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Integration of an end-of-line system for vibro-acoustic characterization and fault detection of automotive components based on particle velocity measurements

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Abstract

The automotive industry is currently increasing the noise and vibration requirements of vehicle components. A detailed vibro-acoustic assessment of the supplied element is commonly enforced by most vehicle manufacturers. Traditional End-Of-Line (EOL) solutions often encounter difficulties adapting from controlled environments to industrial production lines due the presence of high levels of noise and vibrations generated by the surrounding machinery. In contrast, particle velocity measurements performed near a rigid radiating surface are less affected by background noise and they can potentially be used to address noise problems even in such conditions. The vector nature of particle velocity, an intrinsic dependency upon surface displacement and sensor directivity are the main advantages over conventional solutions. As a result, quantitative measurements describing the vibro-acoustic behavior of a device can be performed at the final stage of the manufacturing process. This paper presents the practical implementation of an EOL system based on data acquired with a single 3D probe containing three orthogonally placed acoustic particle velocity sensors. Aspects such as installation process, feature extraction, classification, fault detection and diagnosis are hereby discussed. The presented results provide experimental evidence for the viability of particle velocity-based solutions for EOL control applications.

Introduction

In recent years, End-Of-Line (EOL) tests are required for most NVH applications in order to detect defective parts during the manufacturing process. Traditionally, subjective rating has been used as a standard for estimating the quality of the object tested. However, results are often biased, possibly leading to contradictory scores depending on the evaluator. As a result, there is a growing trend of developing EOL solutions based on objective criteria that correlate well with controlled subjective scores.

The vibro-acoustic signature of a device has proven useful for detecting problems and classifying manufacturing defects [1]. The signature is highly dependent upon the excitation and load, which can reveal a series of problems relative to the operating condition. Each defect is typically assessed independently, linking the measured quantity to the physical cause of the problem. Understanding the root cause allows for designing test procedures that capture a particular vibro-acoustic behavior related to the defect.

For rotating machinery in particular, it is know that the vibro-acoustic signature relates to periodic events, such as a rotating shaft, gear-mesh or ball-bearing movement. For that reason, many diagnosis techniques, like order analysis, require an exact measure of the rotational speed of the shaft. Traditionally, direct measurement of the shaft requires the placement of tachometers, which needs set-up time and proper handling to avoid errors during the measurement. However, during end of line testing, direct measurement is not always possible due to time constraints or shaft location not being accessible after assembly. As a fast and non-invasive alternative, the rotational speed can also be extracted from the vibro-acoustic signature providing that it contains tonal components [2]. This approach allows for obtaining order analysis features without a dedicated tachometer sensor.

Conventional sound pressure-based techniques are often not viable on a production line. The high levels of background noise and reverberation, along with the low excitation emitted by the device under assessment, prevent the gathering of acoustic data in-situ. In contrast, the use of acoustic particle velocity transducers offers a significant advantage over conventional testing techniques. Measurements performed under near-field conditions are proportional to the surface vibration and hardly affected by noise generated by the surrounding machinery [3, 4].

Although particle velocity measurements have already proven useful for detecting vibro-acoustic anomalies [2, 3, 5], there are multiple unresolved aspects concerning the practical implementation and integration of such novel approach in an industrial production line. This paper is focused on presenting all the elements involved in an EOL solution based on particle velocity measurements. In the case studied, a single 3D probe comprising three orthogonal particle velocity sensors vector sensor is used for fault detection and classification of rotating machinery.

EOL system

The integration of a complete acoustic testing unit into a production line is a challenging task. Multiple elements common in a factory floor have to be linked and automated while ensuring reliability and robustness of the whole system.

