Condition Monitoring using Standoff Vibration Sensing Radar

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Abstract

This paper introduces a stand-off vibration sensor based on the Doppler radar principle and its application to helicopter drive train monitoring. The noncontact advanced vibration sensing radar (ADVISER) provides a wide field of view for comprehensive monitoring of systems and non-moving support structures within a common framework. The baseline performance of ADVISER is compared with a high-quality accelerometer in a well-controlled laboratory environment. In this paper we present the preliminary comparison of ADVISER with the accelerometers on the drive train setup at University of South Carolina. The evaluation includes a study on location sensitivity for ADVISER. The results show the ADVISER viability for drive train CBM.

Introduction

Vibration is the most widely used measurement for condition based maintenance (CBM) systems. Single axis accelerometers are the most commonly used sensor type for vibration sensing within the aerospace CBM applications. While these accelerometers come in various forms, their basic principle remains the same: make physical contact with the machine being monitored to generate a signal that is proportional to the harmonic motion experienced at the point of contact. Although mounting these sensors can be intrusive, they cannot be mounted on moving parts. This makes it impossible to monitor "locations" that may be critical from a vibration standpoint. Signals generated from sensors mounted "far away" from a potential failure point can pick up background noises, such as those generated by a helicopter body. This can obscure important signatures of failing gears or bearings.

Mechanical components within the Drive System contribute significantly to maintenance drivers. For example for UH-60 phase maintenance check is done every 360 hours and requires about 3 days & 3 people [1]. Critical vibration checks are a significant part of this check. Failure of any one mechanical component in the drive system can lead to a complete loss of directional control, and a forced landing or crash. A survey of the US Army TAMMS-A data shows that the tail rotor gearbox, intermediate gearbox and aft hanger bearing are top contributors to drive train failures.

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In this work, we describe standoff vibration monitoring using a noncontact advanced vibration sensing radar (ADVISER). This makes vibration monitoring of previously un-instrumented parts possible. The radar sensor detects only the motion of the machinery relative to the sensor. Further, ADVISER's radar antenna has wide field of view and therefore enables it to effectively monitor larger targets such as the gearbox with just one sensor.

ADVISER Principle of Operation

ADVISER is a Doppler radar that transmits RF energy toward the target. The RF energy reflects from target surfaces and edges, and returns a signal to the sensor. The reflection phase change is equal to the displacement of the target surface relative to the radar divided by the RF frequency signal wavelength. The RF frequency was selected at 24 GHz since it is an unregulated frequency band, and the wavelength of the signal is short (e.g., 1.25 cm). The short signal wavelength accounts for high sensitivity and small size of the sensor. The ADVISER does not measure velocity of the target, but its displacement.

The reflected signal is modulated proportionally to 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 beam of 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 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 Figure 1. The detailed working principle of the sensor has been presented in an earlier publication [2].

