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.

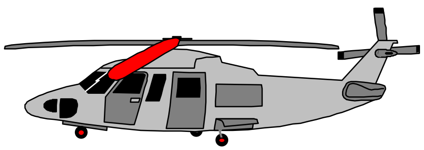
Outline

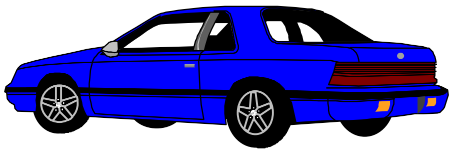
- Order Analysis
- Applications
- The various steps
- Pre-analysis using STFT
- Tachometer setup
  - RPM estimation
  - RPM curvefit
- Filter setup
- Typical output
  - Phase assigned orders
  - Order waveform
- Filter characteristics
- Close and crossing orders
- Conclusion

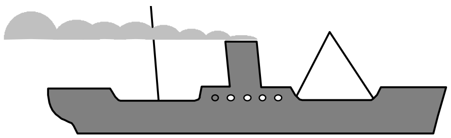
Order Analysis

- 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







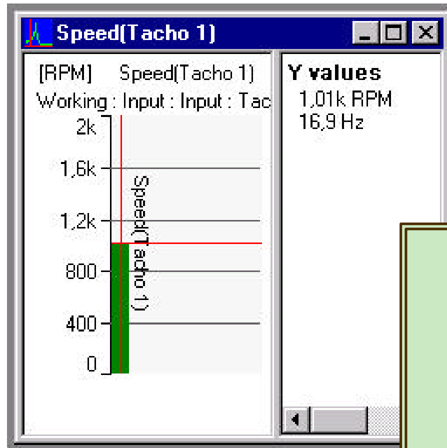
Applications of Vold-Kalman Filters

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

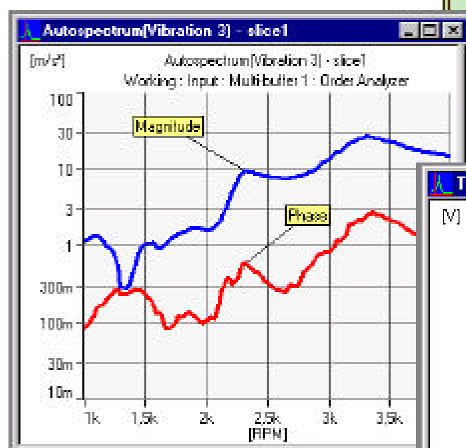


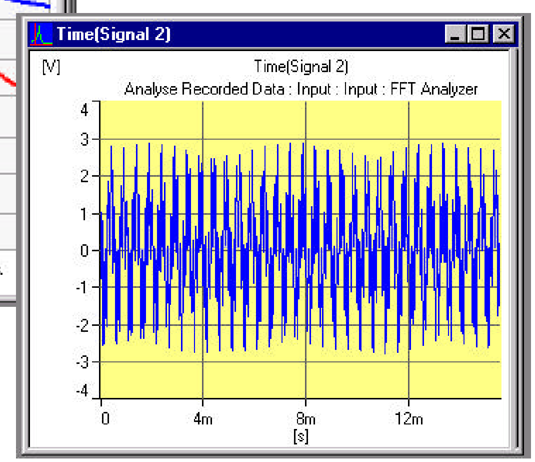
$$\Theta_k(t) = \exp(2pki\int_0^t f(u)du),$$

