Measurements Versus Simulation

Kari Saine, 9-10.5.2023

Introduction

- Kari Saine, Noise & Vibration engineer, whole my carier I have worked at R&D department at Wärtsilä Vaasa Factory
- Graduated at Tampere University of technology 1986
- Be supervisor about 35 M.Sc or B.Sc thesis
- Published about 60 papers in international conferences or magazines
- Last 25 years kept this kind of vibration and noise courses

Contents

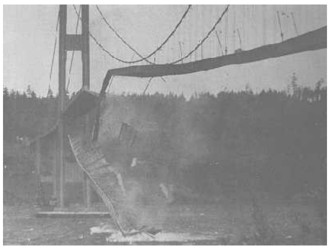
Background

- Since man began to build machines for industrial use and especially since motors have been used to power them, problems of vibration and isolation have engaged engineers.
- Early days the machines were heavy and slow-speed engines. Nowadays with finite element method (FEM) it is possible to optimize the structures. As consequence the natural frequencies of the structures have fallen down to the rotating speed of the engines.
- Gradually as vibration isolation and reduction techniques have become an integral part of the machine design, the need for accurate measurement and analysis of mechanical vibration has grown.
- A whole new technology of vibration measurement has been developed which is suitable for investigating modern highly stressed, high-speed machinery. What is possible today, was not possible 25 years ago.
- Measurements are one of most undervalued science today.

Tacoma bridge

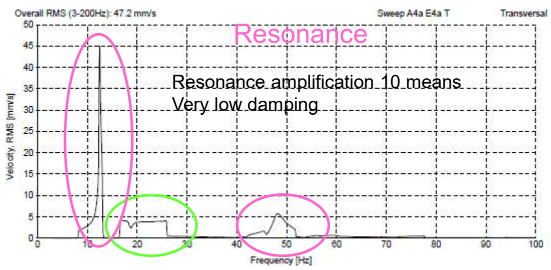
http://www.youtube.com/watch?v=3mclp9QmCGs

Tacoma bridge, 1.9 km, was collapsed
at November 7 1940, four months after opening
at wind speed 65 km/h

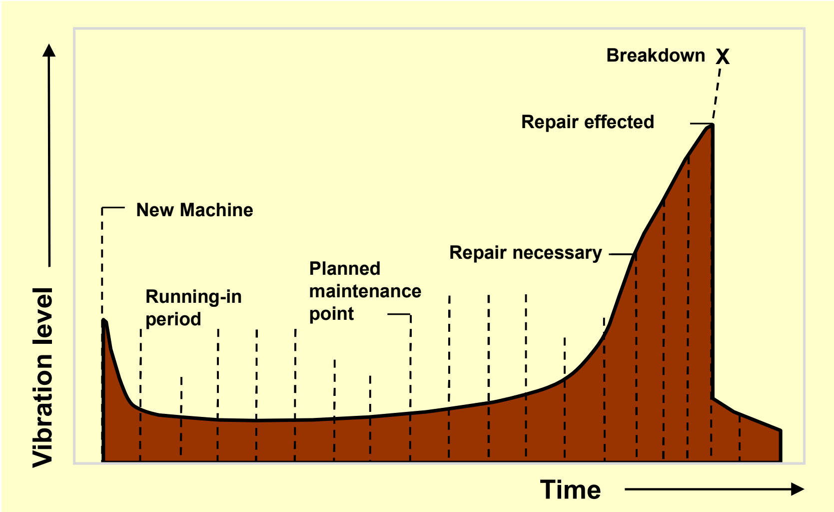


Resonance

– When a system is in resonance the excitation force has the same frequency as the natural frequency of the structure.
– A small change in the excitation frequency causes an increase/decrease in the system response or small forces can cause high vibration level. Most vibration problems are related to resonance phenomena.



Introduction to Vibration



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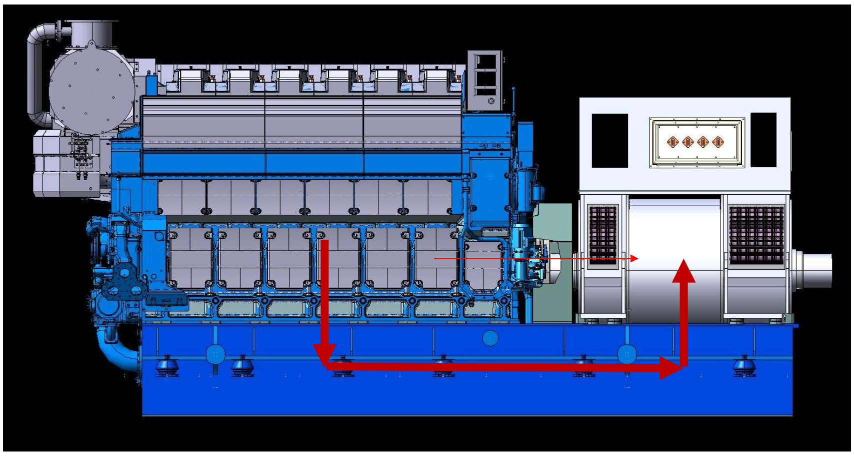
Aggregate