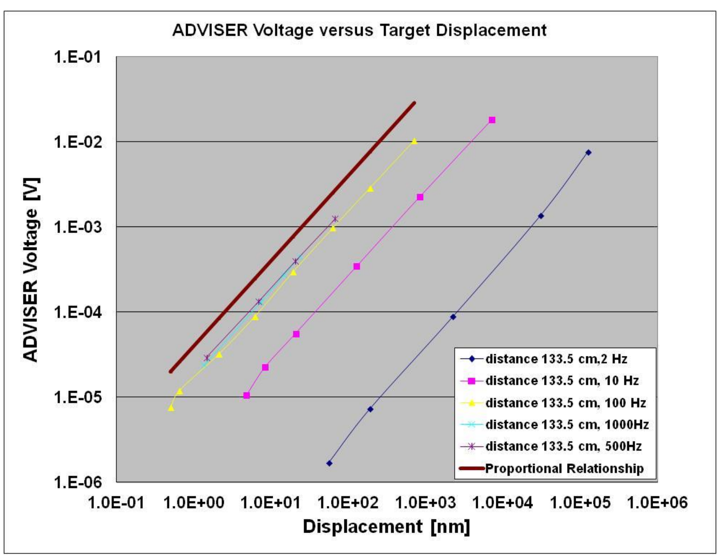

Figure 1: Radar output for different displacement and frequencies of the target

Experimental Setup

This section presents the experimental evaluation of ADVISER for standoff vibration measurement. The objective of these experiments is to gather experimental data from a test setup with actual helicopter drive train components under realistic operating conditions. The experiments use the data from the ADVISER and accelerometers on the University of South Carolina (USC) AH-64 test bed. This test setup uses a full AH-64 tail rotor drive system, namely; Intermediate gearbox (IGB), Tail rotor gearbox (TGB) and the aft hangar bearing (AHB).

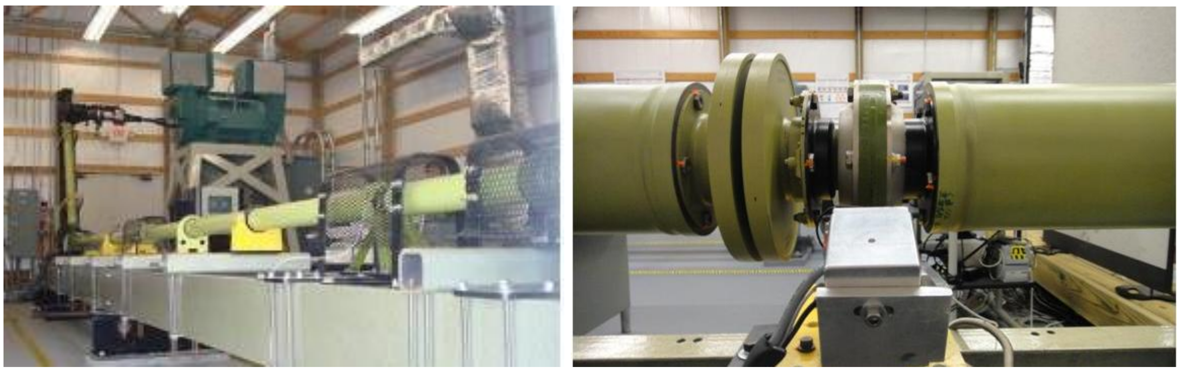

Figure 2: Tail Rotor Drive Train test stand. ADVISER monitoring the aft hanger bearing

Figure 2 shows the USC experimental setup and zoomed focus on the ADVISER mounting for aft hanger bearing monitoring. The standard USC AH-64 tail rotor drive train was used for testing. Three ADVISER sensors were placed at the AHB, IGB and TGB locations. USC also attached three accelerometer sensors on the same three articles. The sampling frequency for the ADVISER and accelerometers were 48 kHz. Figure 3 shows the block diagram of the data acquisition scheme in the experimental setup.

