Approaches to the improvement of order tracking techniques for vibration based diagnostics in rotating machines

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Overview

- Current research on order tracking methods
- Towards the improvement of order tracking analysis
- Novel methods to order tracking
- Theoretical discussions
- Simulation studies
- Experimental demonstration

Current research on order tracking methods
- Classification of order tracking methods

- Time waveform non-reconstruction order tracking

  Computed order tracking(COT).

- Time waveform reconstruction order tracking.

  Vold-Kalman filter order tracking (VKF-OT)

  Intrinsic mode function (IMF) from empirical mode decomposition(EMD)

Current researches of order tracking methods
- Classification of order tracking methods

- Fourier transform based order tracking methods
- Time variant discrete Fourier transform order tracking
- The Prony residue estimation process
- Maximum likelihood process

- Blough(2003)

Current researches of order tracking methods
- Pros and cons of different order tracking methods

- Computed order tracking (COT) - advantages

  - Transformation of signals where frequency variations in speed has been excluded.

  - Easy to access due to the use of common Fourier transform.

  - COT analysis may provide a clear picture of the raw signal in terms of rotational speed.

  - COT has been proved very useful in real practice (such as Eggers, Heyns and Stander, 2007)

Current researches of order tracking methods
- Pros and cons of different order tracking methods

- Computed order tracking (COT) - disadvantages

  - Multiple orders may co-exist in one order map.

  - Signals that are not strictly related to rotational speed information will be naturally de-emphasized, such as: natural frequencies.

  -Unavoidable assumptions and different interpolation errors will, of course, influence the accuracy of the results.

  -Rotational speed information is crucial for its calculation.

Current researches of order tracking methods
- Pros and cons of different order tracking methods

- Vold-Kalman filter order tracking - advantages

  - Does not involve the assumptions and interpolations as are done in COT.

  - The use of an adaptive filter also leads to the order signals remaining in the familiar time domain.

  - Focusing on the order of interest, excluding the influences from other signals.

  - Provides a pair of spectacles to specifically see certain information of interest.

Current researches of order tracking methods
- Pros and cons of different order tracking methods

- Vold-Kalman filter order tracking - disadvantages

  - The signal variation, such as frequency variation caused by rotational speed, still remains in the filtered order signal.

  - The technique is not easy to grasp for an inexperienced analyst

  - It may easily lose vibration signals that modulate orders of interest, which usually contain useful machine condition information.

Current researches of order tracking methods - Pros and cons of different order tracking methods

- Intrinsic mode function (IMF) form empirical mode decomposition(EMD) - advantages

  - Analysing nonlinear and non-stationary signals.

  - Complicated data set can be decomposed into a finite and often small number of intrinsic mode functions (IMFs)

  -IMFs were viewed as mono-components representing some intrinsic physical meaning.

  -Empirical nature and adaptive filter to extract time domain signals

  -No limitations to the case where rotational speed must be available

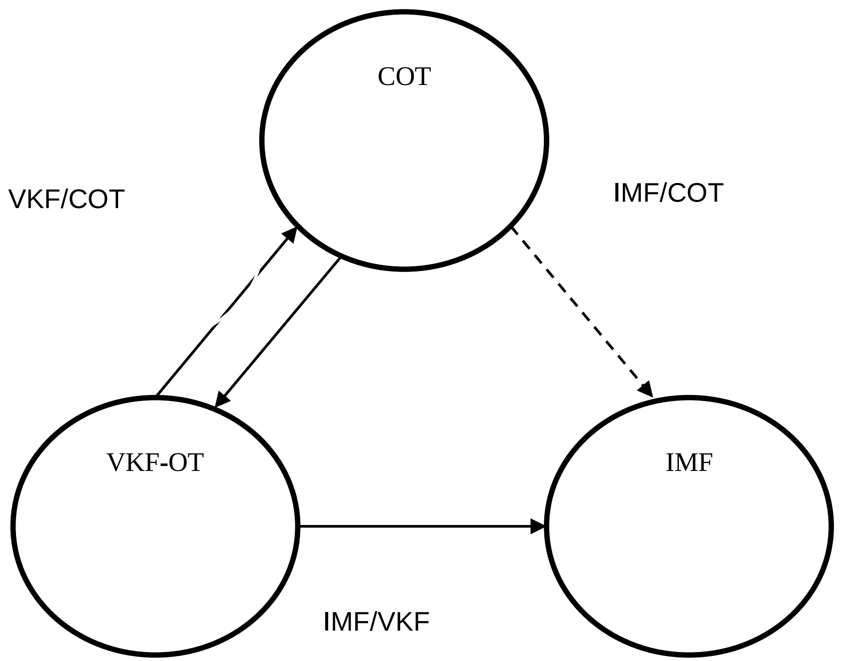
Current researches of order tracking methods
- Pros and cons of different order tracking methods

Intrinsic mode function(IMF) form Empirical mode decomposition(EMD)- disadvantages

- It is usually not easy to extract single order signals alone through an IMF

- The resolution of IMF however limits its ability to vibration monitoring

Towards the improvement of order tracking analysis



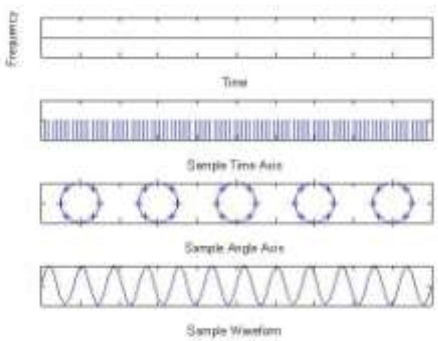
Novel methods to do order tracking

VKF/COT $\Longrightarrow$ **VKC-OT**

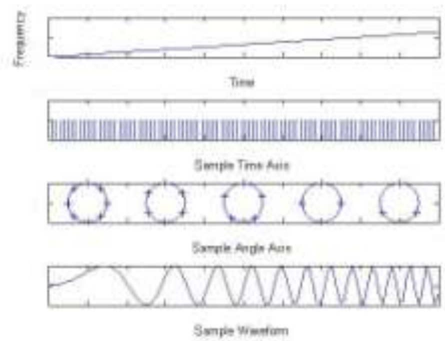
IMF/VKF $\Longrightarrow$ **IVK-OT**

IMF/COT $\Longrightarrow$ **ICR**

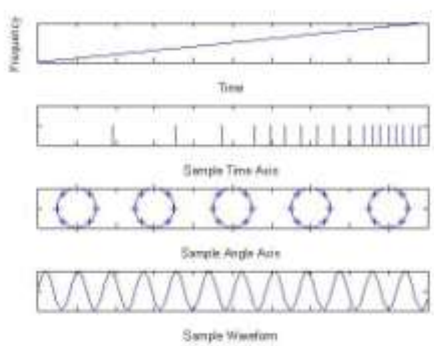
Theoretical discussions
- Computed order tracking (COT)



(a) Note: Constant $\Delta t = \Delta\theta$



(b) Note: Constant $\Delta t \neq \Delta\theta$



(c) Note: Variable $\Delta t \rightarrow \Delta\theta$

Theoretical discussions
- Vold-Kalman filter order tracking(VKF-OT)

- Data equation

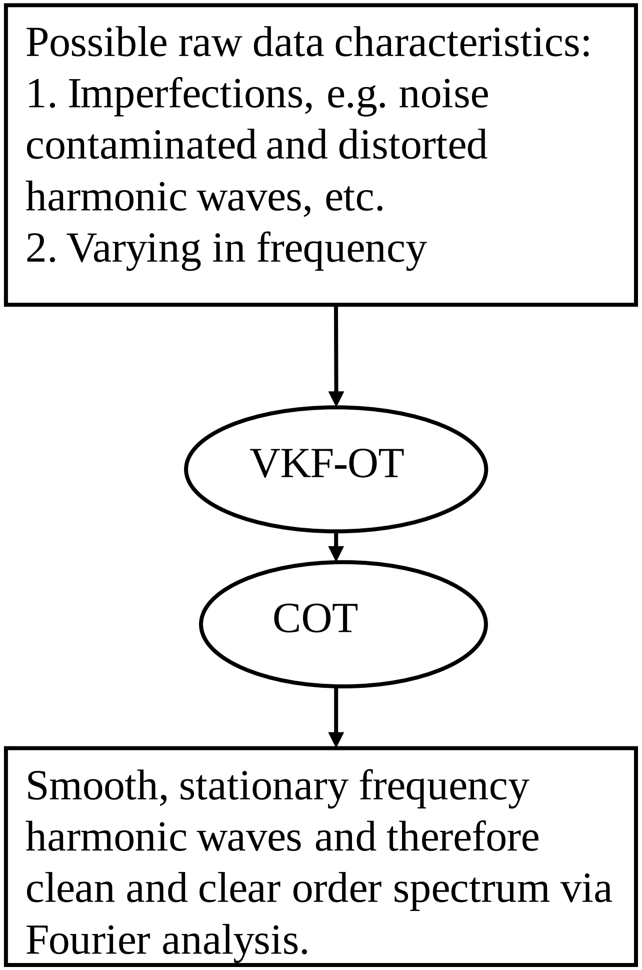
$$y(n) = x(n)e^{j\Theta(n)} + \eta(n)$$

$$\Theta(n) = \sum_{i=1}^{n} \omega(i)\Delta t$$

- Structure equation(2 pole filter as an example)

$$x(n) - 2x(n+1) + x(n+2) = \varepsilon(n)$$

Theoretical discussions - VKC-OT



Theoretical discussions
- Intrinsic mode function (IMF) from Empirical mode decomposition

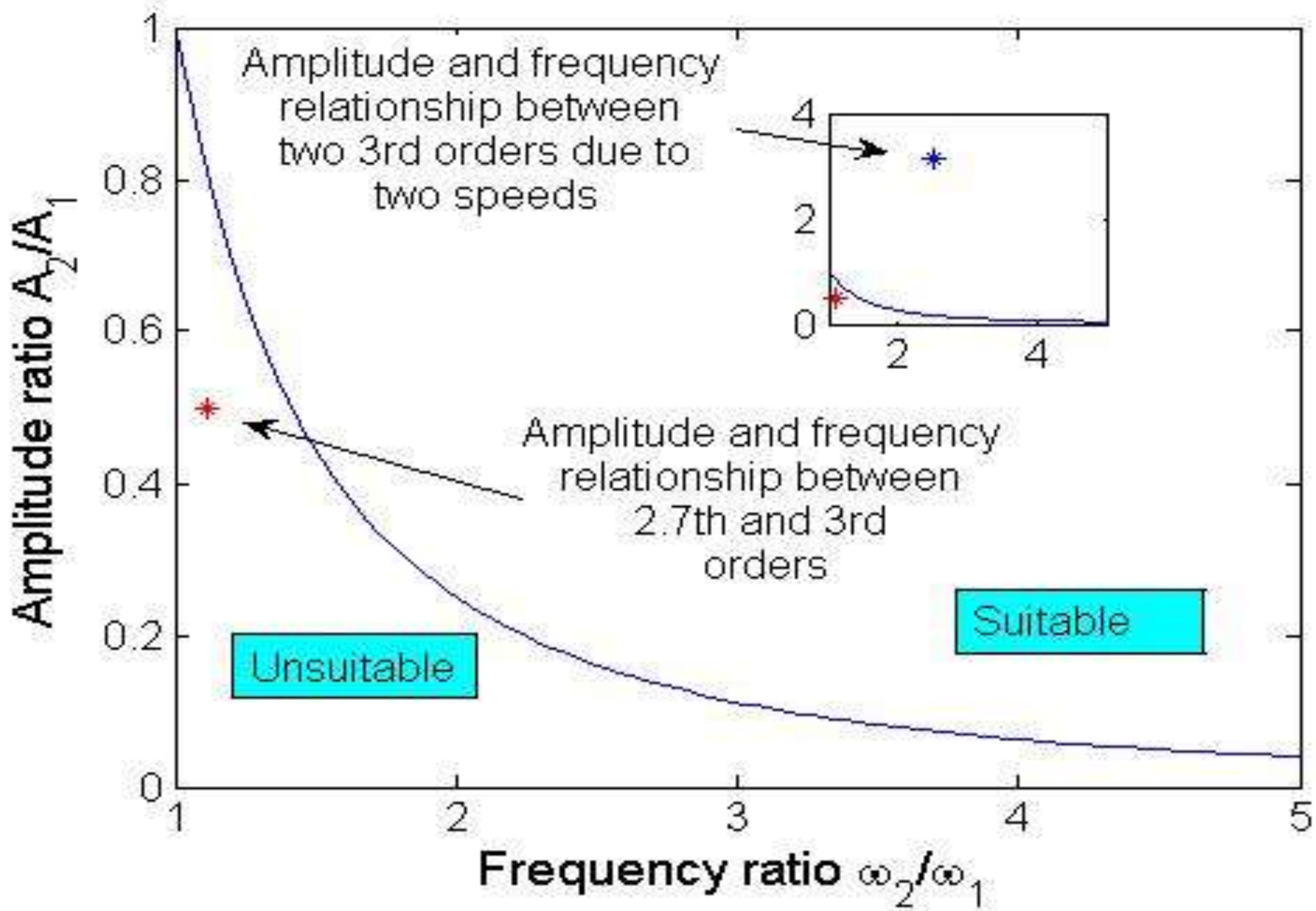
- An order signal

$$x(t) = A(k,t)\sin\left(2\pi i\left(\frac{k}{p}\right)t + \phi_k\right) \qquad x(\theta) = A_o(k,\theta)e^{jk\theta}$$