As for most production lines, the entire testing process is managed using a programmable logic controller (PLC). The PLC is communicated with most of the testing elements including optical sensors, pneumatic actuators, motors, electrical driving signals and other peripheral devices. In the case hereby presented, the PLC has also been linked to an industrial computer using a customized communication protocol throughout a serial port. As a result, the PLC can automatically position the device under assessment, run multiple consecutive tests and send commands to the industrial computer in order to acquire acoustic signals when it is required. On the other hand, the industrial computer is in charge of the data acquisition, signal processing and storage of the acoustic data. The vibro-acoustic signature captured by the recorded signals is used in combination with a customized software module in order to detect any defects or anomalies. Fig. 1 shows a sketch of the elements involved in the testing process.

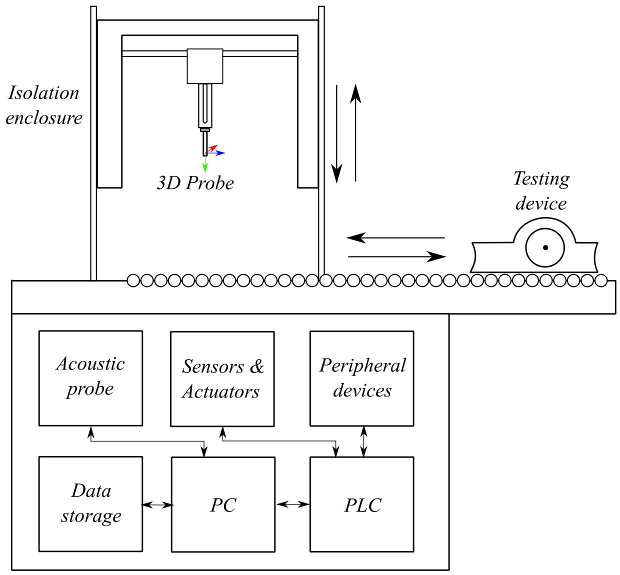

Figure 1. Sketch of the elements involved in the acoustic EOL system.

The following sections aim to provide further information about the elements involved into the EOL system as well as the testing process.

3D Sound Intensity Probe

The EOL system hereby presented was designed to perform the acoustic data acquisition through a single sensor position. As such, a 3D sound intensity probe was the selected acoustic transducer, since providing access to all available acoustic information at one single point [6]. Although this probe contains one microphone and three orthogonal particle velocity sensors, the sound pressure signal is not used in the analysis due to limitations in the noise floor, as it is shown in the following section.

Acoustic particle velocity sensors, or microflown sensors, are transducers which are able to measure the acoustic particle velocity field in air. Similarly to hot wire anemometers, the measuring principle relies upon a pair of wires that are heated up by an electrical current and are cooled down when exposed to an acoustic flow. Due to temperature changes in the wire, its resistance changes accordingly, producing a variable electrical signal proportional to the incident flow. A measure of the acoustic particle velocity can be estimated from the difference in temperature between the two closely-spaced heated wires. The small size of this device allows multiple orthogonal sensors to be placed close to each other to characterize the acoustic particle velocity vector of the sound field. As shown in in References [2] through [5], this property has a key importance for detecting vibro-acoustic anomalies, since different mechanical defects can be detected using one particular particle velocity transducers or even combinations of several orthogonal sensors.

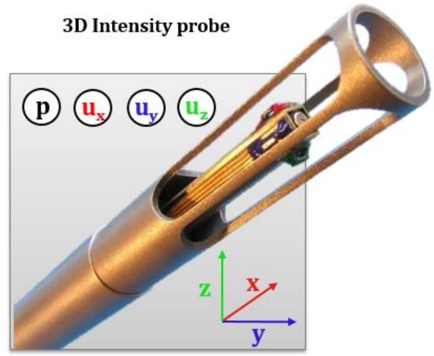

Figure 2. Picture of a 3D sound intensity probe.

