MÜLLER-BBM
VibroAkustik Systeme

ROTATIONAL ANALYSIS IN THE ANGULAR DOMAIN

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1. INTRODUCTION

It is commonly agreed that unwanted noises are usually created either by vibrations or rotations at some point. Both phenomena are frequently propagating through the entire structure and finally result in either structure or airborne annoyance. Considering the powertrain of a vehicle as the most dominant source in a classic vehicle, components such as clutch, gearbox, and crankshaft have to be investigated thoroughly. Further, it can be assumed that the rotating parts are the source of most noises. While each rotating element creates noise and vibration itself, all components are connected to others and therefore eventually passing on vibrations either to other rotating parts or to the connected structure. While the FFT is already a powerful analysis itself, a wide range of analyses, especially for rotating parts, have been integrated in the past. Some commercial and non-commercial products have already implemented these approaches, but usually appear as “black box”. In this work we will focus on the three most popular approaches, namely order analysis, torsional vibration, and Crank Angle Analysis, and give a brief introduction to the theory and possible applications.

All these methods are usually based on a highly precise acquisition of the rotational speed, where a wide range of sensors can be applied. All methods have in common that they do not only intend to count the individual cycles, which is easily performed with one pulse per revolution (PPR), but try to describe the rotation in a more thorough way by adding more pulses, e.g. 360 PPR. This now allows the transformation of the acquired acoustic signal from the time domain to the angular domain, which has several advantages.

The dominant noise in a rotating system will usually be represented by a frequency correlated to the rotational speed and its multiples. While these so called orders can be easily calculated with the FFT as baseline, it lacks of precision for fast changing systems, which can be compensated by the so called digital order tracking. Furthermore, the angular domain provides the opportunity to describe the motion of the rotating part which is not necessarily uniform. While the rotation itself might not be perfect, there may also appear a superimposed vibration. The rpm signal will appear perfectly fine at a first glance, but with the transformation into the angular domain a further analysis of the angular speed can be performed in order to detect torsional vibration.

Figure 1: Exemplary application for rotational analysis at the pistons of an engine

Rotating systems furthermore create periodically repeated phenomena, which are usually appearing only at a certain position of the system, e.g. a defective gear or an explosion in the cylinder during the combustion process. With the analysis based on just one revolution instead of the entire frequency band, the exact position can be determined using the so called Crank Angle Analysis (CA) [1].

The white paper is structured as follows: Section 2 will cover the topic of data acquisition for rotational analysis, starting with possible transducers and alternatives followed by a short reminder on the importance on processing of raw tacho signals. The standard in rotational analysis, namely digital order tracking, will be introduced in section 3 and compared to the standard FFT. Section 4 will focus on the topic of torsional vibration which can be considered as a non-uniformity of the rotation. The investigation of periodically reappearing phenomena will be discussed in section 5, where the so called Crank Angle Analysis will be used. Last, a short conclusion will be given in section 6.

2. DATA ACQUISITION AND PROCESSING

For all following methods of rotational analyses, the data acquisition and processing of the rotational speed and the base signal is considered as crucial. Only a clean and flawless signal can be used for the analysis and has a huge influence on the results. The most important factor is the precision of the signal. With the demand of transforming the signal from the time domain into the angular domain, usually high PPRs are required and hence demand an acquisition system with a high sampling rate on the tacho input in order to capture all pulses. With this prerequisite bus-based digital RPM signals, e.g. from CANbus or FlexRay™, are not applicable due to a possible delay and low precision.

Depending on the application and the possible placement, the correct transducer, based e.g. on induction or optical systems, has to be chosen from a wide range of possibilities. Whereas an optical sensor needs some kind of black and white pattern, which has to be applied to the rotating part, and a direct visibility, induction-based transducers are able to detect changes in the magnetic field created by the rotating gear. Both usually provide sufficient accuracy for the following tasks.

Nevertheless it is frequently necessary to take care during the processing of the tacho times. As these are the base of the computed rotational speed, even the averaging process of the determined RPM has a huge influence as shown in Figure 2. Faulty parametrization of the signal conditioning can lead to unwanted side effects, such as a rather sloppy RPM signal with fast changes, although it should be a rather smooth run-up. Such phenomena can also be created due to errors in the acquired tacho signal. Following phenomena should be considered in the raw tacho signal:

- Filling of gaps in the tacho signal
- Elimination of double pulses
- Cog error correction

All these correction algorithms are required to receive a smooth and correct RPM signal.

