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IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING ANALYSIS FOR DAMAGE IDENTIFICATION ON A ROTOR.

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Abstract. *Impedance-based structural health monitoring method uses electromechanical impedance to identify possible damages and improve safety of operation. This experimental analysis used patches of piezoelectric material bonded to different rotor axes positions. An evaluation impedance board acquired data to be treat on the method. To better understand the impedance signal changes on a working rotor compared to a stopped one the data acquisition happened in different rotational speeds. It is possible to identify the correlation between stopped and non-stopped impedance signal, so compensation shift was introduced to improve results quality. We introduced a simulation of damage, using a known weight fixed in the axes of the rotor, so we could compare the differences of signal between heath and damaged condition. The purpose of this work is to evaluate different damage metrics to identify damage on a rotor and understand relations between changes on impedance signal and rotational speed.*

Keywords: *impedance-based, piezoelectric, rotor, damage, health monitoring.*

1. INTRODUCTION

In brief, a health structure or system is a set of inter-connected parts that must function together to be effective and accomplish its mission without compromise itself and others around it. In contrast, a non-health or damage structure or system does not present itself as a health structure once it might have changes on its geometric shape or/and physical properties. These variations on geometric and properties may represent risk of a failure or reduce efficiency on operation. So then for which structure it is necessary qualified people to evaluate the operational state. This can be seen on an aircraft wing as example, because a wing shape is different when we compare in flight and on ground states, but it does not necessary means an inefficient operation or a risk of failure condition.

As the name says, the Structural Health Monitoring (SHM) techniques try to estimate if a system works in a health state by a Non-Destructive Evaluation. For this purpose, a SHM method usually present a result for example as: possible damage condition or health condition. A possible damage condition means that the response of the structure is out of the considered normal or health range, and a health condition indicates a state as expected for a regular performance. To present a safety margin is not a simply method, and of course, it depends for each analysis and system, so in this work we will not determine a known as threshold to identify this safety margin. However, it is sometime visually identifiable a deponent variation on a SHM results, then a qualified person can do a second inspection or propose a deeper inspection method.

The SHM method can reduce the amount of times it is necessary to do inspections. For example, cars, hydroelectric turbines, aircrafts, and a lot of other expensive and necessary machines need many periodic inspections, so these machines must stop for long period of time several times to accomplish the schedule inspection. By using the SHM as a

preventive inspection, a quantity of not necessary long pause of operation can be reduced once an identification of health condition is obtained.

In the last decades the SHM method studies and applications have increased, for example it has been used on seismic protection after an earthquake, on bridges to prevent failures along the years, on railway to avoid problems with trains, on different pipelines to reduce problems during operation and on rotating machines. One field yet to be better studied is the implementation of SHM technique for rotation machines in operation. Nowadays many machines use rotors to supply needs on its operation such as aircraft engines, gas turbines and general refrigeration systems. Also, understanding that a rotating machine usually works at high speed, so a failure can cause major problems. Therefore, to know if a rotating machine is in health condition or not, can make de difference and avoid such problems. Subsequently, to approach a rotating machine with a monitoring of its behaviour on operational condition implies in understand the different signals for different speeds and so avoid failures and waste of money.

Different approaches for SHM are known, all of them has in mind the idea of a non-destructive evaluation and to understand the system health condition state. In this work the method of SHM is the impedance-based, this method selects a range of frequency where the structure is more sensitive to changes due to geometric or properties variation. Again, those variation of properties or/and geometric shape may or may not represent a possible damage, and it is necessary a qualified evaluation. The Impedance-based Structural Health Monitoring also works in a way to predict the behaviour of a component and avoid its failure or helps to identify a need of maintenance by prognostics.

1.1 Impedance-based structural health monitoring (ISHM)

The impedance-based structural health monitoring method evaluates variation in the dynamic behavior of a structure caused by changes in physical properties such as stiffness, mass or damping and relates these variations with the structure health. All these variations are quantified in an electromechanical impedance signal, which is an ultrasonic technique that has been considered as one of the most attractive methods for monitoring systems. The structure impedance sensors are piezoelectric (PZT) patches, and they attach to the structure and measure the local dynamic response.

Once it is possible to identify and separate health and possible damage states based on electromechanical impedance signal for a given structure, so we can use statistic metrics for pattern recognition to reduce the number of time machine is stopped for not needed maintenance, and stop it if a failure or crack is coming up in a gap that a maintenance is not scheduled. Due this procedure money can be saved, and number of accident can be reduced.