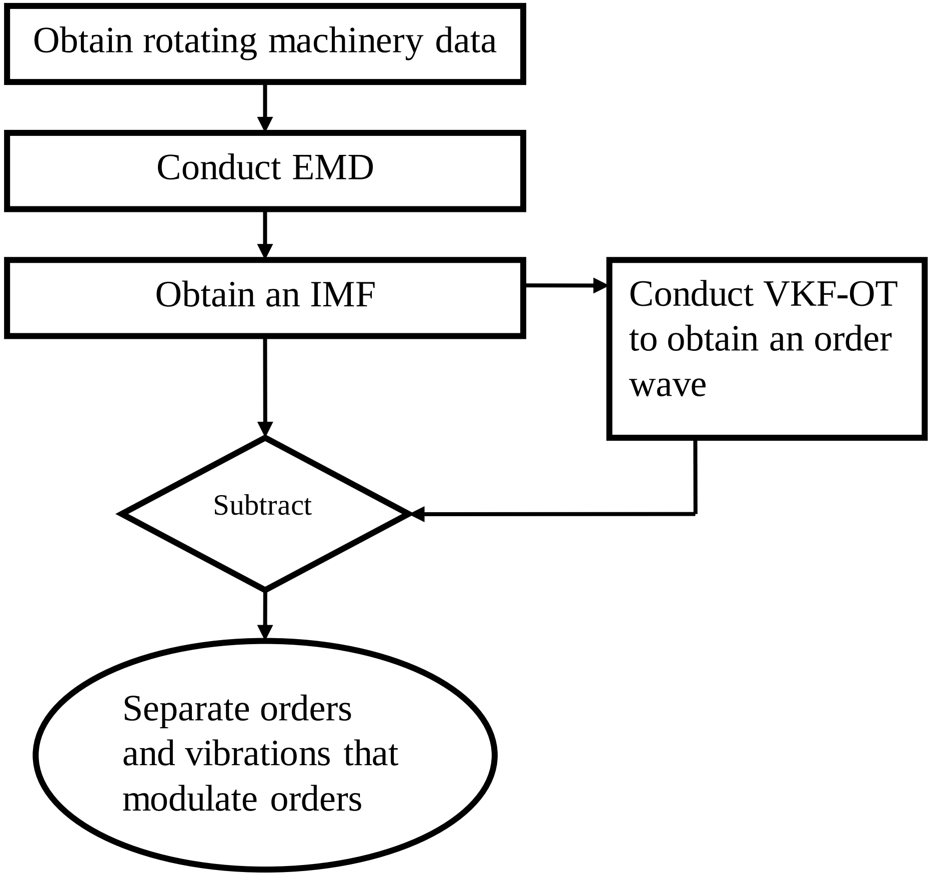
- Intrinsic mode function (IMF)

$$d(t) = A(t)\cos\phi_e(t) \qquad d(\theta) = A_o(\theta)\cos\phi_o(\theta) = \sum_{n=1}^{\infty} C_n(\theta)e^{jn\theta} + R(\theta)$$

Theoretical discussions
- Resolution of IMF



Theoretical discussions
-Intrinsic cycle and Vold-Kalman filter order tracking (IVK-OT)



Theoretical discussions -Intrinsic cycle re-sampling (ICR)

- Intrinsic mode function(Huang et al., 1998)
- In the whole signal segment, the number of extrema and the number of zero crossings must be either equal or differ at most by one.
- At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

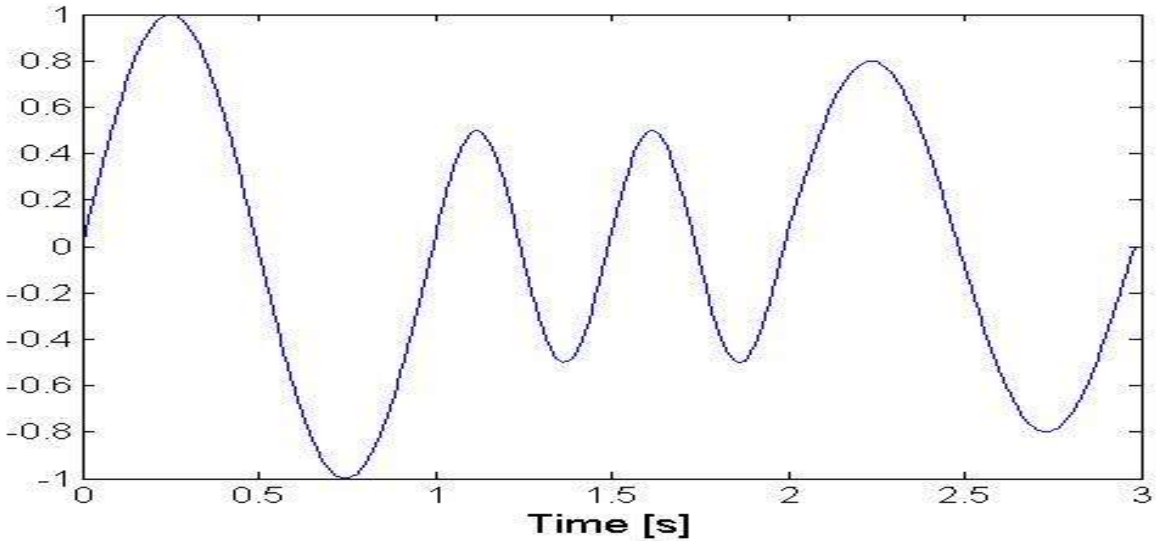
Theoretical discussions -Intrinsic cycle re-sampling (ICR)

- Intrinsic cycle(IC)

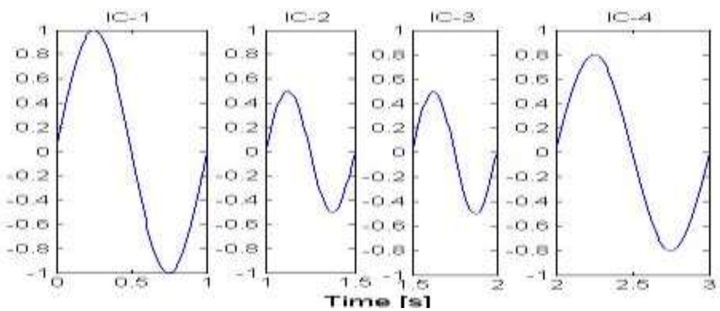
- Start from the first zero crossing of an IMF and consider two successive zero crossings. The entire signal within these three zero crossings constitute one intrinsic cycle. In the same way, the signal from the last zero crossing of a previous intrinsic cycle and including the following two successive zero crossings, constitute another intrinsic cycle, and so on.

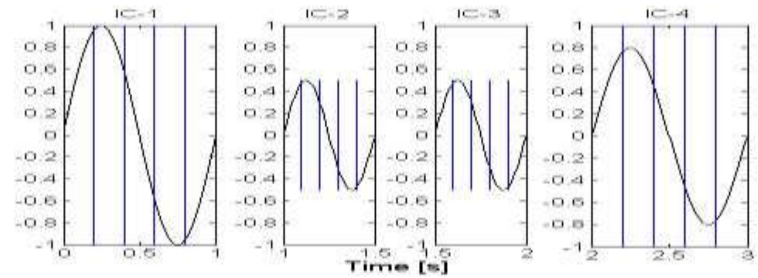
Theoretical discussions -Intrinsic cycle re-sampling (ICR)

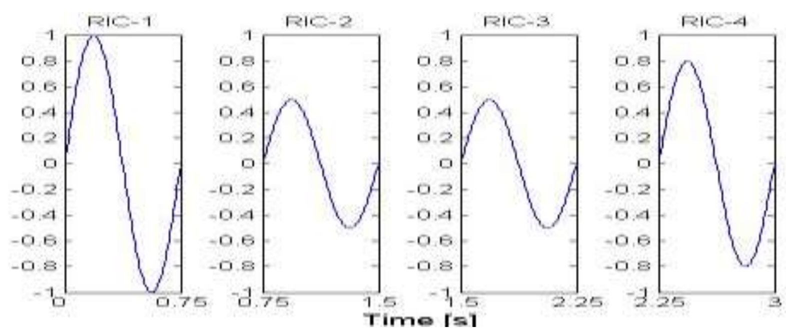
- Frequency variation within Ics
- Frequency variation between Ics



Theoretical discussions -Intrinsic cycle re-sampling (ICR)







•Theoretical discussions
-Intrinsic cycle re-sampling (ICR)

- New sampling frequency

$$f_{new} = \frac{t_{period}}{S_{resample}}$$

Developed intrinsic mode function

$$d(t) = A(t)\cos\phi_e(t) \Longrightarrow d_{ICR}(t) = A_{ICR}(t)\cos(2\pi f_{ICR} t)$$

$$f_{ICR} = \frac{N_{ICR}}{T_{ICR}}$$

Theoretical discussions
-Intrinsic cycle re-sampling (ICR)

Obtain one mode of possible non-stationary and nonlinear intrinsic mode function (IMF) signal

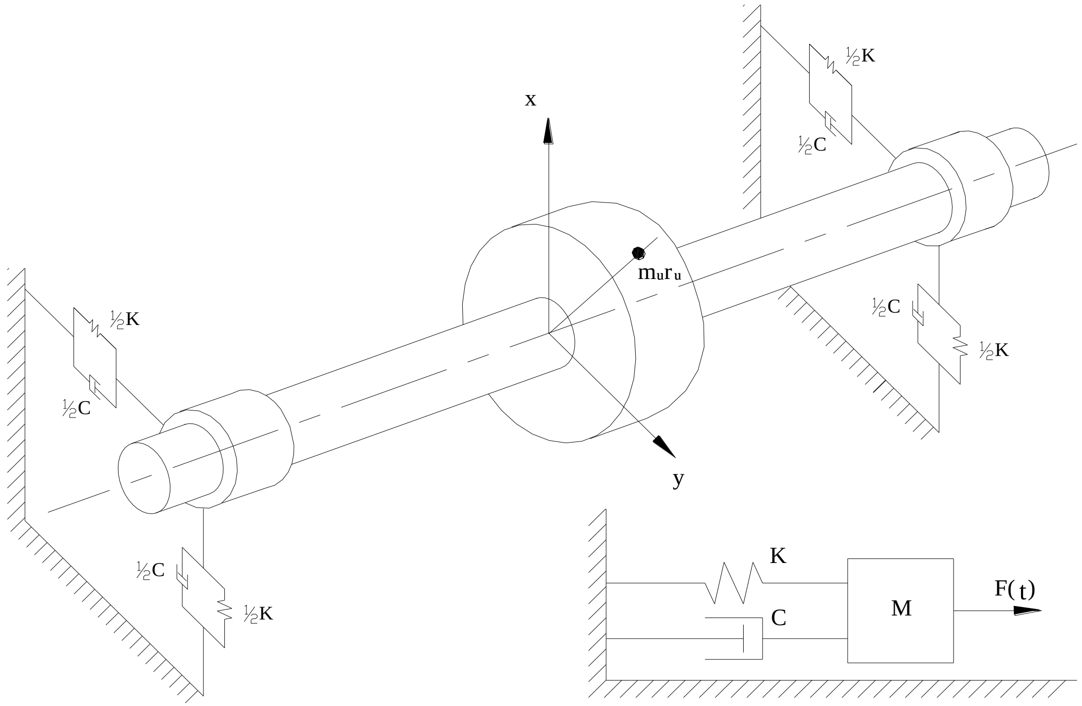
↓

Find ICs and resample ICs with equal number of points in each IC.

↓

Perform Fourier analysis to approximate computed order tracking effects and reflect the signal changes in spectral map.