Aggregate W6L32 engine together with steel common base frame and alternator

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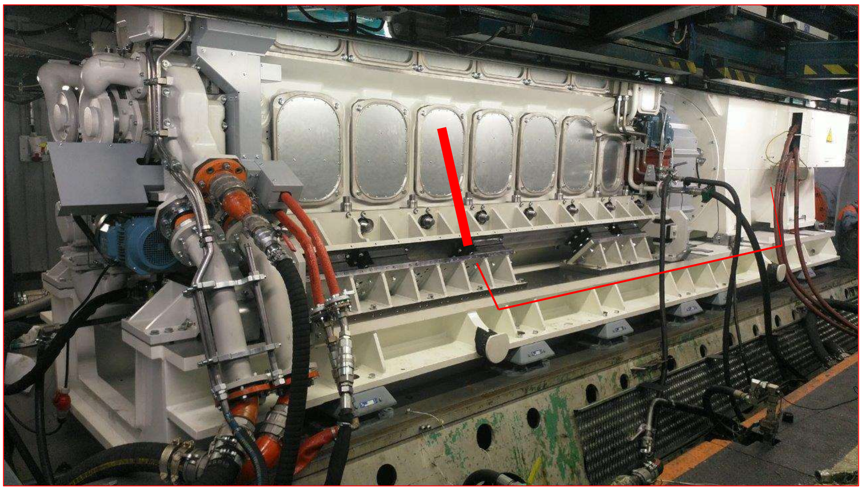
Double flexible aggregate



Rubber elements are eliminated 90% engine excitations when is used flexible mounted engine

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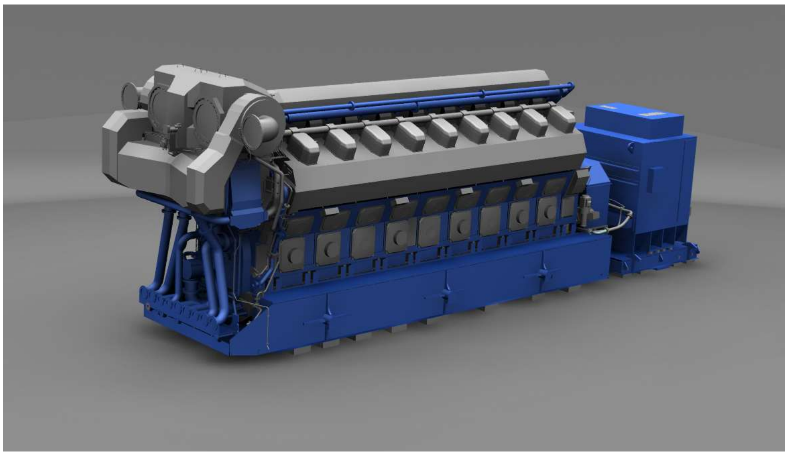
Back to Basic = New aggregate



Today is used separate engine frame. Now alternator can design as normal cases.

