Characteristics of the Vold/Kalman Order Tracking Filter

Henrik Herlufsen, **Svend Gade** and **H. Konstantin-Hansen**, Brüel & Kjær, Nærum, Denmark

Håvard Vold, Vold Solutions, Inc., Cincinnati, Ohio

This article presents the filter characteristics of the Vold-Kalman Order Tracking Filter. Both frequency response as well as time response and their time-frequency relationship have been investigated. Some guidelines for optimum choice of filter parameters are presented. The Vold-Kalman filter allows for the high performance simultaneous tracking of orders in systems with multiple independent shafts. Using this new filter with multiple tacho references, waveforms as well as amplitude and phase may be extracted without the beating interactions that are associated with conventional methods. The Vold-Kalman filter provides several filter shapes for optimum resolution and stopband suppression. Orders extracted as waveforms have no phase bias and may hence be used for playback, synthesis and tailoring.

In 1993 Vold and Leuridan[1] introduced an algorithm for high resolution, slew rate independent order tracking based on the concepts of Kalman filters.[8,9] The algorithm has been successfully implemented in a commercial software system for solving data analysis problems previously intractable with other analysis methods. At the same time, certain deficiencies have surfaced, prompting the development of an improved formulation. In particular, the capability of being able to control the frequency and the time response of the filter and to separate close and crossing orders has been implemented.[3] This article presents an introduction to the new Vold-Kalman algorithm, presents the frequency response and the time response of the filters and their time-frequency relationship and gives some examples of their applications using PULSE, the Brüel & Kjær, Multi-Analyzer System Type 3560.[4]

Order tracking is the art and science of extracting the sinusoidal content of measurements from acousto-mechanical systems under periodic loading. Order tracking is used for trouble-shooting, design and synthesis.[5] Each periodic loading produces sinusoidal overtones, or orders/harmonics, at frequencies that are multiples of the fundamental frequency (RPM). The orders may be regarded as amplitude and phase modulated carrier waves that frequency hop. Many practical systems have multiple shafts that may run coherently through fixed transmissions, or are partially related through belt slippage and control loops, or run independently, such as when a cooling fan cycles in an engine compartment. The Vold-Kalman algorithm allows for the simultaneous estimation of multiple orders, effectively decoupling close and crossing orders. This is especially important for acoustical applications, where order crossings cause transient beating events. The new algorithm allows for a much wider range of filter shapes, so that signals with sideband modulations are processed with high fidelity. Finally, systems subject to radical RPM changes, such as transmissions, are also tracked through the transient events associated with abrupt changes in inertia and boundary conditions. The goal of order tracking is to extract selected orders in terms of amplitude and phase, called the Phase Assigned Orders, or as waveforms. The order functions are extracted without phase error and may hence be used in synthesis applications for sound quality and laboratory simulations.

Vold-Kalman Filter

The basic idea behind the Vold-Kalman filter is to define local constraints which state that the unknown Phase Assigned Orders are smooth and that the sum of the orders should approximate the total measured signal. The smoothness condition is called the structural equation, and the relationship with the measured data is called the data equation.

Structural Equation. The Phase Assigned Order is the low frequency modulation of the carrier wave, which is RPM related. Low frequencies entail smoothness and one sufficient condition for smoothness is that the local function can be represented by a low order polynomial.

Data Equation. The structural equation only enforces the smoothness conditions on the estimates of the phase assigned orders such that we need an equation that relates estimates to the measured data. The Data Equation states that the sum of orders differs from the total signal by only an error term.

Decoupling. When several orders are estimated simultaneously, the data equation ensures that the total signal energy will be distributed between these orders. With the smoothness conditions of the structural equation, this forces a decoupling of close and crossing orders. The mathematics of this procedure is analogous to the repeated root problem in modal analysis.[7] When orders are coincident in frequency over an extended time segment, the allocation of energy to such orders is poorly defined and numerical ill-conditioning may ensue. Widening the filter bandwidth is one possible remedy in this case.

Vold-Kalman Filter Process, Step by Step Example

To illustrate the ease of use of the Vold-Kalman filter process as implemented in the Brüel & Kjær PULSE, Multi-analysis System Type 3560, a run-up measurement on a small single shaft electrical motor has been performed. Figure 1 shows the vibration response signal which was recorded together with a tacho signal. A 1.6 kHz frequency range and a total recording time of 20 sec have been selected using a PULSE Time Capture Analyzer. The number of samples recorded is 81,920 in each channel; 18 sec of the recorded signal was extracted for Vold-Kalman tracking using a delta cursor.

Overview Using Fourier Analysis. The first step is to use conventional techniques in order to gain some insight of the harmonic orders of interest, gearshifts, etc. Figure 2 shows a contour plot of an STFT (Short Time Fourier Transform) of the vibration signal. The record length for each transform is set to 125 msec (512 samples) resulting in 200 lines in the frequency domain (linespacing Δf of 8 Hz). An overlap of 66% is used resulting in a multi-buffer of 500 spectra covering the selected 18 sec. From the contour plot it is revealed that the dominating orders are numbers 1, 3, 9 and 10 and as expected, no gear-shift is present.

Tacho Processing. Any high resolution method needs proper controls. For the Vold-Kalman filter, this means a very accurate estimate of the instantaneous RPM such that the tracking filter will follow orders correctly. The method that has been chosen is that of fitting cubic splines in a least-squares sense to the table of level crossings from a tacho waveform. Figure 3 shows a superimposed graph of the measured and the curve fitted RPM profiles. The maximum slew rate in this case is seen to be approximately 800 RPM/sec and the range is between 1000 and 6000 RPM.