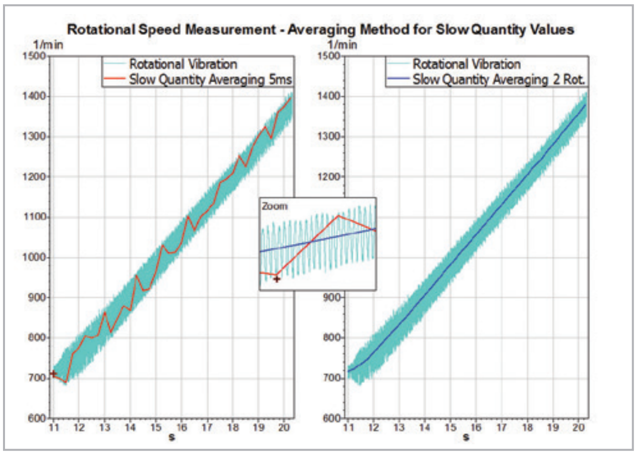

Figure 2: Possible errors in the rotational speed due to faulty processing during the averaging process

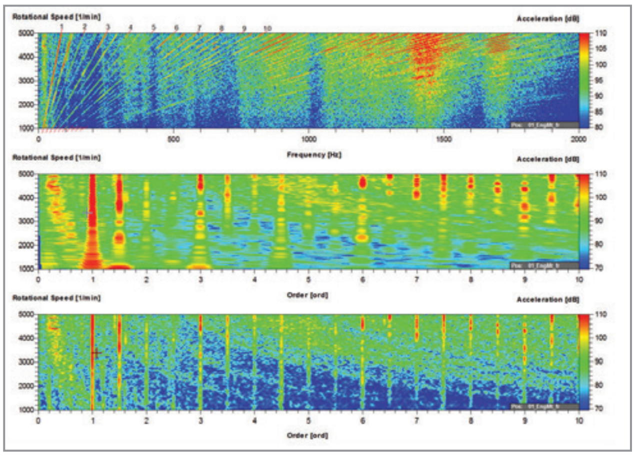

Figure 3: Exemplary order analysis for an engine run-up. The upper diagram shows the FFT of a signal with rotational speed as track quantity. The order analysis can be performed directly from the FFT, resulting in blurred lines as displayed in the middle. Using digital resampling, the lines are finer and a more thorough analysis can be performed

3. ORDER ANALYSIS

The standard in acoustic analysis is probably the standard Fast Fourier Transformation (FFT), which is perfectly suitable for frequency analysis and sufficient for most of the tasks. With various settings, e.g. block size, overlap, averaging, etc., it provides a perfect insight into both stationary and instationary phenomena. As already stated earlier, a wide range of engine and gearbox noises are directly connected to rotating components. Frequencies in structure-borne or airborne signals – corresponding to the current rotational speed or their multiples – are regarded to as so-called orders. In the field of musical acoustics these would be considered as harmonics. The first order is representing the actual rotational speed, the second order is the rotational speed multiplied by two and so on. Consequently, the level is computed along each individual order. With the FFT as baseline for the analysis, it is now possible to compute the order O according to

$$O = \frac{f}{n/60} \quad (1)$$

with n representing the rotational speed and the current frequency f. Figure 2 illustrates this process at a run-up. The upper diagram shows the FFT with the dominant orders which are created by the rotating camshaft at different rotational speeds. With the rather simple formula, it is rather difficult to exactly correlate frequency and rotational speed. Usually one would set a corridor around the observed order and try to average this into one line. This method is usually sufficient for slowly changing rotational speeds. As the diagram in the middle of Figure 2 shows, this frequently leads to rather blurred lines in the order spectrum in case more rapid changes appear. Hence, a method to guarantee rather thin lines seems

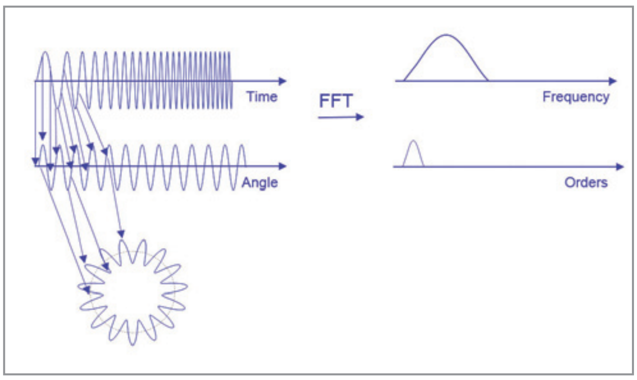

Figure 4: Digital resampling for order analysis. The signal in the time domain is transformed into the angular domain prior to the FFT, resulting in a detailed representation in the order domain