Isolation Enclosure

One of the main difficulties of EOL pressure-based solutions is the necessity of achieving low background noise levels in a wide frequency range. Simple enclosures are very effective for obtaining a large noise reduction at high frequencies. However, mitigating low frequency noise is not straightforward, and it usually involves large structures and/or heavy acoustic treatments. On the other hand, the use of particle velocity sensors near a high impedance surface can benefit from its vector nature, presenting a series of advantages over traditional pressure microphones [3, 4]. Incoming and reflected sound waves are perceived with opposite phase in terms of acoustic particle velocity, yielding low levels near a rigid boundary that acts as a reflector. This effect causes a significant background noise reduction which is dependent upon the sound wavelength, being more prominent for large wavelengths, therefore at low frequencies. As an example, Fig. 3 shows the noise reduction that can be achieved when a sensor is positioned 0.01 m away from a high impedance surface (red line).

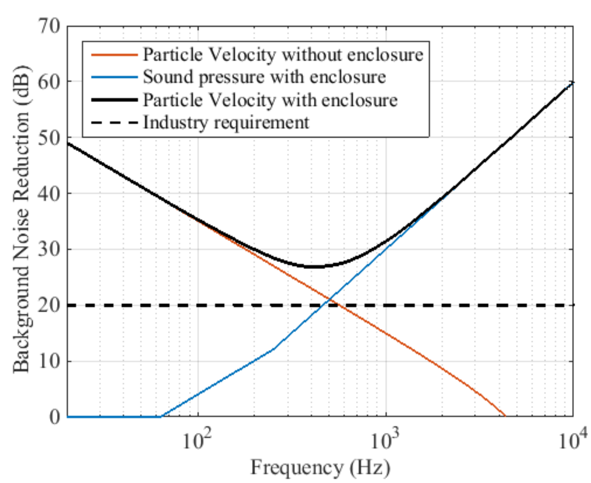

Figure 3. Background noise reduction levels that can be achieved with a sensor placed 0.01 m away from the testing object.

The background noise reduction shown above was computed as the level difference between a microphone and a particle velocity transducer located at the same position. Despite the good performance at low and mid frequencies, the industry requirements imposed would not be met above 600 Hz. Due to the broadband nature of the device being tested, it was necessary to incorporate an additional isolation enclosure with a light acoustic treatment. The noise reduction introduced by the enclosure it is shown for both sound pressure (blue line) and particle velocity (solid black line) transducers in Fig. 3. As can be seen, the combination of a particle velocity sensor located close to the testing device with an isolation enclosure leads to a broadband noise reduction of more than 20 dB, which was above the initial requirement imposed by the customer.

Probe mounting

One of the main requirements of an EOL system is to guarantee repeatability regardless of any substitution of the elements involved in the measurement process. Sensor maintenance and failures should be handled in the shortest possible time while ensuring that positioning and orientation are preserved. Consequently, one of the key elements on the acoustic measurement chain is the probe mounting strategy.

The designed solution used in this work comprises three main elements of anodized aluminum:

- A head holder that can be permanently mounted into the isolation enclosure. Two layers of viscoelastic material were added between the head and the adjustable body element in order to add mechanical damping to the structure. Hence, reducing the influence of structural vibration on the probe.
- An adjustable body structure that can be finely adjusted in both vertical and horizontal plane. It also has two openings to guide the cable through it.
- A customized 3D intensity probe that can be directly attached to the probe holder in a fixed and unique orientation, facilitating the probe replacement process. The sensor can easily be substituted by unscrewing the probe from the body and attaching its replacement, as shown in the Fig. 4.