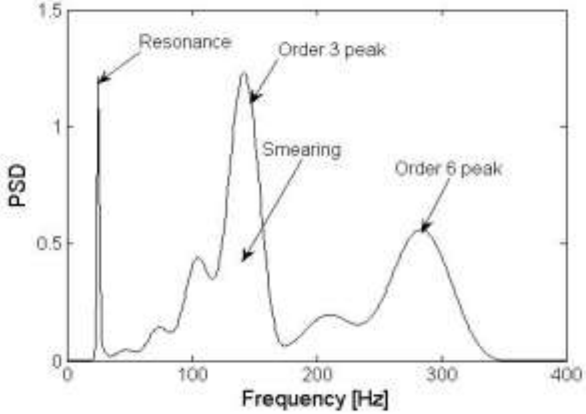
Simulation studies
model 1- SDOF rotor model



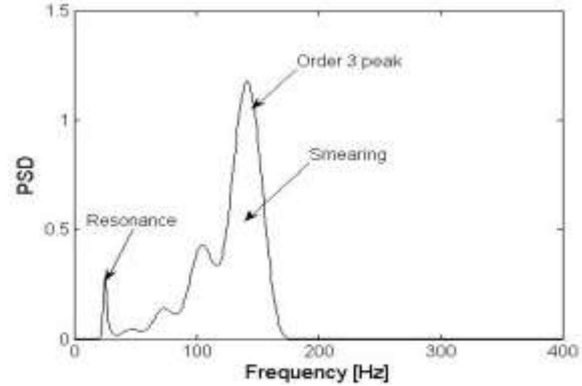
Simulation studies
model 1- SDOF rotor model – VKC-OT

Parameter	**Value**
Rotor mass	20 kg
Damping coefficient	100 Ns/m
Stiffness	500 000 N/m
Eccentricity	0.1 m
Unbalance mass	0.05 kg
Initial time	0 s
Final time	5 s
Time steps	4096
Number of revolutions	100
Number of re-sampling intervals	100
Angular speed	$15.0796t^2$
Scenario 1	Excitation: $F = m_u \omega^2 r_u \sin(3\omega t) + m_u \omega^2 r_u \sin(6\omega t)$
Scenario 2	Excitation: $F = m_u \omega^2 r_u \sin(3\omega t) + m_u \omega^2 r_u \sin(6\omega t)$ Final System response = system response to +Noise Noise: $100 \times randn(4096,1)$ (Normally distributed random noise with mean zero and standard deviation one).

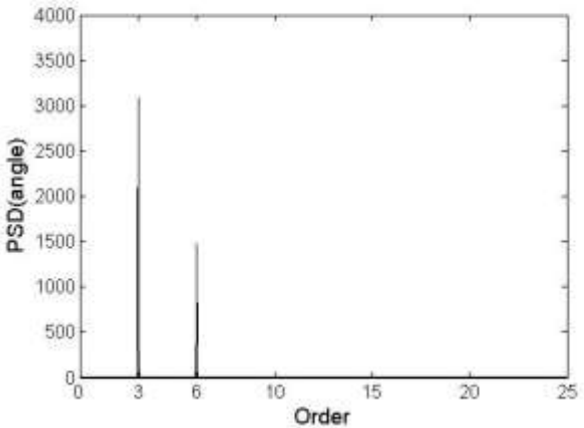
Simulation studies VKC-OT results



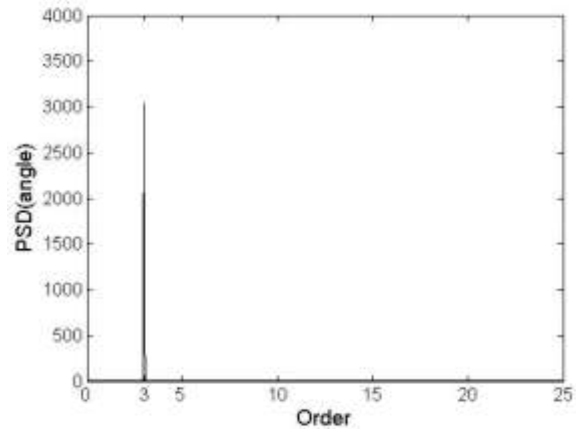
(a)PSD on raw data



(b) PSD on VKF-OT for 3rd order

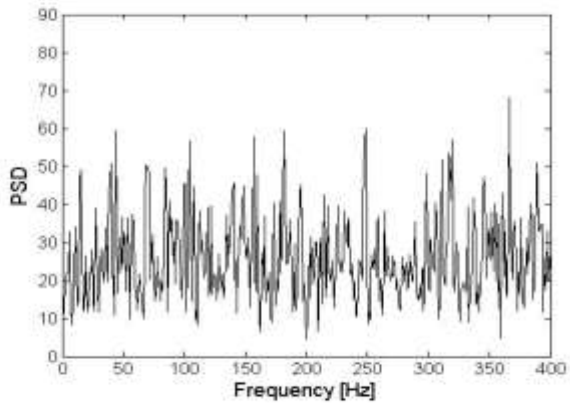


(c)PSD on COT data

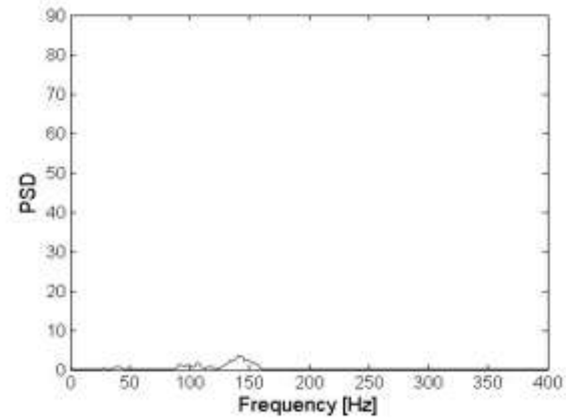


(d) PSD on VKC-OT for 3rd order

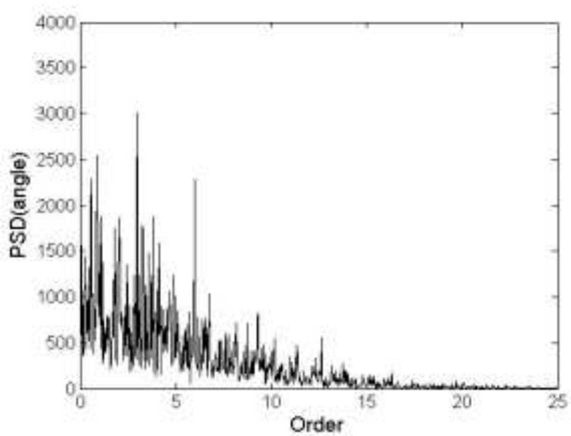
Simulation studies
VKC-OT results



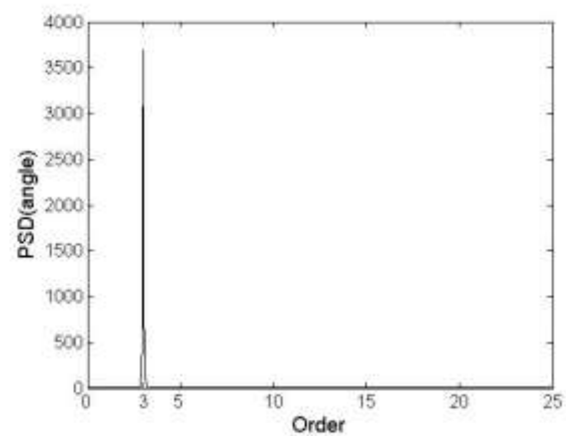
(a)PSD on raw data



(b) PSD on VKF-OT for 3^{rd} order



(c)PSD on COT data

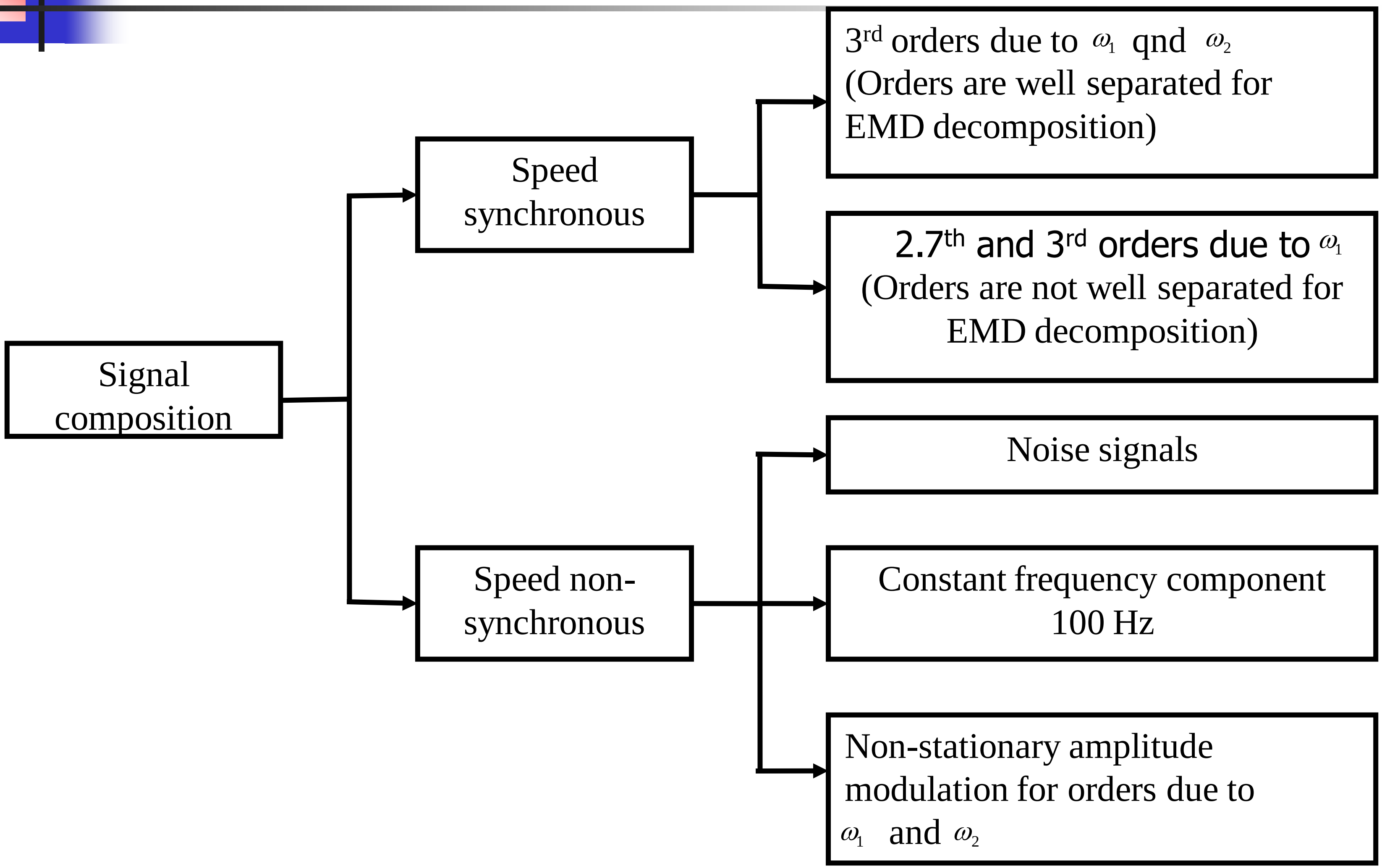


(d) PSD on VKC-OT for 3^{rd} order

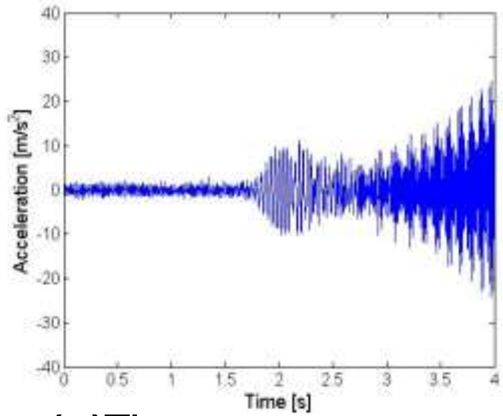
Simulation studies
model 1- SDOF rotor model – IVK-OT

Number of revolutions	100
Number of re-sampling intervals	100
Angular speed	$\omega_1 = 15.0796\ t^2$ rad/s
Angular speed	$\omega_2 = \frac{\omega_1}{2.5} = 6.0318\ t^2$ rad/s
External excitation	$F = A_{m1}\sin(3\omega_1 t) + 0.5A_{m1}\sin((3\times 0.9)\omega_1 t)$ N $+ A_{m2}\sin(3\omega_2 t)$ 1)Speed synchronous amplitude $A_{m1} = m_u\omega_1^2 r_u$ $A_{m2} = 2m_u\omega_2^2 r_u$ 2) Speed non-synchronous amplitude $f_m = 5Hz$ $A_{m1} = m_u\omega_1(1-\sin(2\pi f_m t)^2 r_u$ $A_{m2} = 2m_u\omega_2(1-\sin(2\pi f_m t)^2 r_u$
Observed signals	$y = y_F + A\sin(2\pi f t) + noise$ 1) y_F is the response due to the external excitation 2) $A\sin(2\pi f t)$ is a constant sinusoidal component at $f = 100Hz$ $A = 7.5\% rms(y_F)$ 3) Random noise is set to be $noise = 5\% rms(y_F)$ in amplitude.

