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CHARACTERIZATION OF VIBRATION TRANSMISSION PATHS FOR GEARBOX CONDITION MONITORING

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Abstract

For gearbox condition monitoring, the position of the accelerometers can be crucial for the detection of possible defects. However, little information can be found in the literature for engineers in setting up condition monitoring. This study is to investigate the characteristics of gear vibration and its transmission path for sensor placement and reliable fault diagnosis. Vibration sources produced by gear meshing are transferred to the accelerometer through a path of shafts, bearings, and gearbox housing. Each transfer path has its own transfer function which is almost impossible to predict accurately that changes the vibrations in both magnitude and phase, varying significantly with the operating conditions. This study begins with the estimation of the path by the Frequency Response Function (FRF) technique and then it develops a response based estimation method to revise the base path adaptive to operating conditions for more accurate fault estimation. Both theoretical analysis and test result show that a better diagnosis when the path information is included in vibration signal processing and feature selection.

Keywords: Gearbox, Frequency Response Function, Fault detection, Condition monitoring.

1 Introduction

Gearboxes are among the most important mechanisms in industrial applications. Monitoring the condition of gearboxes plays an essential role in ensuring the reliability and low cost operation of industrial facilities[1]. When the gearbox is operating, it is impractical to measure the vibrations directly at their source; instead it is common practice to measure the vibration at a remote location. Typically, a convenient point is chosen on the outside of the gearbox casing. With a vibration transducer such as a piezoelectric accelerometer, the mechanical vibration is converted into an electrical signal for analysis. This inevitably leads to some corruption of the vibration signal due to the effect of the transmission path from vibration sources to the measurement position.

The transmission path consists of the structures providing a mechanical path from the vibration source to the measurement point. Typically, this will contain both the static structure of the gearbox casing and the rotating elements between the source and the transducer such as shaft, bearings, and gears. By using signal processing analysis techniques, measurements performed on the operating gearbox can be used to analyse potential faults [2, 3, 4]. However the frequency spectra measured are actually a combination of the unknown excitation forces – caused by wear of gear teeth, etc. – and the transmission path. Information about the characteristics of the structure itself is generally ignored. This often leads inaccurate results in performing fault diagnosis.

In this study, an approach is investigated to take the structure of the gearbox into account in analyzing vibration signals. The frequency response function (FRF) was obtained at different position of the gearbox casing in including places close to the driving motor. Two measured points are focused on to reveal the impacts of transmission on fault detection and diagnosis.

2 Brief Explanation of Frequency Response Functions

The Frequency Response Function (FRF) is a fundamental measurement that isolates the inherent dynamic properties of a mechanical structure [5]. Several experimental modal parameters such as natural frequencies, mode shapes and associated damping ratios can be extracted from a set of FRF measurements. The FRF describes the input-output relationship between two points on a structure as a function of frequency.

An FRF is a measure of how much acceleration response a structure has at an output Degree of Freedom (DOF), per unit of excitation force at an input DOF. As seen in Fig.1 the FRF can be defined as the ratio of the Fourier transform (FT) of an output response X(ω) divided by the Fourier transform of the input force F(ω) that caused the output.

In the input/output measurements, the gearbox casing is excited at exactly one point, namely the shaft, and the response is measured at different points using transducers distributed at different position on the gearbox casing. These types of measurements are usually performed by using a specialist multi-channel digital analyzer. By moving the response point while the excitation point remains fixed an entire row or column of the n-DOF system FRF matrix can be measured, respectively.

The relationship between input (force excitation) and output (vibration response) of a linear system is shown in Figure 1 and can be described by:

$$Y_i = \sum_j H_{ij} X_j \tag{1}$$

where Y_i is the output spectrum at DOF *i*, X_j is the input spectrum at DOF j, and H_{ij} is the FRF between DOF j and i. The output is the sum of the individual outputs caused by each of the inputs. Equation (1) gives the output at any DOF *i*, with the input at DOF *j*, as:

$$Y_i = \sum_j H_{ij} X_j \quad \text{or} \quad H_{ij} = Y_i / X_j \tag{2}$$

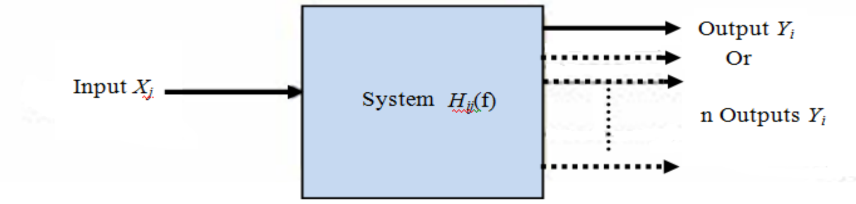

Figure 1 Single input multiple outputs system

In order to explore the effect of transmission paths on vibration signals due to path attenuation and interference noise, an experiment has been carried out based on an industrial helical gearbox.