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

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

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



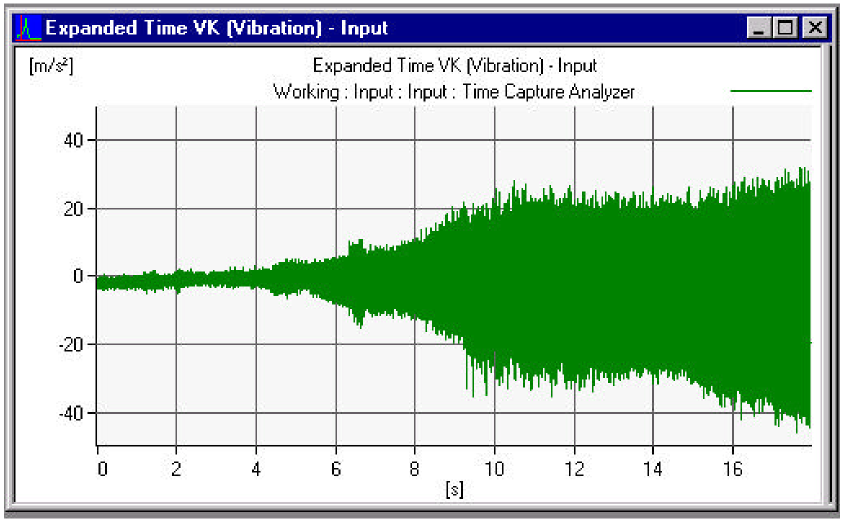


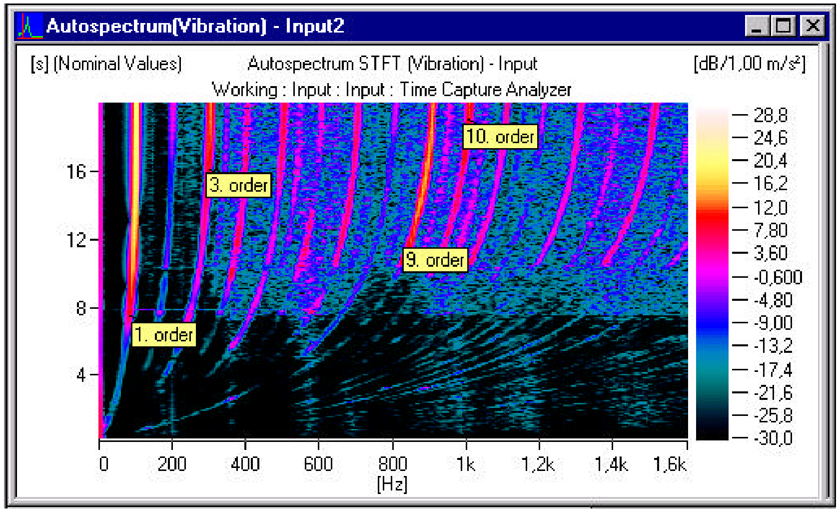
Time signal example and its STFT

- 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

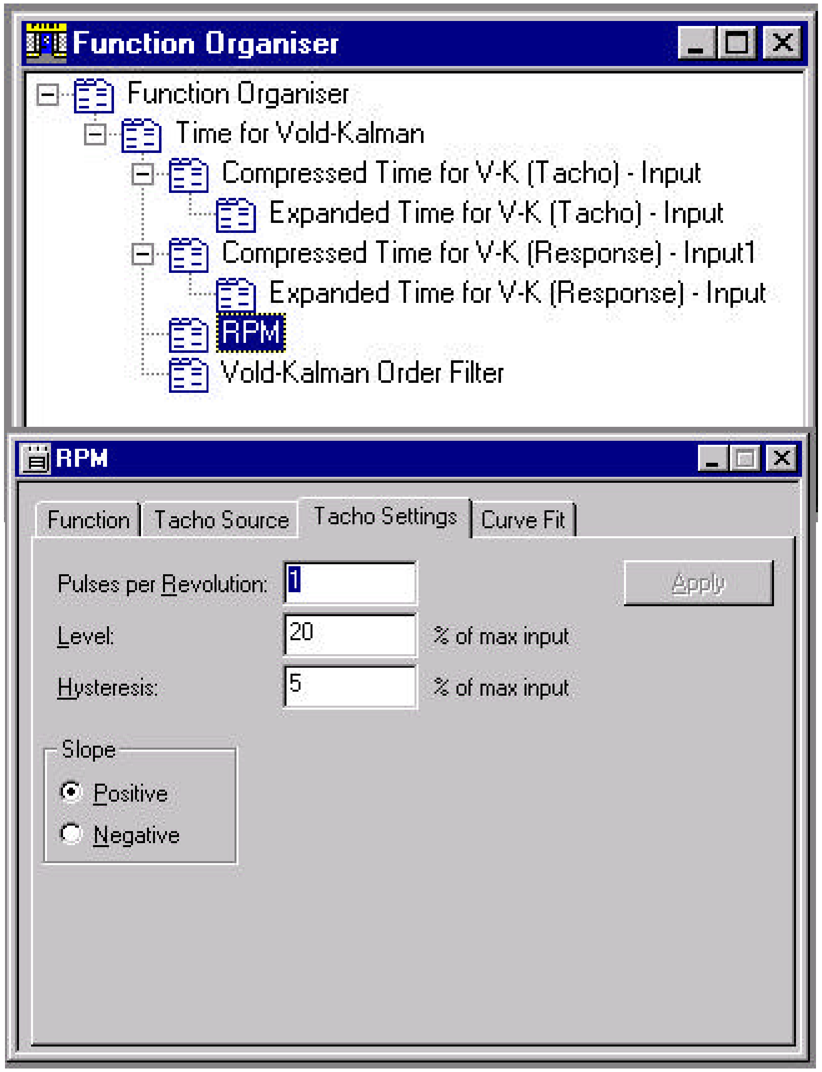
- Short Time Fourier Transform
  - for overview and inspection
  - dominating orders nos. 1, 3, 9 and 10