The spline fit also allows for an automatic rejection of outlying data points (such as tacho dropouts) with a subsequent refit on an edited table of level crossings. Note also that this procedure allows for an analytic expression of RPM as a con-

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tinuous function of time with true tracking of the shaft rotation angle for phasing fidelity. There is also the option of specifying hinge points in the spline fit such that sudden changes in inertial properties can be tracked, as in the case of clutching and gearshifts.

Vold-Kalman Filtering. Orders can now be extracted from the signal in terms of waveforms or as Phase Assigned Orders. Figure 4 shows the waveform of the 3rd order extracted using a two-pole Vold-Kalman filter with a bandwidth of 10% (i.e., 10% of the fundamental frequency). Extracted waveforms can be played via a soundboard and they can be exported as a wave-file. Sound Quality measurement is an example where this is very useful.

Extracted as Phase Assigned Orders means that the orders are determined in terms of magnitude and phase. Figure 5 shows the magnitude of the Phase Assigned Orders of the 1st, 3rd, 9th and 10th orders, which were the 4 most dominating orders. A two-pole Vold-Kalman filter with a bandwidth of 10% was used.

Filter Characteristics in Frequency and Time Domain

Bandwidth selection is done in terms of constant frequency bandwidth or proportional to RPM bandwidth (i.e., constant percentage bandwidth). The bandwidth specification is in the Brüel & Kjær Vold-Kalman implementation in terms of the half power points, i.e., 3 dB bandwidth. The proportional to RPM bandwidth is recommended for analysis of higher harmonic orders or analysis of wide RPM ranges. The filter shape is measured by sweeping a sinewave through a Vold-Kalman filter with a fixed center frequency and fixed bandwidth. A sweep rate of 1 Hz/sec is used for measuring the filter shapes, shown in Figure 6, of a Vold-Kalman filter with a center frequency of 100 Hz and a bandwidth of 8 Hz. The x-axis, which is a time axis scaled in sec, can be directly interpreted as a frequency axis scaled in Hz (with a fixed offset). It is seen that a one-pole filter has very poor selectivity, a two-pole filter has a much better selectivity, whereas a three-pole filter provides the best selectivity. The 60 dB shape factor, i.e., the ratio between the 60 dB bandwidth and the 3dB bandwidth is often used for describing the selectivity of a filter. The 60 dB shape factor has been measured for the one-, two- and three-pole filter for bandwidths in the range from 0.125 to 16 Hz. These tests showed that the 60 dB shape factor for a given pole specification is slightly increasing as a function of bandwidth. The one-pole filter has a 60 dB shape factor of approximately 50 (variation from 48.8 to 50.8), the two-pole filter has a 60 dB shape factor of approximately 7.0 (variation from 6.80 to 7.07) and the three-pole filter has a 60 dB shape factor of approximately 3.6 (variation from 3.58 to 3.68), i.e., the three-pole filter has a 2 times better selectivity than the two pole filter and a 14 times better selectivity than the one-pole filter.

Another characteristic of the filter is the frequency response within the passband. As seen in Figure 7 the two- and three-pole filters have a much flatter frequency response in the passband compared to the one-pole filter and the three-pole filter has the flattest frequency response. The flatness of the frequency response in the passband is important when analyzing the amplitude and phase modulation of the harmonic carrier frequency. Amplitude and phase modulation correspond in the frequency domain to sidebands centered around the harmonic carrier frequency component. This means that the flatter the frequency response the more correct the modulation will show in the filter analysis.

The time response of Vold-Kalman filters is important to understand when analyzing transient phenomena and responses to lightly damped resonances which have been excited during a run-up or a run-down. The time response has been investigated by applying a toneburst with a certain duration to a Vold-Kalman filter with a fixed center frequency corresponding to the frequency of the toneburst. In Figure 8 the magnitude of the response of a filter centered at 100 Hz with a bandwidth of 8 Hz is shown using a logarithmic y-axis. A 100 Hz toneburst with a duration of 1 sec is applied to the filter. One very important feature is that the time response is symmetrical in time, i.e., it appears to behave like a non-causal filter. This is because Vold-Kalman filtering is implemented as post processing allowing for non-causal filter implementation and extraction of order waveforms with no phase bias, i.e., without a time delay. Figure 8 shows the time response for the one-, two- and three-pole filters with a bandwidth of 8 Hz.

The one-pole filter has, as expected, the shortest decay time and a decay which appears as a straight line when displayed with a logarithmic y-axis, while the two-pole and three-pole filters, in addition to the longer decay times, also show some lobes. The main lobes of all three filter types show, on the other hand, nearly the same chracteristic in the upper 25 dB, i.e., the same "early decay," which means their behavior in terms of how fast they can follow amplitude changes of orders is nearly identical.

