Main Principles and Limitations of Current Order Tracking Methods

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Order tracking is a widely used tool for analysis of vibrations generated in vehicle drivetrain components, since many vibrations are related to engine RPMs. In recent years, offline order tracking has become suitable due to enhanced computer speeds. Many methods, some patented, for both online and offline order tracking have been presented over the years. This article reviews some basic ideas behind current methods and compares their main advantages and limitations. Some basic time-frequency concepts and time window effects are reviewed. Questions on suitable tachometers and their number of pulses per revolution are also addressed. The possibility of processing RPM dependent data without tachometers is also discussed.

Frequency analysis of the instantaneous root-mean-square (rms) values of periodic components of rotating machine vibrations as a function of rotational speed is usually referred to as order tracking. The component under test is either run up in speed or coasted down, the latter often for electrical equipment that cannot be run at continuously increasing or decreasing rpm. Order tracking is an important tool in development and diagnostics of many components such as gear boxes, reciprocating engines, exhaust systems, electrical generators, and paper mill rollers, for example.

For many years, order tracking was performed using analog tracking filters and elaborate instrumentation with analog-to-digital converters controlled by some rpm sensing unit (PLL, phase-locked loop), and performance was far from ideal. In 1989, Hewlett-Packard[1-3] introduced a novel resampling method, in which the original signal sampled with a fixed sampling frequency was digitally resampled at synchronous sampling intervals. The HP method was implemented in DSP technology, and the processing was done in real time.

With the advance in computing speed and reduction in digital storage cost, it is now generally prefered to store raw data on a hard disk, and perform all subsequent analysis as post-processing. The era of online processing, largely driven by the need to quickly reduce the amount of data due to large costs per megabyte, is today rather obsolete, except in some cases where results are used only for acceptance or rejection (e.g., production testing). Storing raw vibration data to disk offers many advantages, mainly because of the important bandwidth-time limitations present in all kinds of experimental frequency analysis. When the raw time data of a vibration signal together with a tachometer signal are stored, the data can be analyzed with many methods, some of which will be covered below. Blough[4] includes an excellent review of present methods, and the following discussion will complement that paper with some additional thoughts.

With the development of Vold-Kalman filter technology in the 1990s,[5-8] a parametric method (not FFT based) became available that has some advantages over FFT based methods, but which also needs experience in use and interpretation of results. The Vold-Kalman method has been successfully applied in many fields, including sound quality evaluations.

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Methods and Discussion

The main difficulty in analyzing a vibration signal sweeping in frequency (rpm), is due to the bandwidth-time limitation. In essence, this limitation comes from the fact that the frequency domain (Fourier transform) of a signal is an unlimited integral over infinity. If a signal is truncated in time, as it must be for measurement, the spectrum of the truncated signal will be different from the 'true' spectrum of the entire signal. Frequency analysis can be interpreted as measuring the output of a filter (see Figure 1). It is very important to realize that the this illustration describes all frequency analyses, not only FFT (DFT) analysis, but also wavelet analysis, Wigner-Ville analysis, and all other methods that can be conceived for general frequency analysis, present and future, that do not use *a priori* information.

An important aspect of general frequency analysis, illustrated in Figure 1, is the effect of the filter bandwidth. With any kind of analysis, the product of the bandwidth (usually equal to the frequency increment) B (in Hz) and the integration time T (in sec) of the rms estimation, is limited by the bandwidth-time relationship

$$B \cdot T \geq Const. \tag{1}$$

for some bandwidth-time constant τ. Each type of frequency analysis principle may have a different bandwidth-time constant, and for DFT analysis (FFT), it is unity. The constant can never be less than $1/4\pi$,[9] which is related to the Heisenberg uncertainty principle. It should be noted that by adding a priori information, in principle more information can be extracted without the limit of Equation 1.[10] Vold-Kalman filtering, as we will mention later, is a case where some a priori information (the RPM) is used, but where the BT product still affects the time constant of the filters, and thus the rate at which the output signal can change (for a particular bandwidth).

