Advanced Vibration Sensing with Radar - ADVISER

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ABSTRACT

A new low-cost stand-off vibration sensor based on the Doppler radar principle is presented. The baseline performance of this sensor was compared with a high-quality accelerometer in a well-controlled laboratory environment. This advanced vibration imaging sensor (ADVISER) was also validated for its prognostic health monitoring ability with a fault emulator. The ADVISER was able to detect machine misbalance and bearing damage at a distance of 4 feet without making any contact. This exceeded the performance of a high-quality screw accelerometer mounted directly on the bearing enclosure. In this paper, we present the sensor's principle of operation, summarize results of comparing it with standard accelerometers, and conclude with its potential use in industrial and aerospace applications. *

1 INTRODUCTION

Vibration is the most widely used measurand for prognostic and health management systems (PHMs). Accelerometers are the workhorses of vibration sensing and find widespread use in both industrial and aerospace health monitoring applications. While these accelerometers come in various forms, their basic principle remains the same—make physical contact with the machine being monitored and generate a signal that is proportional to the harmonic motion experienced at the point of contact. Permanently installed accelerometers are often screwed in with wired connections. Besides their intrusive nature (designed while the machine is assembled), such sensors cannot be mounted on moving parts, making it impossible to monitor some "locations" that may be critical from a vibration standpoint. Signals generated from sensors mounted "far away" from failure pick up background noises such as those generated by a helicopter body. This can obscure important signatures of failing gears or bearings. The wireless technology introduced recently by several manufacturers (Harry Forbes, 2008) can alleviate those problems only in some cases.

Permanently mounted accelerometers are often complemented with handheld vibration monitoring equipment (Fluke, 2010). Despite the accelerometer's ability to monitor instrumented parts of the machine, the tethered accelerometer heads suffer the same limitations as its permanently installed counterpart. That is, it needs to make good mechanical contact with the machine and often requires supplemental measurements such as an optical tachometer. Further, it may not be safe to approach the machine with an attachable handheld sensor and try to make the sensor head reach the remote location of interest.

Although permanently installed accelometers provide accurate measurements, economic reasons may limit the locations where they can be installed. Handheld accelerometers can provide a wider range, but their accuracy depends on the skill level of the technician. Many PHM engineers often wish they had access to the vibration data from an un-instrumented part of the machine.

All of these problems can be alleviated by a noncontact or stand-off vibration sensor based on laser or radar. The laser sensors have been used to detect vibration with high accuracy (Polytec GmbH), however, they tend to be expensive. Radar sensor was shown to detect a bearing fault as well as Eddy current sensor (Chuckpaiwong 2003). The radar was also used for sensing acoustic emissions (Smith, 2008) and human respiration and pulse (Droidcour et al. 2004) . We propose a noncontact radar vibration sensor that could (a) sense vibration from a considerable distance (e.g., 4 feet); (b) provide a wide field of view that could be adjusted to monitor the entire machine or specific parts of the machine; (c) be tuned to detect only the motion of the machinery and reject background vibration; and (d) provide vibration data from under-instrumented parts of the machine without incurring additional costs.

In this work, we describe an advanced vibration imaging sensor using radar called ADVISER. We show that this sensor can sense vibration accurately from a distance of 4 feet. This makes acquiring vibration data from previously un-instrumented parts not only cost-effective, but also safe. Moreover, the radar sensor detects only the motion of the machinery relative to the sensor, and hence rejection of background vibration is inherent to the sensor. ADVISER's radar antenna could also be configured to have no more than a 10-degree field of view and therefore could be used as a handheld or spot sensor.

When compared with other noncontact vibration sensing techniques based on laser technology, the ADVISER has several advantages: (a) its cost is an order of magnitude lower; (b) it is capable of wide field sensing with no moving parts; (c) it can penetrate nonconductive protection layers; and (d) it lacks delicate optical components and connections.

The ADVISER's principle of operation is presented in section 2 and its baseline performance is documented in section 3. Section 4 describes the benchmarking of the ADVISER versus permanently mounted accelerometers for PHM application.