The test rig and FRF measurement system is shown in Figure 2. The schematic diagram in Figure 3 consists of the structure (gearbox) to be tested, a force impulse shaker and five acceleration sensors located in different location fixed on the gearbox casing.

3 Measurement of FRF of Motor-Gearbox System

The equipment used for the shaker test is shown in the schematic diagram, Figure 3. A LDSTM shaker (type 201) is used to excite the structure (the gearbox shaft) to which it is attached by a suitable thin metal rod (stinger), enabling the shaker to impart force to the structure only along the axis of the stinger, the axis of the force measurement. The FRFs were measured with the shaker both in a horizontal and a vertical position (see Figure 2).

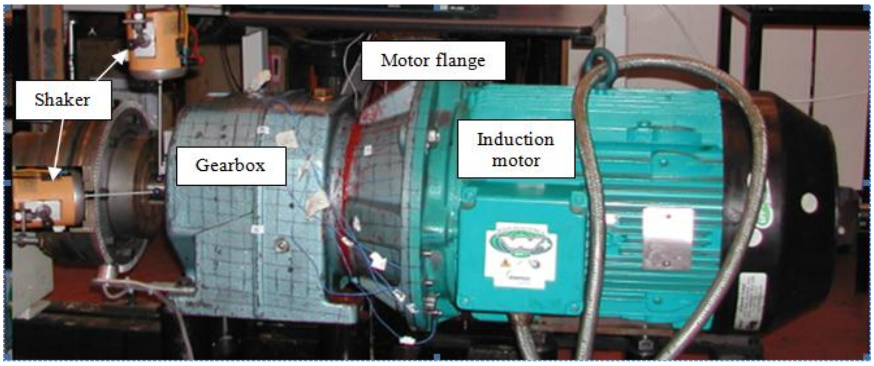

Figure 2 Test rig showing shaker position and accelerometer grids on gear casing

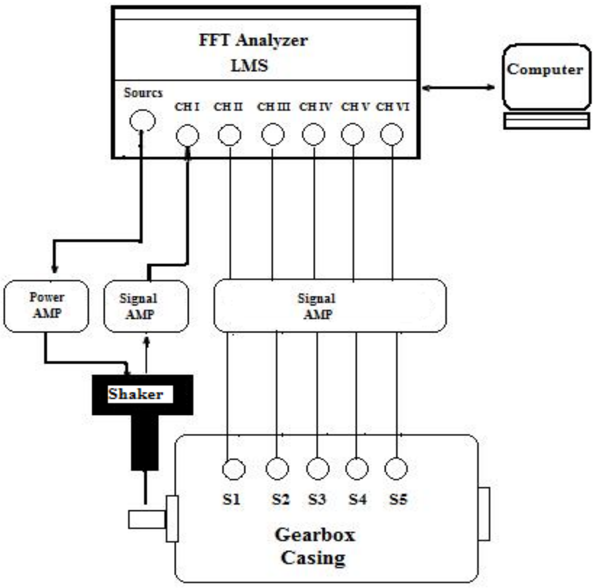

Figure 3 Schematic diagram of the shaker test setups

A high accurate force transducer was connected between the shaker and the stinger to measure the input force. The shaker is suspended using a rigid supporting fixture and by making its rigid body suspension frequency much lower than the fundamental frequency of the gearbox casing. Five ICP type accelerometers with a frequency band up to 5kHz are attached at different locations of the gearbox casing with a thin film of wax, enabling five FRFs to be obtained simultaneously at a time. By moving the accelerometers around the gearbox casing it was possible to determine the FRFs at over 200 different nodes.