In order tracking applications, Eq. 1 has the implication that the narrower the bandwidth of the analysis filter, the longer the time constant of the filter. The time constant tells how slowly the output of the filter will be adapting to a change on the input. A long time constant means it takes a long time for the filter to adapt to a change at the input, and essentially, for practical purposes, with digital bandpass filters, the time constant τ is approximately

$$\tau \approx \frac{1}{B} \tag{2}$$

In order tracking applications, the limitations related to the bandwidth-time product should be interpreted as an uncertainty in the rms value vs. frequency content of the signal. In other words, the 'true' rms value of a vibration signal at a particular instant in time can only be estimated within a particular uncertainty. Failing to realize this can result in much confusion in order tracking applications. If you choose a large bandwidth, the signal can potentially change very quickly with time (or, if RPM changes with time, then the rms value changes with RPM), whereas if you choose a narrower filter, the signal will seem to vary more slowly. Neither of these two results can be conceived to be 'wrong;' they are simply effects of the bandwidth-time limitation. The principle is illustrated in a spec-

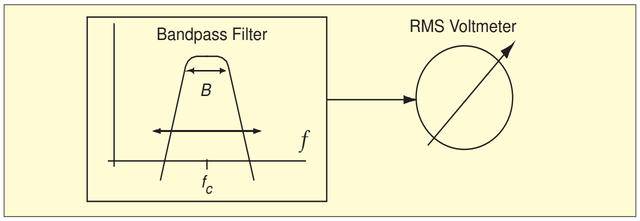

Figure 1. Principle of all frequency analysis. Each estimated frequency value is in effect the result of bandpass filtering data, and subsequently estimating the rms value (or some other value, such as peak value) of the band limited signal. The bandpass filter is centered at the center frequency f_c and a bandwidth B is chosen.

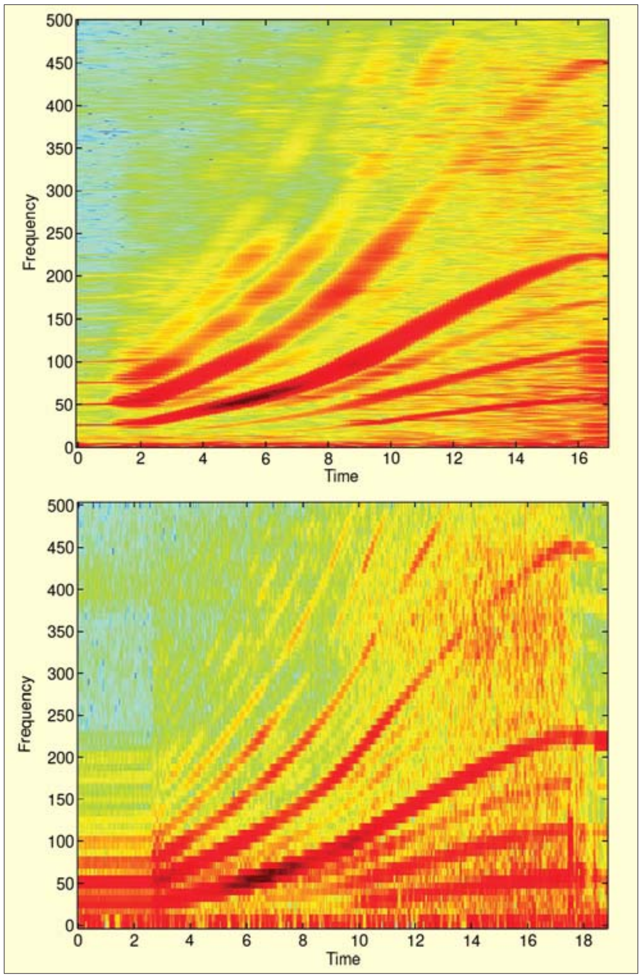

Figure 2. Illustration of high frequency resolution and low time resolution (top) vs. low frequency resolution and high time resolution (bottom). The signal is a noise signal from an exhaust system under rapid speedup of the engine from approximately 1000 to 6700 RPM.

trogram, a plot of frequency vs. time, in Figure 2. From this figure it is clear that with high frequency resolution, such as in the top plot in Figure 2, the time resolution is low, and vice versa.