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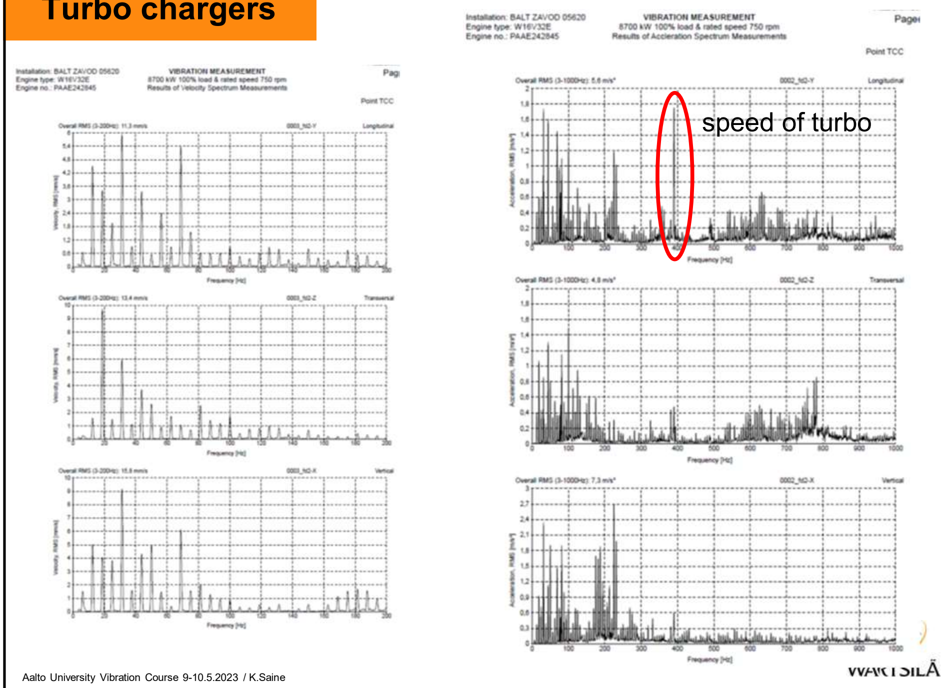
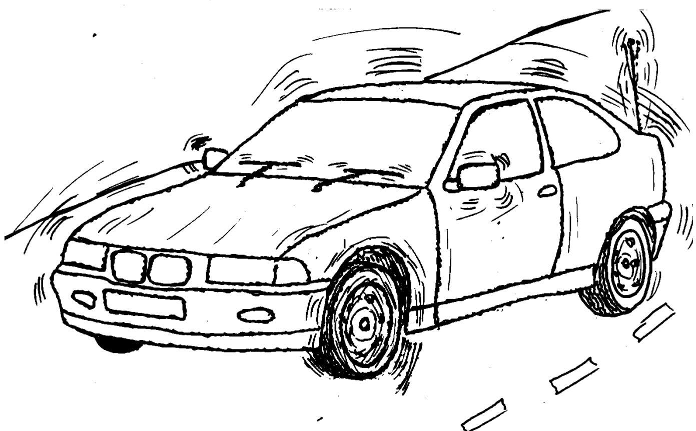
Turbo chargers



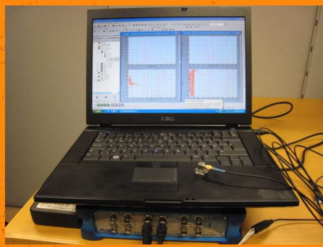
Introduction to Vibration



Tyre change.

Why car is shaking more when speed increase?

Vibration instruments



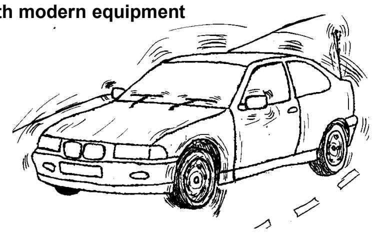
OROS – Measurement and Analysis Solutions

- Today multi channels FFT (Fast Fouries Transformation) analyzers are light, portable and very powerful instruments.
- 3D accelerometers are standard sensors. With these could be measured easy way up to 10 kHz at temperature 150 degree.
- The advance of the multi channels analyzers it is possible to measured mode shapes of the sturucture
- Today 8-channels analyzers are basic instruments, even 32 or 64 channels are quite common

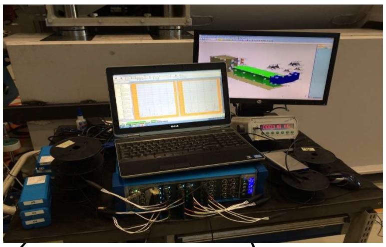
- Instruments
- Software
- Services

Vibration measurements & analyses

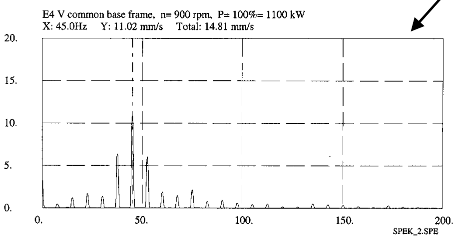
Evaluation of the vibration results with modern equipment



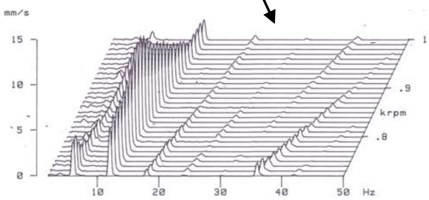
Hand-held meter and multi channels analyser



Vibration spectrum



Waterfall diagram



Measurement

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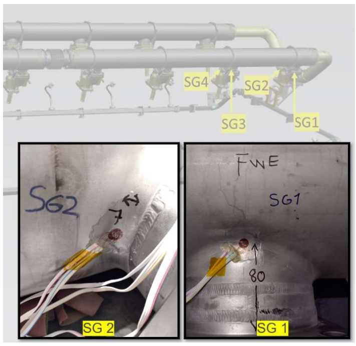
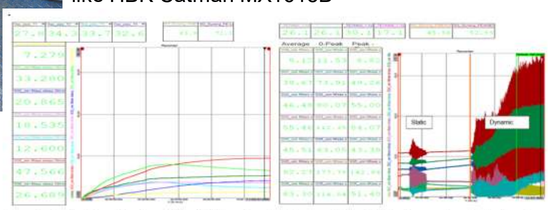
Stress measurements