Figure 9 shows the time response with a one-pole filter for 3 different choices of filter bandwidth. As expected the decay time is inversely proportional to the bandwidth. Since the slope for a one-pole filter is very similar to the slope of the early decay for two- and three-pole filters with the same bandwidth, we can extract the following important time-frequency relationship for all three types of Vold-Kalman filters:

$$B_{3\mathrm{dB}} \times \tau = 0.2 \tag{1}$$

where $B_{3\mathrm{dB}}$ is the 3 dB bandwidth of the Vold-Kalman filter and τ is the time it takes for the time response to decay 8.69 dB. If reverberation time, T_{60} instead of time constant τ is preferred, the relation becomes:

$$B_{3\mathrm{dB}} \times T_{60} = 1.4 \tag{2}$$

When zooming in around the beginning or the end of the toneburst, a difference between the three filter types is revealed as seen in Figure 10. The one-pole filter has a smooth decay before the stop of the toneburst, whereas the two-pole and the three-pole filters show a ripple with a maximum deviation (overshoot) from the steady state response of 0.28 dB and 0.46 dB, respectively. This overshoot phenomena is only seen in analysis results when analyzing signals with abrupt amplitude changes (such as in the case of a toneburst) or when a too narrow filter bandwidth was selected for the analysis (i.e., the time constant τ of the filter is too long for the signal to be analyzed).

As an additional observation, all time responses have decayed to −6 dB at the location where the tone burst stops, irrespective of the chosen filter parameters, see Figure 9. That is where the energy of the order signal inside the analyzed time window is reduced by 3 dB. Due to the sudden change in the nature of the signal, from a sinewave to nothing, a further leakage of the order, into neighboring frequencies by 3 dB is seen. A similar effect is observed using FFT analysis.

Selection of Bandwidth and Filter Type

Selection of the filter bandwidth is basically a compromise between having a bandwidth which is sufficiently narrow to separate the various components in the signal and a bandwidth which is sufficiently wide, giving a short filter response time, in order to follow the changes in the signal amplitude. The contour plot of the STFT analysis can be used for evaluating the separation of the various components. Various research tests have shown that when orders are going through a resonance, the time constant of the filter τ should be shorter than 1/10 of the time $T_{3\mathrm{dB}}$ it takes for the particular order to sweep through the 3 dB bandwidth of the resonance $\Delta f_{3\mathrm{dB}}$. This ensures an error of less than 0.5 dB of the peak amplitude at the resonance using a one-pole filter. For two- and three-pole filters the error of the measured peak will be less.

For the time constant of the filter we thus have that:

$$\tau \le 0.1 \times T_{3\mathrm{dB}} \tag{3}$$

or in terms of the bandwidth of the filter

$$B_{3\mathrm{dB}} = 0.2 / \tau \ge 2 / T_{3\mathrm{dB}} \tag{4}$$

The time it takes for order number k to sweep through the 3dB bandwidth is:

$$T_{3dB} = \Delta f_{3dB} / (k \times SR_{Hz}) \quad (5)$$

or

$$T_{3dB} = \Delta f_{3dB} / (k \times SR_{RPM} / 60) \quad (6)$$

where SR_{Hz} and SR_{RPM} is the sweep rate in Hz/sec and RPM/sec, respectively. This means that the bandwidth B_{3dB} of the Vold-Kalman filter extracting order number k should follow,

$$B_{3dB} \geq (2 \times k \times SR_{Hz}) / \Delta f_{3dB} \quad (7)$$

or

$$B_{3dB} \geq (k \times SR_{RPM}) / 30 \times \Delta f_{3dB} \quad (8)$$

Example 1. In the first example a linear sweep of a squarewave, with a sweep rate of 17,200 RPM/sec from 12,000 to 63,000 RPM (286.7 Hz/sec from 200 to 1050 Hz), going through a known resonance is analyzed. The resonance frequency is 795 Hz and the 3 dB bandwidth of the resonance is 16 Hz, corresponding to 1% damping. The first three orders are analyzed. Using Equation (8) we have for the 1st order:

$$B_{3dB} \geq (1 \times 17{,}200) / (30 \times 16) \text{ Hz} = 35.8 \text{ Hz}$$

for the 2nd order:

$$B_{3dB} \geq (2 \times 17{,}200) / (30 \times 16) \text{ Hz} = 71.6 \text{ Hz}$$

and for the 3rd order:

$$B_{3dB} \geq (3 \times 17{,}200) / (30 \times 16) \text{ Hz} = 107.4 \text{ Hz}$$

The Vold-Kalman filter bandwidth can be specified in terms of a constant frequency bandwidth or proportional to RPM bandwidth (i.e., constant percentage bandwidth). Proportional bandwidth is the best choice when analyzing over wide RPM ranges or when analyzing higher orders. A bandwidth of 35.8 Hz for the 1st order at the resonance frequency of 795 Hz corresponds to 4.5% bandwidth. A bandwidth of 71.6 Hz for the 2nd order at 795 Hz corresponds to 18% bandwidth and a bandwidth of 107.4 Hz for the 3rd order at 795 Hz corresponds to 40% bandwidth. Figure 11 shows the magnitude of the Phase Assigned Orders extracted with a two-pole filter with proportional bandwidth of 4.5%, 18% and 40% for the 1st, 2nd and 3rd orders, respectively.

The peak amplitudes measured with one-, two- and three-pole filters with bandwidths of 4.5 and 18% for the 1st and the 2nd orders, respectively, are given in Table 1. The correct peak amplitudes were found by widening the filter bandwidth until the amplitude did not increase any more.

The peak amplitude errors for the one-pole filter is thus 0.3 dB and within 0.1 dB for the two- and three-pole filter having a minimum bandwidth given by Equation (8). A second resonance at 1900 Hz, being excited by the second and the third order, is also seen in Figure 11.