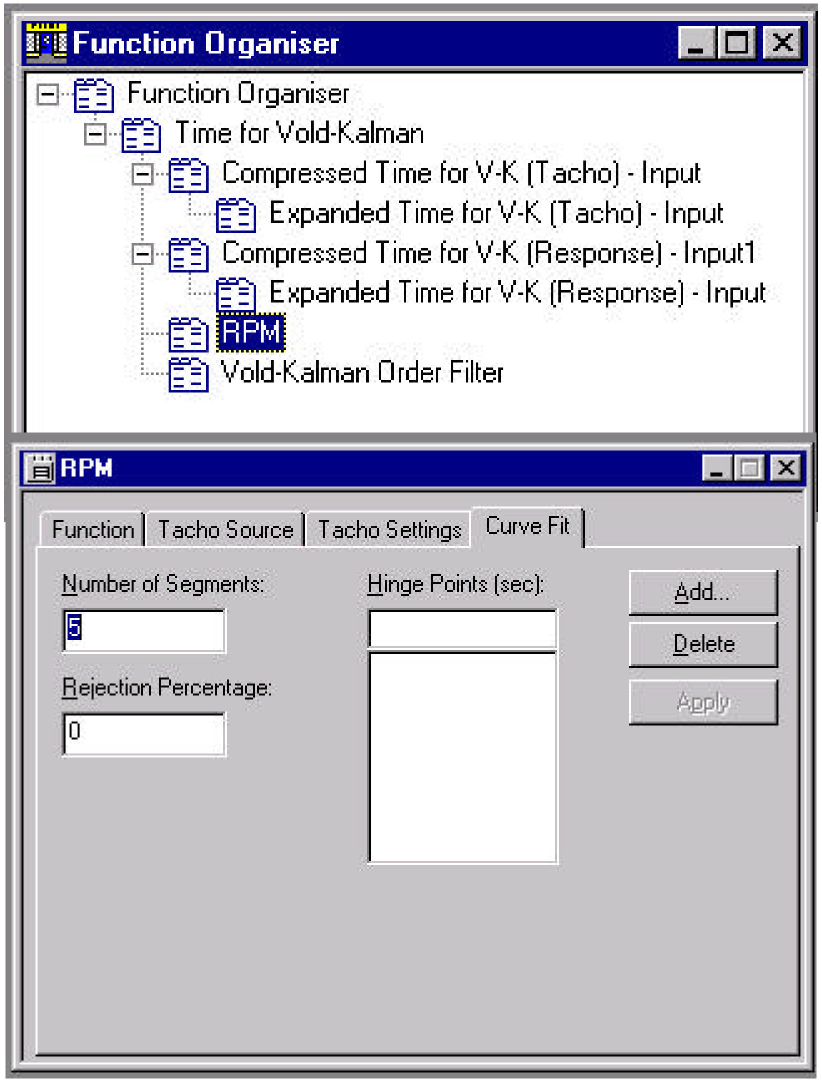
Tachometer Analysis — RPM Estimation

- Use Brüel & Klær 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



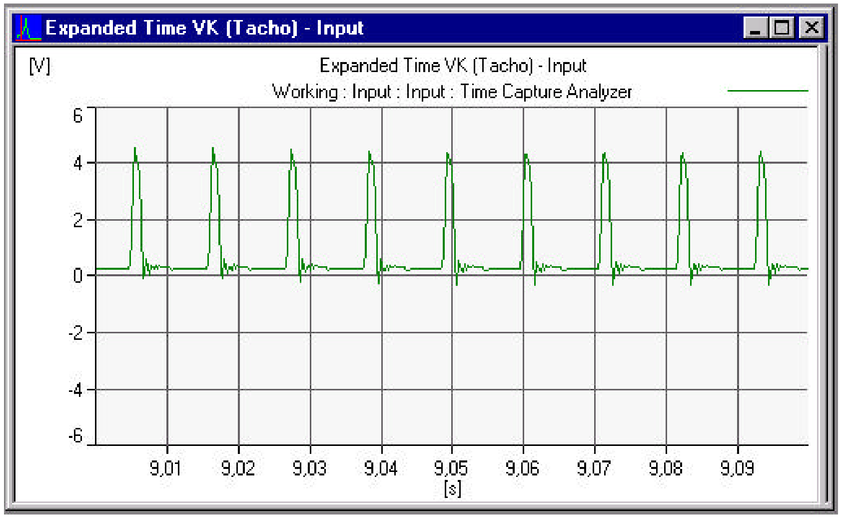
Tachometer Analysis — RPM CurveFit

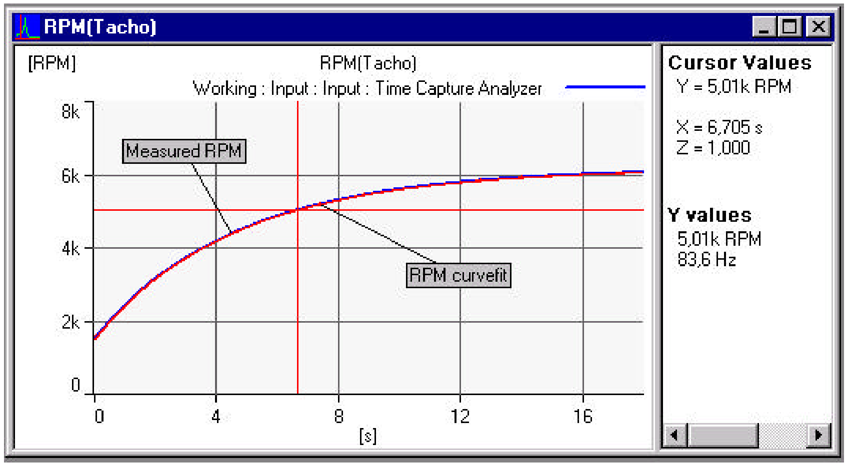
- Cubic least squares spline fit to smooth data
  - » continuity and first derivative continuity between segments
- Singular events such as gearshifts allowed
  - » relaxing first derivative continuity condition at hinge points
- Rejections of outlier data, such as tacho dropouts