RPM Extraction

The first computational step in most order tracking applications is the extraction of instantaneous RPM. However, it is also possible, using some a priori information, to perform order tracking without the use of a tacho signal.[11] This can be particularly interesting in production environments where the need to add a tachometer can be costly. Sometimes the RPM is computed in the data acquisition unit, in other cases the tacho signal is recorded along with the vibration data and later processed on the computer. To be able to synchronously resample data, or to apply digital tracking filters such as Vold-Kalman filters, a high resolution RPM vector is needed, preferably with the same sampling frequency as the vibration signal. This can

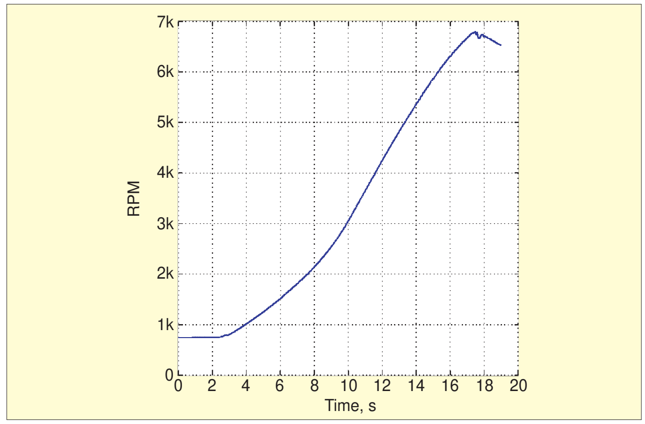

Figure 3. RPM vs. time signal from an engine runup from approx. 1100 to 6600 RPM. The RPM vector has the same resolution as the original vibration signal.

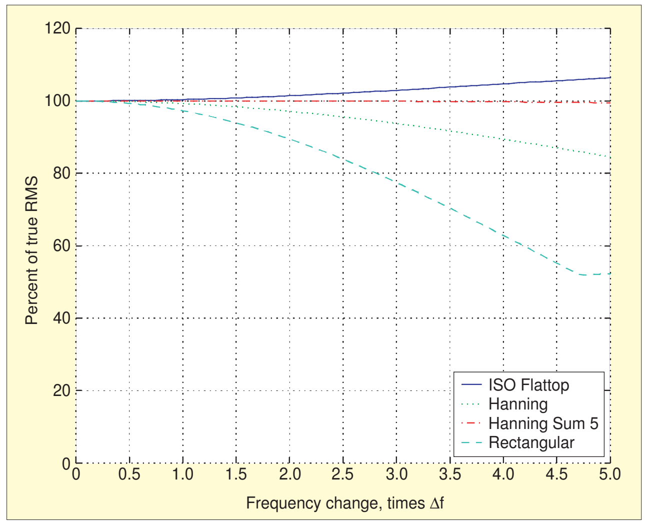

Figure 4. Effect of smearing. The error in the peak value of the DFT is plotted as a function of frequency change of a sinusoid, relative to the frequency increment of the DFT. The result denoted "Hanning Sum 5" is the result of summing 5 frequency lines of a spectrum computed with a Hanning window, as is common practice.

require some filtering of the original tacho pulses, and requires some interpolation scheme to be applied between the tacho pulses. All analyses in this article have been done in MATLAB with The VibraTools Suite™ toolboxes, and a simple command, 'getrpm,' results in the RPM-time signal shown in Figure 4. This tacho signal comes from a measurement on a four-cylinder, four stroke car engine while revving the engine from approximately 1100 RPM to 6600 RPM in approximately 18 sec. We are going to use this tacho signal and a simultaneously recorded microphone signal throughout the article.