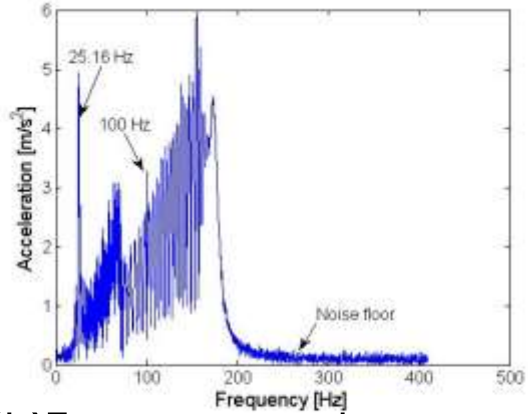
Simulation studies
model 1- SDOF rotor model – IVK-OT



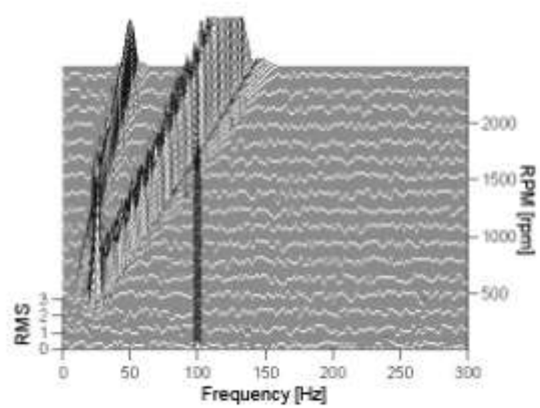
Simulation studies
IVK-OT results



(a)Time response

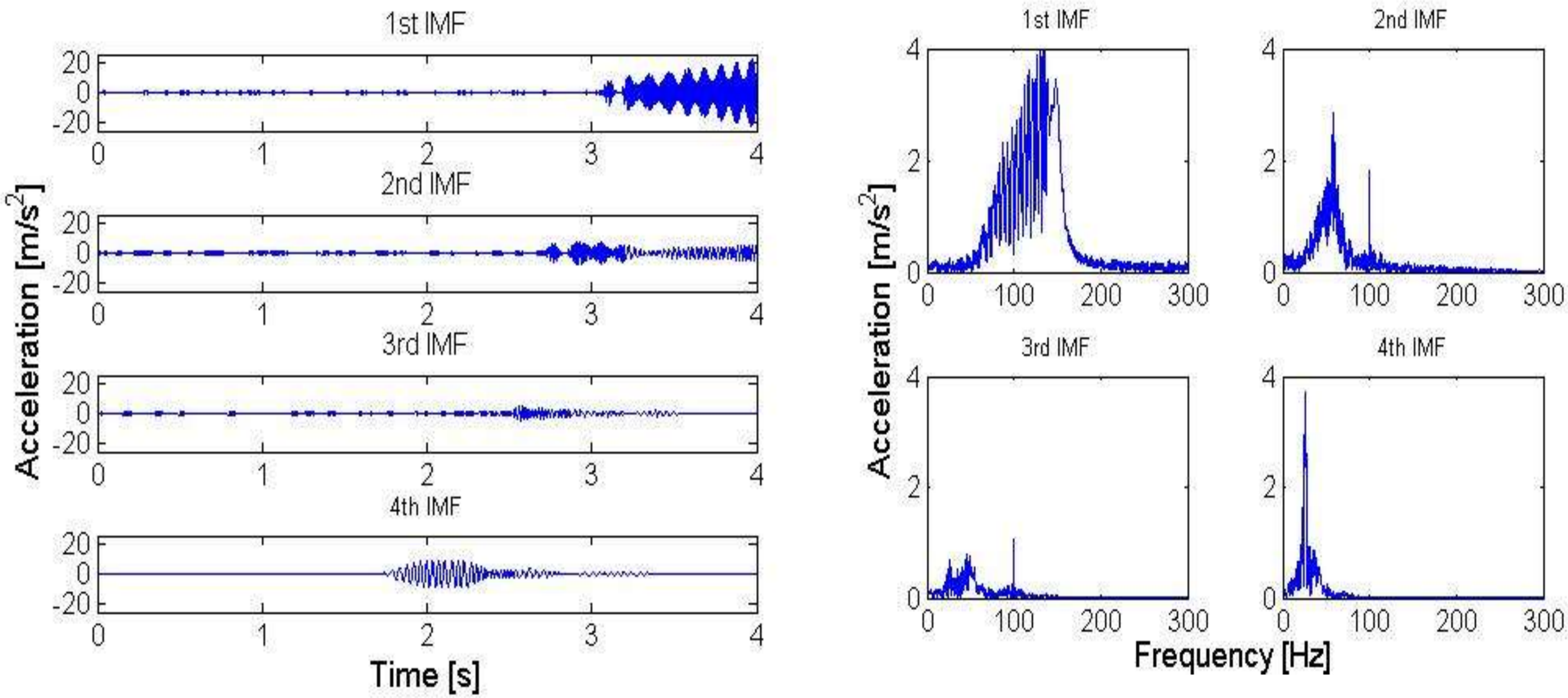


(b)Frequency spectrum



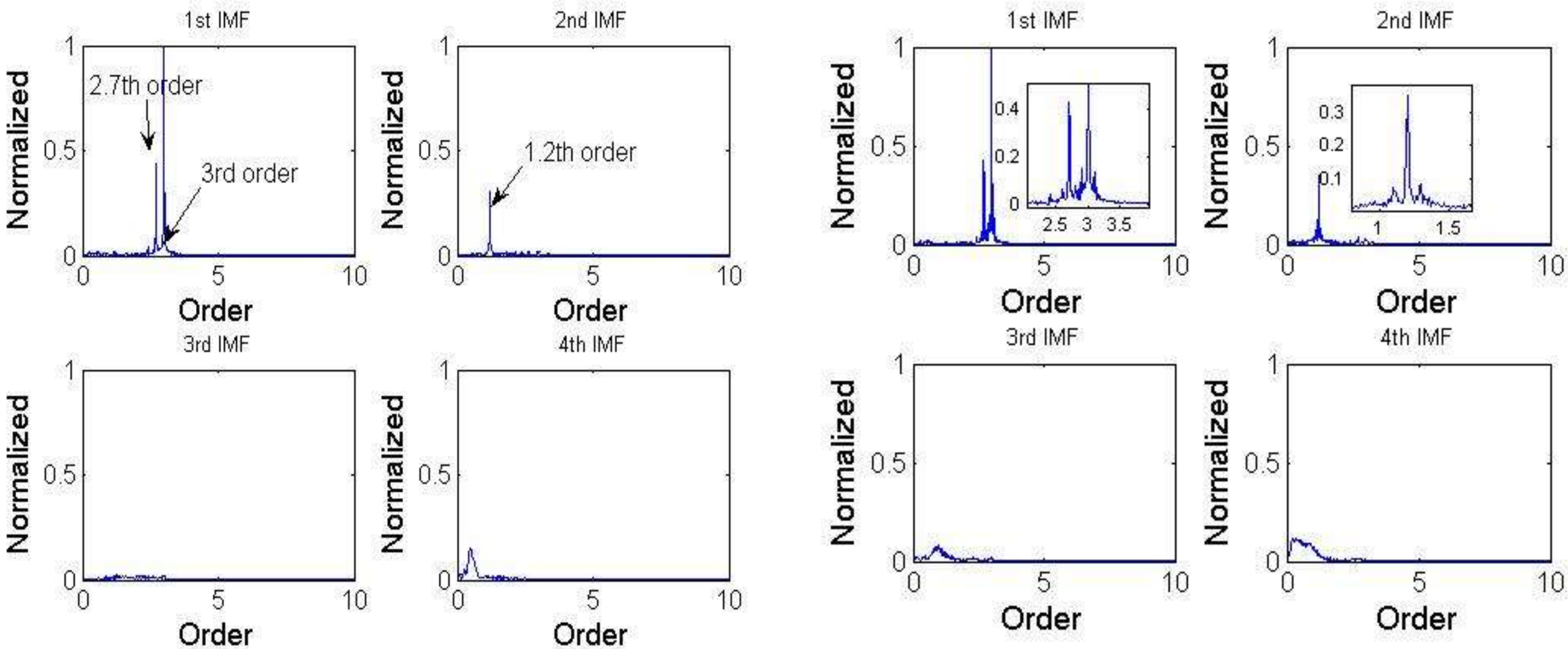
(c)RPM spectrum map

Simulation studies
IVK-OT results



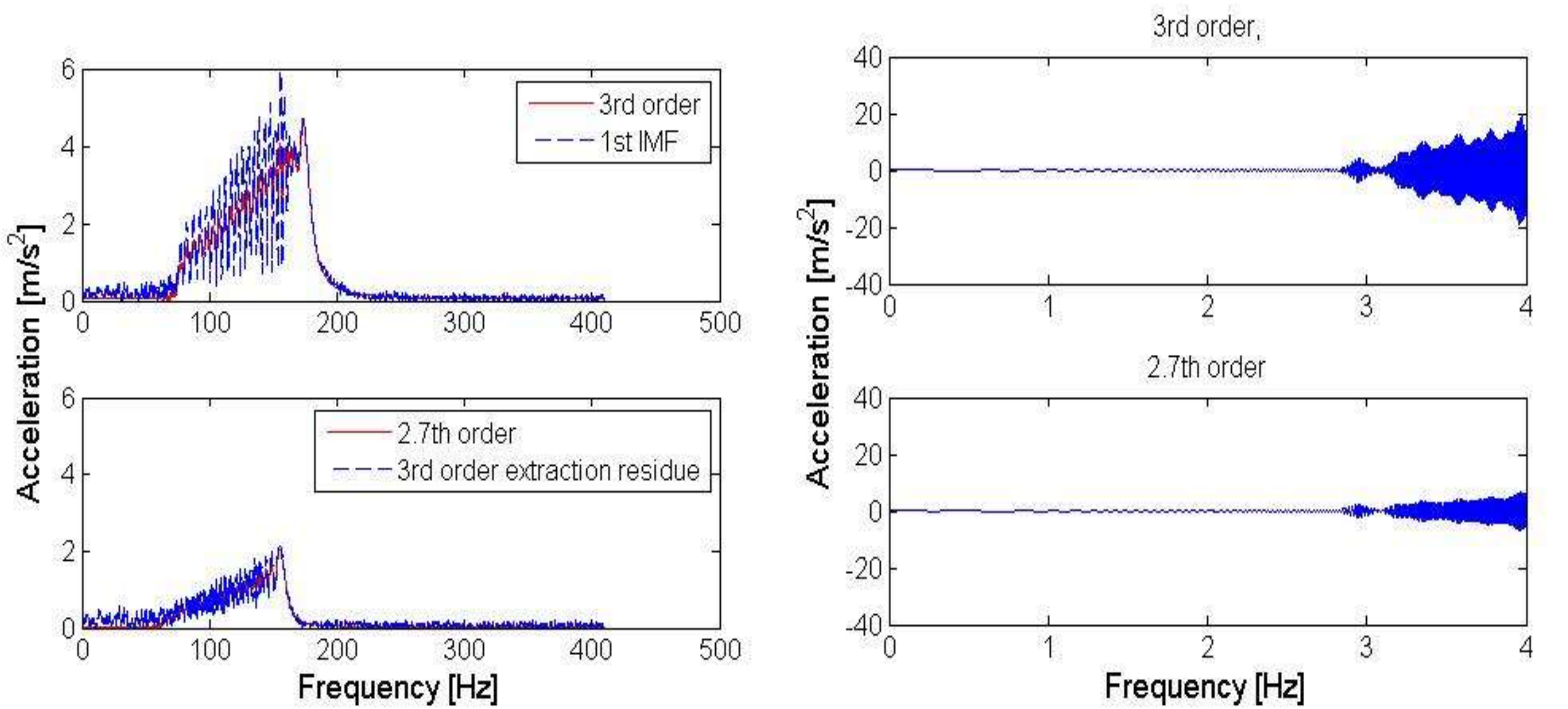
(a) IMFs (b) Frequency spectrum of IMFs

Simulation studies
IVK-OT results



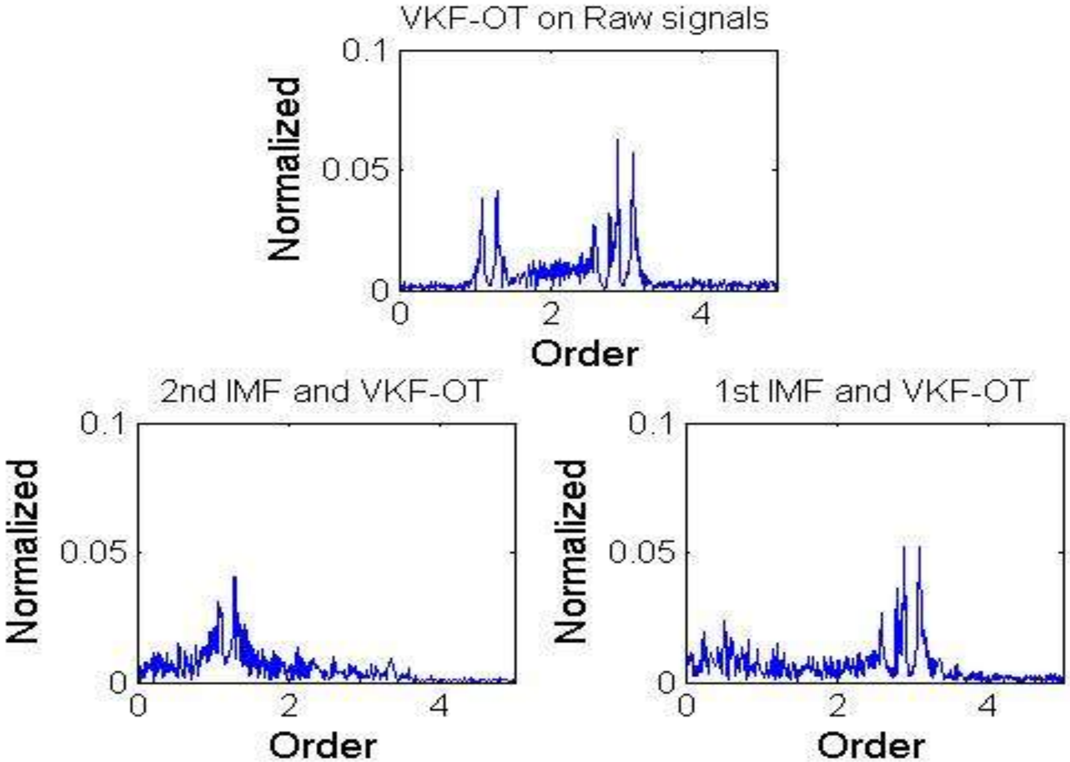
(a) Speed synchronous amplitude (b) Speed non-synchronous amplitude