Using a filter with proper selectivity is very important for the analysis. This is illustrated in Figure 12, which shows the result of Vold-Kalman filtering using the one-pole filter instead of the two-pole filter used in Figure 11. All other analysis parameters remain unchanged. The limited selectivity of the one-pole filter causes a lot of interference from the other orders especially at the positions where these pass through the resonances. The interference is most dominating for the 3rd order due to the wider bandwidth needed to extract this order. The interference from the 2nd order can even lead to misinterpretations of "nonexisting" resonances. Decoupling cannot be used to avoid this kind of interference over a wide time span. Using the two-pole filter (Figure 11) a small amount of interference is still seen for the 3rd order in the analysis. The three-pole filter will completely suppress the interference from the other orders in this case.

The ripples indicated in Figure 11, on the decaying slope after the orders have passed the resonance still need some explanation. These ripples are caused by an interaction between the order component and the free decay of the natural frequency for the lightly damped resonance. This phenomenon can be investigated by looking at the contour plot of an STFT analysis. Figure 13 shows a detailed view of the part in the contour plot where the 2nd and 3rd order component excite the first resonance. A 3200 line analysis, giving a Δf of 2 Hz, and a step of 10 msec between the spectra (corresponding to 98% overlap), is used. The free decay of the resonance after the point in time where the orders have "crossed" the resonance frequency is clearly seen. When the decaying oscillations of the damped natural frequency are inside the passband of the filter extracting the given order, the beating interference will occur. The beating is most severe for the third order because of the wider bandwidth used in the analysis. Since there is no "natural" tacho signal which relates to the damped natural frequency, it is not possible to make decoupling of these components. The only way to get less beating interaction is to use a narrower filter bandwidth in order to get the free decaying natural frequency more quickly outside the passband bandwidth after the resonance crossing of the order. This will, however, cause violation of the requirement for the minimum bandwidth given by Equations (4), (7) or (8).

Example 2. In this example, a fast run-up of a spin drier is analyzed. A tacho signal giving 12 pulses per revolution is used and the vibration response in the tangential, radial and axial direction is measured. Figure 14 shows the contour plot of the STFT analysis of the radial response. It is seen that the response is dominated by the 1st order (unbalance) and the 22nd order (raised by the 22 winding slots in the electrical motor). Each Fourier transform is based upon a record length of 250 msec giving a line spacing Δf of 4 Hz.

The 1st order is dominated by one resonance. The run-up takes approximately 6 sec and the curvefitted RPM profile is shown in Figure 15.

The peak value and the time T_{3dB} it takes for the 1st order to sweep through the 3 dB bandwidth of the dominating resonance is found by applying a three-pole filter with wide bandwidth (up to 100%). Using a bandwidth of more than 100% gives ripples due to beating interference even with the three-pole filter. From these analyses T_{3dB} is found to be 464 msec and the peak of the resonance is found to be 12.6 dB. Using Equation (4) this means that the minimum bandwidth should be 4.31 Hz. The peak of the resonance is at 681 RPM (11.3 Hz) which means that the minimum bandwidth should be 38%. Using a bandwidth of 38% gives a peak value of 12.2 dB (i.e., an error of 0.4 dB). The same peak value is found using one-pole and two-pole filters. For the one-pole filter with 38% bandwidth the extracted order is contaminated by ripples (beating interference), even at the resonance, due to the limited selectivity. Figure 16 shows the 1st order of the radial, tangential and axial response extracted using a three-pole filter with a bandwidth of 50%. The same resonance is seen in the axial response, whereas the dominating resonance in the tangential response is at 911 RPM (15.2 Hz). A smaller resonance at 375 RPM (6.25 Hz) is seen in the radial and axial response and at 388 RPM (6.47 Hz) in the tangential response. T_{3dB} for this resonance is found to be 415 msec for the radial response meaning that the bandwidth should be at least 76%. Using 50% bandwidth with a three-pole filter gives an underestimation of about 0.8 dB. A two-pole filter gives a beating interference at this resonance with bandwidth larger than 50%. Proper measurement of this resonance is not possible with a one-pole filter due to strong beating interference even for bandwidth as narrow as 20%. The 22nd order can be extracted using a three-pole filter with a bandwidth of 60%, which is found to be the minimum bandwidth for the dominating resonance at 933 RPM (15.6 Hz) in the radial response. A two-pole filter introduces a small interference at the resonance with 60% bandwidth. For a one-pole filter, interference is experienced for bandwidths wider than 40%.

Crossing Orders

To illustrate the power of the Vold-Kalman filter with decoupling of close and crossing orders, two signals have been mixed, a 1 kHz signal and a 300 Hz to 2000 Hz swept signal containing several orders as shown in the STSF contour plot in Figure 17. The duration of the signal is 6 sec. The example simulates a system with two independent axles. All orders and the 1 kHz sine wave were generated with constant amplitude.

The two first swept orders and the 1 kHz signal were extracted using 10% bandwidth (0.1 order resolution) two-pole Vold-Kalman filters without decoupling. The magnitude of the two swept orders is shown in Figure 18 and the 1 kHz signal is shown in Figure 19. In this case the 1 kHz order strongly interacts with the swept 4^{th} order around time = 0.1 sec, the 3rd order around time = 0.4 sec, the 2nd order around time = 1 sec and the first order around time = 2.7 sec, respectively, showing strong beating phenomena.