With very small and powerful instrument could be measured both statical and dynamical stress levels, like HBK Catman MX1615B



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QuantumX Strain Gage Bridge Amplifier

Bridge module with universal inputs and unique channel density

- 16 universal **inputs** measure (Push-in, 8p)

Every single input supports

- Strain gage **full bridge** with 6 wire technology
- Strain gage **half bridge** with 5 wire technology
- Strain gage ¼ **bridge** in 3 or 4 wire configuration, **MX1615B**: 120 and 350 Ohm completion resistor inside **MX1616B**: 350 and 1000 Ohm
- internal shunt resistor (100 kOhm)
- Selectable excitation voltage: 0.5 / 1 / 2.5 or 5 V (DC or CF with 1200 Hz)
- Voltage +/- 15 V, differential
- PT100, Potentiometer, Resistance

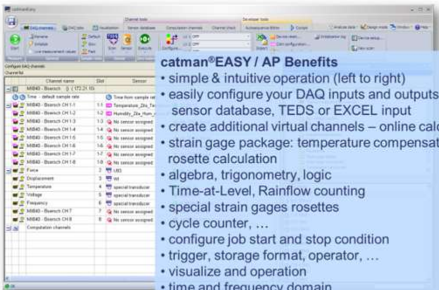
Data rates up to **20 kS/s** per channel (signal bandwidth up to 3 kHz)

16 plugs included

Easier than ever - one single cable

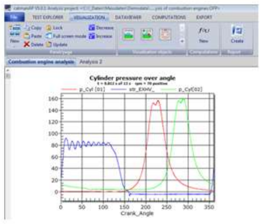
- Power distribution (1.5 A left and right of the powered module)
- Up to 5 m cable in between every module (12 in a row makes 60 m)
- Data transport from input to Data Recorder, PC or Gateway
- Highly time-sync'd with < 1 µs module to module (auto master)
- Real-time isochronous EtherCAT, voltage output or CAN bus

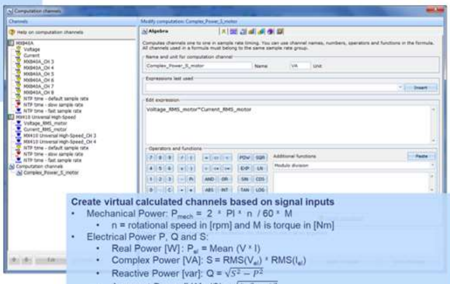
CATMAN - Software



catman®EASY / AP Benefits

- simple & intuitive operation (left to right)
- easily configure your DAQ inputs and outputs via sensor database, TEDS or EXCEL input
- create additional virtual channels – online calculation
- strain gage package: temperature compensation, rosette calculation
- algebra, trigonometry, logic
- Time-at-Level, Rainflow counting
- special strain gages rosettes
- cycle counter, …
- configure job start and stop condition
- trigger, storage format, operator, …
- visualize and operation
- time and frequency domain
- push button to operate (start, stop, panels)
- automate by script
- create report in word or pdf format





Create virtual calculated channels based on signal inputs

- Mechanical Power: P_{mech} = 2 * PI * n / 60 * M
  - n = rotational speed in [rpm] and M is torque in [Nm]
- Electrical Power P, Q and S:
  - Real Power [W] : P_{el} = Mean (V * I)
  - Complex Power [VA]: S = RMS(V_{el}) * RMS(I_{el})
  - Reactive Power [var]: Q = $\sqrt{S^2 - P^2}$
  - Apparent Power [VA] : |S| = $\sqrt{P_{el}^2 + Q^2}$
- Power Factor cos φ = P_{el} / S
- Overall Efficiency: η = P_{mech} / P_{el}

OROS - Portable Noise & Vibration Analyzers

Made for the Field
- 2 to 64 channels
- Portable
- Rugged
- Real-time Analysis

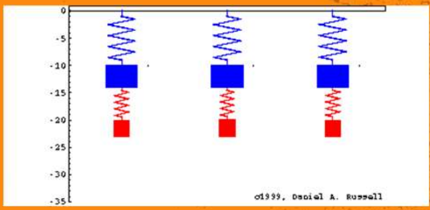
Flexible
- Online & Post Analysis
- Signal Conditioning
- Multi-Analysis
- Remote Access
- PC Free Operation
- Cascadable: 320+ ch.
- Customization