2 PRINCIPLE OF OPERATION

ADVISER is a Doppler radar that transmits RF energy toward the target. The RF energy reflects from metal surfaces and edges and returns to the sensor. The reflection phase changes proportionally to the displacement of the reflective surface relative to the radar divided by the RF frequency signal wavelength. We selected the RF frequency at 24 GHz since it is an unregulated frequency band committed to the automotive radar sensor. The wavelength of the signal is short (e.g., 1.25 cm) for high sensitivity of the sensor. The cost of the RF components is also low because of the large-volume production for other automotive sensors.

The reflected signal is modulated by the target vibration magnitude, and any movement that is common to the target and the antenna is rejected. Upon return to the sensor, the return signals are mixed (beat against each other) with transmitted signals. The output signal phase of the sensor follows the radial displacement (in a direction perpendicular to the antenna) of the target in the time domain. Usually, the output signal is converted in the frequency domain by fast Fourier transform (FFT). If the reflecting surfaces in the radar antenna's field of view move at different frequencies or amplitudes, they will contribute different spectral peaks in the sensor signal. Thus, one sensor with a wide field of view can monitor many moving parts at the same time.

The sensor has two other important properties: high sensitivity that decreases for longer distances and an output signal that is decreasing with increased distance.

The sensor can detect displacement as small as 0.1 nm at a distance of 50 cm and 0.5 nm at a distance of 133.5 cm, as shown in Fig. 1.

The very high sensitivity is due to the very short round-trip time for the return signal (e.g., 3 nsec for 50 cm). Therefore, the local oscillator does not drift much and the phase noise of the sensor is very low. The round-trip time and thus the phase noise are larger for longer distances. The amplitude of the sensor decreases proportionally to the distance (Fig. 2) because the other half of the mixing energy comes from the local oscillator in the sensor and does not change with the distance. Therefore, large sensing distances are feasible for comparatively low transmission power (e.g., 50 mW). Two sensors with different antenna fields of view are shown in Fig. 3.

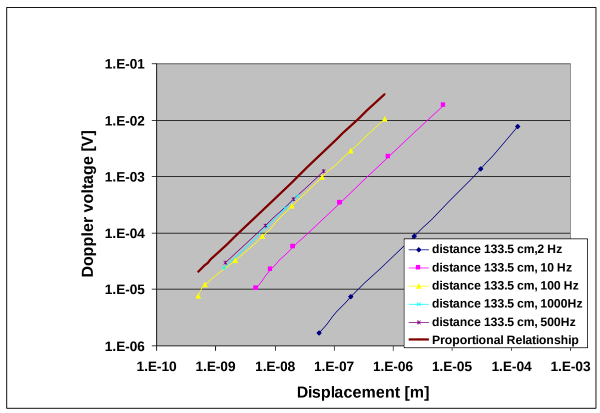

Figure 1: Radar output for different displacement and frequencies of the target

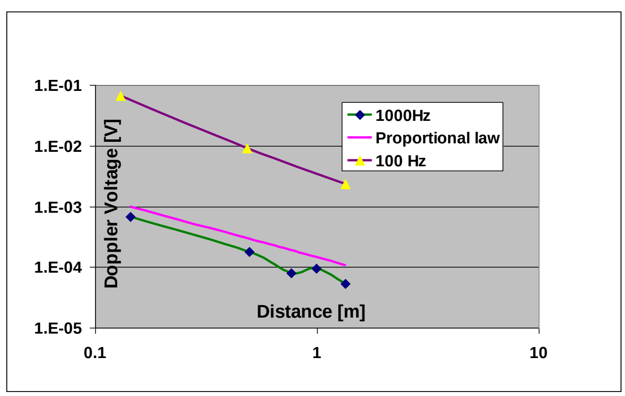

Figure 2: Radar output for distances to the target

Each sensor has a separate transmit and receive antenna. An antenna that consists of a 2x4 array of half-wavelength patches has a field of view of 30x60 degrees. Low-cost narrow field of view (e.g., 10 degree) horn antennas with no side lobes could also be used (Fig. 10).

