Measurement of Shaft Vibration Using Radar for Rolling Element Bearing Diagnostic

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Abstract

This paper demonstrates the use of a new position sensor using continuous wave radar in measuring shaft vibration for bearing diagnostic. The new radar sensor recently developed at Georgia Tech allows the position measurement to be made with many advantages over available sensors. The sensor has tested for its performance in a control environment with satisfactory result. In order to verify that the sensor is capable of measuring shaft vibration, experiments must be conducted. The radar sensor is tested in comparison to an eddy current probe. The shaft vibration measurements taken from the radar sensor and eddy current probe can be compared directly. The result shows high correlation between the measurements of both sensors, which support the fact that they measure the same quantity. In addition, an accelerated life tested is performed to test capability of the radar sensor in bearing diagnostic application in comparison with the eddy current probe. The result shows that the radar sensor is capable of detecting the progressing bearing damage as sensitive as the eddy current probe by monitoring shaft vibration.

Key Words: Continuous Wave Radar, Bearing Diagnostic, Vibration

1. Introduction

The purpose of bearing diagnostic is to detect early damage of bearing elements in order to prevent their catastrophic damage. This type of monitoring is commonly found on bearings in large capital equipment. Many signal processing techniques have been developed in the past to improve detection performance of sensors. The current state-of-the-art in bearing condition monitoring techniques is reviewed in (Zhang, 2001) and (Billington, 1997).

Bearing diagnostic typically bases on information from at least one of these measurements: housing acceleration, acoustic emission or shaft vibration. In the past eddy current probe is the only industry standard for non-contact displacement transducer for measuring shaft vibration. However, the measurement quality of eddy current probe is affected by many unsuitable environments where surface roughness, magnetic field, inconsistent target metallurgical irregularities, high temperature or shaft current may exists. Recent development of a new displacement sensor using phase-based continuous wave radar offers an alternative to measure shaft vibration in the environment where the eddy current probe capability is limited.

The new signal processing techniques based on phase detection, rather than timing, have been developed at Georgia Tech (Geisheimer et al., 2002; Chuckpaiwong et al., 2002) to permit radar-based systems to make measurements of motion at significantly smaller length scales, in sub-wavelength accuracy. The measured distances resulting from these techniques are on the order of millimeters and micrometers. These developments permit radar to be used as a precision position sensor that has several key advantages, including being non-contact, relatively inexpensive, and capable of penetrating a variety of substances (including oil and coolant) at certain frequencies. Because of this, measurement is viable in harsh environments (e.g., in the presence of dust, smoke, and fluid that can build up on the sensor). These measuring conditions are commonly found in a variety of manufacturing processes.

The radar-based technique is fast and efficient allowing the measurement to be made at a high acquisition rate. In addition, radar components have a wide band of frequency response, whose measuring performance is not affected by a high-speed target. This feature is useful in various vibration applications.

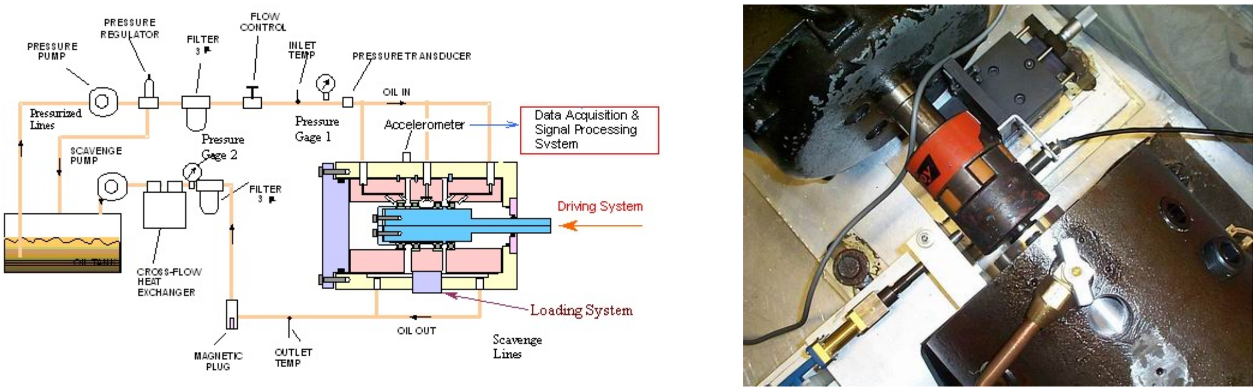
Wagner et al., published results of a microwave vibration monitoring system for power generating turbines (Wagner et al., 1998). Wagner and his Siemens-Westinghouse team used Inconel waveguides to “pipe” the signal from a radar transponder outside the turbine into the combustion chamber aimed at the turbine vane. Although the signal processing method did not measure sub-wavelength vibration, the viability of using radar in combustion environments was demonstrated.

In this paper, experiments are designed to test the capability of the new radar sensor in bearing diagnostic application. The radar sensor is tested against an eddy current probe, which is an industry standard for non-contact proximity sensor. Since both the radar sensor and eddy current probe are non-contact, they can directly measure the vibration of the running shaft simultaneously. Finally, they are used in an accelerated life testing to monitor the development of bearing damage.