desirable. The basic idea is here to further investigate the rotational speed and align the acoustic signal to the tacho signal measured with the system. Here the so-called digital resampling is coming into play. As Figure 4 depicts, the original signal is resampled into the angular domain. Using the rotational speed with high precision and a sufficient amount of pulses per revolution, an exact correlation between angle and time can be provided. In this way the signal is transformed from the time domain into the angular domain and can be exactly aligned to a 360° cycle. Analogous to the original signal in the time domain a simple FFT is now performed. As can be seen in the lower diagram in Figure 3, the result is more precise than the FFT based computation.

4. TORSIONAL VIBRATION

Torsional vibration can be simply described as angular vibration of a rotating object in the powertrain and often leads to failures at couplings and rotating shafts if not controlled. Ideally the torque would be smooth and only applied to the rotational part. In reality it is not that smooth and it has an effect on the component in the plane. Hence, it is required to compute the torsional vibration of each component. The prerequisite for this is once more a very precise RPM signal with at least 360 pulses. Figure 5 illustrates the determination of the angular velocities. With the known regular distance of the tacho pulses of the tacho times signal, the angular velocity can be easily computed by measuring the time *dt* between two pulses. Thus it is now possible to determine the torsional vibration of the rotating part.

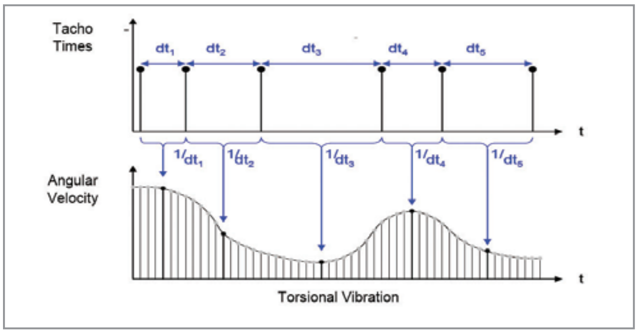

Figure 5: Computation of the angular velocity applying a high precise tacho signal

An exemplary application is shown in Figure 6 where the torsional vibration is measured between the coupling of the engine and the clutch. As shown on the top left, a high angular velocity can be seen on the 3rd order. The aim is now to design a torsional damper that at least avoids the transmission from the engine to the clutch. With the correct design of the torsional damper, the angular velocity will be lower as illustrated in Figure 6 top right. Nevertheless some effects can be also observed when changing the gear. On the lower left the process of pressing the clutch and changing the gear is shown. This process creates a short additional torque on the 1st and 3rd order.

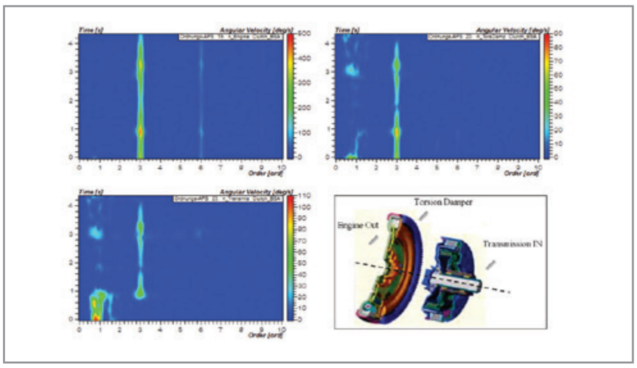

Figure 6: Exemplary coupling of engine and clutch and the computed torsional vibration with two differently designed torsional dampers

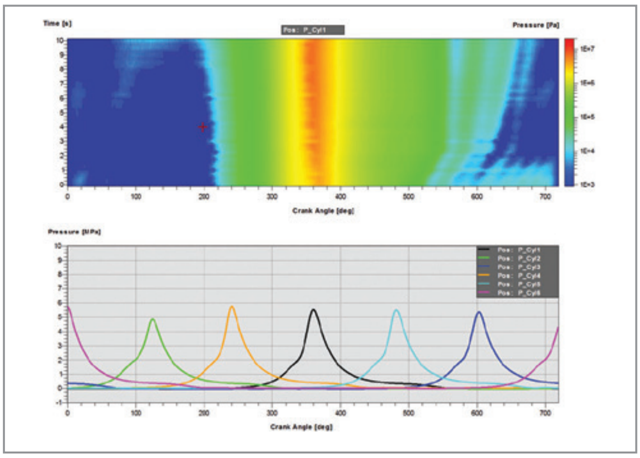

Figure 7: Exemplary measurement of the cylinder pressure and a plot of all 6 cylinders in one diagram according to the angular position in one cycle. The upper image shows the 3D diagram of the cylinder pressure during a run-up