  - » Data refitted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



Tacho Signal and RPM profiles

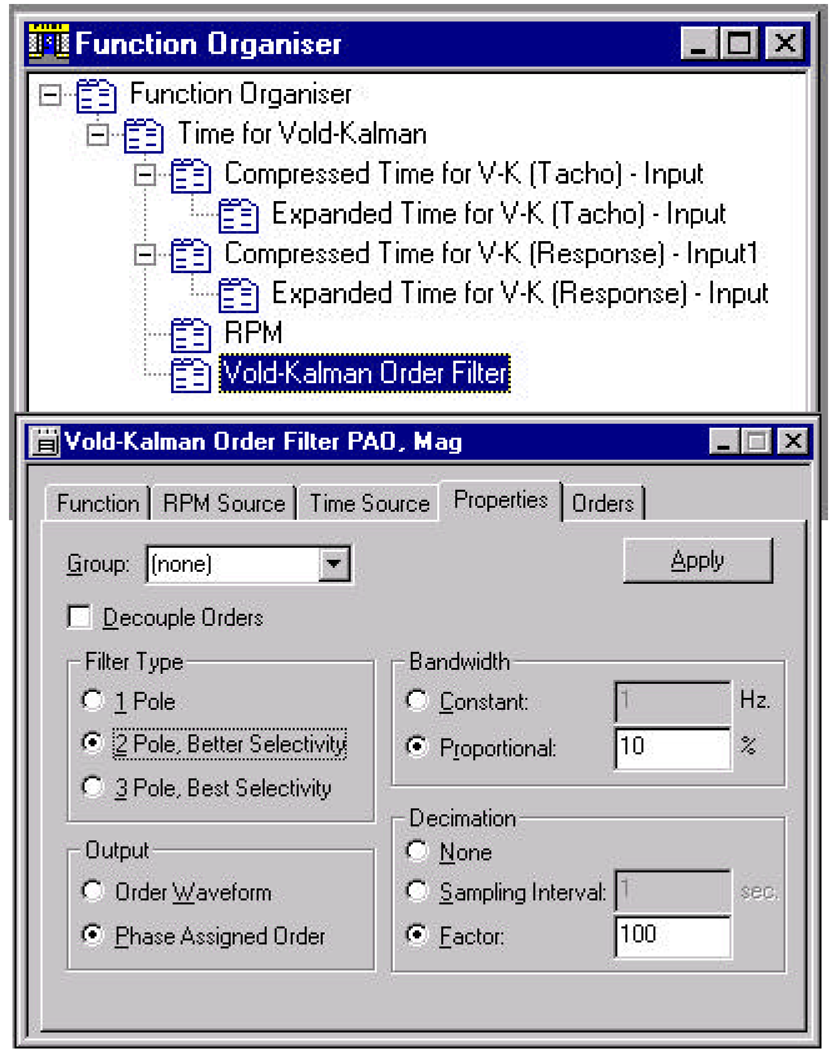
- Tacho signal (expanded)
- RPM Detection example
  - level 30%, slope +, hysteresis 5%
  - 15 segments, 0% rejection, no Hinge Points
- RPM profiles
  - Raw estimate
  - Curvefitted results
- Step by step procedure
  - data recording and selection
  - use conventional analysis techniques first, e.g.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