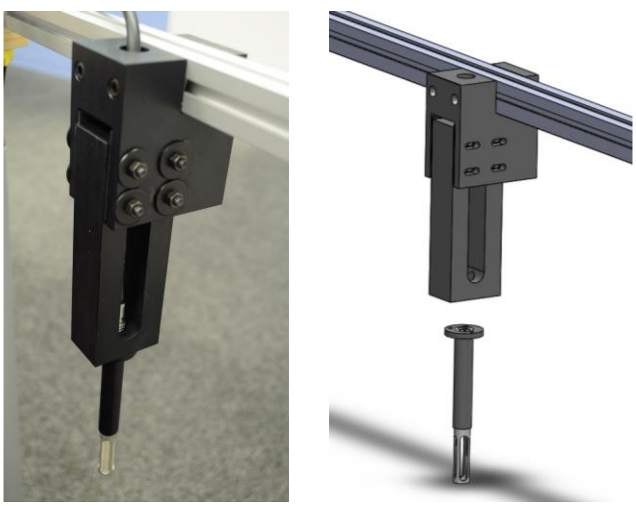

Figure 4. 3D probe attached (left) and detached (right) from the sensor holder.

Tachless RPM tracking

Tachometers are typically used to measure the shaft speed of rotating machinery by counting the amount of pulses per shaft revolution. Although their accuracy can be high, the installation of such sensors may not be suitable for applications where time is limited, such as end-of-line tests [7]. As an alternative, this paper will follow the approach proposed in [2] to estimate the instantaneous rotational speed. Acoustic particle velocity is used in combination with a priori information about the dominant orders during the run-up to extract an RPM signal.

The order spectrum

Analyzing rotating machinery it is often desirable to study the vibro-acoustic response as a function of harmonics or orders of the shaft speed [1]. If the data acquired is synchronized with the rotational speed, the Fourier transform of the signal will directly lead to the order spectrum, i.e.

$$X(\Omega) = \int x(\phi) e^{-\mathrm{j}\Omega\phi} \mathrm{d}\phi \qquad (2)$$

where Ω is the evaluated order and ϕ is the shaft angle. Although analog phase-locked systems were formerly used for this purpose, practical limitations leaded to the search for alternative digital solutions.

Nowadays, the most extensively used method to convert the data to the order domain is by resampling the recorded signals using the corresponding rotational speed via digital interpolation. However, significant improvements can be obtained by using the Velocity Synchronous Discrete Fourier Transform (VSDFT) introduced by Borghesani et al. [8]. The order domain conversion of the VSDFT is derived from the fundamental relationship shown in Eq. 2, applying a change in the domain of integration, i.e.

$$X(\Omega) = \int x(t)\omega(t) e^{-\mathrm{j}\Omega\phi(t)} \mathrm{d}\phi \qquad (3)$$

where $\omega(t)$ denotes the instantaneous shaft speed. The implementation of the above expression requires the discretization of both order and time domain, i.e.

$$\mathrm{VSDFT}[\kappa] = \frac{\Delta t}{\Theta} \sum_{n=0}^{N-1} x[n\Delta t]\omega[n\Delta t] e^{-\mathrm{j}\Omega[\kappa\Delta\Omega]\phi[n\Delta t]}\, \mathrm{d}t \qquad (4)$$

where Θ is a normalization factor related to the acquisition time window in the angular domain. In practice, $\omega[n\Delta t]$ is computed from the vibro-acoustic signal following the RPM extraction procedure introduced in [2]. In addition, $\phi[n\Delta t]$ can be estimated using numerical integration on $\omega[n\Delta t]$. Fig. 5 shows an example of the conversion from the time-frequency domain (left) to the RPM-order domain (right) using the VSDFT.

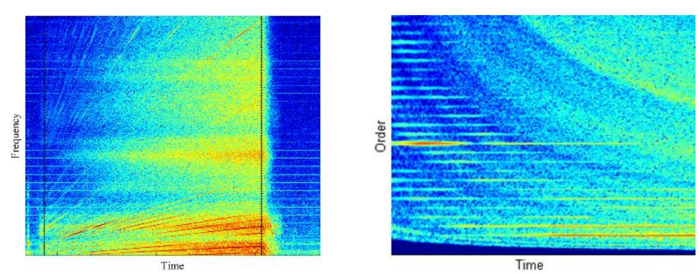

Figure 5. Time-frequency domain spectrogram during a run-up (left) and its equivalent order domain (right) computed using tach-less order tracking.

