

JSAE 98, Yokohama, Japan

Order Tracking using the Vold-Kalman Order Tracking Filter

Svend Gade

H. Herlufsen

H. Konstantin-Hansen

Brüel & Kjær A/S

H. Vold

D. Corwin-Renner

Vold Solutions, Inc.

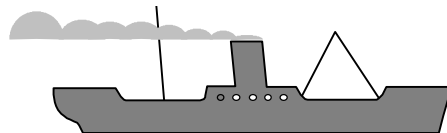
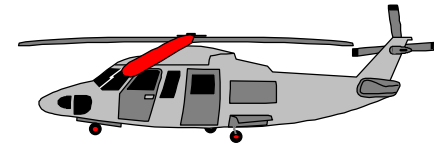


Outline

- Order Analysis
- Applications
- The various steps
- Pre-analysis using STFT
- Tachometer setup
 - RPM estimation
 - RPM curvefit
- Filter setup
- Typical output
 - Phase assigned orders
 - Order waveform
- Filter characteristics
- Close and crossing orders
- Conclusion

Order Analysis

- Order Analysis is the art and science of extracting sinusoidal contents of measurements from acousto-mechanical systems under periodic loading
- Order Analysis is used for
 - troubleshooting
 - design
 - synthesis



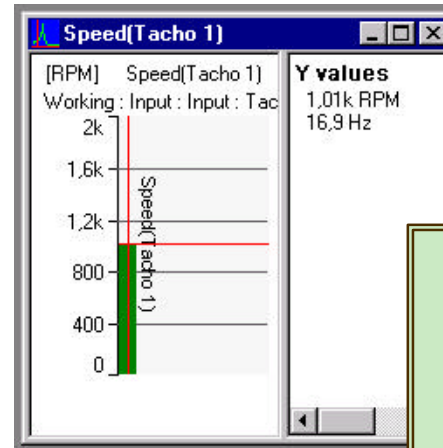
Applications of Vold-Kalman Filters

Typical Application

- Order Tracking Analysis
 - Order analysis at extreme slew rates
 - » including gear shifts
 - Separation of orders in multishaft systems
 - Order Waveform extraction
 - » Playback of individual orders

Steps of Vold-Kalman Filtering

- Record time signals
 - select part of time signals to be analyzed
- RPM determination
- Order Waveform tracking
 - Structural equation
 - » sinewave model
 - Data equation
 - » energy conservation
- Output:
 - Phase assigned order
 - » i.e. Magnitude / Phase
 - Order waveform
 - » from RPM and phase assigned orders