2. Test Equipments and Methodology

2.1. Test Equipments

The bearing test system consists of the following subsystems: a test housing, a loading system, an oil circulation system, a driving system, sensors, and data acquisition and signal processing systems. Figure 1(a) is a schematic diagram of the bearing test system. The test housing is made of cast iron, which houses 3 large pieces of steel called tooling. The test system is capable of adjusting desired loads to the tested bearing in both axial and radial directions. A piston hydraulic cylinder is located under the middle piece of tooling to apply a desired radial load to the two bearings. Axial load is applied through a steel end cap, which pushes the tooling that holds the outer-race of the test bearing. The axial load is regulated by changing the torque applied to 6 bolts that hold end cap with the test housing. The oil circulation system is used to remove heat generated inside the test housing in order to prevent premature failure of bearings due to high temperature.



(a) (b)

Figure 1. Schematic diagram of the bearing test system and sensor configurations

A Kamen KD-2300-2S1 eddy current probe is used to measure shaft vibration in direct comparison with the radar sensor. The eddy current probe is installed to measure vibration from the coupling, which is attached firmly to the shaft due to space limitations, as shown in Figure 1(b). The standoff distance of the eddy current probe from the measuring surface is 0.56 mm (0.022”). The probe is calibrated by using a micrometer stage prior to the measurement. The radar sensor is located at the direct opposite side (180° apart) of the coupler to the eddy current probe. The radar sensor is a two-channel 34.5-GHz continuous wave radar that is assembled with off-the-shelf components. The radar sensor is capable of measuring linear displacement with up to 0.2% accuracy (Chuckpaiwong, 2002). The standoff distance from the surface of coupler to the tip of the radar antenna is 0.76 mm (0.030”).

2.2. Test Methodology

Two set of tests are performed in order to validate the shaft vibration measurements of the radar sensor in comparison with eddy current probe. First is to measure correlation of the shaft vibration measurement of the radar sensor and the eddy current probe. The correlation between the two measurements identifies their similarity. If the two sensors obtain similar measurements, they will result in high correlation between them. Second is to use both sensors to acquire shaft vibration measurement during an accelerated life test. The measurements from the eddy current probe and the radar sensor will be used to identify bearing damage.

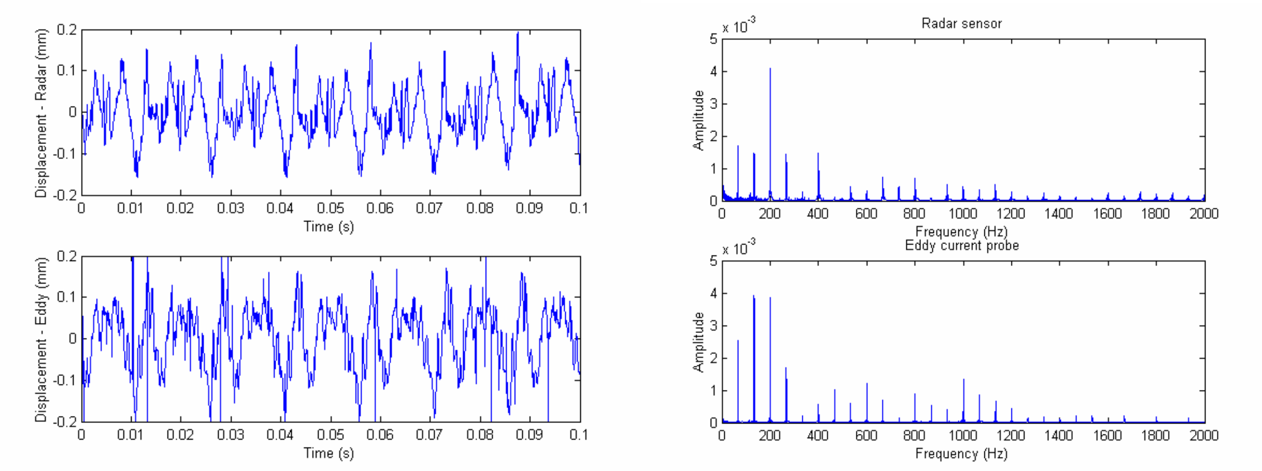
3. Experimental Results

3.1. Correlation between the Eddy Current Probe and Radar Sensor

The correlation between the eddy current probe and radar sensor is investigated in order to demonstrate that the radar sensor is capable of measuring shaft vibration. A 306K bearing with a known natural spall damage on its inner race is used in the test housing. Data are acquired from the eddy current probe, radar sensor, and accelerometer when the shaft is rotating at a speed of 4000 rpm.