Fault assessment and features extraction

The EOL system hereby presented was designed for identifying units that produce excessively high noise levels as well as for detecting several known anomalies. Some defects may only appear at certain operating conditions, and therefore designing a customized testing process is key for achieving a reliable vibro-acoustic assessment.

Anomalies can be caused during the assembly process or by the subcomponents integrated in the unit. In [2], fault detection strategies for identifying motor unbalance and unexpected vibro-acoustic problems were proposed. In the present work, the discussion is focused on detecting excessive excitation at low rotational speeds.

Low frequency vibrations may not appear to be a problem in terms of noise when the modules are tested at the end of the production line. However, it certainly can have a dramatic impact on the vehicle when the unit is installed. Despite the low acoustic radiation of a small subcomponent, the structure-borne excitation can directly be transmitted to the vehicle producing excessive noise or vibrations. This particular problem was one of the known defects that the EOL system had to be able to identify. In our case, the root cause was traced back to the main motor, being the differences between modules more pronounced when observing the main motor orders at low RPM. The excitation measured by a 3D sound intensity probe positioned near 9 defective modules is hereby presented along with a comparison to 94 regular modules. Several details are omitted due to a confidentiality agreement with the manufacturer.

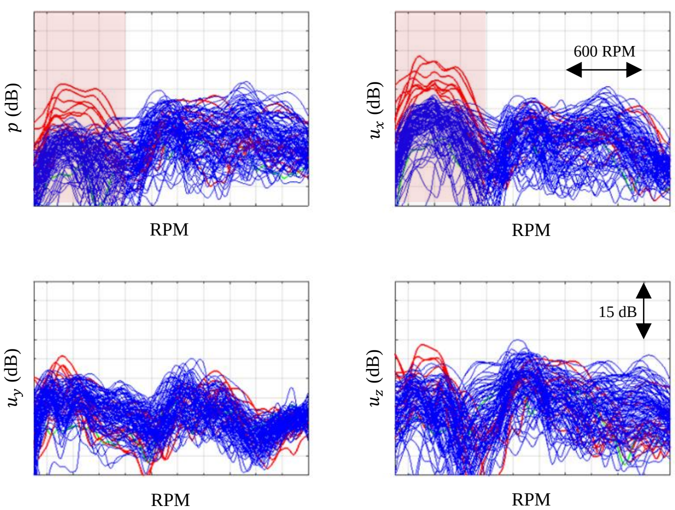

Figure 6. Comparison of the main motor order excitation level of regular (blue) and defective (red) units in terms of sound pressure (top left) and acoustic particle velocity in *x* (top right), *y* (bottom left) and *z* (bottom right) directions.

The data gathered was converted to the order domain using the VSDFT transform described above in combination with tachless RPM tracking extracted from the particle velocity sensor oriented along the *z*-axis. The resulting order-spectrogram was filtered for selecting the energy related to the main motor orders. As shown in Fig. 6, the anomaly is not apparent in all the measured channels, denoting that the excitation is dominant along the *x*-axis when this problem occurs. The differences between regular and faulty modules are more evident during an operational band that covers the first 700 RPM of the test. Consequently, the initial features used to describe this defect were extracted from the energy of the motor orders measured in terms of microphone and the *x*-component of the acoustic particle velocity.

A simple linear classifier was built using features from individual channels based on the total energy measured at two different RPM bands. Results of this preliminary assessment are shown in Fig. 7, where B1 and B2 are used to denote two different operational bands. A threshold line has been calculated (discontinuous black line) imposing the constraint that all defective modules should be detected.