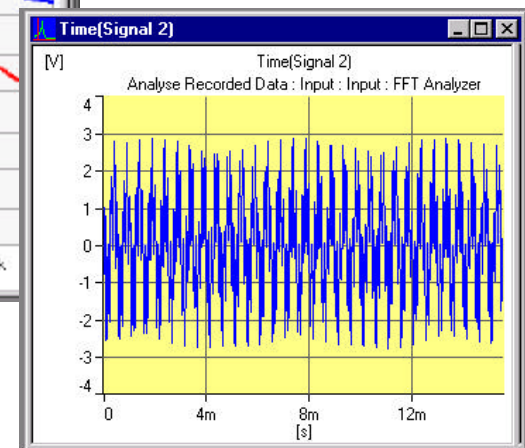


$$\Theta_k(t) = \exp(2pki \int_0^t f(u) du),$$

$$\Theta_k(t)\Theta_j(t) = \Theta_{k+j}(t).$$

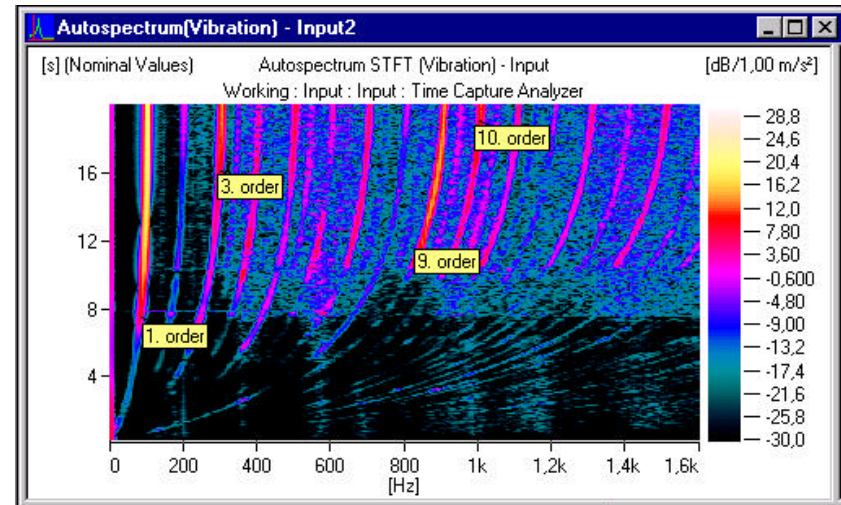
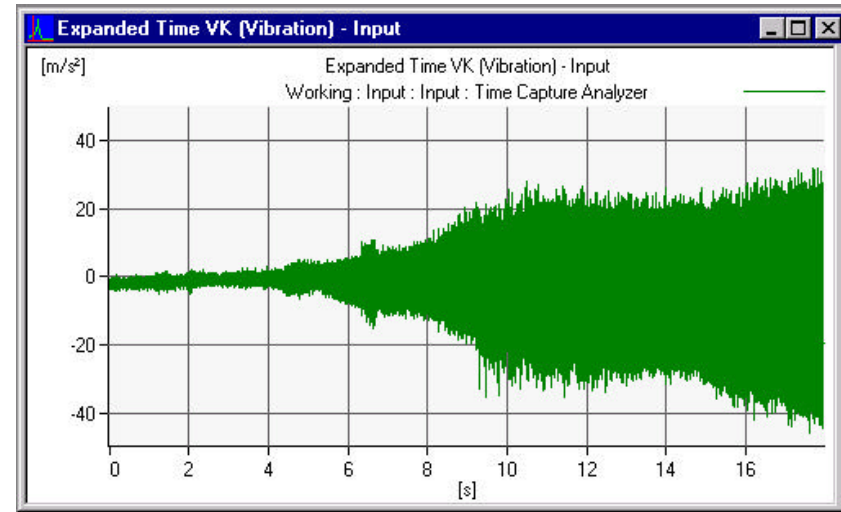
$$\frac{d^s A_j(t)}{dt^s} = e(t),$$

$$X(n) - \sum_{j \in J} A_j(n)\Theta_j(n) = \tilde{d}(n),$$



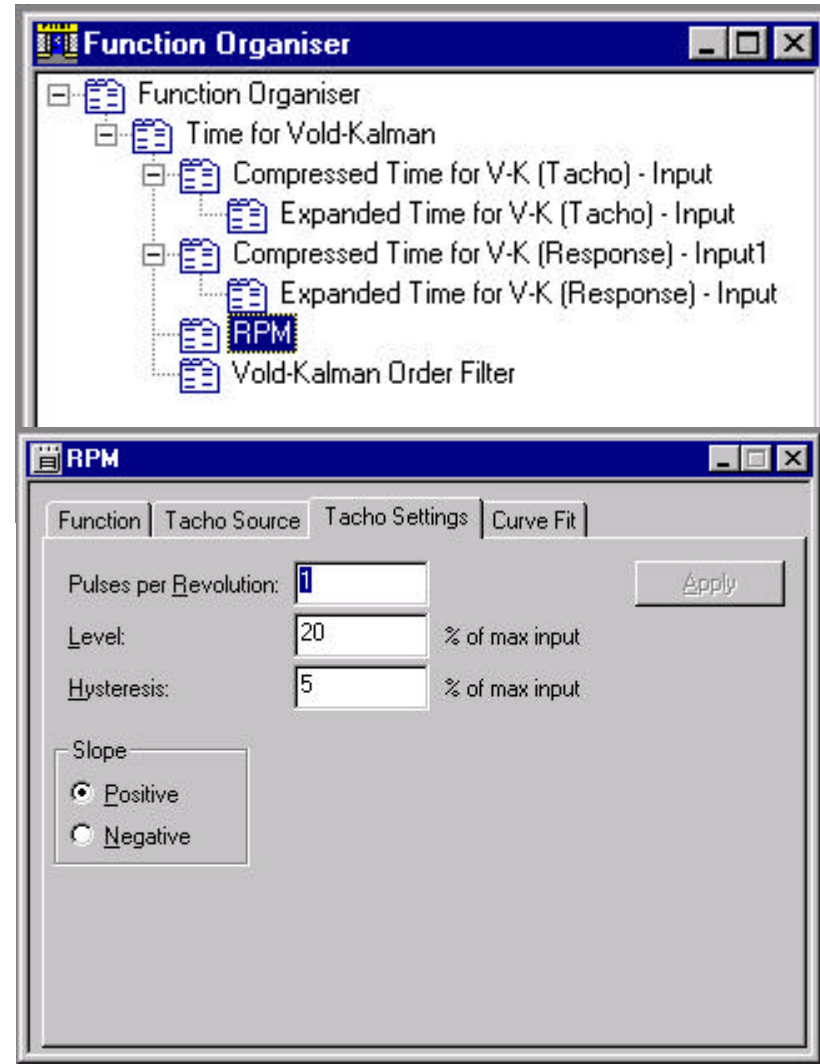
Time signal example and its STFT

- Use Brüel & Kjær Time Capture Analyzer Type 7705 to select data
 - » from input / frontend
 - » from 7701 Data Recorder
 - » from Sony DAT
- Selected time signal
 - small electrical motor
 - 18 sec. duration
- Short Time Fourier Transform
 - for overview and inspection
 - dominating orders nos. 1, 3, 9 and 10