A PZT patch can be used for both actuation and sensing of the structure response, and a simple impedance model is the result of interaction between PZT and component in analysis. Figure 1 shows the diagrammatic representation for an idealized one-dimension electromechanical modelling between PZT sensor and host structure. Also, the Eq. (1) represent the electromechanical impedance function of the coupled system, $Z(\omega)$, can be represented as a function of frequency:

$$Z(\omega) = \left[i\omega C(1 - K_{31}^2 \frac{Z_{str}(\omega)}{Z_{str}(\omega) + Z_{PZT}(\omega)}) \right] \quad (1)$$

where ω is the excitation frequency, C and Z_{PZT} are electrical capacitance and impedance of the PZT patch, respectively, and the structure's mechanical impedance is Z_{str} . K_{31}^2 is the electromechanical coupling coefficient of PZT.

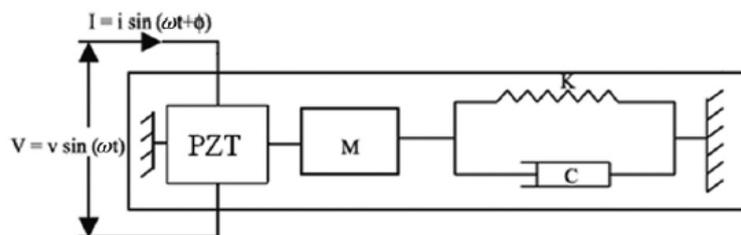


Figure 1 - 1D modeling for piezoelectric patch and structure interaction (Giurgiutiu V. and Rogers C.A., 1997)

Figure 2 shows electromechanical impedance baseline signal acquired for this work. There are six different baselines, three for each PZT attached to the rotor. It is possible to observe the differences of signal for each PZT, once each one is attached in one position they have different sensibility for different frequency excitation. However, for the same PZT and different rotating speed, a pattern exists. In the same PZT, the signal sometimes has a reduction on the peak region when the velocity increases, but it is not a linear behavior, so a simply interpolation is not enough to present

good quality results. The reason of this work study rotor in operation is exactly understand the behavior at high speed rotation.

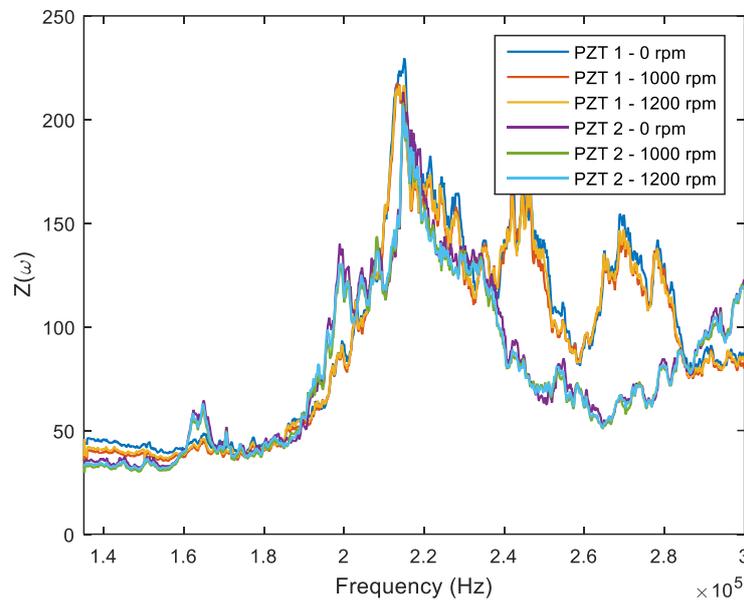


Figure 2 - Electromechanical impedance baseline for two PZT attached on a rotor operating on different speed.

1.2 Temperature compensation and damage metrics

Due to the size of the rotor in analysis in this work, it was not possible to acquire all data in the exactly same temperature, however, all data acquisition happened in a small variation of temperature. As Ali Bastani *et. el* (2011) say in their work, temperature effects on the received signal. For this reason, on this work a compensation of temperature is applied to the electromechanical impedance signal. A correlation coefficient analysis for simply steps of horizontal shift produces a better signal comparison on this work.