5. CRANK ANGLE ANALYSIS

Rotating systems often create also reoccurring periodical phenomena. Their frequency of appearance is usually directly correlated to the rotational speed of the component. Its periodicity is created by reoccurring events during one or more circulations, e.g. the ignition in a cylinder or flaws in the gear. With changing rotational speed, it is consequently rather difficult to localize the actual source with just a normal FFT. Therefore, it seems reasonable to not only analyze the signal in the time domain, but also in the angular domain. This way it is possible to localize the exact position of the creation of such an event. In addition to a high resolution rpm signal, sampled with at least as many pulses as the desired angular resolution, a so-called duty signal (OT) is required. This is used to detect the start and end of a cycle. In most common cases one would use two signals with 1 and 360 pulses per cycle respectively, where the low resolution signal represents the initial position of the system. In case only one rpm signal can be acquired, the OT can be computed by a gap within the signal. Now it is possible to transform the time signal into the angular domain. In the simplest case each sampled point in the time raw data is assigned to a dedicated angle, which can be easily done with the highly precise rpm signal. For a more detailed analysis now the OT signal is being used to divide the signal into the individual cycles and then stack the individual segments into a 3D diagram. Thus the explosion in the individual cylinders of an engine for example can be aligned to a specific angle position of the camshaft, as illustrated in Figure 7. A possible application is illustrated in Figure 8. A microphone has been applied to acquire the sound pressure near the engine in order to investigate a knocking signal that can be seen as impulsive part in the time raw data.

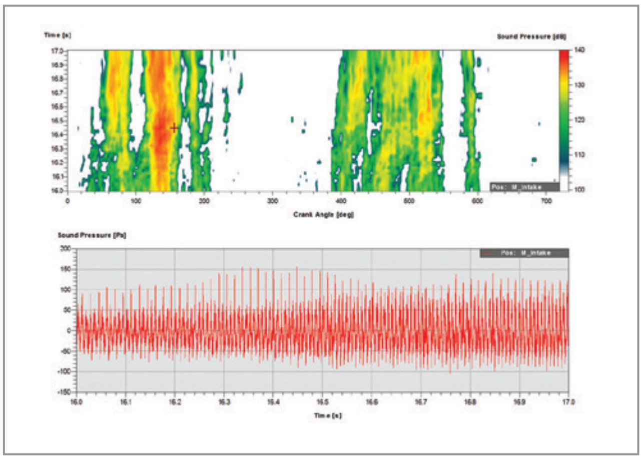

Figure 8: Sound pressure of a knocking signal investigated by the Crank Angle Analysis

The periodicity of the signal led to the assumption that the impulses are created by the rotating parts. Applying the Crank Angle Analysis and transforming the signal into the angular domain, shows that the impulses are being created at a position of roughly 140° of the rotating system.

6. CONCLUSION AND OUTLOOK

In the current work we have presented three different approaches for rotational analysis of both structure-borne and airborne phenomena in the angular domain, namely order analysis, torsional vibration and crank angle analysis. All analyses are fully integrated in the NVH development process of vehicles. The base is still a highly precise acquisition of the rotational speed with a high number of PPR and tacho times acquired with a high sampling rate. Experience has shown that this is crucial, and should be further investigated with new alternative powertrain concepts. The start and the stop process of an engine have to be considered with special care, as here the rotation of the camshaft is quite irregular and usually leads to a faulty RPM signal. A post-processing seems reasonable in order to be able to investigate these thoroughly.

7. REFERENCES

[1] S. Wartini, B. Virnich,: Crank it up – Modern emerging powertrain noise analysis techniques allow more precise results in: Testing Technology International, May 2000, pp. 28...30

About Us

Müller-BBM VibroAkustik Systeme is one of the world's leading suppliers of vibroacoustic measurement technology. We focus on the interpretation of dynamic or physical data, especially in the fields of NVH, strength and comfort. For more than 30 years, our system competence results in innovative solutions that seamlessly integrate into existing environments.

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