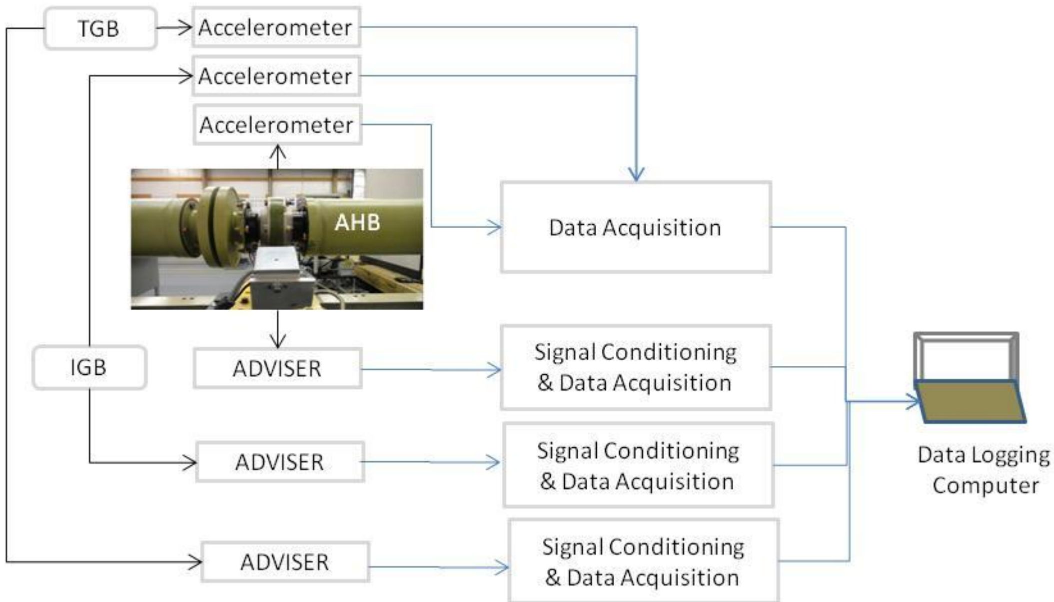

Figure 3: Data Acquisition Block Diagram

Preliminary Experimental Results

There were two primary objectives of running these experiments on the no-load test stand at USC. These are:

1. Validate that ADVISER is collecting the right data that can be explained using simple laws governing rotating shafts, bearing and gears. The intent was to make sure that with the documents provided by Honeywell, the USC team feels confident that they can exercise the ADVISER hardware and software.
2. Formalize a procedure for evaluating suitable ADVISER positions for the three components (Aft hangar bearing AHB, Intermediate gearbox IGB and the Tail gearbox TGB).

Since the IGB is a relatively large component, the team decided to evaluate three possible placements for the ADVISER. Figure 4 shows three candidate locations for pointing the ADVISER on the IGB and marked A, B, and C respectively.

A. Horizontal shaft bearing ring (closest to ADVISER)
B. Center point of IGB (closest to ADVISER)
C. Vertical shaft bearing ring (closest to ADVISER)

The procedure for evaluating ADVISER positions uses well-known spectral facts arising in rotating machines.

1. The evaluation consisted of several factors such as spectral peaks at fundamental frequencies and known harmonics.
2. Each factor was given a “weight factor” based on our understanding of the information it provided. These factors were jointly reviewed by Honeywell and USC.
3. For each position, a weighted sum established its “figure of merit”. Position with a greater

merit was determined as more favorable than others and recommended as our “going-in” position for the TRD experiments.

Two sets of data were collected for each of the three positions.

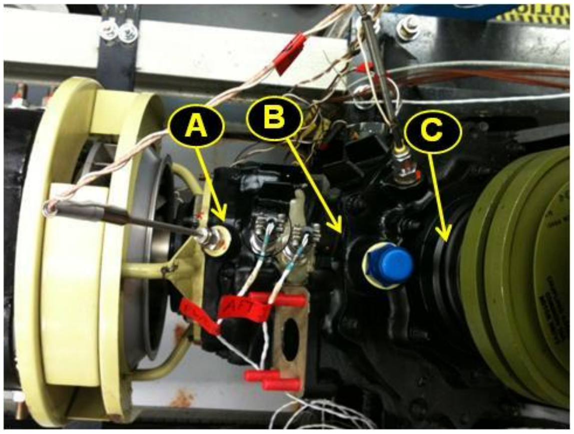

Figure 4: Three locations to point the ADVISER on the IGB

A systematic process for evaluating the three ADVISER positions on the IGB was devised based on references [3]-[4]. A set of seven spectral features was set to evaluate the sensor effectiveness for the three candidate positions on the IGB. The selected features are listed below:

1) Peak amplitude at the fundamental of input shaft rotating frequency.
2) Peak amplitude at the fundamental of gear mesh frequency.
3) Sum of peak amplitudes at 5 largest harmonics of input shaft rotating frequency.
4) Peak amplitude at the 2^{nd} harmonic of gear mesh frequency.
5) Number of harmonics showing the peak at the harmonics of input shaft rotating frequency.
6) Numbers of harmonics showing the peak at the harmonics of gear mesh frequency.
7) Noise level represented by the average of ratio of [RMS at peak to RMS around peak] computed at 8 peaks (fundamental of input shaft rotating frequency, 5 largest harmonics of input shaft rotating frequency, fundamental of gear mesh frequency, and 2^{nd} harmonic of gear mesh frequency)