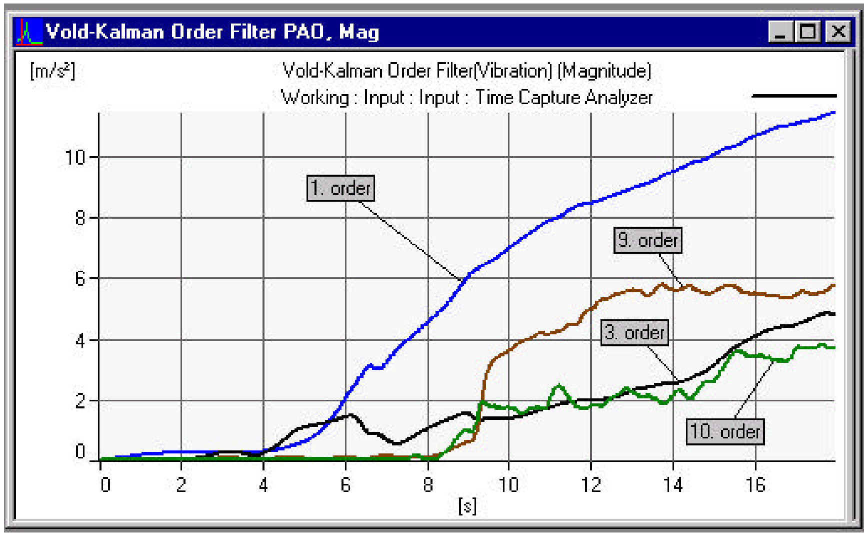
Vold-Kalman filter setup

- 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

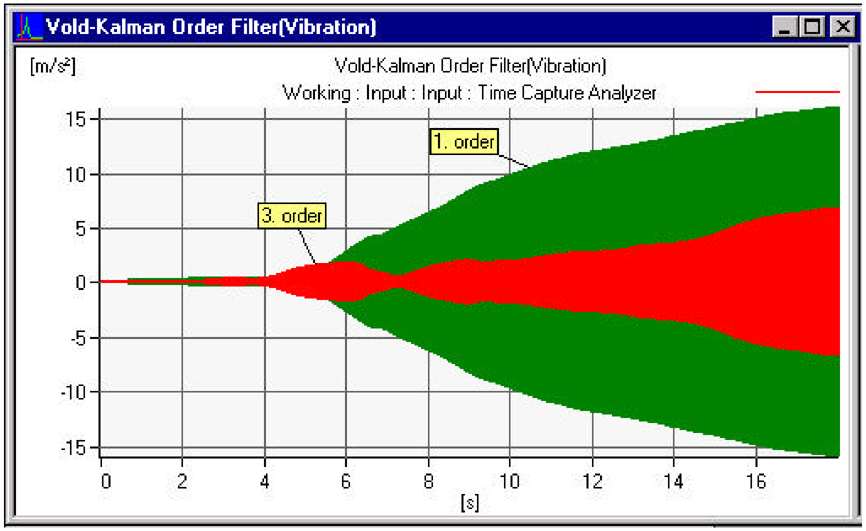


Output from a Vold-Kalman analysis

- Phase assigned orders
  - Formats available: real, imag, mag, phase, nyquist
  - Magnitude of the 4 selected orders is shown