Signals from the force transducer and the accelerometers were fed into to an LMSTM Scadas multichannel signal processing unit, from which an output signal was used to drive the shaker through a power amplifier. Typically a random signal, band-limited to a frequency range of 5kHz (easily covering the frequency range of interest for the gearbox), and with a Hanning window to minimize leakage effect was used. The signal processor was connected to a PC computer running suitable data acquisition and FRF analysis software, enabling averages to be taken that can virtually eliminate non-coherent noise and to effectively cancel out nonlinear distortion.

The excitation signal of the shaker and the response signal of the test sensor location are acquired in the time domain by the multi-channel analyzer and averages taken over five or more inputs. The Fast Fourier Transform (FFT) provides the corresponding power spectral densities. Performing the division of power spectrum response/ power spectrum excitation results in the FRF.

Two frequencies, the first stage meshing frequency (= 802.5Hz) and the second stage meshing frequency (= 350Hz) were selected to study the effect of the transmission path on the vibration signal. The FRF amplitudes at these frequencies from different locations on the gearbox casing and motor casing are shown in Figures 4 and 5.

4 Result and Discussion

4.1 Characteristics of the FRFs

The most direct way to evaluating the effect of the transmission path on the vibration signal is to compare the FRF measured at different locations on the test rig using the shaker test. The meshing frequencies can be extracted from a set of FRF measurements between one reference position (on the shaft) and a number of measurement positions required in the model.

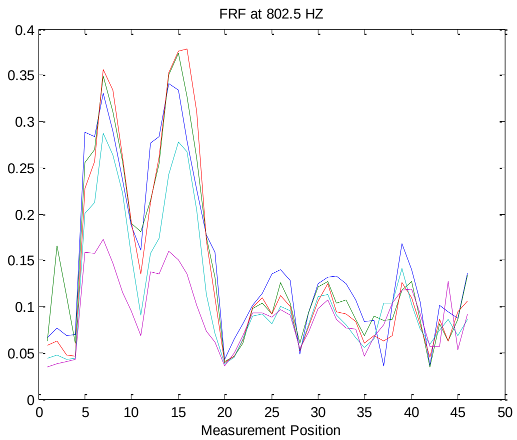

Figure 4 FRF amplitudes at 802.5Hz

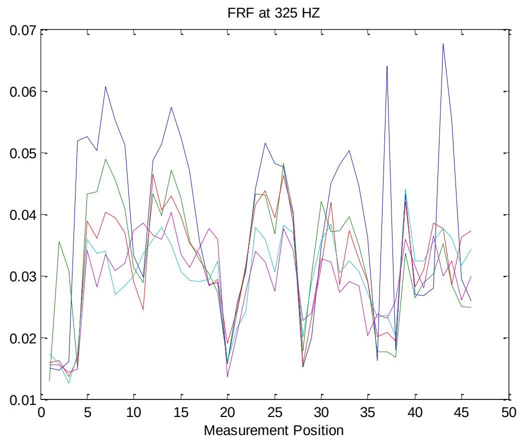

Figure 5 FRF amplitudes at 325Hz

These figures show how the FRF and hence the vibration signal changes with the path transmission on the gearbox casing and the motor flange. Sensors at location node number 16 give the highest frequency response for both meshing frequencies, whilst node position 20 gives the lowest frequency response.

Figures 6 and 7 show the location of the sensors on the gearbox casing (grey nodes) and motor flange (pink nodes), the size of the nodes giving information about how the FRF amplitude at 802.5 Hz and 325 Hz changes with the location of the sensor due to the transmission path effect. The enlarged nodes were chosen to take both FRF measurements, shown below in Figure 8, and signals for fault detection on both the gearbox casing and on the motor flange that are discussed in the next section.

FRF amplitudes on the gearbox casing and motor flange measured at the enlarged nodes are shown in Figure 8. In both spectra, there are several peaks at frequency bands (500Hz-1500Hz and 1900Hz-2200Hz). These peaks may due to several test rig component resonances. That there are clear differences between the FRFs confirms of the attenuation or amplification of the vibration signals due to the transmission path effect, i.e. amplitudes of the FRF at the motor flange are lower than on the gearbox casing. Furthermore the FRF for the motor flange is relatively flat over the whole frequency range, compared to that from the casing.