The frequencies of interest include the input shaft rotating frequency, the output shaft rotating frequency, and the gear mesh frequency. Since on the no-load test stand the output shaft is not connected with the IGB, the ADVISER signal does not show any peak at the output shaft rotating frequency. Thus, the evaluation is done with two frequencies – the input shaft rotating frequency, and the gear mesh frequency. Also note that the peaks at the gear mesh harmonic frequencies only show up to the 2^{nd} harmonic. This is why only the amplitude at the 2^{nd} harmonic is evaluated for the gear mesh harmonic frequencies. For the number of harmonics showing the peak, only the peaks having the amplitude of 10% of the largest peak amplitude or higher are counted.

Figure 5 shows the ADVISER signal spectrum at three positions. All three plots show similar spectral properties – a little difference with the peak amplitudes but the frequency locations of the peak are same. The major peaks are all at the harmonics of the input shaft rotating frequency. Table 1 shows the metrics to evaluate the effectiveness of ADVISER with respect to the three positions. The scores are computed from the spectrum. The score represents the relative discrimination of the three positions by computing the ratio over the average of the raw data at three positions – for example, the score of 'Peak amplitude at fundamental of input shaft rotating frequency' for Position A is computed by 'Peak amplitude at fundamental of input shaft rotating frequency' divided by the average of 'Peak amplitude at fundamental of input shaft rotating frequency' at three positions, i.e., 7.2e-3/average(7.2e-3, 3.8e-3, 6.2e-3). The scores are multiplied by the weighting factor which is defined based on the relative importance of the metrics. The sum of the weighted scores is the final metric to evaluate the effectiveness of the three ADVISER positions. The results show that ADVISER position C yields a better spectral signal. However the similarity of weighted clearly indicates that ADVISER position and focusing does not significantly change the spectral observability of the vibration signal on the no-load test stand. This in turn allows flexibility in mounting of the ADVISER sensor on the aircraft.