Simulation studies
IVK-OT results



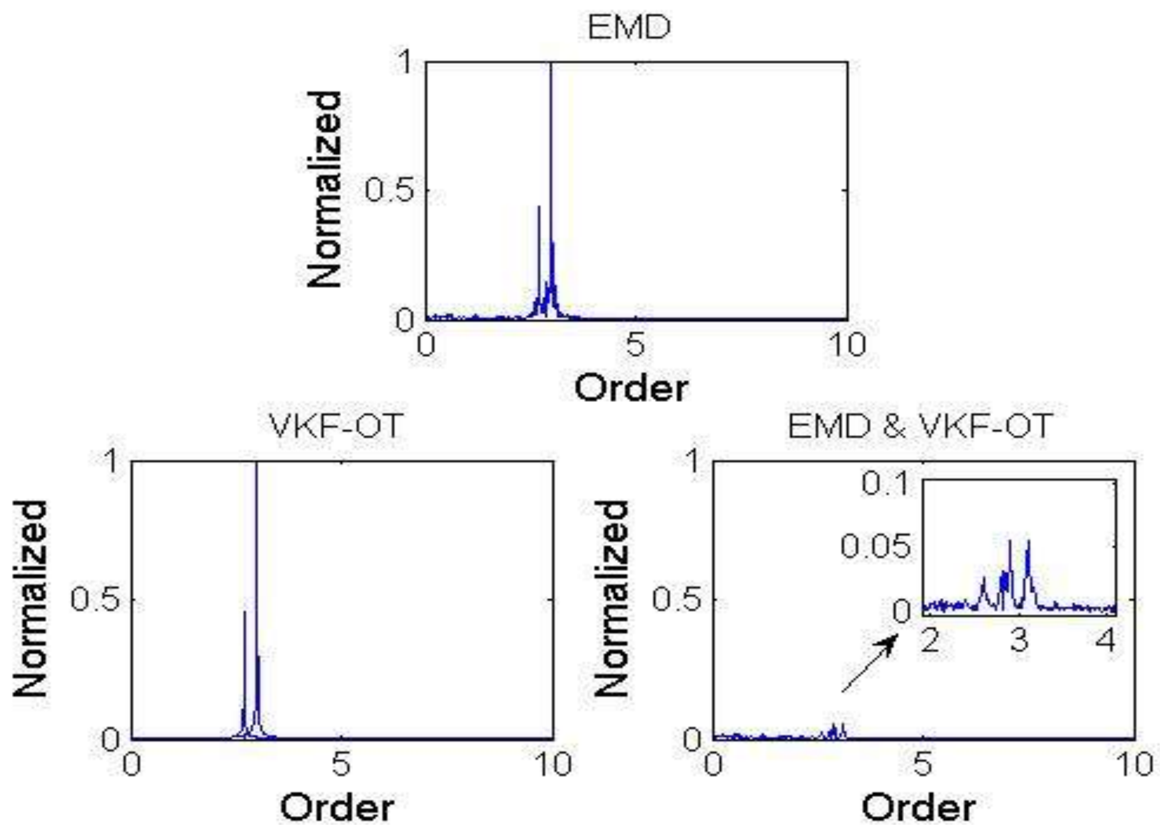
(a) Spectrum map (b) Time waveform

Simulation studies
IVK-OT results



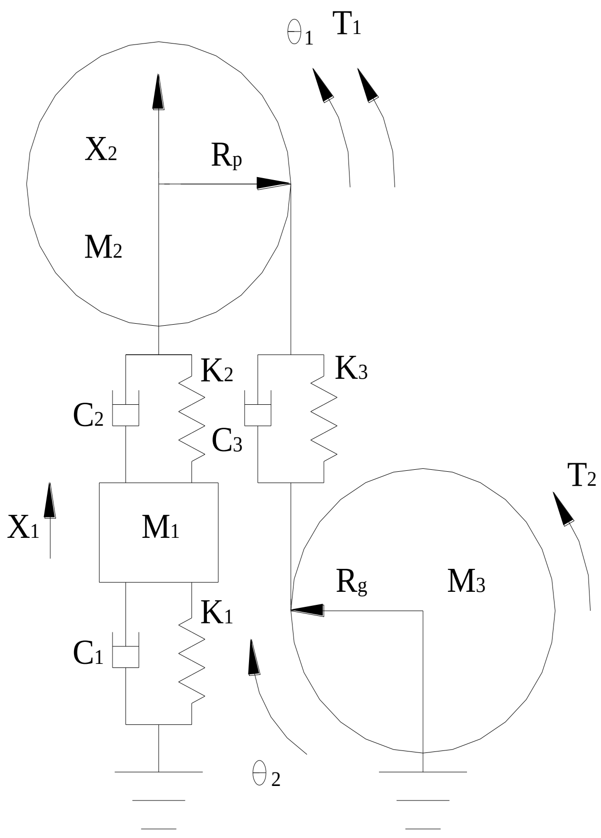
Separation of 1.2th and 3rd order sidebands

Simulation studies
IVK-OT results



Results comparison of EMD, VKF-OT and sequence use of EMD & VKF-OT (use 1st IMF to illustrate)

Simulation studies
model 2- gear meshing model



Dynamic gear meshing model (Stander and Heyns, 2006)

Simulation studies
model 2- gear meshing model

M_1	Translating mass	0.05 kg
M_2	Pinion mass	0.05 kg
M_3	Gear wheel mass	0.05 kg
I_1	Inertia of pinion gear $I_1 = \frac{1}{2} M_2 R_p^2$	2.5×10^{-6} kg • m^2
I_2	Inertia of gear wheel $I_2 = \frac{1}{2} M_3 R_g^2$	2.5×10^{-6} kg • m^2
K_1	Structural damping	100 kN/m
K_2	Bearing stiffness	100 kN/m
K_3	Gear mesh stiffness	$100\{1 - 0.01\sin(N \times \theta_1)\}$ kN/m
C_1	Structural damping	1.2 Ns/m
C_2	Bearing damping	1.2 Ns/m
C_3	Gear mesh damping	1.2 Ns/m
R_p	Pinion base circle radius	0.01 m

Simulation studies
model 2- gear meshing model

R_g	Gearwheel base circle radius	0.01 m
N	Number of gear teeth	10
GR	Gear ratio	1:1
f_s	Sampling frequency	8192 Hz
I	Number of re-sampling intervals within one revolution	2000
Input torque	, $T_1 = 1 + 0.1\sin\omega t$ $\omega = 2\pi \times 25$	
Load	, $T_2 = K_s\dot{\theta}_2^2$ $K_s = 16.2$	

Simulation studies
model 2- gear meshing model

$$M_1\ddot{X}_1+\left(C_1+C_2\right)\dot{X}_1+\left(K_1+K_2\right)X_1-C_2\dot{X}_2-K_2X_2=0$$

$$M_2\ddot{X}_2+\left(C_2+C_3\right)\dot{X}_2+\left(K_2+K_3\right)X_2-C_2\dot{X}_1-K_2X_1-C_3R_g\dot{\theta}_2$$

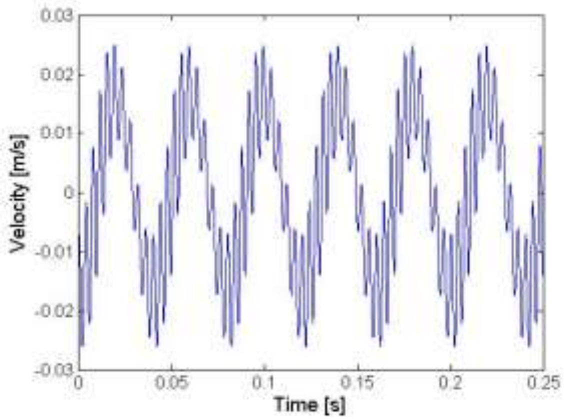
$$-K_3R_g\theta_2+C_3R_p\dot{\theta}_1+K_3R_p\theta_1=0$$

$$I_1\ddot{\theta}_1+R_p{}^2C_3\dot{\theta}_1+R_p{}^2K_3\theta_1-R_pR_gC_3\dot{\theta}_2-R_pR_gK_3\theta_2+R_pC_3\dot{X}_2+R_pK_3X_2=T_1$$

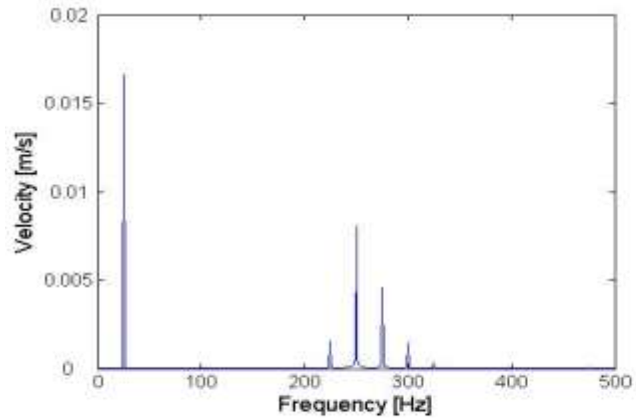
$$I_2\ddot{\theta}_2+R_g{}^2C_3\dot{\theta}_2+R_g{}^2K_3\theta_2-R_gR_pC_3\dot{\theta}_1-R_gR_pK_3\theta_1-R_gC_3\dot{X}_2-R_gK_3X_2=T_2$$

The equations of motion describing the model

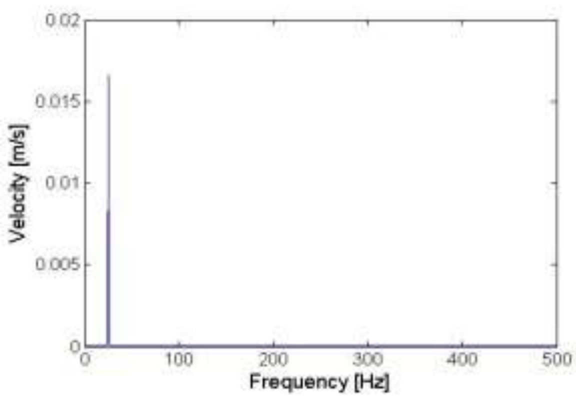
Simulation studies
gear meshing model - results