Smearing

The most basic method used for order tracking is to use a fixed sampling frequency to acquire the vibration signal. The instantaneous RPM as a function of time is estimated, and is used to extract time blocks for spectrum computation. The underlying assumption in this type of analysis is that the frequency change within a single time block is small, so that the assumption of stationarity necessary for frequency transformation to be rigidly valid is not largely violated.

If the frequency of a periodic component changes within the time block, the DFT will produce an error called smearing, which results in a peak value that is different from the actual rms value of the sweeping sinusoid. The smearing effect is strongly influenced by the time window used in the spectrum computation. In Figure 4 the error in the spectrum peak, as a function of the total frequency change of a sinusoid within the time window, is plotted for three common time windows. A

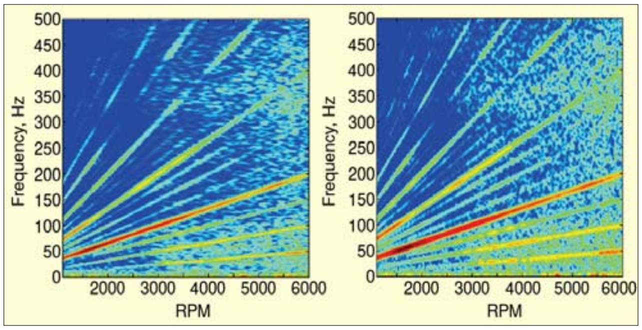

Figure 5. Color intensity RPM maps using a Hanning window (left) versus using a flattop window (right).

fourth function is obtained by applying a Hanning window, and summing the total rms value over five frequency lines symmetrically around the peak. It is interesting to notice that the flattop window produces a small positive error, which can likely be explained by the unusual shape of the flattop window in the frequency domain. Other windows, such as the rectangular (uniform) and the Hanning window result in negative errors. New flattop windows could be designed to give less error due to smearing.[12] In our analysis we have used an ISO standardized flattop window, according to ISO standard 18431-1.

The errors plotted in Figure 4 are approximately independent of the location of the sine wave relative to the frequency resolution, i.e., the plot includes effects of leakage. From Figure 4, a fair conclusion seems to be that the best practice, when using a fixed sampling frequency, is to apply a Hanning window and sum a number of spectral lines to obtain orders. Using a Hanning window also has an advantage due to its lower bandwidth, which causes peaks to be less 'rounded' and provides for better resolution in RPM maps, as shown in Figure 5. Color maps are shown of the same signal analyzed with Hanning and Flattop windows, with all other parameters equal.

Order Tracking Methods

Order tracking using fixed sampling frequency suffers from smearing of RPM dependent spectral components. On the other hand, spectral components that are not changing with frequency, such as resonance peaks, for example, are resolved well with this technique. Thus an *RPM map* from a measurement with fixed sampling frequency is often a suitable first step in a trouble-shooting scheme, in order to investigate whether a vibration problem is caused by order related components or resonances. The extracted second order from the left plot of Figure 5 is shown in Figure 6. A Hanning window and summation over five frequency lines was used for order extraction. For comparison, a single pick, not using bandwidth summation, of the second order from the right-hand plot in Figure 5 is included in Figure 6. It is evident that there is some overestimation of the second order when using a flattop window, due to smearing as shown in Figure 4.

To improve the resolution of order related components, the fixed frequency sampling is replaced by a synchronous sampling frequency, at fixed positions (angles) around the rotation of the engine. The time axis of seconds is thus replaced by a number of periods, and an FFT result has a "frequency axis" which is physically scaled in orders (i.e., times rpm); order n corresponds to an event taking place n times per revolution. As mentioned in the introduction, HP was the first to publish the use of digital resampling. Today, however, all major manufacturers of vibration analysis systems use some implementation of this technique, including our MATLAB toolboxes. It is then interesting to study how different resampling schemes vary in performance. In principle, synchronous resampling can be performed with arbitrary accuracy. At frequencies much lower than half sampling frequency, a straight forward linear interpolation is adequate. At high frequencies when analyzing orders close to the Nyquist freqency, the standard oversampling factor of 2.56 used by most recording devices is not adequate.