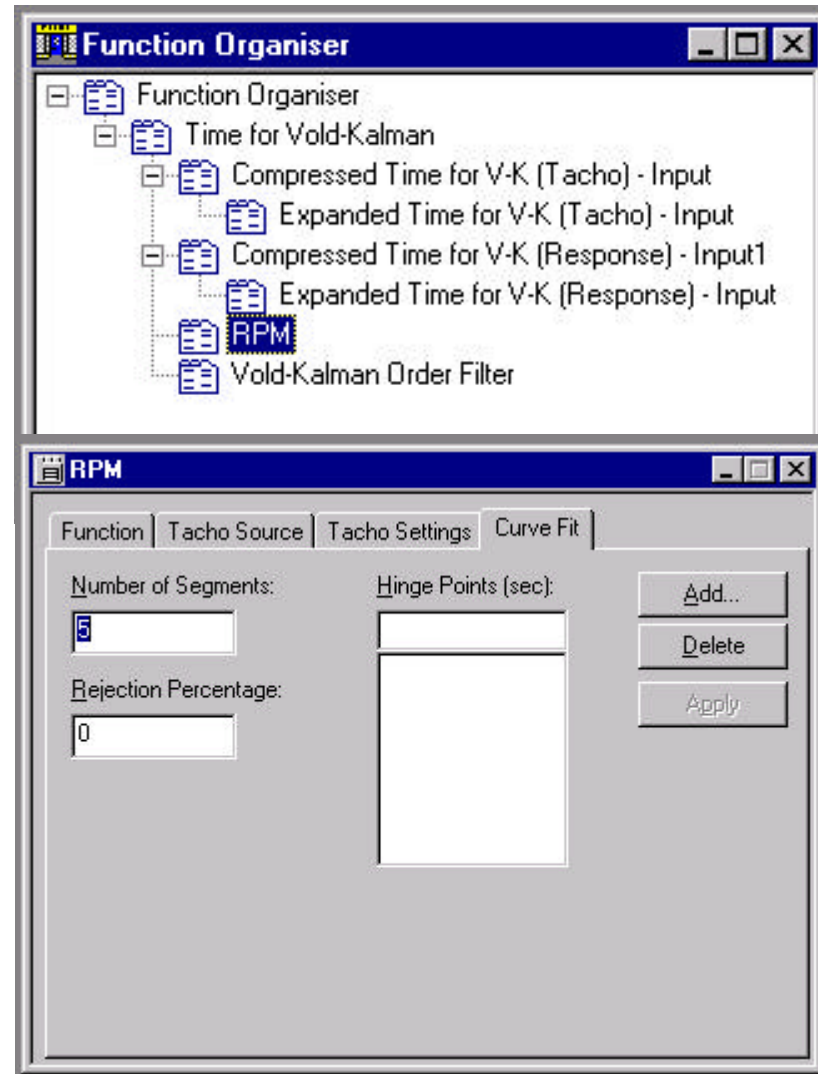
Tachometer Analysis — RPM Estimation

- Use Brüel & Kjær Vold-Kalman Order Tracking Filter, Type 7703
- RPM estimation is a post processing facility found in the Function Organizer
- Level crossings determined to define a table of RPM values as a function of time - called raw RPM
 - including slope, hysteresis and gearing