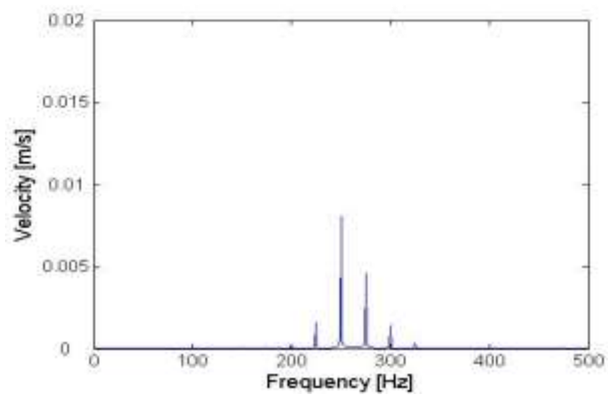
(a) Velocity waveform



(b) Fourier spectrum

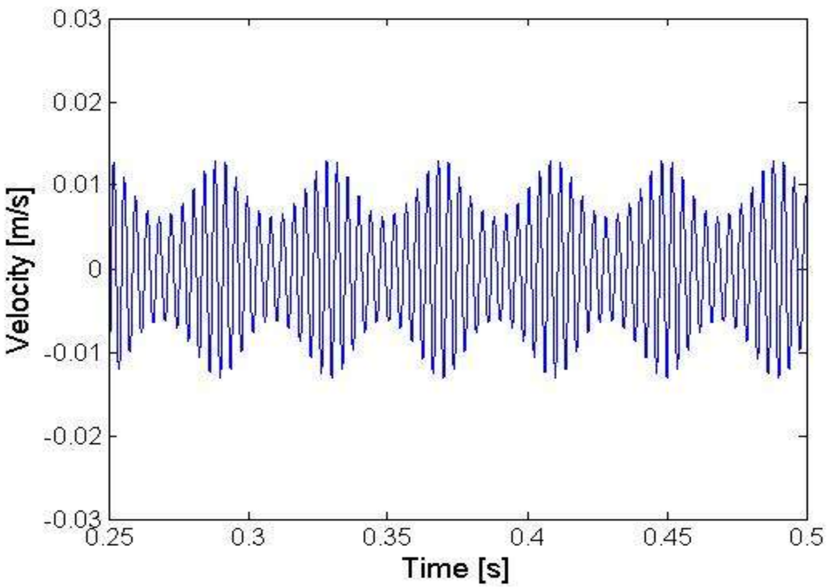


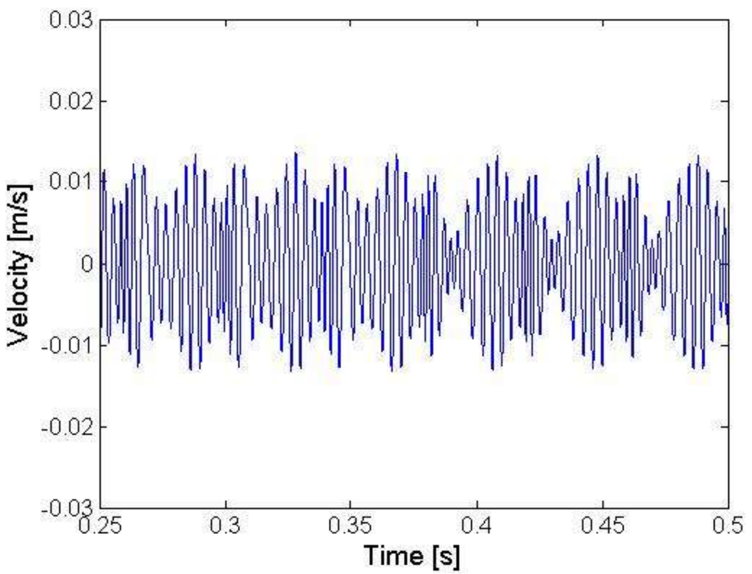
(c) Fourier Spectrum of 2^{nd} IMF



(d) Fourier spectrum of 1^{st} IMF

Simulation studies
gear meshing model - results

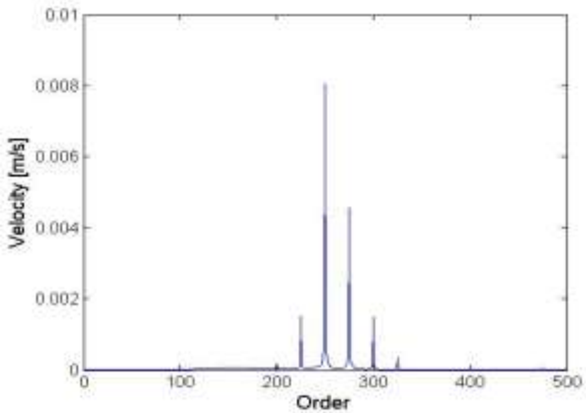




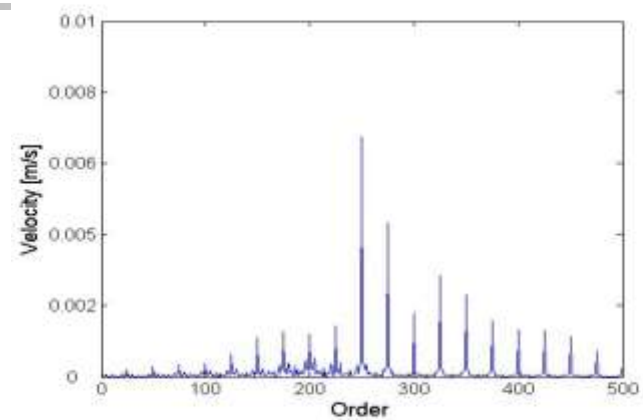
(a) 1st IMF for good condition

(b) 1st IMF for fault condition

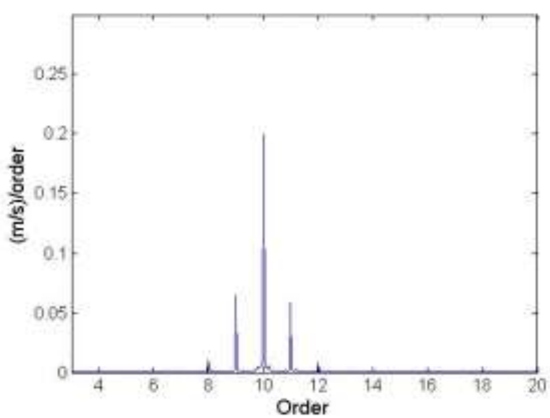
Simulation studies gear meshing model - results



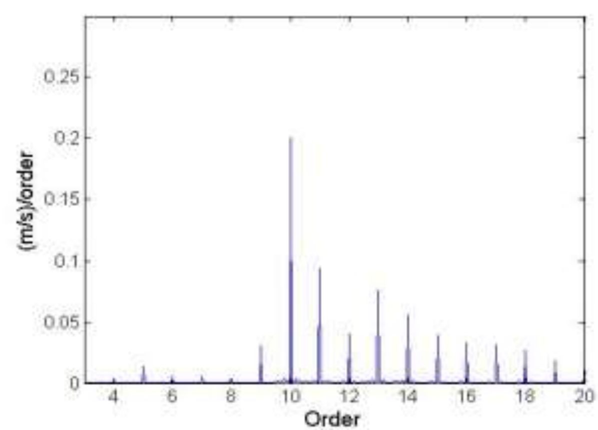
(a) FFT on 1st IMF for good condition



(b) FFT on 1st IMF for fault condition

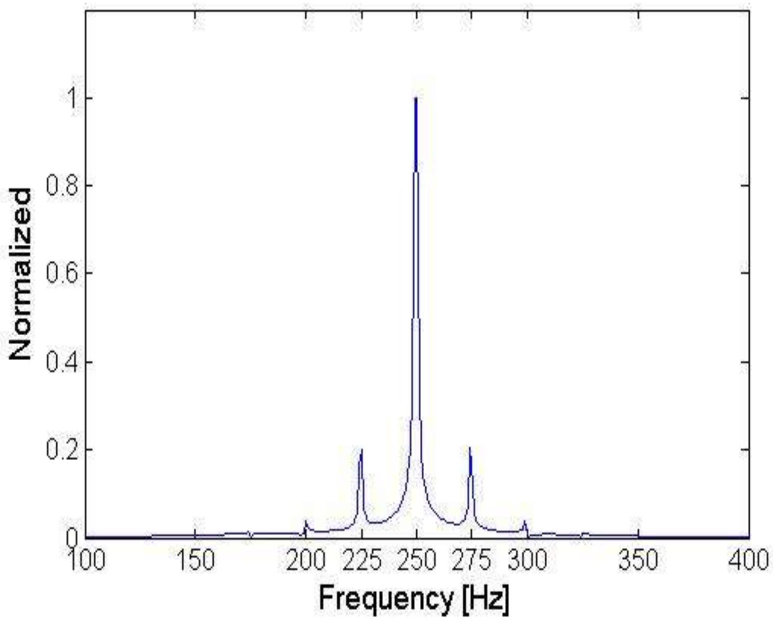


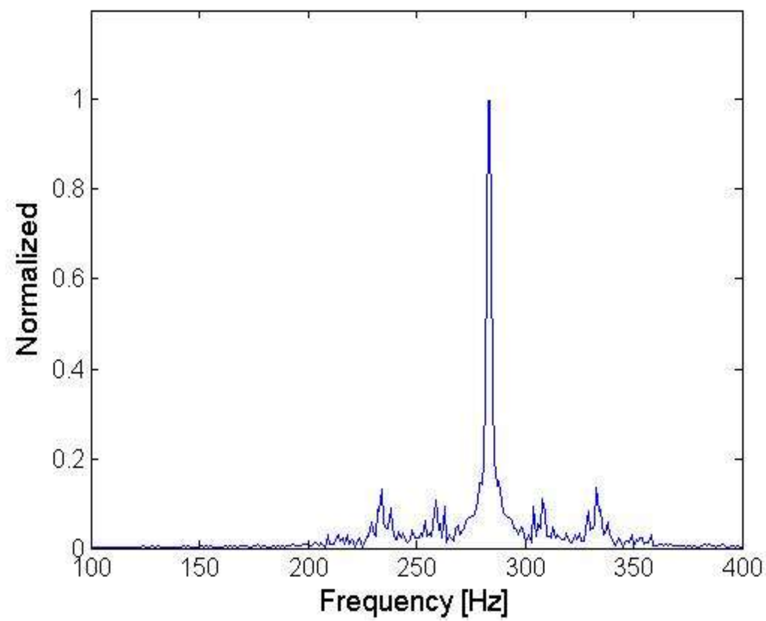
(c) Order tracking for good condition



(d) Order tracking for fault condition

Simulation studies
gear meshing model - results

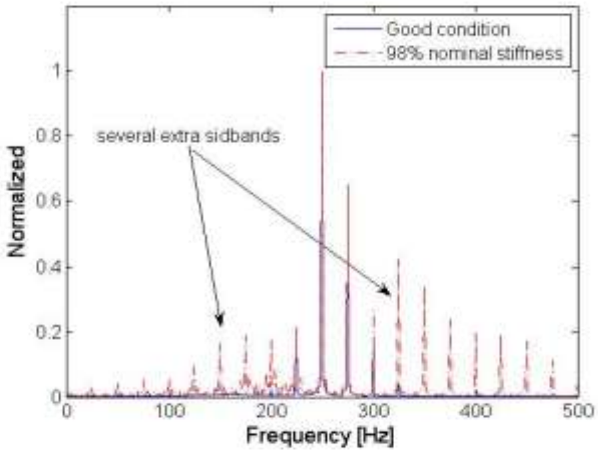




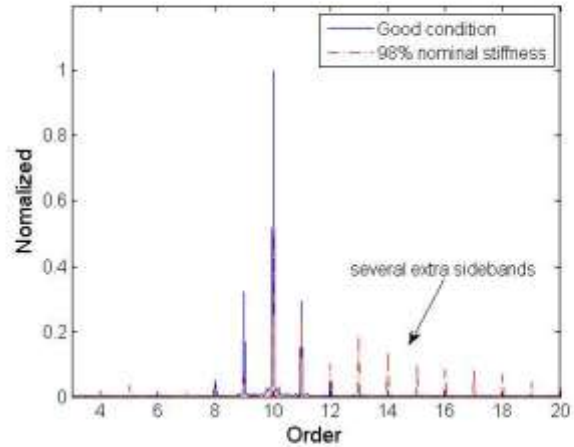
(a) 1st IMF good condition
S.V.: two clear sidebands
peak ratio 0.2
M.F.: 250 Hz

(b) 1st IMF fault condition
S.V.: more deformed sidebands
M.F.: 283 Hz

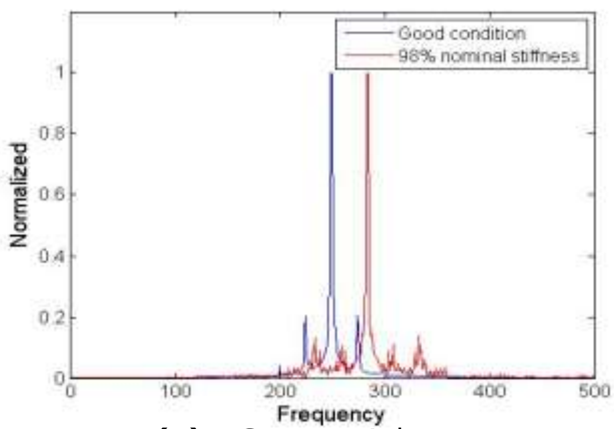
Simulation studies
gear meshing model - results