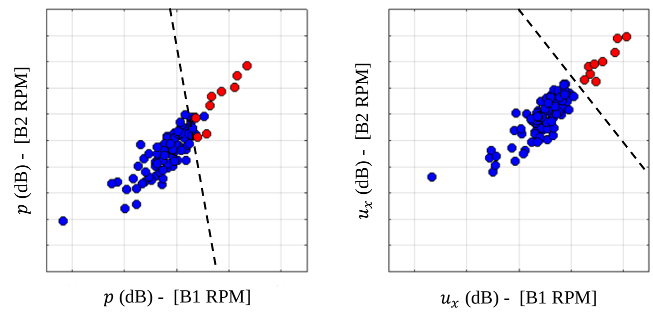

Figure 7. Linear classifier based on features extracted from two different RPM bands (B1 and B2) using sound pressure (left) and acoustic particle velocity oriented along the *x*-axis (right). Defective modules are depicted in red, regular modules in blue and the limit between them with a discontinuous black line.

As shown above, the features extracted from the sound pressure signal would allow for identifying all defective modules with certain degree of misclassification. Sound pressure being of scalar nature, captures the net resulting excitation. In contrast, measurements performed with an acoustic particle velocity transducer aligned appropriately can filter out misleading information due to its intrinsic directivity. As a result, there is an unambiguous classification of the dataset evaluated.

It can be concluded that it is feasible to implement a test procedure to detect defective modules that cause excessive vibrations at low RPM. In this case, the best performance is achieved using the signals of the particle velocity transducer oriented along the *x*-axis.

Classification methodology

After a feasibility study, more complex classification algorithms are implemented in order to maximize the performance for large datasets. The selected approach hereby studied is based on a supervised learning method using Gaussian Mixture Models (GMMs) [9]. Such statistical approach has been proven robust for the classification of dynamic signals, making it suitable for the assessment of vibration data subjected to load and fault severity variations [10].

The training process of the classifier starts by selecting a set of features that provide information about a particular defect. Then, it is necessary to define which modules among the entire dataset could be use as "master samples" of good and bad behavior. This information along with an estimation of the complexity of the distribution obtained through cross-validation are used to compute a model composed by multiple Gaussian functions that describes the data. The threshold between good and bad behavior can automatically be computed including certain constrains such as the minimization of misclassified samples or the maximization of anomaly detection. Further details about the mathematical foundation of the classification process can be found in [2, 9, 10].

Testing procedure

The normal working cycle begins by manually positioning the testing device in the intake area of the EOL system. This initial step is the only one that requires the operator involvement, all the following actions are performed automatically.

Several optical sensors are used to ensure that the unit is mounted appropriately. Next, the unit is locked and moved to the testing area. Pneumatic actuators are used to lower an enclosure that contains the

3D sound intensity probe and a power module that is attached to the unit. After some preliminary electrical tests, the PLC initiates the acoustic evaluation by sending a message to the industrial computer requesting to start recording. The module is then driven through its full operational range with a smoothly increasing excitation. Subsequently, the data processing stage is undertaken while the PLC returns the unit to the original position.

The main steps involved into the acoustic data analysis are depicted in Fig. 8. The data gathered is first used for extracting the shaft speed during the measurement. An order domain transformation is then carried out using both the instantaneous RPM and the time signals by applying Eq. 4. The resulting data is used as the basis for several fault detection tests. Finally, the output from all the tests is combined in a report which is stored in the database. The process ends with a message from the computer to the PLC communicating a summary of the results of the vibro-acoustic assessment.

