. Some micro tools may have first bending natural frequencies on the order of 20KHz or more.

Fiber Bragg gratings have been shown to accurately characterize a straight-fluted carbide end mill in modal tests and in a cutting environment. The problems of properly adhering the sensor to the structure under test and protecting the sensor from environmental interference during metal cutting have been addressed.

3.4 Limitations of Approach

Accurate determination of tool tip motion is of paramount importance in metal cutting applications because the tool tip determines surface placement accuracy. Measuring the strain away from the tip does not directly provide the desired information. If it is viable to assume the tool is experiencing simple bending motion, then tool displacement can be determined analytically as a function of strain at a location. However, this is not always the case in metal cutting operations. In down-hole cutting operations bending mode shapes are often quite complex, making prediction of tip motion is a formidable problem. The experiments performed in this study were performed with a single sensor potted in the tool. With a single sensor mounted in the tool, motion on an axis parallel to the mounting axis is indiscernible because the plane in which the sensor is mounted in is coincident with the tool's neutral axis. In this case, only the magnitude of the tool motion on the axis parallel with the sensor can be determined. As such, additional work needs to be done to address full characterization of tool motion. Multiple sensors could provide more complete information about the tool state and increase the accuracy of the prediction process. Sensors mounted on the same axis can be used to map out the mode of vibration and numerical processing signals from sensors mounted multiple locations could fully characterize the tip-displacement vector in the transverse plane. The mounting technique does necessitate through coolant holes in the tool, which may be undesirable in certain applications. Additionally, when mounted on the inside of the tool, the sensor is not easily reusable, a concern in limited budget situations.

Further limitations of the sensing scheme lie in transferring the signal for a rotating tool into the static laboratory frame in which the data filtering and processing generally occurs. Fiber Optic Rotary Joints (FORJs) are the optical equivalent to the electrical slip ring and are used in applications where a twist-free fiber cable is essential, such as missile guidance systems, robotic systems, oil drilling systems, and sensing systems.

5. CONCLUSIONS

This work validates the use of fiber optic Bragg grating strain sensors for the measurement of micro machine tool motion. The sensing system described in this paper addresses several problematic aspects of vibration measurement in metal cutting processes.

6. ACKNOWLEDGMENTS

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