(a) Frequency domain 1st IMF

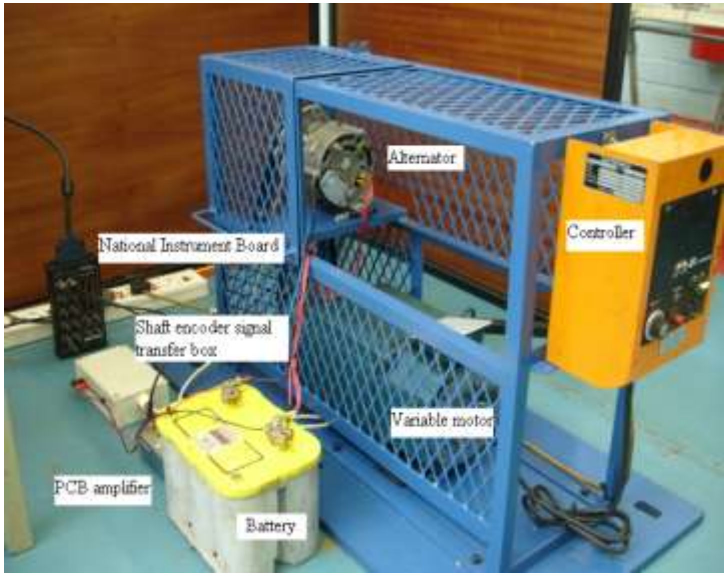


(b) order domain 1st IMF



(c) ICR on 1st IMF

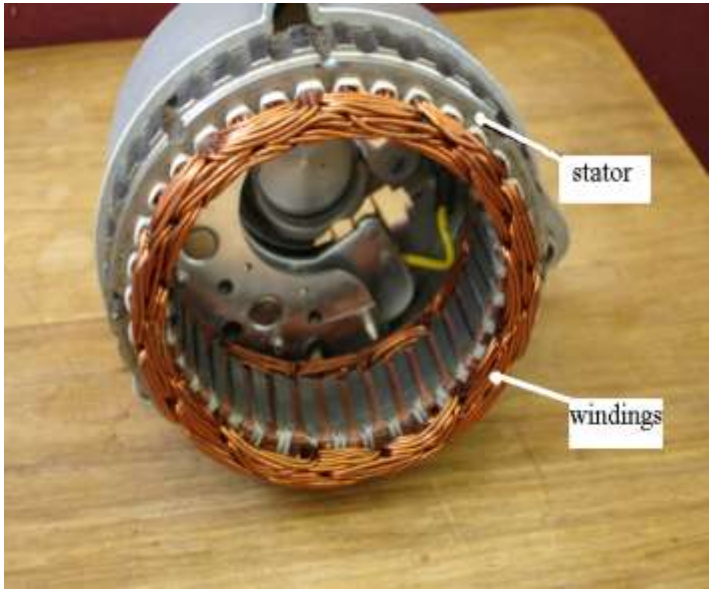
Experimental demonstration VKC-OT and IVK-OT