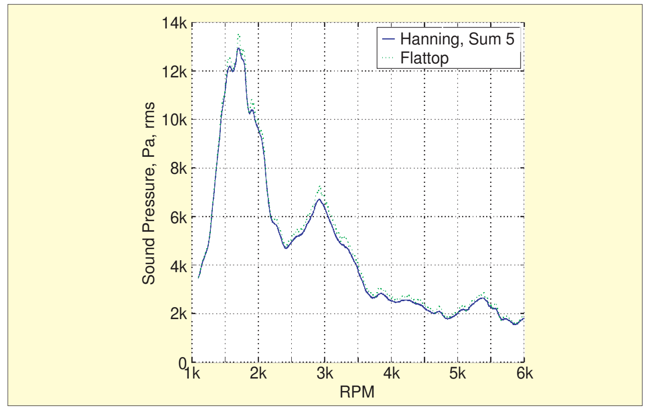

Figure 6. Second order of a fast run-up extracted from the left plot in Figure 5, summing over 5 frequency lines.

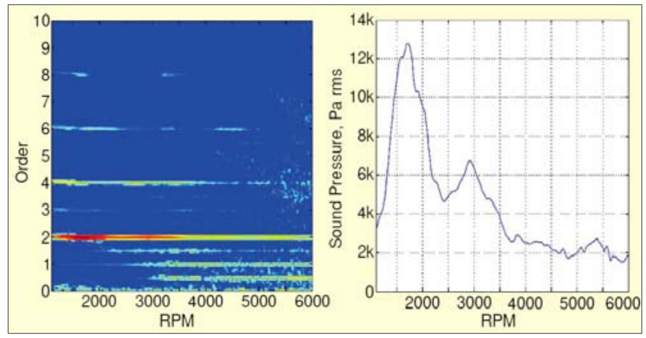

Figure 7. Color intensity RPM map (left) and extracted second order (right) using synchronous resampling of the time signal used in the examples. See text for details.

Using post processing in MATLAB, it is, however, very easy to resample the data with a higher sampling frequency prior to synchronous interpolation. Thus it is easy, at the cost of some computation time, to get an arbitrary accuracy in the interpolation. A color intensity RPM vs. order map and extracted second order are plotted in Figure 7.

A disadvantage of using synchronous sampling followed by a DFT based frequency transformation is the resulting limited order resolution. This is again related to the *BT* product of the DFT, which in the "order domain" becomes a product of order resolution and number of cycles. In order to have a high order resolution, the block length of the DFT has to be high, which means many cycles have to be measured, thereby reducing the RPM resolution.

In order to improve the accuracy of order tracking, especially with very fast run-ups, Vold developed the so-called Vold-Kalman filtering method. The first-generation method essentially computes an adaptive bandpass filter of selected width, which is centered at a frequency controlled by the current RPM at each instant (sample) of the vibration signal. The output of the Vold-Kalman method is thus a new time signal, bandpass filtered around a particular order. This time signal can be analyzed by a running rms computation or some envelope detector to extract an order as a function of RPM, which is a principle of the second-generation filter. The second order extracted with a V-K filter is shown in Figure 8, together with the second order from the synchronous analysis in Figure 7. The number of filter poles can control the selectivity of the second-generation filter. This latest generation of the V-K filter can be designed using a one-pole, two-pole, three-pole or four-pole filter, of which the four-pole filter has the best selectivity. The analysis result presented in Figure 8 was obtained with a two-pole filter. As can be seen in Figure 8, the order extracted by Vold-Kalman filtering shows a slightly increased time detail.