Once understood the impedance signal importance on this work, a statistic baseline is created for a health condition of the rotor, by acquiring an amount of electromechanical impedance samples in health state. This called statistic baseline is the reference for a health condition of the host structure. Subsequently, Eq. (2) to Eq. (6) are statistical metrics used to identify possible damages.

$$RMSD = \sqrt{\frac{\sum_{i=1}^n [\text{Re}(Z_{1,j}) - \text{Re}(Z_{2,j})]^2}{n}} \quad (2)$$

$$RMSD1 = \sqrt{\frac{\sum_{i=1}^n [\text{Re}(Z_{1,j}) - \text{Re}(Z_{2,j})]^2}{\text{Re}(Z_{1,j})^2}} \quad (3)$$

$$RMSD2 = \sqrt{\frac{\sum_{i=1}^n [\text{Re}(Z_{1,j}) - \text{Re}(Z_{2,j})]^2}{\sum_{i=1}^n \text{Re}(Z_{1,j})^2}} \quad (4)$$

$$RMSD3 = \sum_{i=1}^n \sqrt{\frac{[\text{Re}(Z_{1,j}) - \text{Re}(Z_{2,j})]^2}{\text{Re}(Z_{1,j})^2}} \quad (5)$$

$$ASD = \sum_{i=1}^n [\text{Re}(Z_{1,j}) - (\text{Re}(Z_{2,j}) - \delta)]^2 \quad (6)$$

$$\delta = \text{Re}(\bar{Z}_1) - \text{Re}(\bar{Z}_2) \quad (7)$$

where $\text{Re}(Z_{1,j})$ is the impedance of PZT measured in a health state, $\text{Re}(Z_{2,j})$ is the impedance of the baseline state condition and δ is the difference of the averages of each signal represented in Eq. (7). Also, $\text{Re}(\bar{Z}_1)$ and $\text{Re}(\bar{Z}_2)$ are the averages of measurements for the two conditions analyzed.

2. EXPERIMENTAL PROCEDURE

Two PZTs sensors were attached in different positions on the rotor's shaft, and once it is a rotating machine they must work with a *slip ring* and a low-cost evaluation board to acquire the impedance signal in a specified range of frequency. The *slip ring* provides a way to acquire the data even for a rotating system and it transmits the data to the evaluation board, so the evaluation board can provide to a computer the electromechanical impedance signal.

As explained before, we evaluate three different conditions and two states. The three conditions are 0 rpm, 1000 rpm and 1200 rpm, and the states are health and damaged simulated. These three different conditions related to speed bring a better understand of how to interpret the data when the rotor is operating compared to when it is stopped. Also, as discussed before, the first state, health condition, is considered when the rotor do not have any alteration, and the damaged condition bases on a simulation of damaged by attaching a nut at the rotor's shaft. Once that the rotor in analysis has a known critical speed, and its critical speed is around 1700 rpm, we operate in lower rotating speed to avoid errors by critical conditions.

Knowing that the impedance signal shows more sensibility in different frequency regions, a method to determine the better region to study the signal was implemented. The method was based on numerical comparisons between different windows of frequency, the one that showed a larger discrepancy between health and damage simulated states for each velocity was the one used to implement the metrics.

3. RESULTS

The most important result obtained in this work is to comprehend the differences between health state compared to a damage simulation state. On Fig. (3) to Fig. (7) all comparisons show that naturally the state 2 (damage simulation state) always have a bigger metric response when it is compared to state 1 (health state).