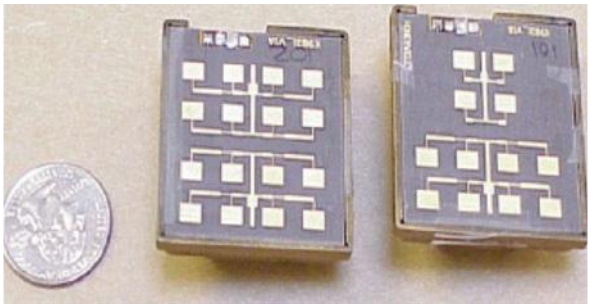

Figure 3: The ADVISER sensor

3 BASELINE PERFORMANCE OF ADVISER

The sensor was first evaluated for basic performance parameters such as sensitivity at different frequencies (2-10,000 Hz) and different distances (14-133.5 cm) using an accelerometer as a reference. We selected the vibration table system with a feedback-stabilized frequency controller (VibLab system VL-144 from Labworks Inc.) as our target. Information about the movement of the table was extracted from the reference Kestler accelerometer that was screw-mounted on the vibration table. The displacement at each frequency was obtained from the acceleration by double integration of sinusoidal function. Data in Figs. 1 and 2 were collected that way.

4 BENCHMARKING ADVISER FOR PHM

We designed and conducted experiments to compare the performance of the radar noncontact vibration sensor with the SKF accelerometer mounted on the enclosure of the bearing and rotating axle, as shown in Fig. 4.

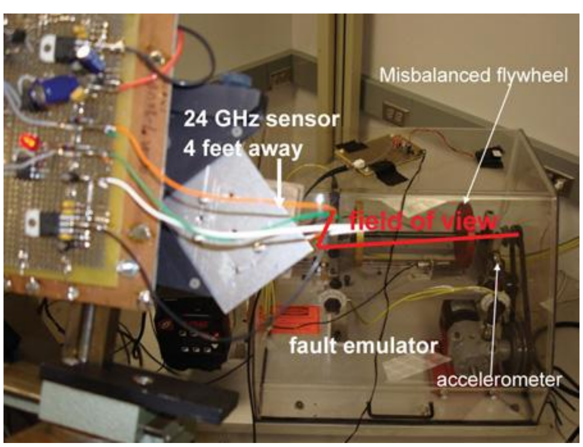

Figure 4: Testbed for benchmarking ADVISER

The ADVISER antenna was positioned 4 feet away from the rotating fault emulator. The entire machine was in the sensor's field of view. The machine was covered with a protective shield made of thick plexiglass that did not significantly affect the sensitivity of the sensor. We collected the ADVISER and accelerometer data at 32,770 samples per second with a 16-bit data acquisition system over a 63.2-second period. The first fault was introduced by using a slightly off center flywheel that had an additional screw attached to the perimeter to increase the misbalance, which was still not visible at 10 Hz. The rotational misbalance manifests itself as two sidebands around the rotation frequency peak, as shown in Fig. 5.

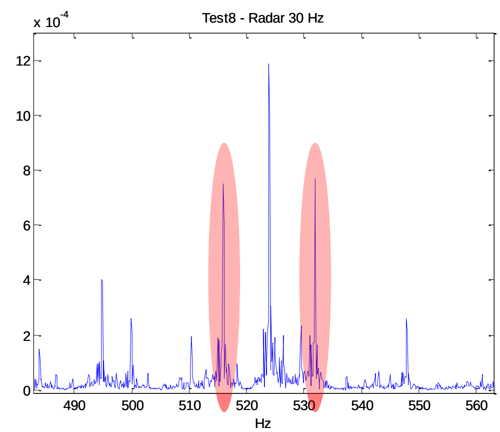

Figure 5: Misbalance side lobes in ADVISER output at 30Hz

We used the same testbed for detecting the intentional damage of the inner race of the bearing with the ADVISER and the accelerometer. The damage in the bearing manifests itself as a fifth harmonic peak in the ADVISER output (see Fig. 6).