When the two tacho signals are used in a simultaneous estimation (i.e., with decoupling), but with the same filter parameters as in the single order estimation (i.e., without any decoupling), we achieve a dramatic improvement in the quality of estimation, see Figures 20 and 21, although the 1 kHz signal still interacts with the swept orders numbers 3 and 4, since they were not included in the calculations.

Conclusion

The Vold-Kalman filter allows for order tracking without slew-rate limitations. Abrupt changes of the RPM, such as in gear shifts and tacho dropouts can be handled.

The characteristics of the one-pole, two-pole and three-pole Vold-Kalman order tracking filter have been investigated in the time and the frequency domain. The three-pole filter has the best selectivity and therefore the best ability to suppress ripples due to beating interference from other order components in the signal. In the time response to a toneburst, the two- and three-pole filters exhibit small ripples (overshoot). This will, however, only contaminate the results when the signal contains abrupt changes in the amplitude or when the filter bandwidth selection is too narrow for the signal.

The time frequency relationship of the three filter types is given by $B_{3dB} \times \tau = 0.2$ where B_{3dB} is the 3 dB bandwidth of the Vold-Kalman filter and τ is the time it takes for the time response to decay 8.69 dB.

Selection of the bandwidth of the filter should follow $B_{3dB} \geq 2/T_{3dB}$, where T_{3dB} is the time it takes for an order to sweep through the 3dB bandwidth of a resonance. In almost all cases the three-pole filter is the best choice due to its better selectivity in the frequency domain. The computation time for the three-pole filter is 10% longer than for two-pole filter. Today, the main use of a single pole filter is to be able to duplicate processing done in earlier implementation of Vold-Kalman filtering.

In situations where different orders related to different rotating shafts (tacho signals) are close or crossing each other, decoupling can be used to separate the orders without beating interference.

Nomenclature

B_{3dB} = 3 dB bandwidth of the Vold-Kalman filter.
τ = Time constant of the Vold-Kalman filter, i.e., time it takes for the time response to decay 8.69 dB.
Δf_{3dB} = 3dB bandwidth of a resonance.
T_{3dB} = Time it takes for an order to sweep through the 3 dB bandwidth of a resonance.
SR_{Hz} = Sweep rate in Hz per sec.
SR_{rpm} = Sweep rate in RPM per sec.
k = Order number.

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Table 1. Peak amplitudes in dB for the 1st, 2nd and 3rd order component extracted with one-, two- and three-pole Vold-Kalman filters with a bandwidth of 4.5%, 18% and 40%, respectively.

Table of Measured Peak Amplitudes	One-Pole Filter 4.5%, 18%, 40%	Two-Pole Filter 4.5%, 18%, 40%	Three-Pole Filter 4.5%, 18%, 40%	Correct Amplitude
1st Order	–5.3 dB	–5.1 dB	–5.0 dB	–5.0 dB
2nd Order	–6.3 dB	–6.0 dB	–6.0 dB	–6.0 dB
3rd Order	–7.4 dB	–7.2 dB	–7.1 dB	–7.1 dB

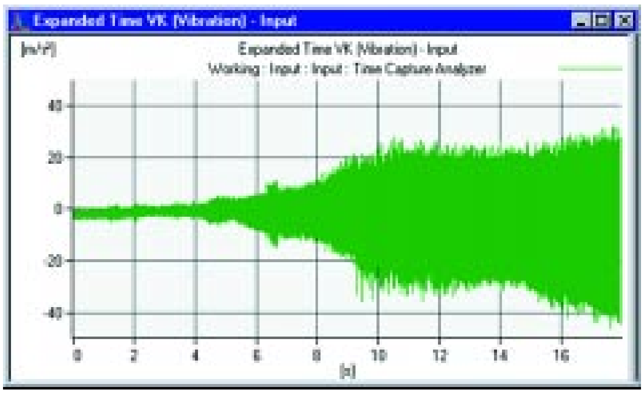

Figure 1. Vibration time signal of the run-up.

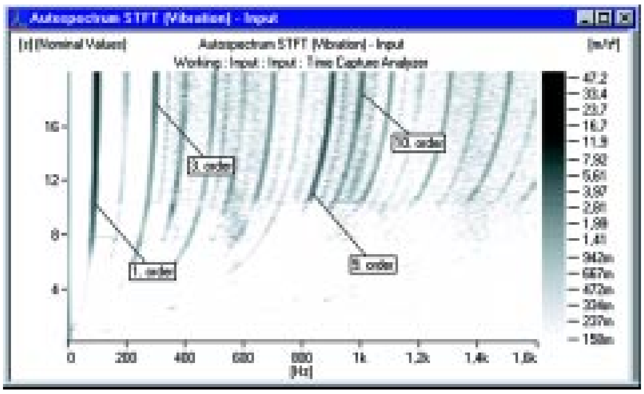

Figure 2. An STFT of the vibration signal.

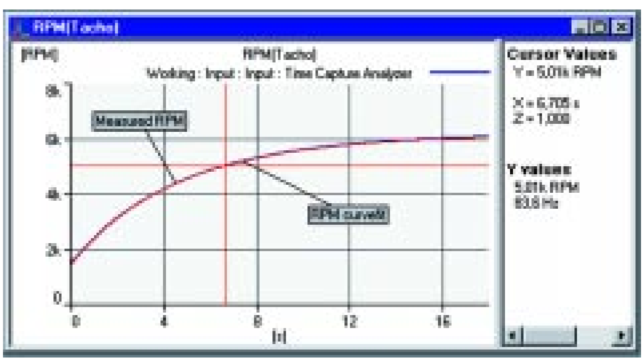

Figure 3. Comparison of the measured and curve fitted rpm profiles.