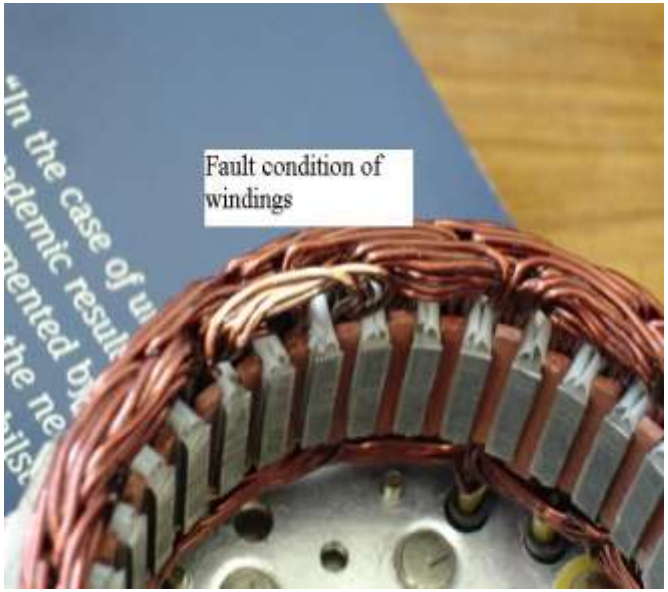
(a) Experimental setup

(b) Monitoring device

Experimental demonstration VKC-OT and IVK-OT

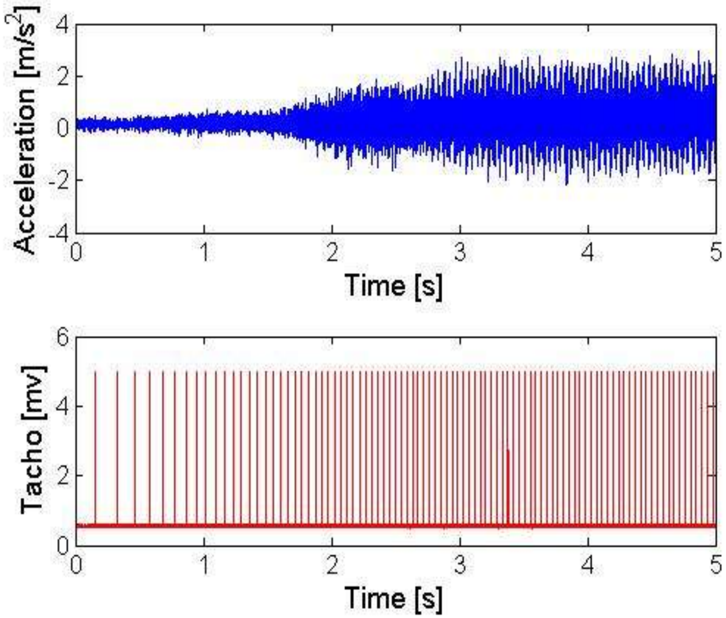


(a) Stator end winding

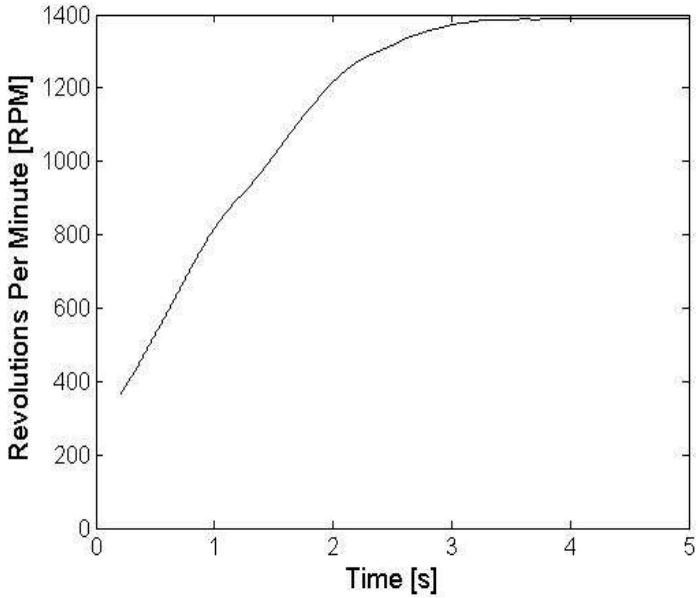


(b) seeded fault on winding

Experimental demonstration VKC-OT and IVK-OT

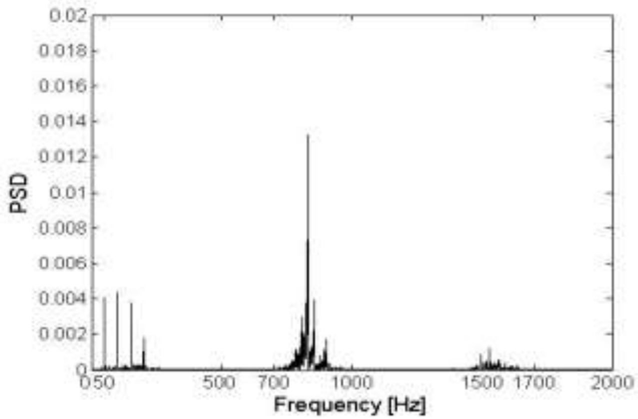


(a) Measured data

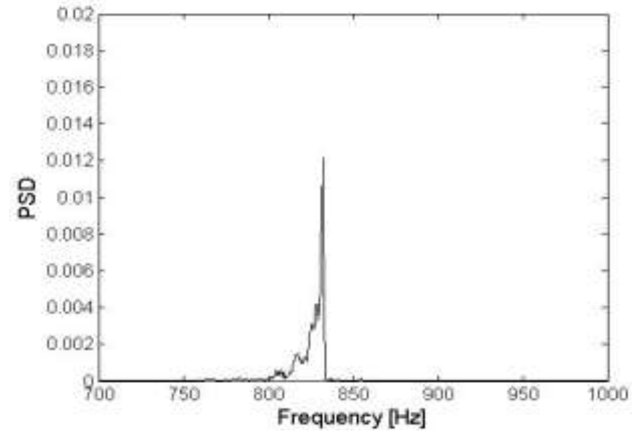


(b) RPM

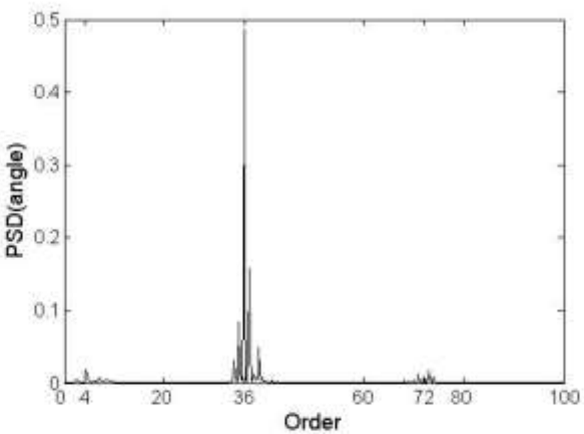
Experimental demonstration VKC-OT



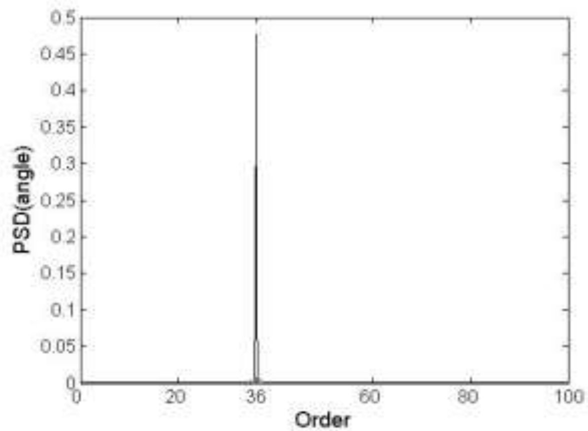
(a) PSD on raw data



(b) PSD on VKF-OT for 36^{th} order

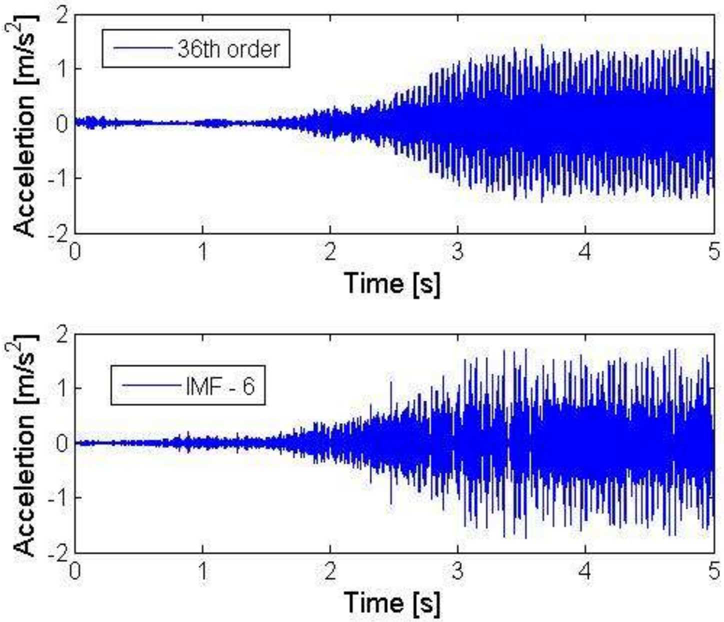


(c) PSD on COT data

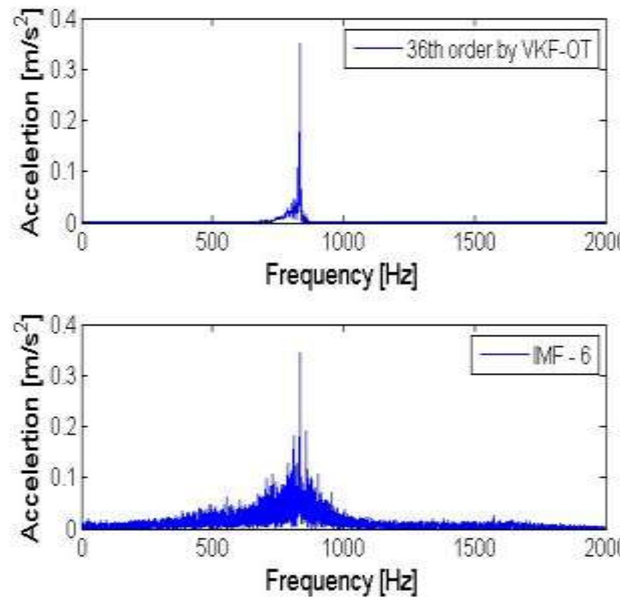


(d) PSD on VKC-OT for 36^{th} order

Experimental demonstration
IVK-OT

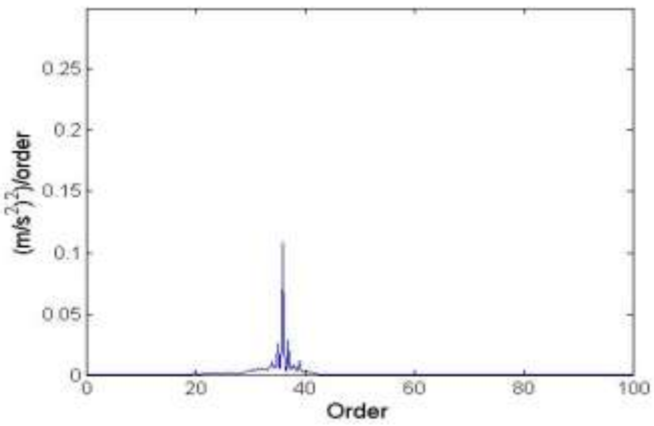


(a) Time domain waveforms

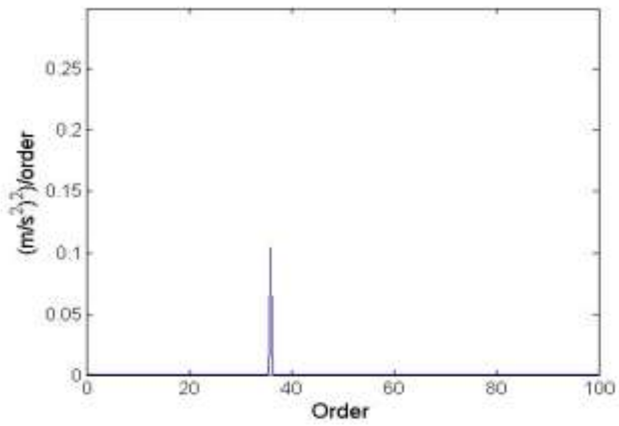


(b) Frequency domain spectrum

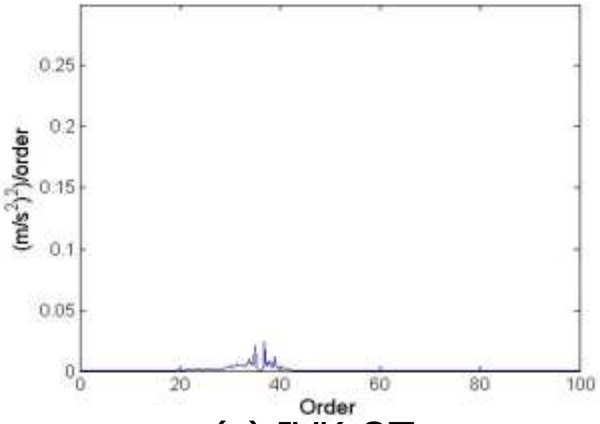
Experimental demonstration
IVK-OT



(a) 6th IMF

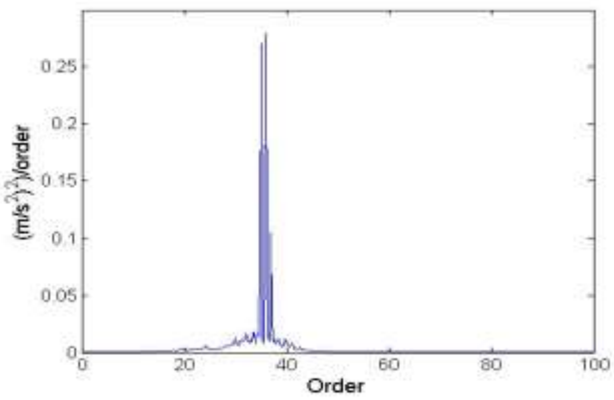


(b) Vold-Kalman filter for 36th order

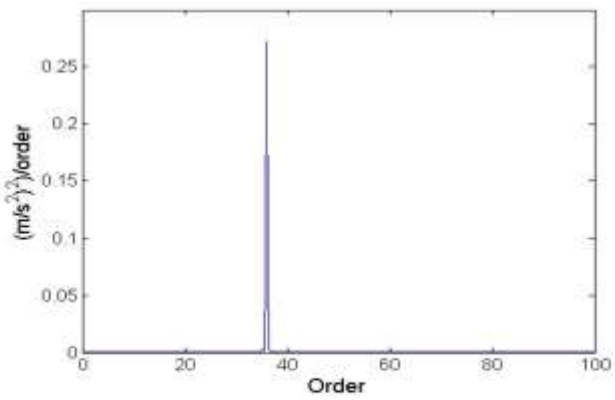


(c) IVK-OT

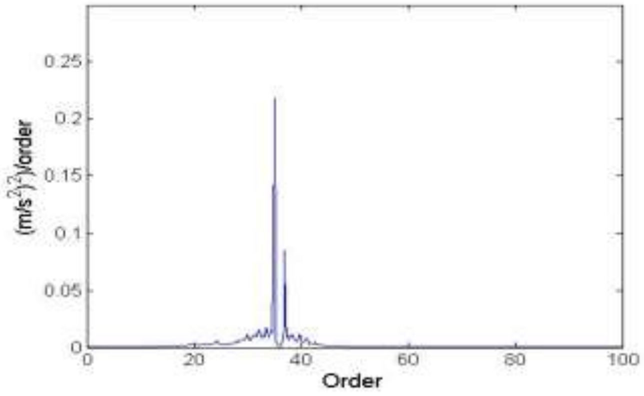
Experimental demonstration
IVK-OT



(a) 6th IMF

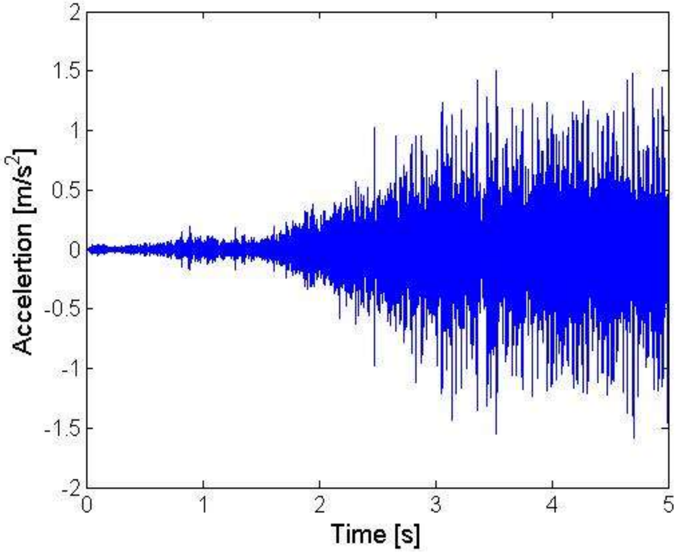


(b) Vold-Kalman filter for 36th order

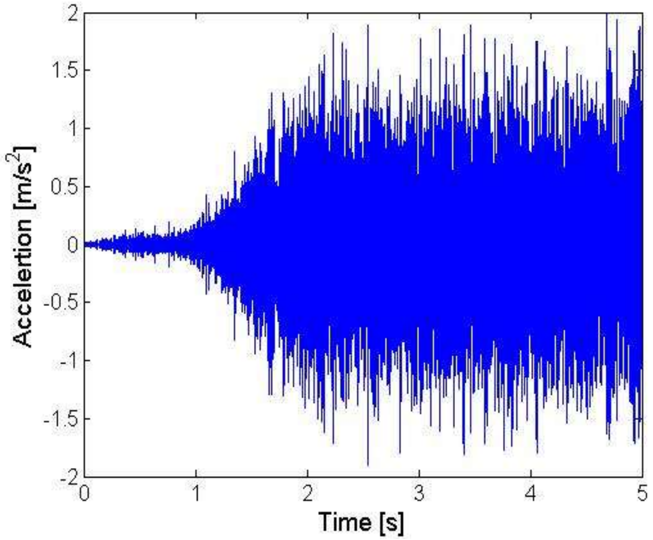


(c) IVK-OT

Experimental demonstration IVK-OT



(a) Good condition



(b) seeded fault condition

Experimental demonstration IVK-OT

Table 4.1 RMS for different signals

Signals	RMS - good	RMS - seeded fault	$\frac{(RMS(fault) - RMS(good))}{RMS(good)}\%$
IMF-6	0.3244	0.5758	77.5%
36^{th} order from IMF-6	0.1568	0.2686	71.3%
Residue	0.2770	0.4974	79.57%

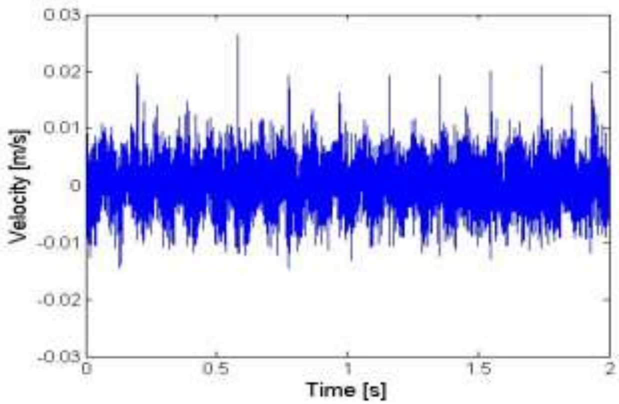
Experimental demonstration ICR

Experimental demonstration
ICR

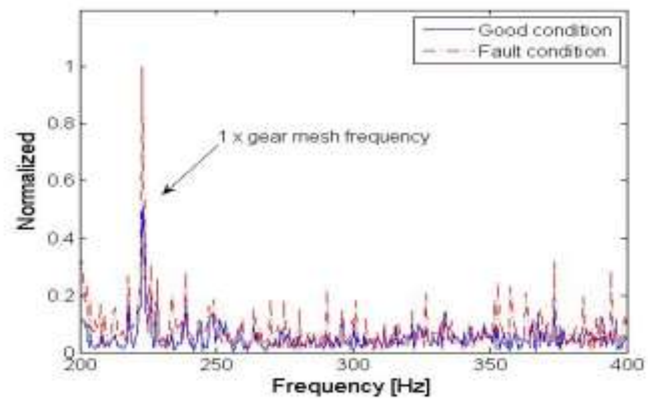
(a) Original status of drive gear

(b) Final status of drive gear

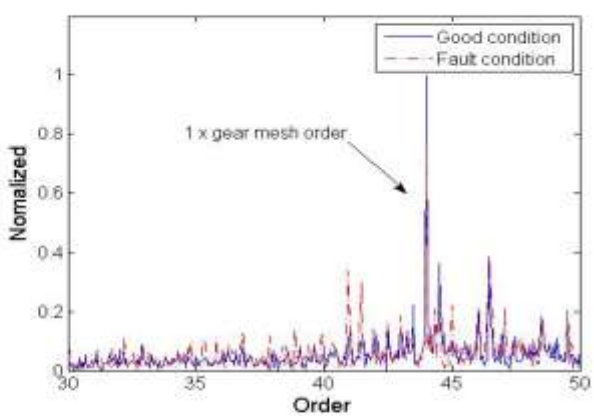
Experimental demonstration
ICR



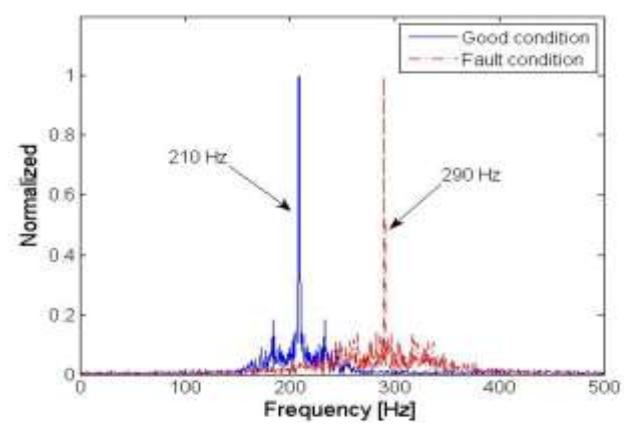
(a) Time domain signal (fault)



(b) zoomed in 1 x gear mesh frequency



(c) Zoomed in 1 x gear mesh order



(d) ICR result

Emphasis of three improved order tracking methods

Table 5.1 Emphasis of three improved order tracking approaches

	0rder vibrations	Vibrations that modulate orders
VKC-OT	√	
IVK-OT		√
ICR	√	√

Conclusions and future work

- The improved three order tracking methods have been developed.
- The development of order tracking methods will benefit the practice of order tracking in vibration monitoring of rotating machines.
- Different methods to achieve order tracking is welcomed, such as order tracking without rotational speed information.
- In-depth understanding each order tracking technique is also needed for the development of techniques.

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- South Africa