The displacements from the radar sensor and eddy current probe are plotted in Figure 2(a). It can be seen that the radar sensor is less prone to noise than the eddy current probe. The signals from both sensors are similar in term of main features such as periodic peak amplitude and frequency. The differences in detail are expected because both sensors do not measure identical surfaces. In addition to the fact that the two sensors are located on opposite sides of the coupler, the spot size of the eddy current probe is significantly larger than that of the radar sensor. Therefore, the eddy current probe senses surface deviations that are too broad for detection with the radar sensor.

In addition, the difference in the measurements is also due to the nature of the sensors. The eddy current probe senses irregularities of the surface metallurgical properties in addition to the change in distance, which alters the measurement of the surface profile. On the other hand, the radar sensor that uses phase to determine distance change are unaffected by the surface metallurgical irregularities. This feature is an advantage of the radar sensor over the eddy current probe.



(a) (b)

Figure 2. Time-displacements (a) and amplitude spectra obtained from the radar sensor and eddy current probe

Normalized correlation is a standard measure to determine similarity between two signals. The normalized correlations are obtained in order to compare features in the displacement from the eddy current probe and radar sensor. The normalized correlation ranges between -1 and 1. A value close to 1 or -1 means that the signals are highly correlated, and a close value to 0 means that the signals are uncorrelated. The correlation of a signal with itself is called autocorrelation. Normalized autocorrelation always has the highest peak at zero lag, and that peak is equal to 1. For a periodic signal, the second peak of an autocorrelation next to the zero lag determines the periodicity of the signal, and may compared with a cross-correlation with other signals to determine similarity.

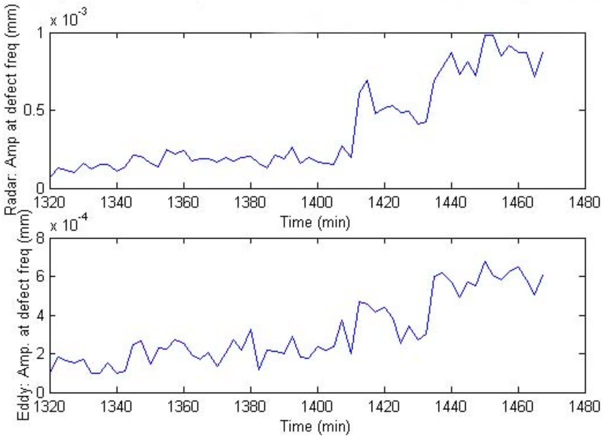
The autocorrelation of the eddy current signal is computed and found to have the autocorrelation of 0.86. The cross-correlation between the eddy current and radar signals cannot be higher than the autocorrelation of the eddy current. The cross-correlation of the eddy current and radar signal is found to be 0.49. This shows that the radar and eddy current signals are significantly correlated. Again, the correlation may not be expected to be close to 0.86 because the eddy current probe also sense surfaces outside those seen by the radar sensor due to many differences in measurement configurations.

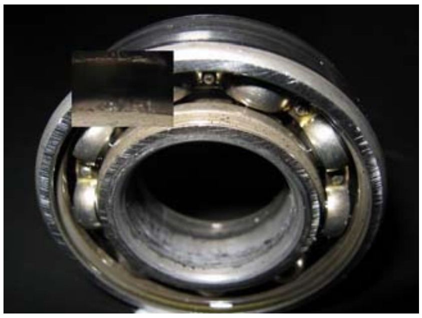
To illustrate the similarity in frequency content, the amplitude spectrum is computed from the displacement of each sensor. Figure 2(b) shows the amplitude spectra of the displacements from the radar sensor (top), and from the eddy current probe (bottom). Both signals show similar harmonic frequencies with the fundamental frequency of 66.67 Hz, corresponding to the speed of motor of 4000 rpm.

3.2. Accelerated Life Test

Acquisitions from the eddy current probe, and radar sensor are commanded by a program in LabVIEW software platform. The software is programmed to acquire and save signals from all sensors every 2.5 minutes. Figure 3(a) shows the plots of the data obtained from the radar sensor and eddy current probe with respect to time during the end of the test. The graph shows the displacement mean amplitudes from the radar sensor and eddy current probe at the defect frequency. The graphs from the test demonstrate that the bearing damage level is detectable through the shaft vibration by both sensors as the level of damage increases. Both graphs in Figure 3(a) show heavily correlated signal increases resulting from progressing bearing damage.

After the test is stopped, the bearings are again inspected for damage on their rolling surfaces. A spall damage is found to have a larger size approximately 2 mm wide, and 2 mm long on the inner race of a bearing as shown in Figure 3(b).





(a) (b)

Figure 3. (a) Amplitude at inner race frequency of the displacement from radar and eddy current sensors on a test performed after damage is detected, (b) Large spall damage found on the inner rolling surface

4. Conclusion

This test demonstrates the capability of the radar sensor in a vibration measurement application. The test demonstrates goods correlation between measurements of the eddy current probe and the radar sensor on shaft vibration. The other test demonstrates that the radar sensor is capable of detecting progressing bearing damage by monitoring shaft vibration. The vibration mean amplitudes from both radar sensor and eddy current probe at the defect frequency are found to be heavily correlated as the bearing damage increases.

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