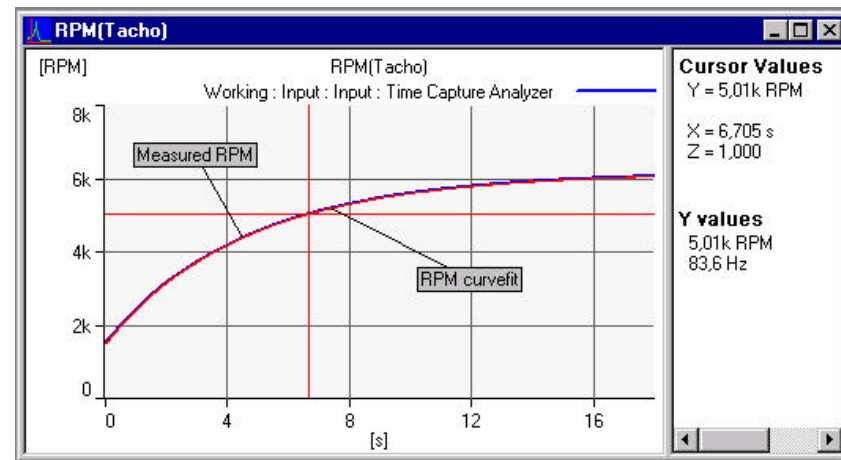
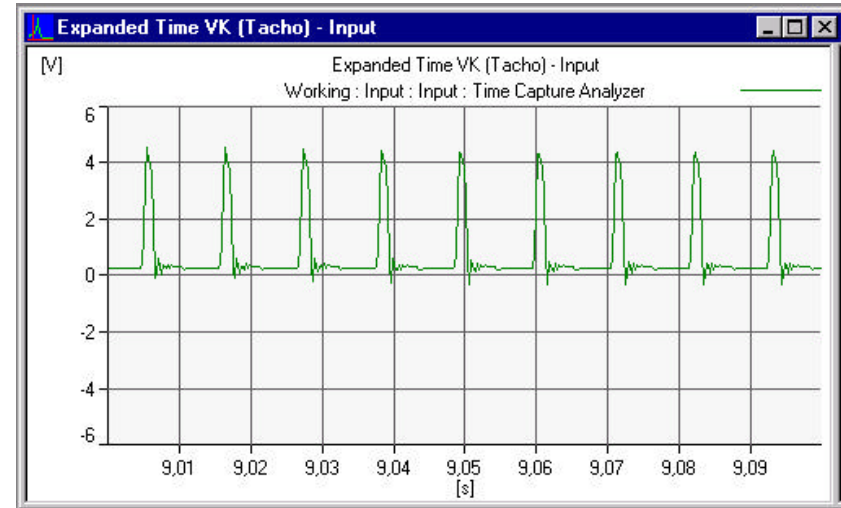
Tachometer Analysis — RPM CurveFit

- Cubic least squares spline fit to smooth data
 - » continuity and first derivative continuity between segments
- Singular events such as gearshifts allowed
 - » relaxing first derivative continuity condition at hinge points
- Rejections of outlier data, such as tacho dropouts
 - » Data refitted using cubic least squares spline fit
- Output
 - » instantaneous RPM (as a function of time)