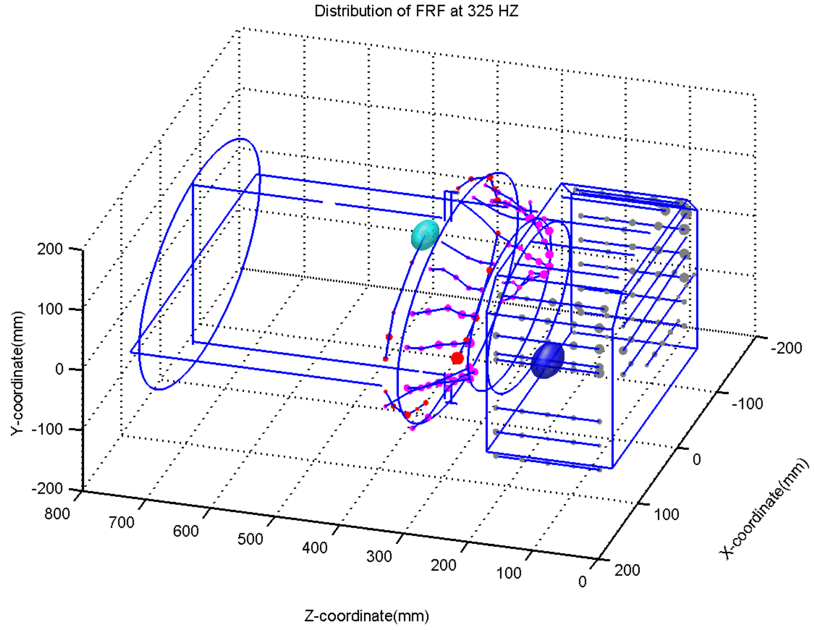

Figure 6 Typical distribution of FRF amplitudes in low frequency range

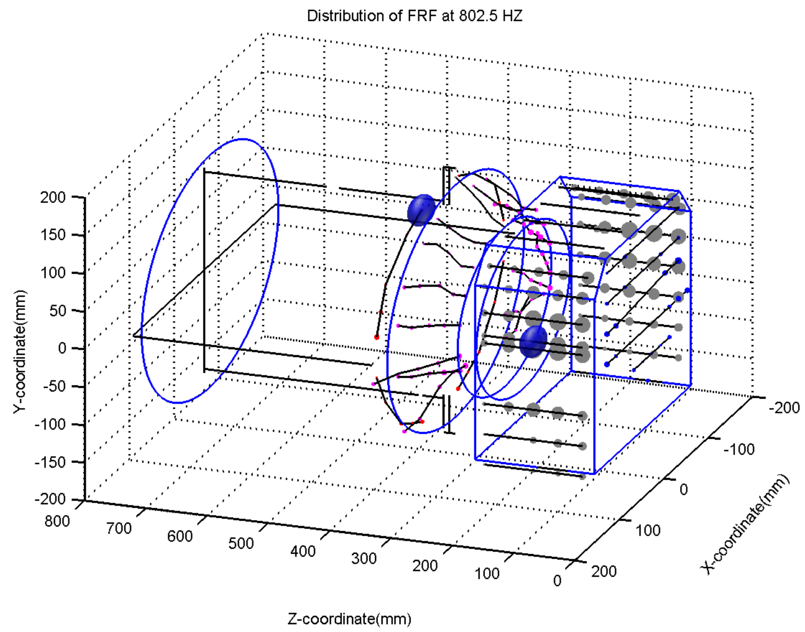

Figure 7 Typical distribution of FRF amplitudes in high frequency range

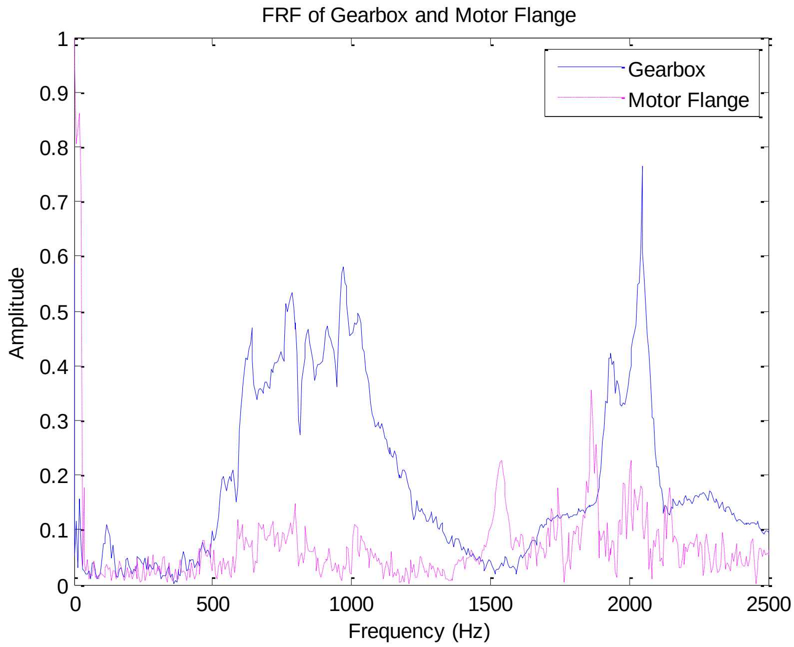

Figure 8 Comparison of FRF measured from gearbox casing and motor flange

4.2 Performance of Fault Detection

Typical frequency spectra measured at the same nodes on the gearbox casing and on the motor flange for 50% motor speed and the same load are shown in Figure 9, and for 100% motor speed and the same load in Figure 10. In both cases the spectra are given both for a "healthy" gearbox and for a gearbox with faults. As mentioned above the peak at 325Hz corresponds to the second stage meshing frequency and the peak at 802.5Hz corresponds to the first stage meshing frequency. It is seen that the higher amplitude for signals from sensors mounted on the gearbox casing compared to the motor flange -- especially in the range 1900Hz to 2200Hz but also in the lower range 500Hz-1500Hz -- is consistent with the FRF measurements taken at the same points. Whilst it would seem that more accurate FRF measurements are needed to give a closer correspondence – theoretically the ratio between the complex frequency spectra of the two signals should be the same as the ratio of the complex FRFs – the results obtained so far do indicate the influence of transmission path on the signals used to monitor faulty gears.