The Vold-Kalman filters provide several advantages over traditional order tracking. The order a filter tracks is arbitrary, and not limited by the order resolution of the DFT. However, as can be seen in Figure 9, the Vold-Kalman technique is still limited

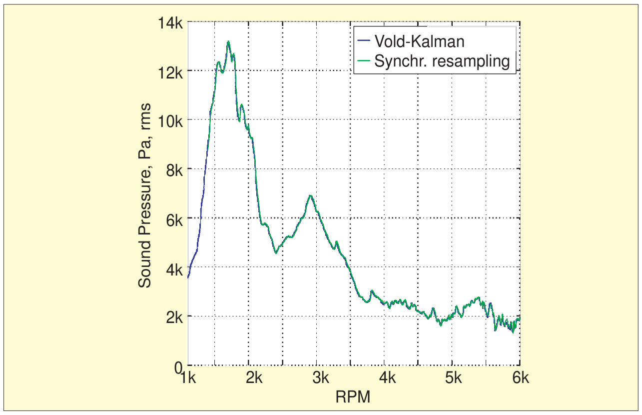

Figure 8. Second order extracted by applying a Vold-Kalman filter to the time signal and applying an envelop detector. The second order from Figure 7 is included for comparison. Very little difference can be seen.

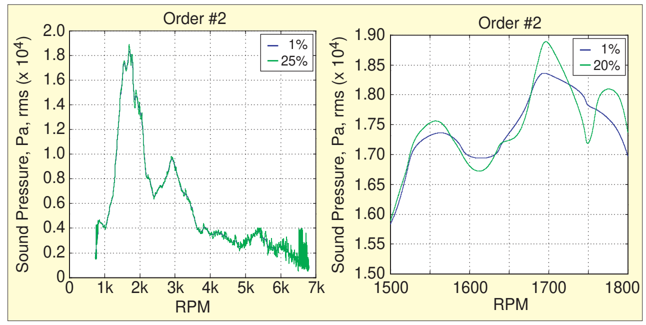

Figure 9. Illustration of bandwidth-time effects using Vold-Kalman filters. A narrow filter (1% relative bandwidth, blue trace) produces slowly varying orders, whereas a wider filter (20% relative bandwidth, green trace) allows faster changes as function of RPM. In the right-hand plot the range from 1500 to 1800 RPM is zoomed in to better visualize the phenomenon.

by Equation 1 in that a smaller bandwidth causes a more slowly varying output signal, and vice versa for larger bandwidth filters. It is thus difficult for an inexperienced user to select an appropriate bandwidth, and indeed this is impossible without some a priori knowledge of the data. A second advantage with the Vold-Kalman filter is that since it produces time signals, these time signals can be listened to, or, for example, subtracted from total engine noise to evaluate sound quality aspects of order related tones. Thirdly, a special formulation of the Vold-Kalman filters allow crossing orders, related to two or more different, independent RPM signals, to be accurately tracked. Unfortunately, it is apparent that the Vold-Kalman filters also exhibit some disadvantages over the robust and rather easy-to-use DFT based methods. One is the computational load which will, of course, be overcome in due time with increase in computer speed. Another problem is the experience needed in order to properly interpret the results. This depends again on the fact that the *BT* product has a bottom limit, and that there is always a trade-off between amplitude variation speed and bandwidth for any time varying signal.

Conclusions

We have discussed some aspects of analyzing rotating machinery vibration and acoustic data with order tracking using fixed sampling frequency, synchronous sampling frequency, and Vold-Kalman filtering. Of particular importance for time-frequency analysis, of which RPM based analysis is an example, is an understanding of the uncertainty that results from the bandwidth-time limitation existent in all frequency analysis. Also, it has been shown that choosing a time window and appropriate order extraction method can result in some differences in the results. Using a Hanning window and frequency bandwidth summation of the rms value of the order was shown to be superior to other currently used windows. As all analyses in the article were performed in MATLAB, it was also shown that this environment is a good platform for analyzing rotating machinery data.

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