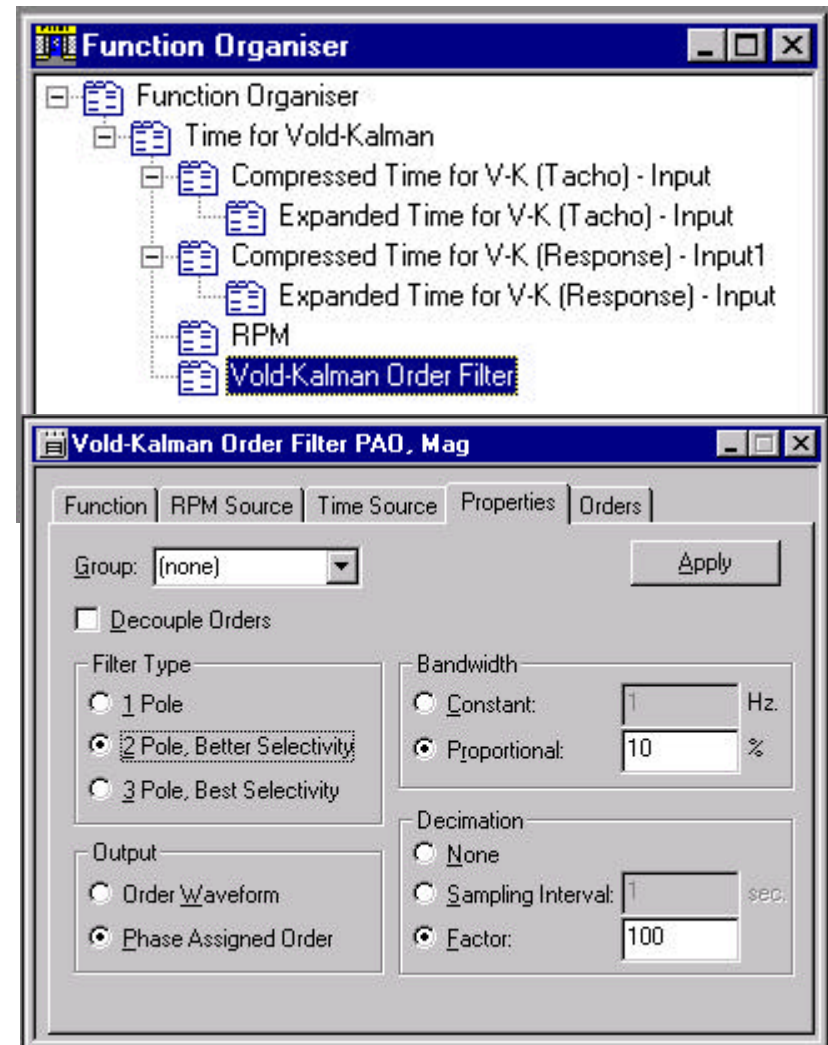
Tacho Signal and RPM profiles

- Tacho signal (expanded)
- RPM Detection example
 - level 30%, slope +, hysteresis 5%
 - 15 segments, 0% rejection, no Hinge Points
- RPM profiles
 - Raw estimate
 - Curvefitted results
- Step by step procedure
 - data recording and selection
 - use conventional analysis techniques first, e.g. STFT
 - compare raw and processed RPM profiles



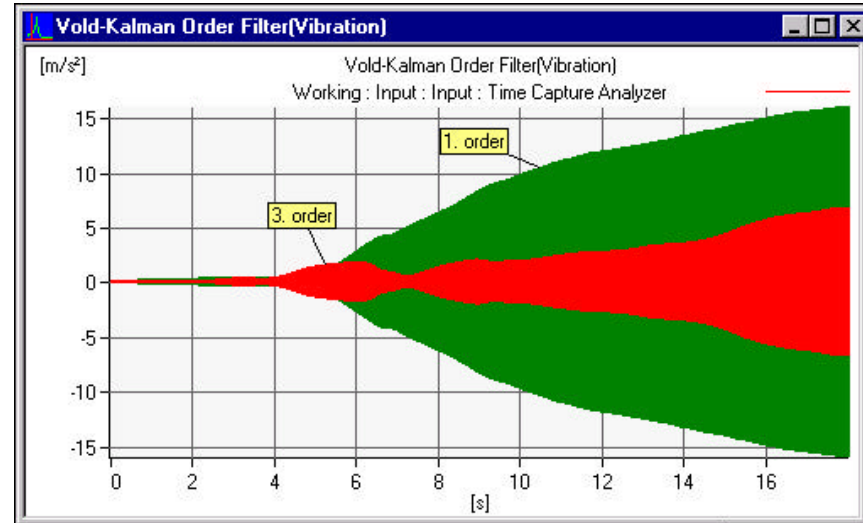
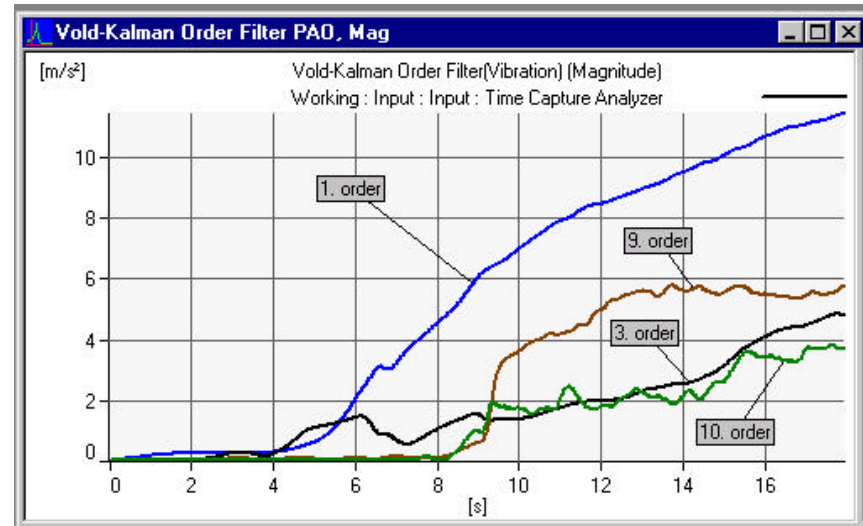
Vold-Kalman filter setup

- Vold-Kalman Order Tracking Filter, is a postprocessing facility
- Step by step procedure (cont.)
 - select filter characteristics
 - » one, two, three pole filters
 - » constant or relative bandwidth
 - apply decoupling if needed
 - select desired orders
 - select output
 - » order waveform or
 - » phase assigned orders
 - apply decimation if needed
 - » for data reduction