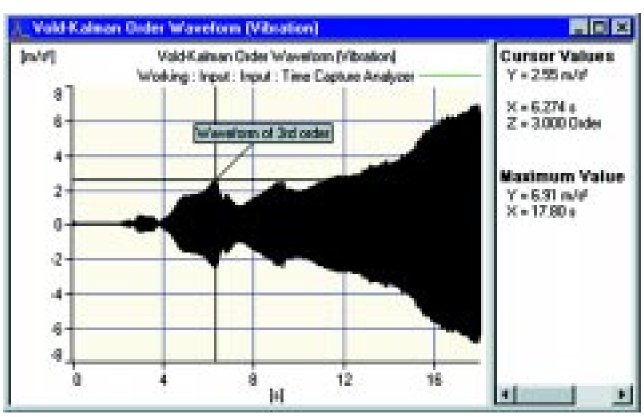

Figure 4. Waveform of the 3rd Order, extracted using a two-pole Vold-Kalman filter with 10% bandwidth.

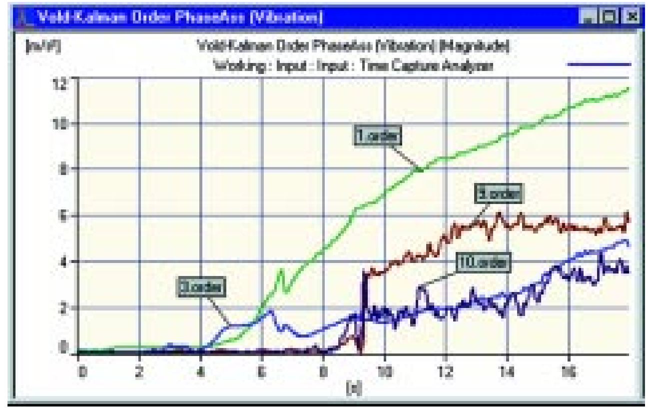

Figure 5. Magnitude of the 4 most dominating orders as a function of time, extracted using a two-pole Vold-Kalman filter with 10% bandwidth.

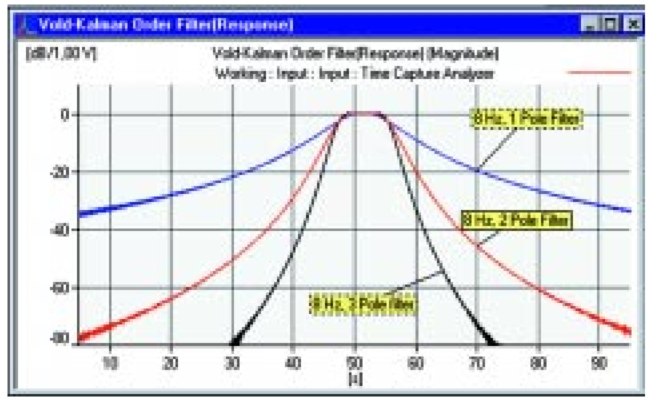

Figure 6. Comparison of filter shapes for one-, two- and three-pole Vold-Kalman filters with a bandwidth of 8 Hz.

Figure 7. Comparison of the frequency response in the passband for one-, two- and three-pole Vold-Kalman filters with the same bandwidth of 8 Hz.

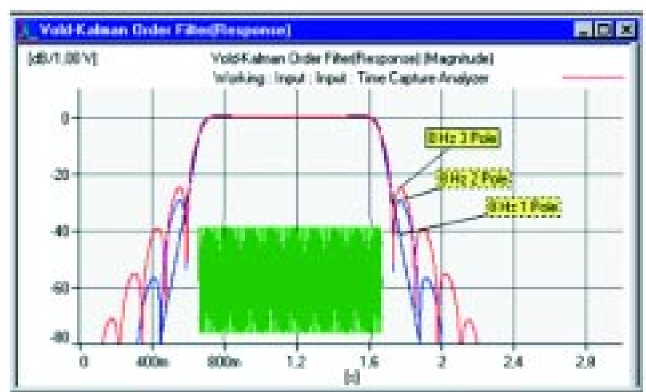

Figure 8. Comparison of the magnitude of the time responses for one-, two- and three-pole Vold-Kalman filters with a bandwidth of 8 Hz. The applied signal, a tone burst of 1 sec duration, is shown as well.

Figure 9. Comparison of Time Responses for one-pole 2 Hz, 4 Hz and 8 Hz bandwidth Vold-Kalman filters. The applied signal is a tone burst of 1 sec duration.

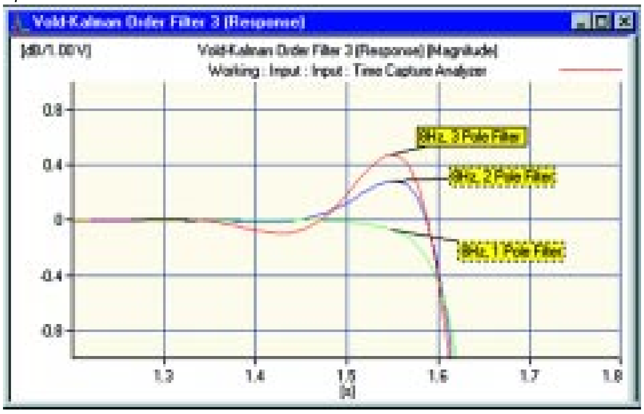

Figure 10. Detailed picture of the time response of the one-, two- and three-pole filters at the end of the toneburst.