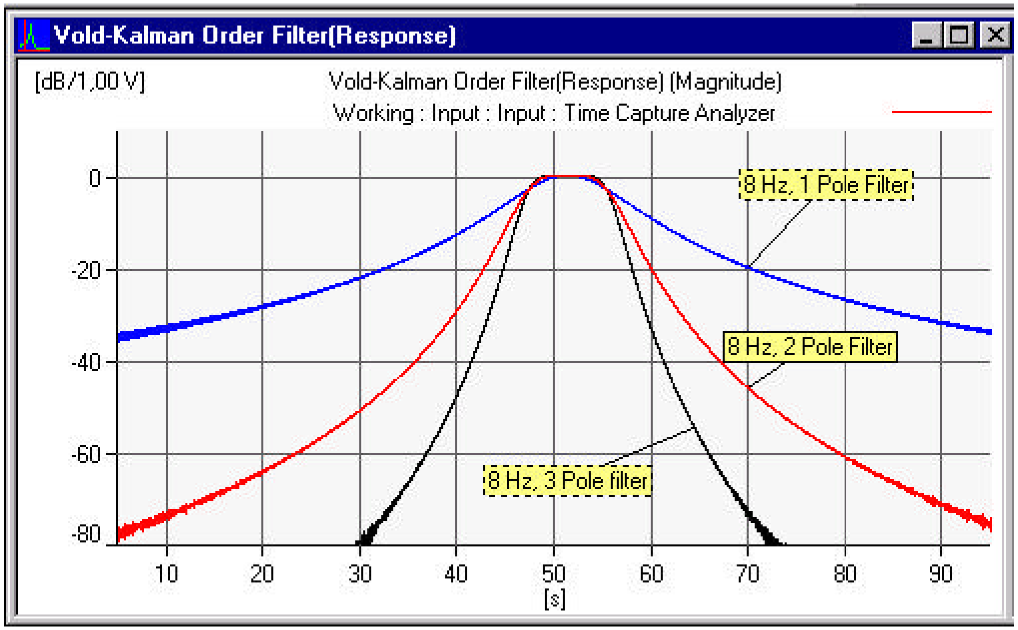
- Order waveform
  - 1. and 3. orders are shown
  - Playback via Sound Board



Brüel & Kjær

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)