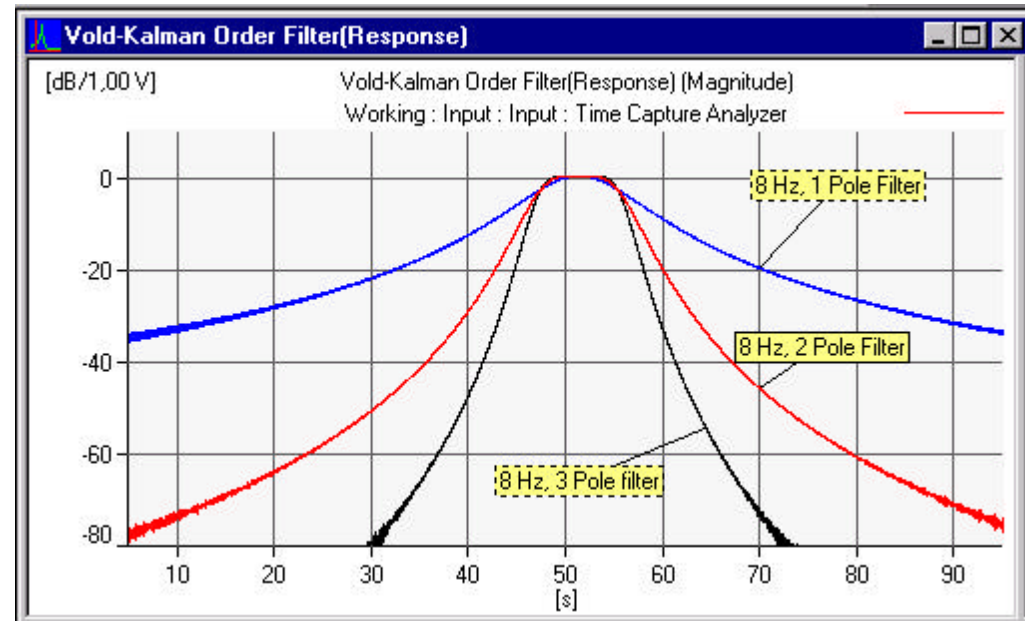
Output from a Vold-Kalman analysis

- Phase assigned orders
 - Formats available: real, imag, mag, phase, nyquist
 - Magnitude of the 4 selected orders is shown
- Order waveform
 - 1. and 3. orders are shown
 - Playback via Sound Board



Filter Shapes

- One pole filter
 - poor selectivity, SF = 50
 - only for comparison with earlier implementations
- Three pole filter
 - flatter passband and much better selectivity, SF = 3.6
 - highest overshoot in time
- Two pole filter
 - good compromise, SF = 7.0
- Filter bandwidth can be specified in
 - order resolution (in % of fund. frequency)
 - frequency resolution (in Hz)

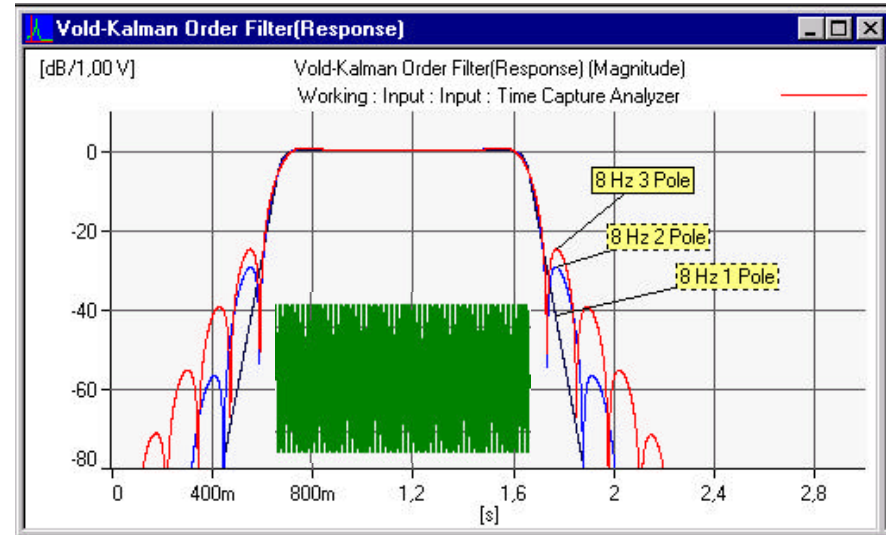


NB! Shape factor, SF is defined as

$$BW_{60\text{dB}} / BW_{3\text{dB}}$$

Time response of filters

- One sec. tone burst applied
 - burst (green curve)
- Symmetrical responses
 - magnitude is shown
 - “Non causal” filter
 - no phase bias
- Decay
 - exponential for one pole
 - multipoles shows lobes and longer decay times
- “Same” early decay for all three types
 - simple time-frequency relationship