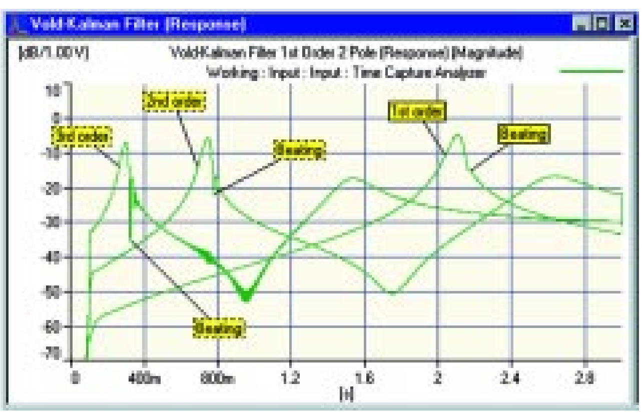

Figure 11. Magnitude of the Phase Assigned Orders of the first three orders extracted with a two-pole Vold-Kalman filters with bandwidth of 4.5%, 18% and 40% respectively.

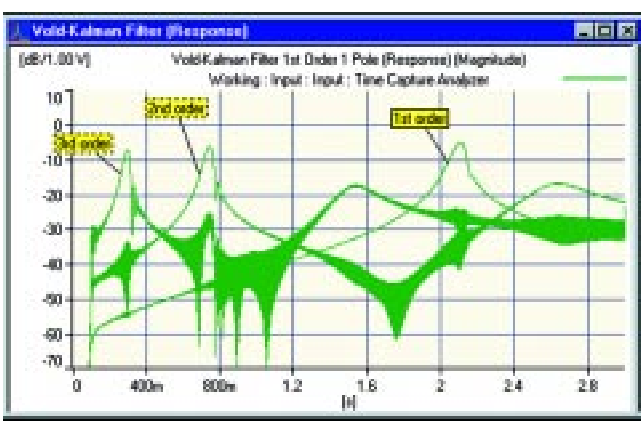

Figure 12. Magnitude of the Phase Assigned Orders of the first three orders extracted with a one-pole Vold-Kalman filters with bandwidth of 4.5%, 18% and 40% respectively. Notice the interference due to the limited selectivity of the one-pole filter.

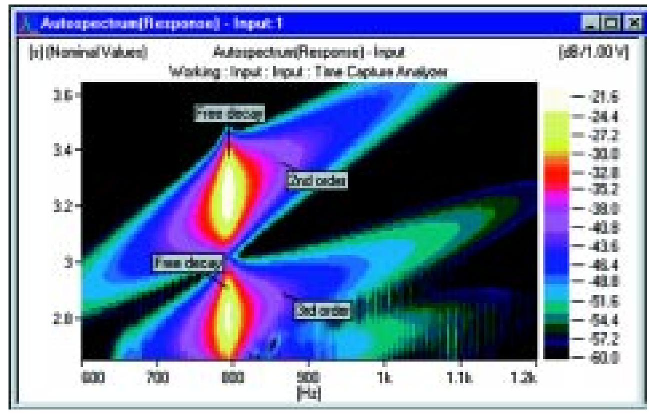

Figure 13. Detailed view of the part in the contour plot where the 2nd and 3rd order component excite the first resonance. The free decay of the damped natural frequency of 795 Hz is clearly seen. A 3200 line analysis, giving (f of 2 Hz, and a step of 10 msec between the spectra is used.

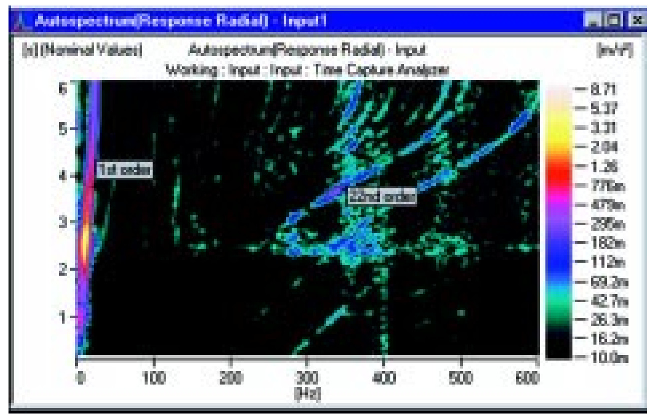

Figure 14. Contour plot of an STFT analysis of a run-up of a spin drier.

Figure 15. Curvefit of the rpm as a function of time used as input for the Vold-Kalman filtering.

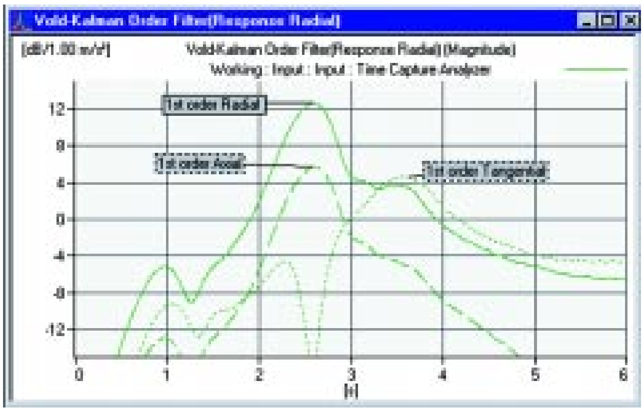

Figure 16. 1st order of the radial, tangential and axial response, during the run-up of the spin drier, extracted using a three-pole Vold-Kalman filter with 50% bandwidth.