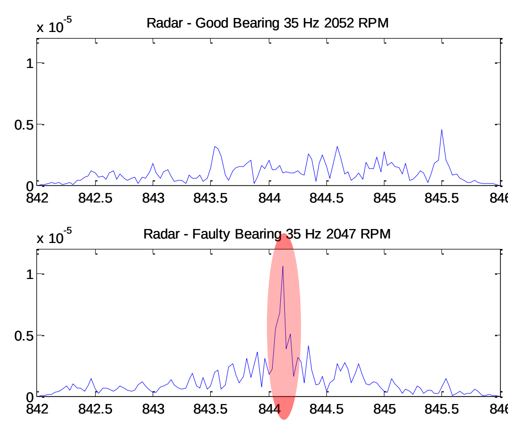

Figure 6: ADVISER output indicating bearing damage

However, the bearing damage signature was not detected in the accelerometer output at that frequency (see Fig. 7). Both radar and accelerometer showed increased bearing energy for faulty inner race. Radar data was less noisy than accelerometer data with 20% versus 35% of noise to bearing energy ratio respectively

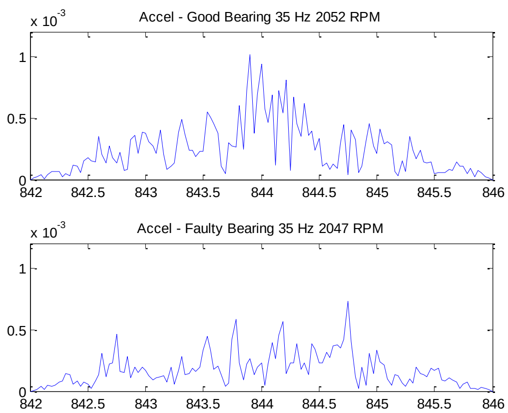

Figure 7: Absence of bearing fault signature in accelerometer output

The ADVISER detected higher harmonic side-bands and higher harmonics than the accelerometer (see Table 1). Moreover the signal-to-noise ratio (energy in the sidebands divided by the noise energy around the sidebands) was consistently higher for ADVISER than for the accelerometer. The data indicate that the ADVISER may have a higher probability of detecting misbalance faults than the accelerometer.

Rotations	Sensors	Number of sidebands indicating unbalance (upto 20th harmonics)	Largest peak at sidebands (% of fundamental frequency)	Average peak magnitude at sidebands upto 20th harmonics (% of fundamental frequency)	Average of peak at sidebands per energy around the sidebands
15 Hz	Radar	9	228	52.2	3.4
	Accel	4	230	45.5	2.6
20 Hz	Radar	15	81.5	26.8	3.3
	Accel	3	47.1	7.9	2.2
25 Hz	Radar	8	38.3	11.6	3.2
	Accel	3	29	6.6	2.4
30 Hz	Radar	10	40	14.1	3.4
	Accel	3	40	8.9	2.4
35 Hz	Radar	11	336	63.2	3.9
	Accel	2	335	26.8	2.4

Table 1: Comparison of ADVISER and accelerometer

As the third benchmark, we tested the ability of the ADVISER to extract the tachometer data from the sensor output. The tachometer data is frequently used in the PHM algorithms and is usually recorded with a separate optical sensor.

We compared the rotational frequency extracted from the baseline frequency and its harmonics in the ADVISER and accelerometer outputs to the optical tachometer data. Both the ADVISER and accelerometer data derived rotational frequency was close to the average frequency indicated by the tachometer; however, the ADVISER data produced less deviation from the tachometer at low harmonics, as shown in Fig. 8.

Characterization of the ADVISER capability for predicting other faults in machines in noisy environment is ongoing.

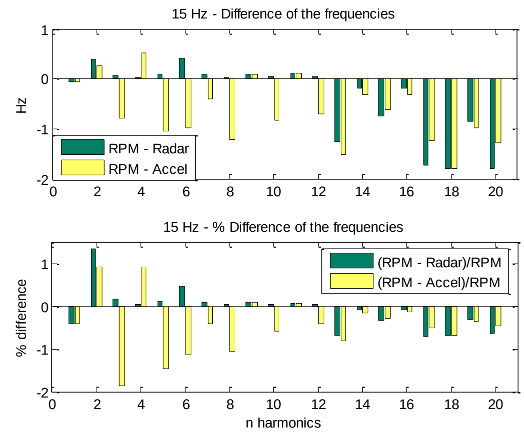

Figure 8: Deviation from optical tachometer average rotational frequency for ADVISER and accelerometer

5 POTENTIAL APPLICATIONS

Our results clearly demonstrate the comparative and in some cases superior performance. Hence, the ADVISER provides a noncontact sensor option for vibration monitoring. Further, ADVISER can be tuned to wide angles and provide a low-cost alternative for replacing several accelerometers. The noncontact aspect also makes it cheaper to install. We estimate that by using off-the-shelf high-volume electronics, the fabrication cost of the ADVISER could be less than $100.