Accurate
- DSP-based
- 24 Bit - 40 kHz
- ± 40V input range
- ±0.02 dB / ±0.02°

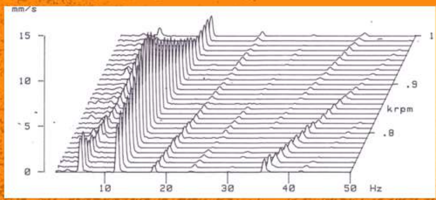
Services
- Customer Care Department
- Expertise and Assistance
- Premium Contracts
- Training
- Customized Applications

OROS Software Designed for your Application

- Unique software platform
  - Recording
  - FFT
  - Time Domain Analysis
  - Monitoring
- Rotating Analysis
  - Rotataing Speed Measurements
  - Envelope Demodulation
  - Constant Band Tracking
  - Synchoronous Order Analysis
  - Turbo machinery Vibration
  - Torsion
  - Balancing
  - Waterfall, data Buffer
- Structural Analysis
  - Operating Deflection Shape
  - Modal Analysis
  - FRF and Cross-Spectrum Acquisition
  - Advanced Swept Sine
- Acoustical Analysis
  - 1/n Octave Analysis
  - Overall Acoustics: Levels & Profiles
  - Sound Power
  - Sound Intensity
  - Sound Mapping and Source Localization
- Stress measurements



Basic Theory



What is vibration?

Noise and vibration in the environment or in industry are caused by particular processes where dynamic forces excite structures.

In any given situation there are always three factors, which have been examined before solving noise/vibration phenomena's

*** Source**	**- where the dynamic forces are generated**
*** Path**	**- how the energy is transmitted**
*** Receiver**	**- how much noise/vibration can be tolerated**

Introduction to Vibration

DISPLACEMENT (mm) relevant at low frequency part of the spectrum. Frequency range up to 30 Hz. Due to Mass forces/resilient mounting system;

VELOCITY (mm/s) corresponds to a given energy level of the system. Typical frequency range 10-300 Hz. It is recommended to use this. It is related to stress level of the measured component.

ACCELERATION (m/s²) measurements are weighted towards high frequency vibration components, used where the frequency range of interest cover high frequencies range from 100 Hz up: turbochargers and electronic components or little mechanical components rigidly connected to engine structure. It is related to force level of the measured component.

The relationship between displacement, velocity and acceleration amplitudes can be described by formulas including vibration frequency and time.

Introduction to Vibration

Relationship between displacement x (t), velocity v (t) and acceleration a (t) amplitudes can be described by derivation or integration.

$$x(t) = X \cdot \sin(\omega \cdot t + \varphi)$$

$$v(t) = \frac{dx(t)}{dt} = \omega \cdot Xp \cdot \cos(\omega \cdot t) = V_p \cdot \cos(\omega \cdot t)$$

$$a(t) = \frac{dv(t)}{dt} = \frac{d^2x(t)}{dt^2} = -\omega^2 \cdot Xp \cdot \sin(\omega \cdot t) = -A_p \cdot \sin(\omega \cdot t)$$

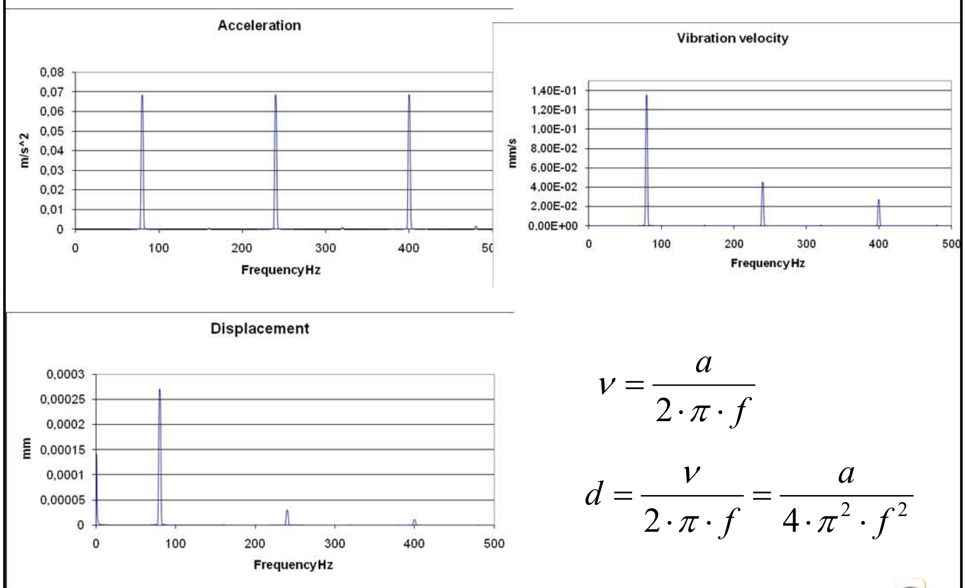
speed

Introduction to Vibartion

AMPLITUDES

- Velocity
- Acceleration
- Displacement
- Strain
- Torque
- Pressure
- Power Spectrum Density
- Energy Spectrum Density
- etc ...