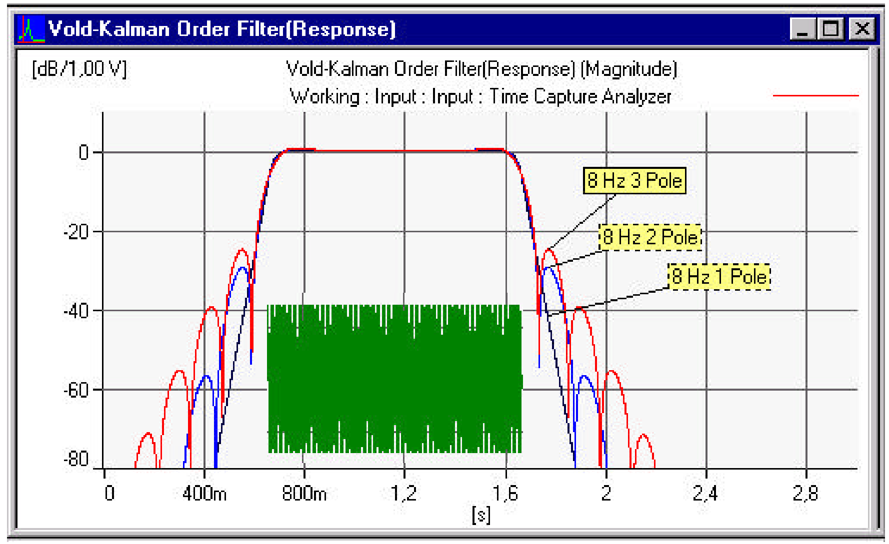


NB! Shape factor, SF is defined as

BW_{60dB} / BW_{3dB}

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} x $tau_{8.69dB} = 0,2$

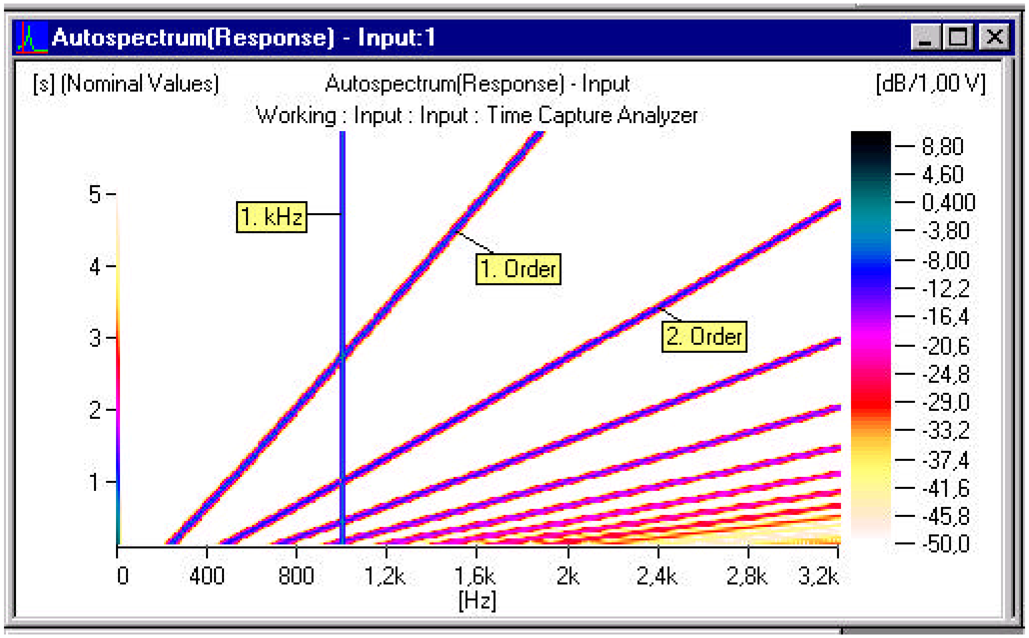
Recommended choice of BW,

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

Brüel & Kjær

Multiaxle Data

- Two axles 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

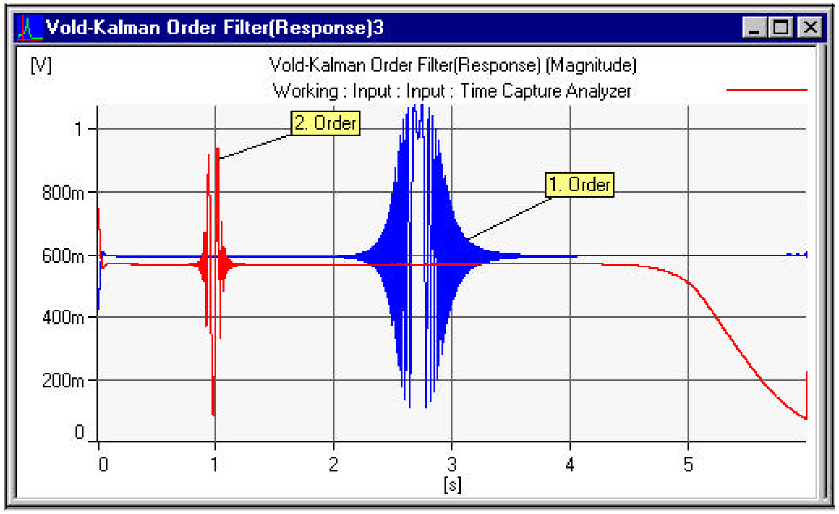