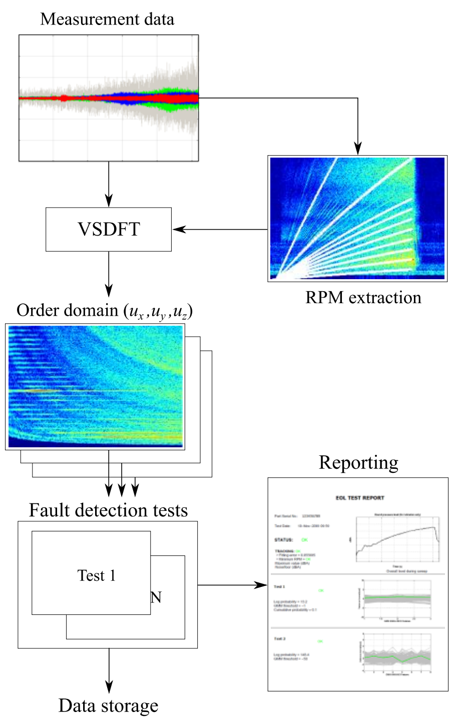

Figure 8. Flow chart of the EOL testing process

In addition, Fig. 8 shows a flow chart of the processes involved in each fault detection test. After extracting a set of features from the input data, that information is introduced in a GMM classifier which will determine the similarity between the evaluated sample and the good and defective models stored in the database. A threshold is then used to decide whether or not a module can be considered to have a defect.

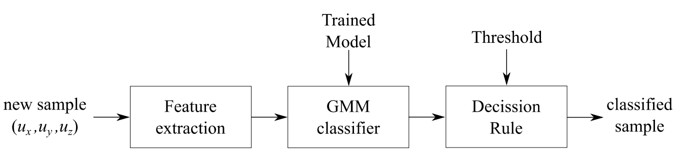

Figure 9. Flow chart of every fault detection test

Conclusions

The integration of a vibro-acoustic EOL system for rotating machinery based upon tach-less order analysis using a 3D acoustic particle velocity sensor has been presented. The use of single probe enables not only the quantification of vibro-acoustic emissions and the detection of noise and vibration problems but also the tracking of the operational speed of rotation. The system is able to perform fault classification and anomaly detection based on features extracted from any of the data channels. In addition, the proposed technique is capable of working in the presence of high background noise due to the overall noise reduction obtained from the combination of particle velocity sensors with a light isolation enclosure. Results provided demonstrate the viability of particle velocity sensors for end of line fault detection using automated quality control systems in factory conditions.

References

1. Randall, R. B., "Vibration-based Condition Monitoring: Industrial, Aerospace and Automotive Applications, " John Wiley & Sons, 2011.
2. Carrillo Pousa, G., Fernandez Comesana, D. and Wild, J., "Acoustic particle velocity for fault detection of rotating machinery using tachless order analysis," in Inter-Noise, 2015.
3. Bree, H. E., and Druyvesteyn. W. F., "A particle velocity sensor to measure the sound from a structure in the presence of background noise," in Proceedings of Forum Acusticum, 2005.
4. Fernandez Comesana, D., Yang, F. and Tijs, E., "Influence of background noise on non-contact vibration measurements using particle velocity sensors," In Proceedings of Inter-Noise, 2014.
5. Carrillo Pousa, G., Korbasiewicz, M., and Fernandez Comesana, D., "Fault detection system using acoustic particle velocity in noisy environments based on kurtosis," In ISMA, 2014.
6. Weyna, S., "Acoustic flow visualization based on the particle velocity measurements," in Forum Acusticum, 2005.
7. Brandt, A., Lago, t., Ahlin, K., and Tuma. J., "Main principles and limitations of current order tracking methods." Sound and Vibration 39(3):19-22, 2005.
8. Borghesani, P., Pennacchi, P., Chatterton, S., and Ricci, R., "The velocity synchronous discrete Fourier transform for order tracking in the field of rotating machinery," Mechanical Systems and Signal Processing 44(1):118-133, 2014.
9. Bishop, C. M., "Pattern recognition and Machine Learning," Springer, 2006.
10. Nelwamondo, F.V., and Marwala, T., "Faults detection using Gaussian Mixture Models, Mel-Frequency Cepstral Coefficients and Kurtosis." In IEEE International Conference on Systems, Man and Cybernetics, vol. 1, 290-295, 2006.

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