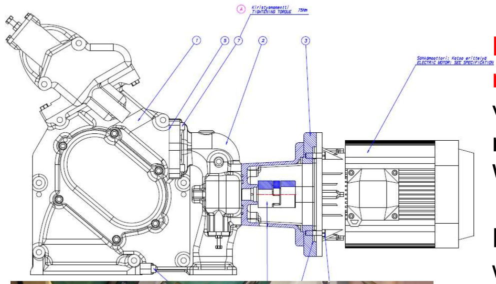
Relation, acceleration, velocity and displacement



$$v = \frac{a}{2 \cdot \pi \cdot f}$$

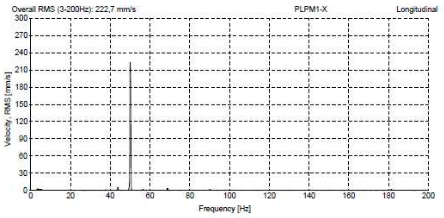
$$d = \frac{v}{2 \cdot \pi \cdot f} = \frac{a}{4 \cdot \pi^2 \cdot f^2}$$

Pre lubricating pump



During our standard vibration measurements were measured very high vibration levels on the motor of the lube oil pump for W8L32 engine

Firing frequency, order 4, 50 Hz with amplitude over 200 mm/s !



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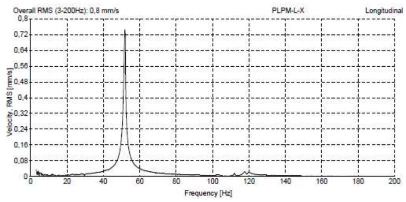
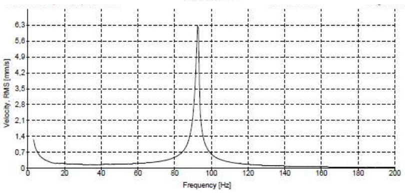
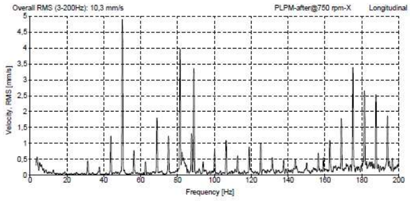
Pre lubricating pump







The reason for high vibration level was the natural frequency of the cantilever, which was 50 Hz (resonance).

After adding the extra support the natural frequency increase to 90 Hz.

In consequence the vibration levels dropped to the tenth, from 200 mm/s to 20 mm/s.

Totally this took nine days.

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What is vibration?

Three significant components of vibration technique are:

AMPLITUDE
FREQUENCY
PHASE

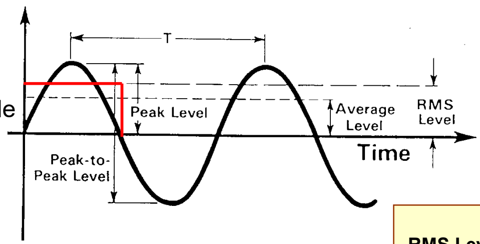
AMPLITUDE is amount of vibration,

FREQUENCY is its repetition,

and PHASE is relationship of one vibration to another.

Quantifying the vibration levels

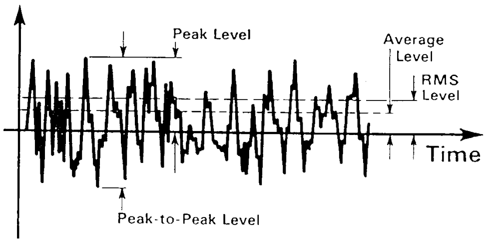
The area of rectangle and sinusoidal are same



RMS Level = $\sqrt{\frac{1}{T}\int_0^T x^2(t)dt}$

Average Level = $\frac{1}{T}\int_0^T |x| dt$

peak ration rms



Quantifying the vibration level

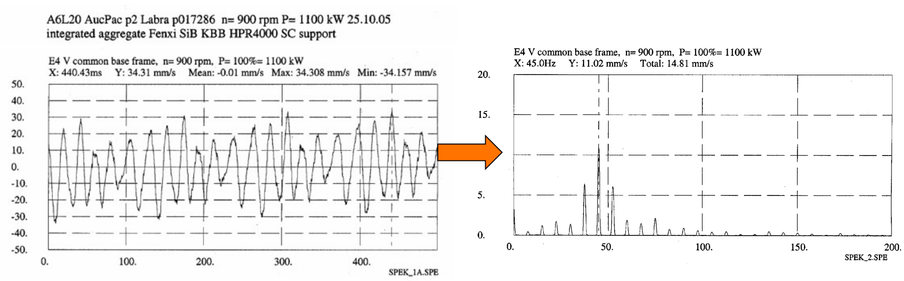
The vibration amplitude can be quantified in a number of ways: peak-peak level, the peak level, the average level, the RMS (root mean square) level.