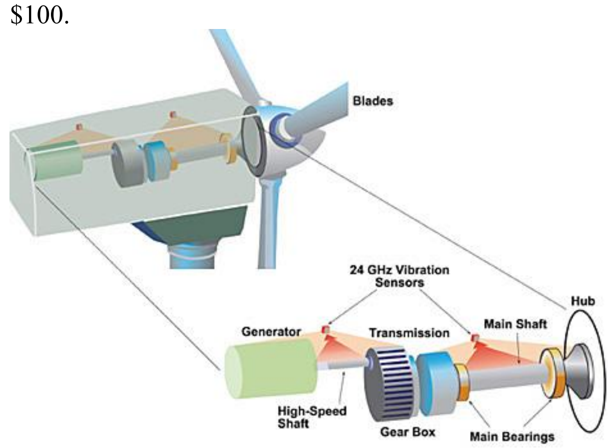

Figure 9: Artist's rendition of ADVISER monitoring wind turbine gearbox

Another important differentiator of ADVISER is its ability to reject the common mode vibration that may be obstructing the fault signature in machines as well as its insensitivity to surface fouling that limits optical sensors in weakly supported platforms such as a helicopter body or the gearbox in a wind turbine nacelle.

The ADVISER antenna could be conformally mounted on the helicopter body or the wind turbine nacelle. A potential application for monitoring wind turbine generators is shown in Fig. 9. The nacelles in majority of the wind turbines are large so the ADVISER could be installed on its interior wall with the field of view encompassing a gearbox or an electric generator.

Since the ADVISER monitors machine vibration up to 10,000 Hz through most nonconductive shrouds, it offers a superior solution over handheld devices that can only detect vibration up to 1000-2000 Hz, *in addition* to needing physical access to the machine. Another use of the ADVISER as a handheld inspection device in a large pump farm is shown in Fig. 10.

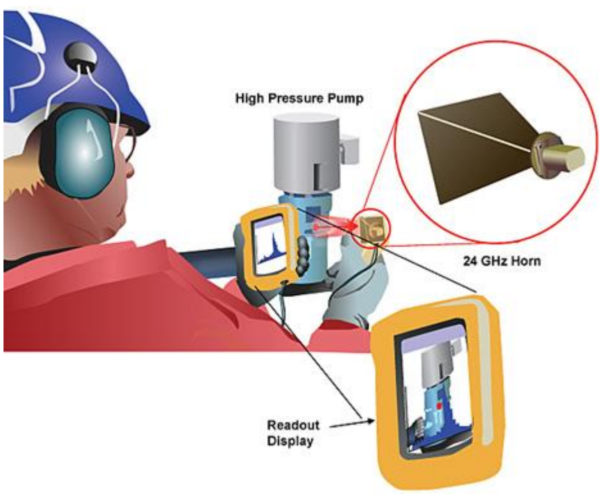

Figure 10: Handheld vibration monitoring device based on ADVISER

6 CONCLUSION

The radar-based noncontact vibration sensor has been evaluated for PHM applications. In our laboratory setup, the sensor could measure nanometer-level movement of a metal object reliably at a distance of 4 feet and detect frequencies of vibration up to 10,000 Hz. While we recognize the theoretical aspects of this claim in a relatively noise-free laboratory environment, our primary interest was its application to PHM. We then proceeded to benchmark the ADVISER against an industrial accelerometer. These experiments verified that detection of shaft misbalance and bearing damage faults by a screw-mounted accelerometer and the ADVISER from a distance of 4 feet were comparable.

In this study, we developed a radar-based sensor for vibration monitoring called the ADVISER. Laboratory validation established that the ADVISER could (a) sense vibration from a distance of 4 feet, (b) provide a tunable field of view to monitor the entire machine or specific parts of the machine, and (c) detect the motion of the machinery and reject background vibration. Initial results from the laboratory tests show promise for the ADVISER to acquire vibration data from under-instrumented parts of the machine without incurring additional costs. Field tests in a helicopter and industrial setup are planned as next steps in its technology maturation cycle.

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