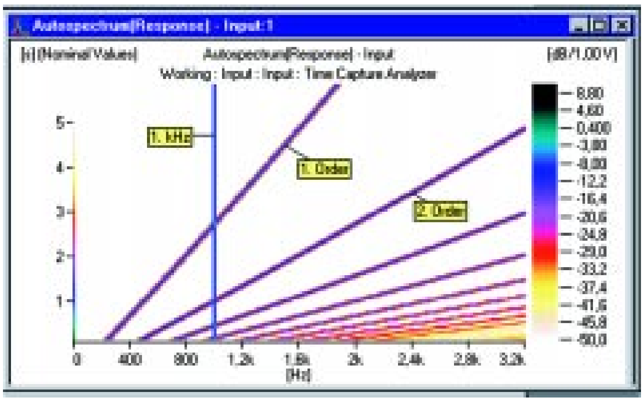

Figure 17. An STFT of a signal mixed from a 1 kHz sine wave and a swept signal containing several harmonics (orders).

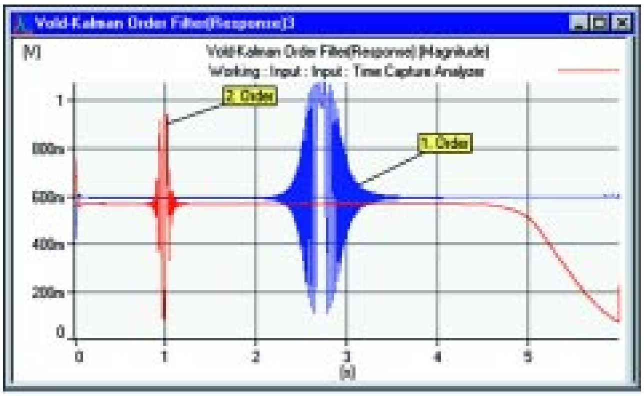

Figure 18. First and second order of the swept signal extracted without decoupling using two-pole Vold-Kalman filter with a bandwidth of 10%.

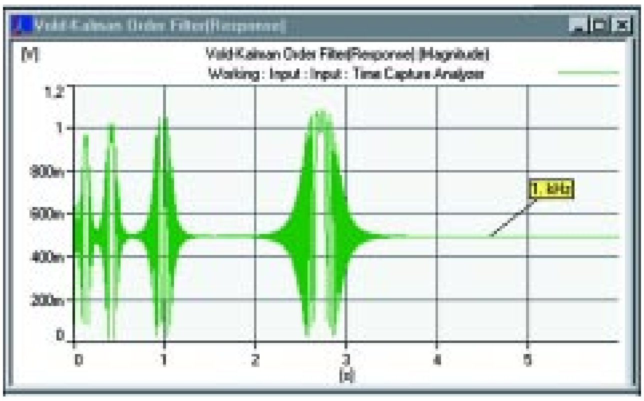

Figure 19. 1 kHz signal extracted without decoupling using two-pole Vold-Kalman filter with a bandwidth of 10%.

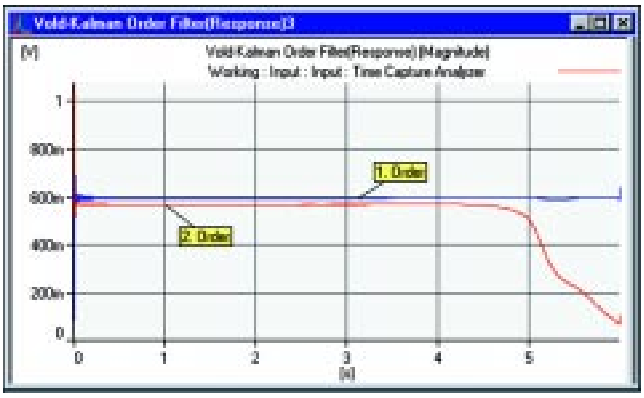

Figure 20. First and second order of the swept signal extracted using decoupling and two-pole Vold-Kalman filter with a bandwidth of 10%.

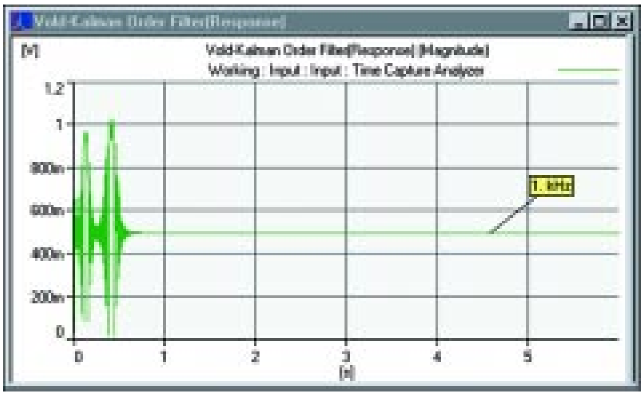

Figure 21. 1 kHz signal extracted using decoupling and two-pole Vold-Kalman filter with a bandwidth of 10%.