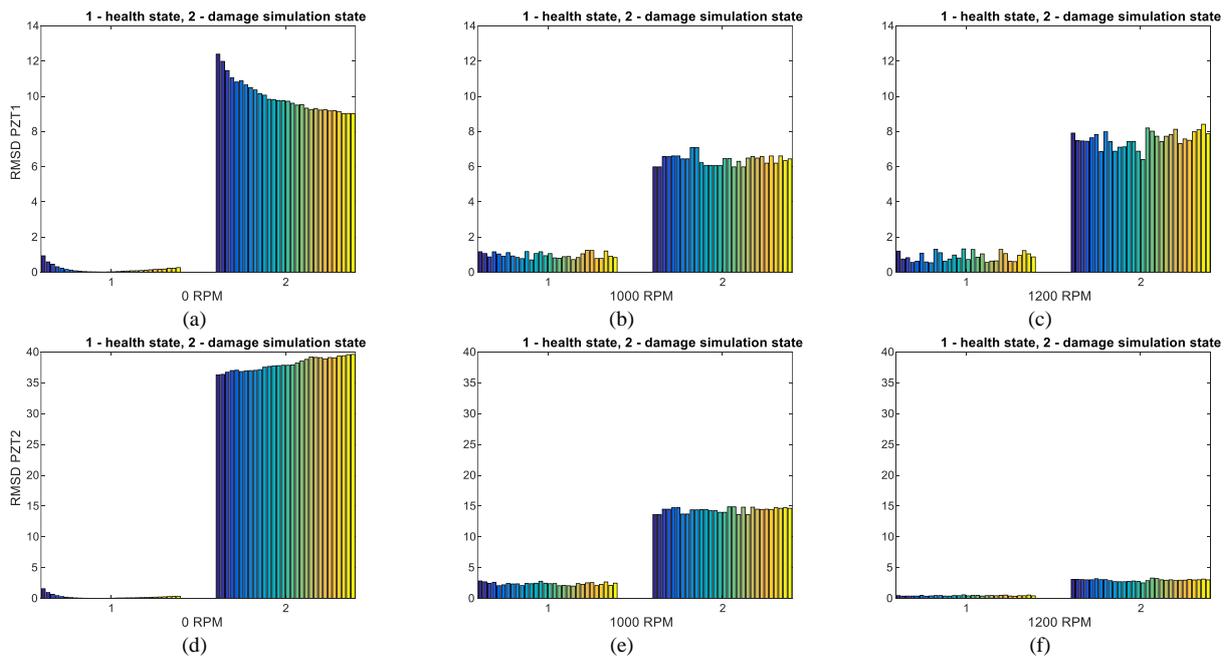


Figure 3. Metric RMSD for PZT1 and PZT2

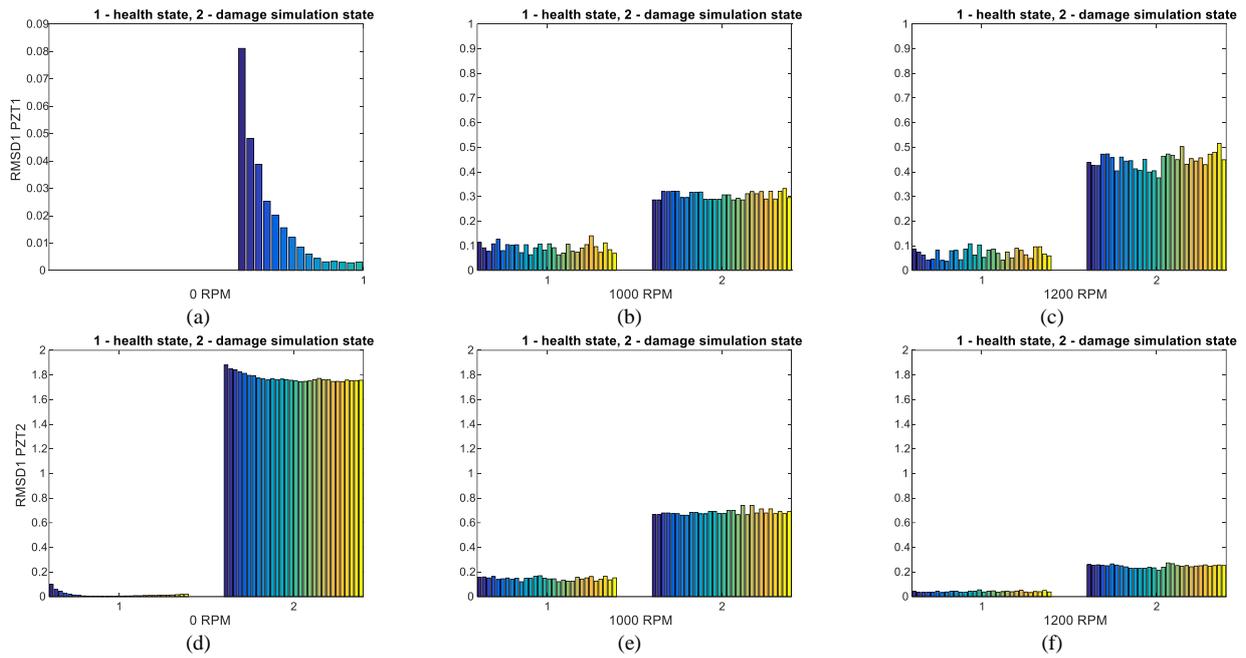


Figure 4. Metric RMSD1 for PZT1 and PZT2

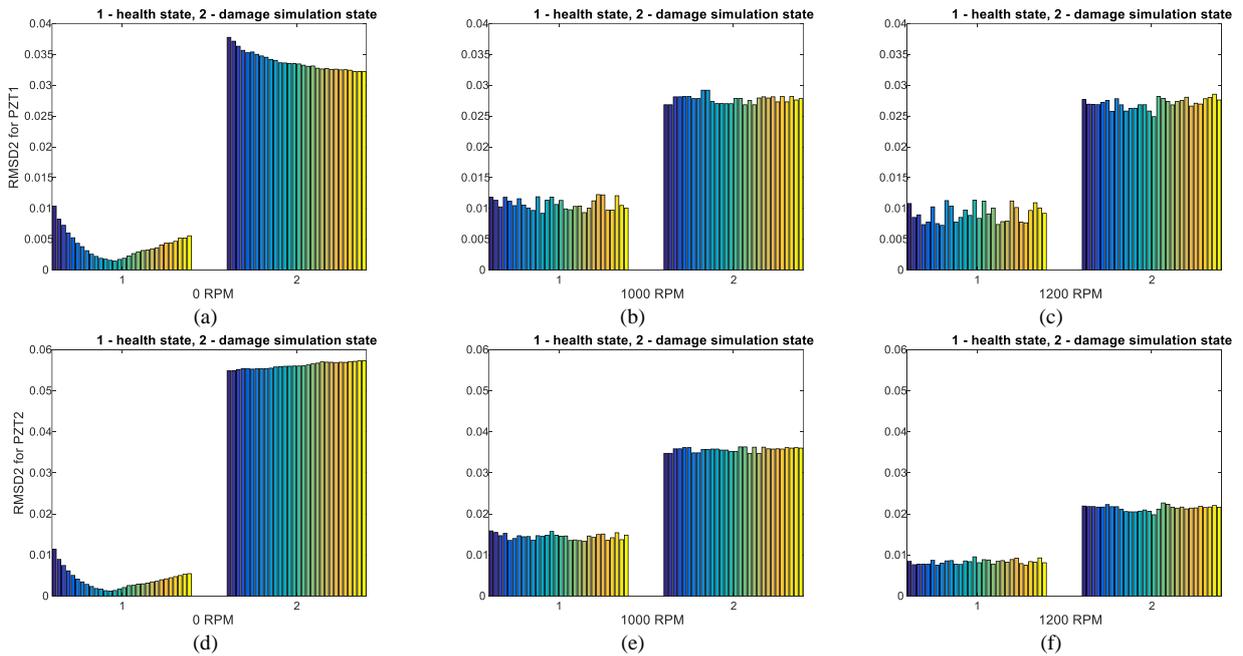


Figure 5. Metric RMSD2 for PZT1 and PZT2

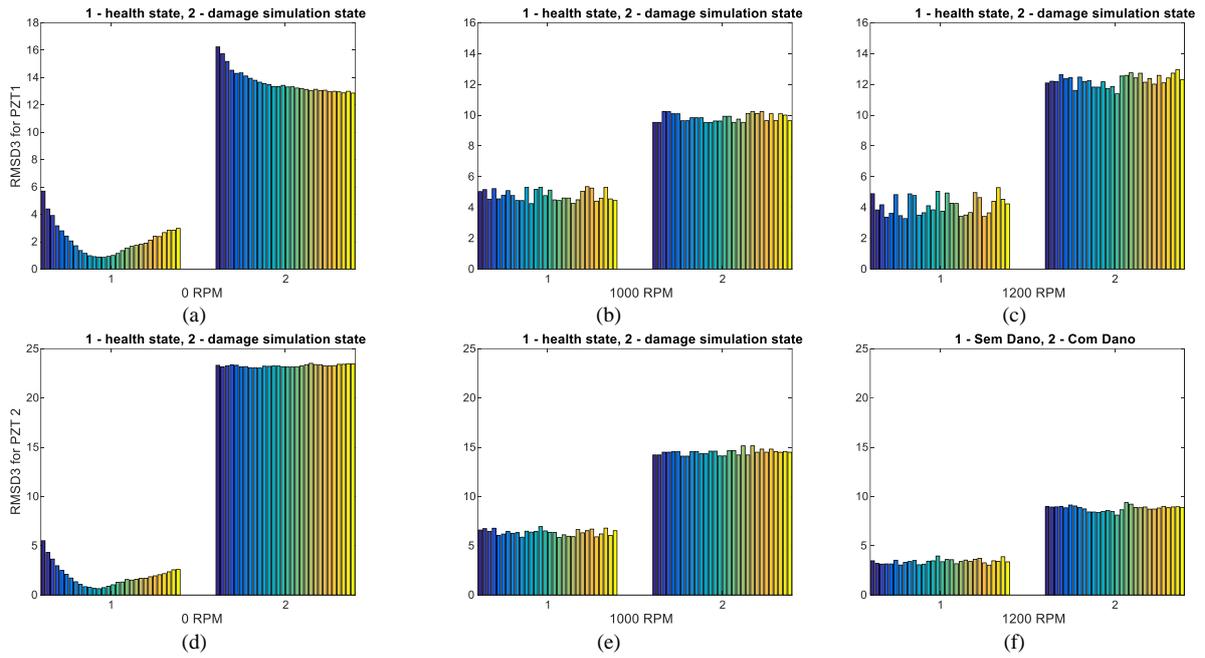


Figure 6. Metric RMSD3 for PZT1 and PZT2

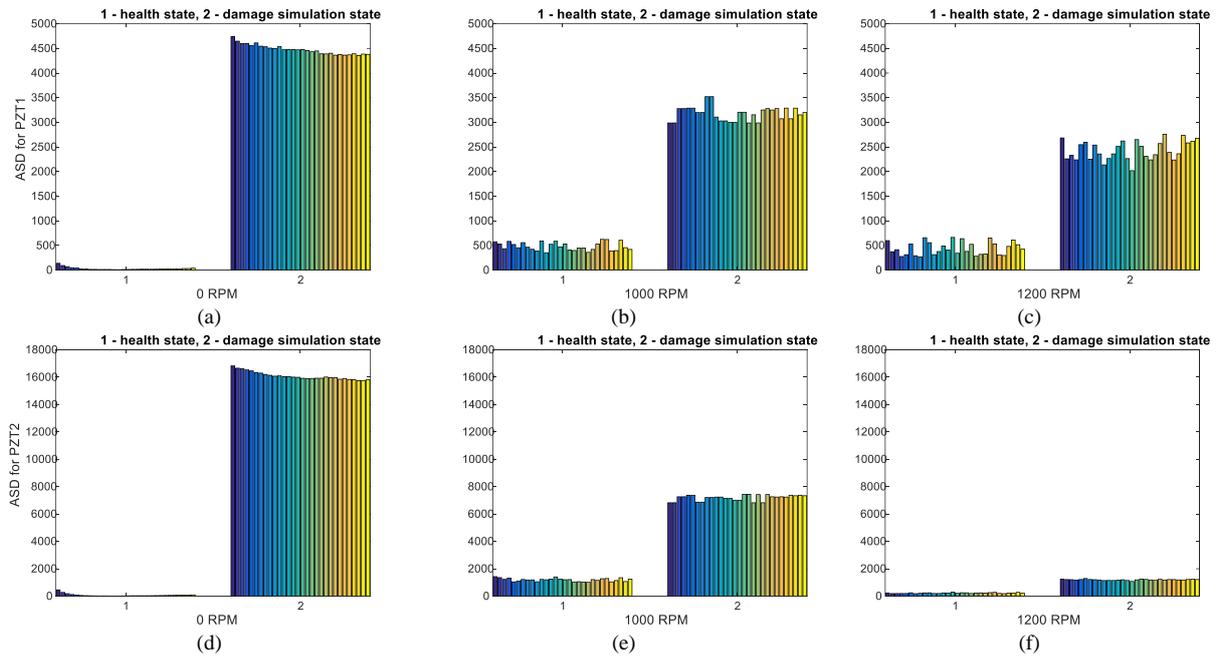


Figure 7. Metric ASD for PZT1 and PZT2

When the rotor machine of this work is stopped, all statistical metrics show a much larger value in damage simulation state compared to health state, so it is super simple identify a damage as the one simulated on this work. However, we can see at Fig. (3) to Fig. (7) that for these same metrics present a smaller difference between states when the rotor is operating. Even in those cases with 1000 Rpm and 1200 Rpm the metric value for damage simulation state is much larger than health state, and it indicates that it is possible to spread these two states with the metrics that we have been using here.

4. CONCLUSION

All things considered, the electromechanical impedance-based structural health monitoring method has showed a consistent way to identify a health state, and starting from this point it is possible to recognize a possible damage state. To improve results, for each system in analysis it is necessary to notice which metrics would present a more trustful result. Therefore, the impedance-based SHM applied to rotating machines could not only help identify possible damages but also save money by adjusting the amount of maintenance necessary.

5. ACKNOWLEDGEMENTS

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