The PEAK values indicate only the maximum level, no account is taken of the time history of the wave.

The AVERAGE value does take the time history of the wave into account, but has no direct relationship with any useful physical quantity.

The RMS value is the most relevant measure of amplitude because it both takes the time history of the wave into account and gives an amplitude value which is directly related to the energy content, and therefore the destructive potential of the vibration.

Time signal versus frequency analysis



- Measured time signal doesn't give very much useful information or it is very difficult to study. After Fourier transformation better knowns FFT you will get spectrum which tells frequency and amplitude of the measured structure (time signal).

Fourier analysis

A Frenchman Jean-Baptiste Joseph Fourier developed Fourier analysis year 1807 during examining heat contractility of a solid structure.

At first he developed theory of Fourier series which he later expanded to Fourier integral.

Fourier transform gives the mathematical connection between time and frequency, and vice versa, and given a time signal allows calculation of the spectrum.

Today we are calling these mathematic tools as FOURIER ANALYSIS by the inventor.

The FAST FOURIER TRANSFORM (FFT, 1967) is merely an efficient means of calculating a Discrete Fourier Transform (DFT). FFT analyzers are widely used in analysis of vibration.

Time domain and frequency domain

Fourier Transform gives the mathematical connection between time and frequency and vice versa. Any periodic curve, no matter how complex, may be looked upon as a combination of a number of pure sinusoidal curves with harmonically related frequencies.

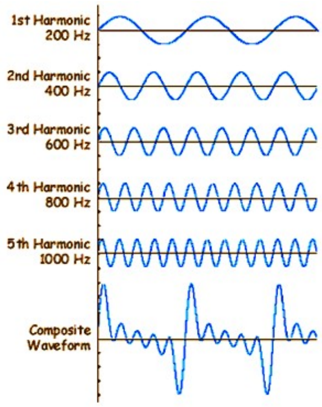
$$F(t) = X_0 + X_1 \cdot \sin(\omega \cdot t) + X_2 \cdot \sin(2 \cdot \omega \cdot t) ...... + X_n \cdot \sin(n \cdot \omega \cdot t)$$
$$+ Y_1 \cdot \cos(\omega \cdot t) + Y_2 \cdot \cos(2 \cdot \omega \cdot t) + ... + Y_n \cdot \cos(n \cdot \omega \cdot t)$$

or

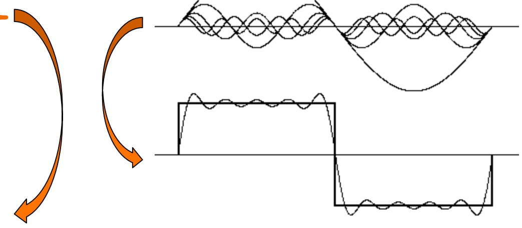
$$F(t) = X_0 + \sum_{n=1}^{\infty} (X_n \cdot \sin(n \cdot \omega \cdot t) + Y_n \cos(n \cdot \omega \cdot t))$$