In addition, in the frequency range from a 500Hz to 600Hz, there are distinctively high amplitudes from the gearbox casing for the faulty condition, showing efficient performance in separating healthy and faulty conditions. This shows the clear effects of amplification by the FRF in this range.

Figure 11 shows the results obtained by averaging the spectral amplitudes in a frequency band of to 3 times the rotating frequency around the meshing frequency. The trend over speed or frequency for the gearbox casing shows a minimal around 685Hz. Once more this shows the effects of the FRF. In contrast, the trend for the motor flange is steadily increasing. This is an expected trend as the excitation sources usually have such an increasing profile with speed increasing, which is not distorted by the transmission path. Therefore, it may be claimed that the latter trend can give a better results in discrimination of fault severity.

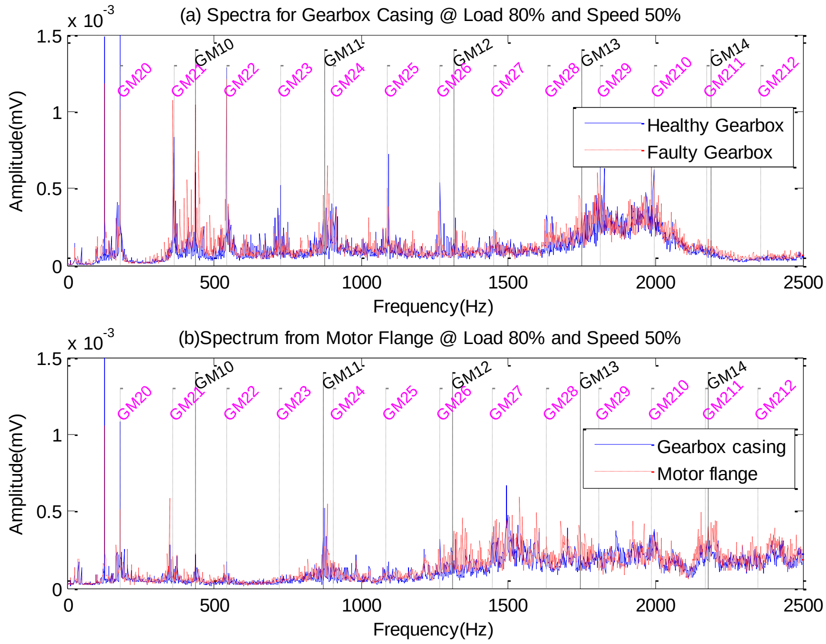

Figure 9 Frequency spectra at 50% speed obtained (a) from the signal obtained from the gearbox housing and (b) obtained from the motor flange.