Time frequency relationship,

$$BW_{3dB} \times \tau_{8.69dB} = 0,2$$

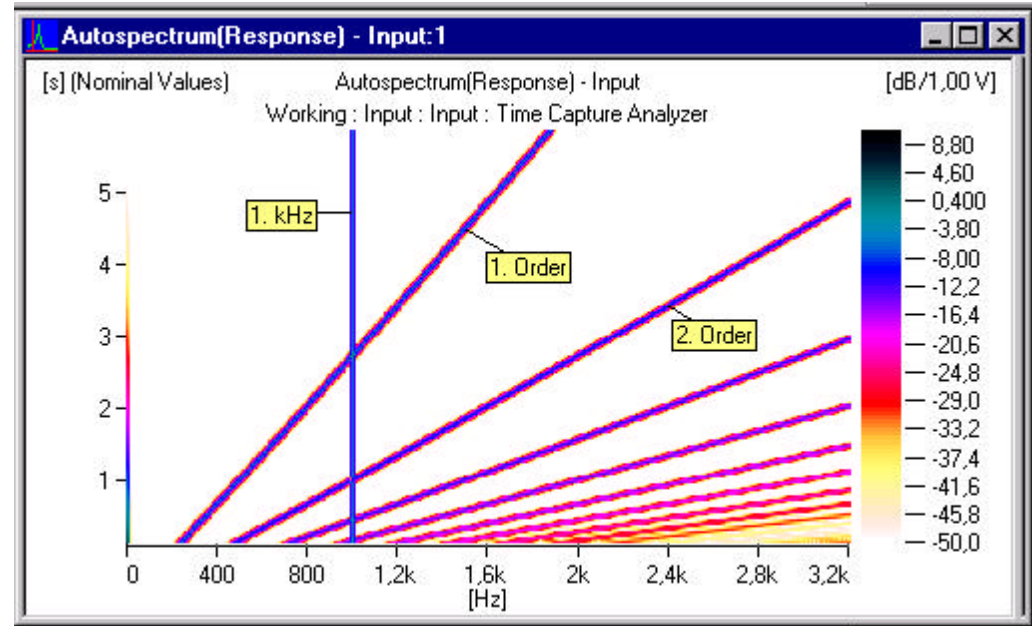
Recommended choice of BW,

$$BW_{3dB} > (k \times SR_{RPM}) / (30 \times \text{Resonance}_{3dB})$$

Multiaxle Data

- Two axes with close and crossing orders “simulated” using sinewave generators

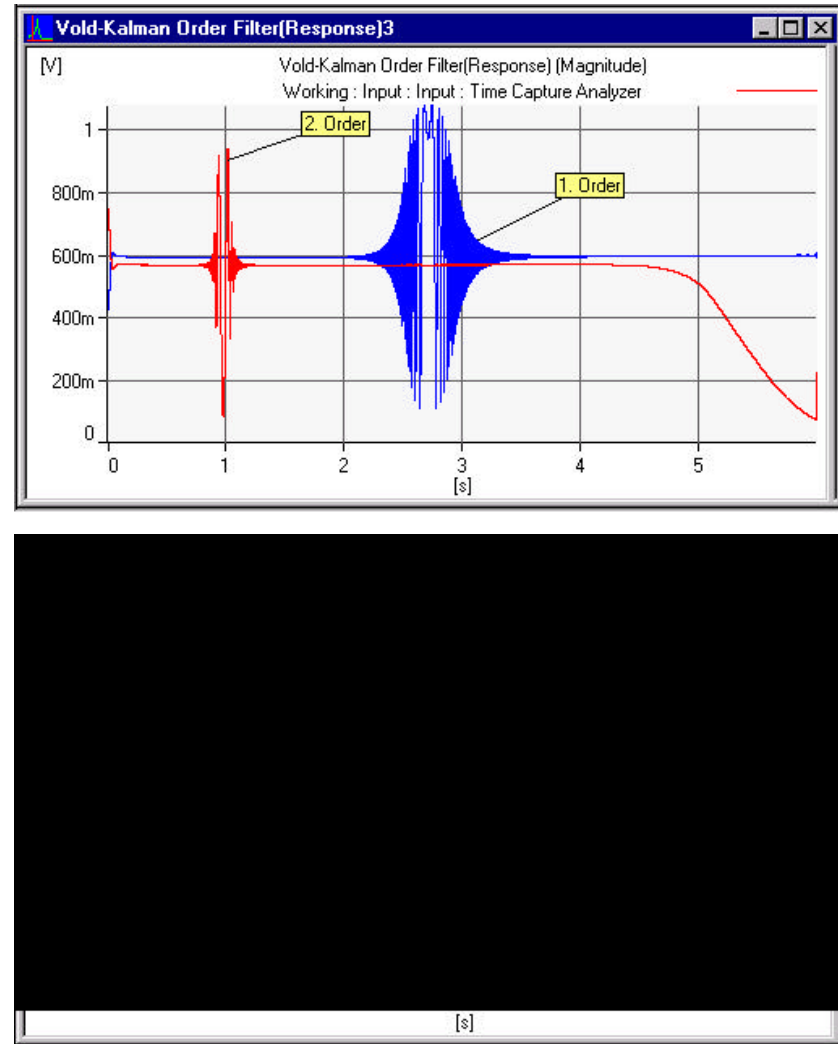
- one axle with constant speed
 - » 1 kHz
- the second axle with increasing speed
 - » 300 Hz per. second
- all orders with constant amplitude
- 6 s recording