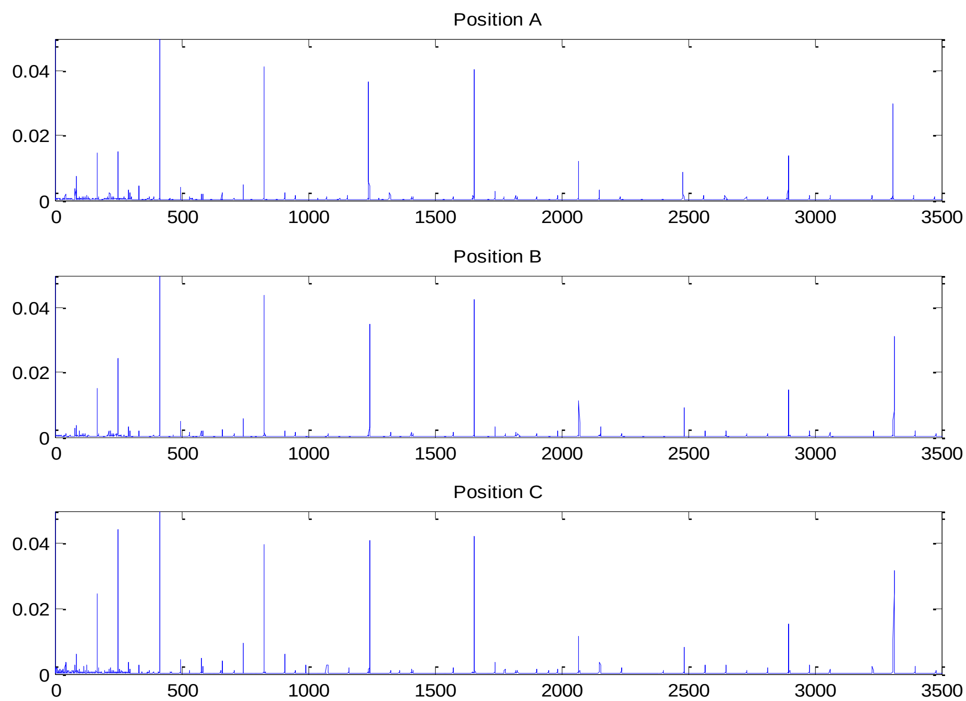

Figure 5 Spectrum of ADVISER Signal at Three Positions (FFT amplitude vs. Hz)

Table 1: Metrics and Results for Evaluating ADVISER on Three Positions

Criteria	WF	Raw Data			Score			Weighted Score		
		Position A	Position B	Position C	Position A	Position B	Position C	Position A	Position B	Position C
Peak amplitude at fundamental of input shaft rotating frequency	3	7.20E-03	3.80E-03	6.20E-03	1.26	0.66	1.08	3.77	1.99	3.24
Peak amplitude at fundamental of gear mesh frequency	3	1.60E-03	2.00E-03	2.80E-03	0.75	0.94	1.31	2.25	2.81	3.94
Sum of peak amplitudes at 5 largest harmonics of input shaft rotating frequency	5	0.24	0.25	0.29	0.92	0.96	1.12	4.62	4.81	5.58
Peak amplitude at the 2nd harmonic of gear mesh frequency	5	4.00E-04	4.00E-04	4.30E-04	0.98	0.98	1.05	4.88	4.88	5.24
Number of harmonics showing the peak at the harmonics of input shaft rotating frequency	5	10	10	11	0.97	0.97	1.06	4.84	4.84	5.32
Number of harmonics showing the peak at the harmonics of gear mesh frequency	5	1	1	1	1.00	1.00	1.00	5.00	5.00	5.00
Noise level (RMS at peak/RMS around peak) - average at 8 peaks	10	95.25	98.16	98.18	0.98	1.01	1.01	9.80	10.10	10.10
							Total	35.15	34.42	38.43

WF - Weighting Factor

Summary and Next Steps

The work described in this paper can be viewed as baseline validation of the standoff sensor (ADVISER) in a relevant installation environment. A radar-based sensor is a new approach for mechanical component monitoring and hence establishing this baseline is a critical milestone on the maturity roadmap. We focused on three mechanical components – aft hangar bearing, intermediate gearbox and tail rotor gearbox. Roughly all three ADVISERS were placed about 2—3 inches away from the component. This provided a wide-angle view for monitoring not only the gearbox, but also input and output shafts. For the IGB, we positioned ADVISER on three locations and based on the data, we concluded that the spectrum signature is relatively invariant to the location.

While this basic feasibility of the new sensor system (sensing head, data acquisition and associated electronics) is necessary to proceed further, it is not sufficient to claim its role for health monitoring. To achieve this, we need to embark on a series of experiments which forms our next steps. Some of these steps are described below:

1. *Data collection for select AH-64 drive-system components*. This set of experiments shall consists of two parts: (a) collection of historical condition indicators and corresponding maintenance records, (b) taking ADVISER measurements using the degraded components within the USC test bed. This data shall be used to develop the necessary prognostic indicators for mechanical components health monitoring. *Successful completion of these experiments shall generate the necessary time-series data to build HI algorithms and fault progression models using signals from an optimal placement of ADVISER*

2. *TRL-4 demonstration of the algorithms together with ADVISER*. This set of experiments shall demonstrate a prognostic health monitoring prototype consisting of the standoff sensors mounted within the AH-64 tail rotor subsystem and signal processing algorithms

running in a desktop PC to support condition-based maintenance policies. *Successful completion of these experiments shall validate the standoff approach consisting of a non-contact ADVISER, signal processing algorithms and generation of predictive indicators to support condition-based maintenance.*

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