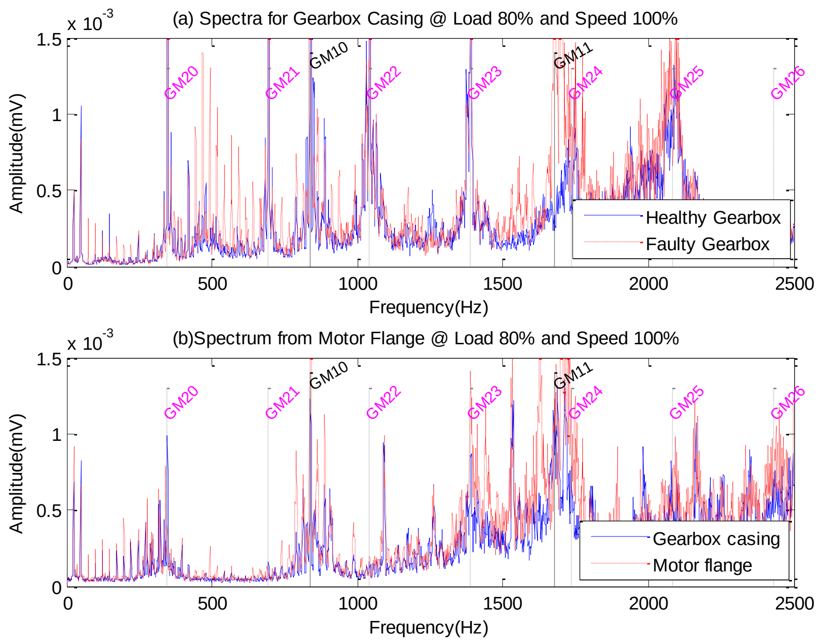

Figure 10 Frequency spectra at 100% speed obtained (a) from the signal obtained from the gearbox housing and (b) obtained from the motor flange.

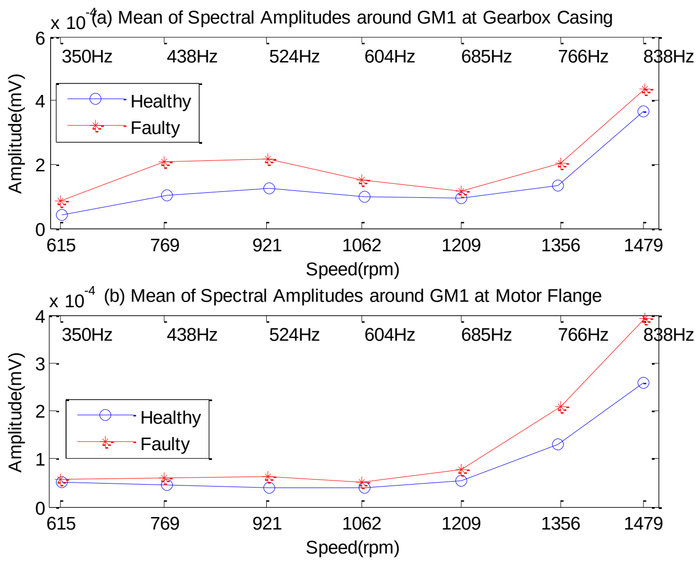

Figure 11 Comparison of vibration amplitudes around meshing frequency.

5 Conclusions

By measuring the FRFs from the input signal of a shaker on the gearbox shaft to outputs from sensors mounted over the gearbox housing and motor flange, it was possible to gain some understanding of how the position chosen for mounting an accelerometer for condition monitoring of a gearbox would affect the outcome. Although the FRFs measured in this way can only give an approximate analysis of the transmission path effects in practice – given that the vibration source is not just the vibrations of one end of the shaft – nevertheless the results obtained were consistent with differences between vibration signals obtained from condition monitoring bearings with known faults. Furthermore, it has found that higher FRF amplitudes will help in improving detection sensitivity but may result in inappropriate severity classification.

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