- Pre-analysis using STFT

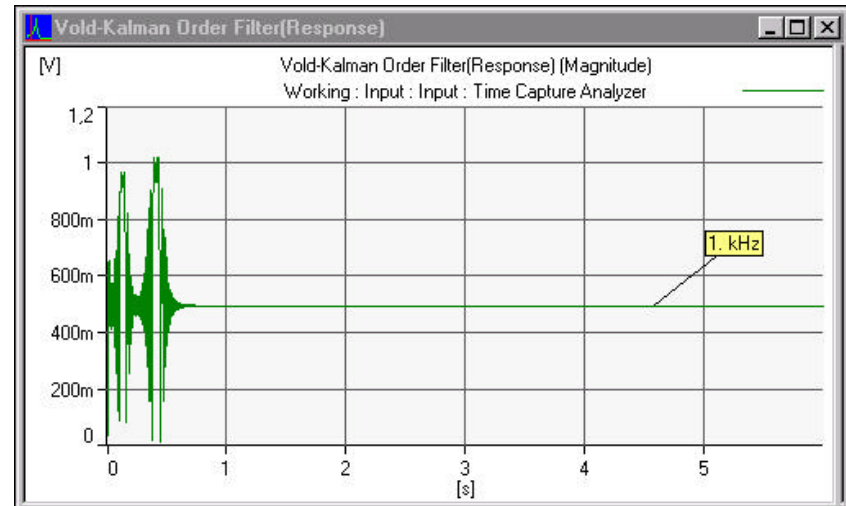
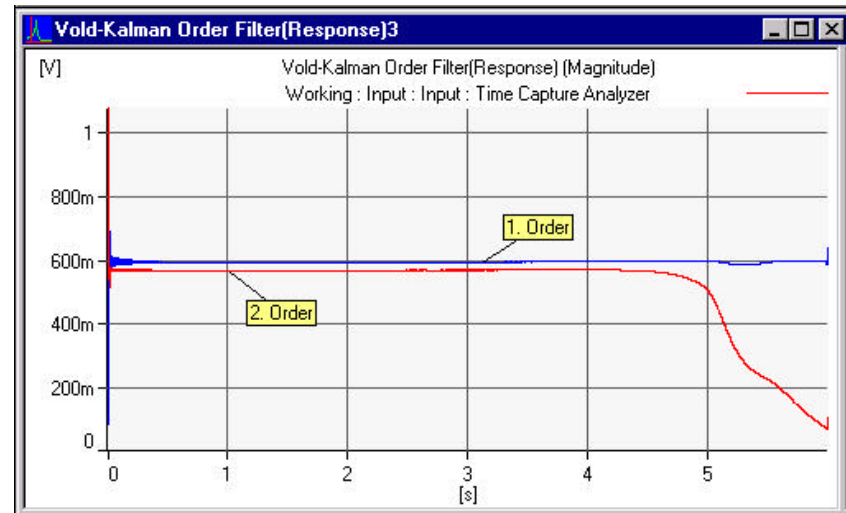
Analysis without decoupling

- Two pole Vold-Kalman filter used
- No decoupling
 - using one tacho signal at a time
- Severe beating in extracted orders at order crossings
 - 1. order at 2.7 s
 - 2. order at 1.0 s
 - 3. order at 400 ms
 - 4. order at 100 ms



Analysis with decoupling

- Two pole Vold-Kalman filter used
- Decoupling applied
 - using two tacho signals in simultaneous estimation
- Dramatic improvement in quality of order function extraction
 - 1 kHz still interacts with the swept orders nos. 3 & 4, since they were not included in the calculations



Conclusion

Second Generation Vold-Kalman Order Tracking Filtering

- Order Tracking Analysis with
 - No slew-rate limitation, can handle gearshifts
 - Beat-free decoupling of close and crossing orders
 - » think SDOF - MDOF curvefitters
 - » think single reference - polyreference curvefitters
 - Advanced Tacho Calculation
 - » including tacho repair
- and improved performance such as*
- Multipole filters
 - » flatter passband and higher selectivity
 - Explicit Bandwidth Specification

State of the art Order Tracking Analysis