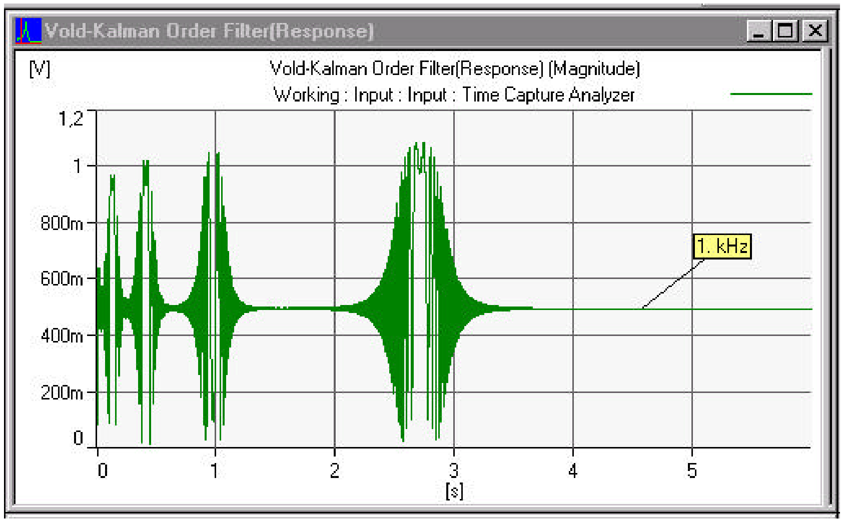
- Pre-analysis using STFT

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

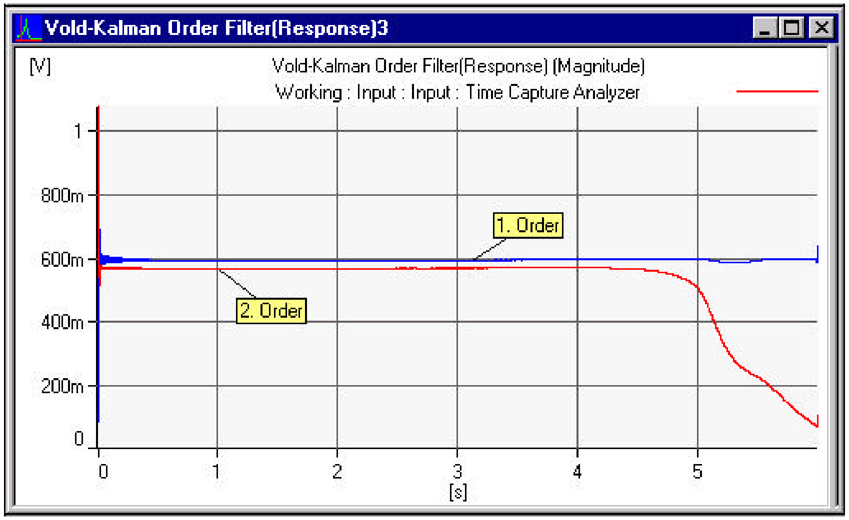
- 1 kHz interacts with
  - 1. order at 2.7 s
  - 2. order at 1.0 s
  - 3. order at 400 ms
  - 4. order at 100 ms

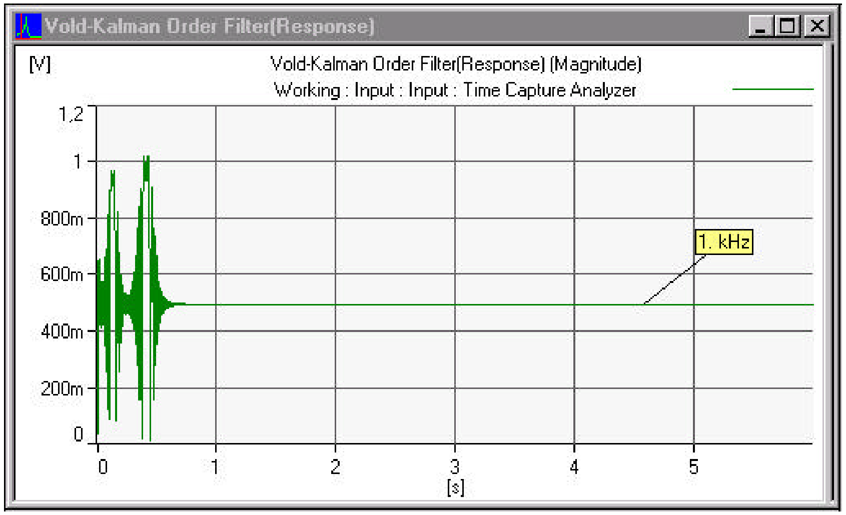




Analysis with decoupling

- 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





Brüel & Kjær

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