Time domain and frequency domain

•*Harmonics?*

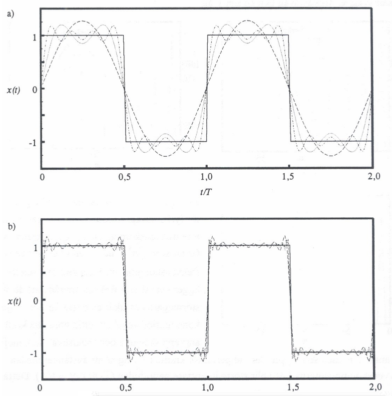


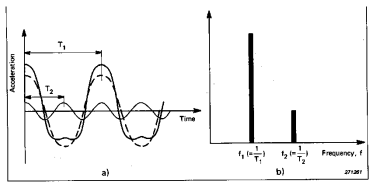
Harmonics components



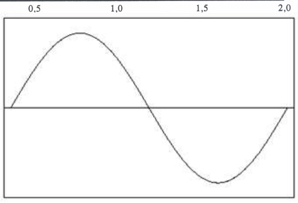
Synthesis

Fourier analysis

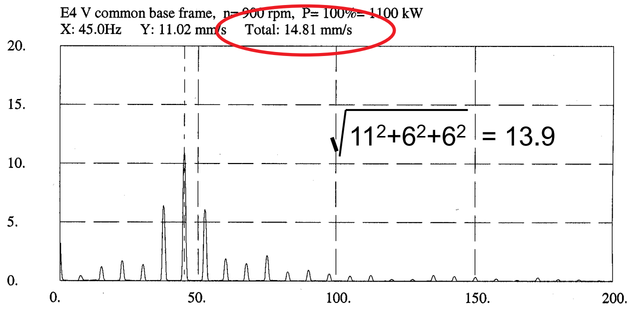




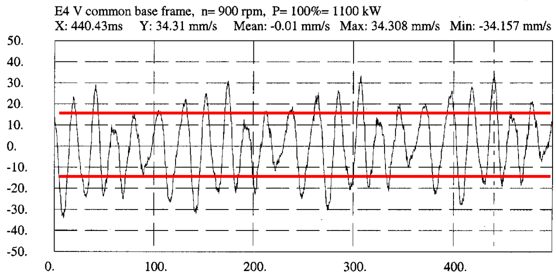
Square wave



Spectrum versus overall level



All peaks to the power of 2 and sum square root



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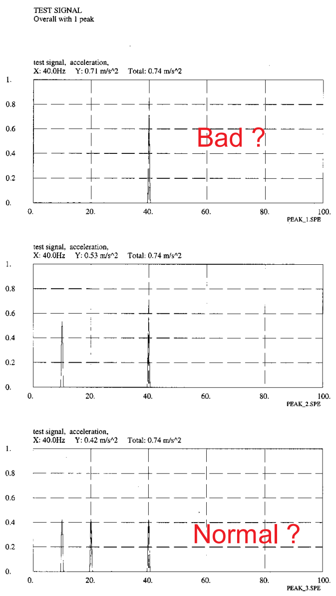
Overall vibration levels



$$\text{Total RMS} = \sqrt{\sum_{i=1}^{n} X_i^2}$$

The influence of the peaks and overall vibration levels.

The overall levels same, but three different states

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Time domain

Calculation of four different time signals, where amplitudes and frequencies are constant, only phases are changing.

$$F(t) = \sum_{n=1}^{3} X_n \cdot \sin(\omega_n \cdot t + \varphi_n)$$

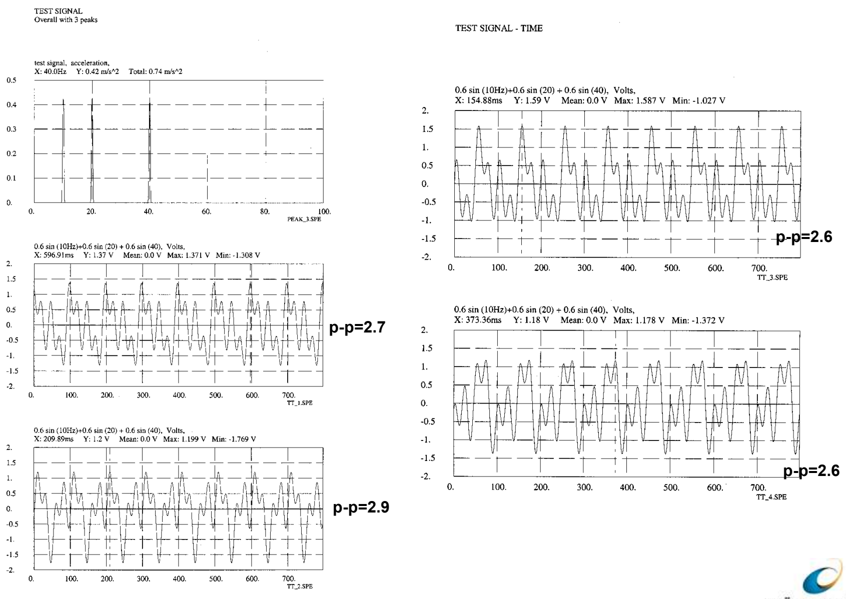
where ω = angular frequency
t = time
φ = phase

$\omega_1 = 10$ Hz , $\omega_2 = 20$ Hz , $\omega_3 = 40$ Hz , $X_{1,2,3\ (peak)} = 0.6$ V

	ω_1	ω_2	ω_3
1)	0	0	0
2)	-90	-45	0
3)	-180	-35	90
4)	-145	-60	0

$$\text{Total RMS} = \sqrt{\sum_{n=1}^{3} X_n^2}$$

Time signal versus spectrum



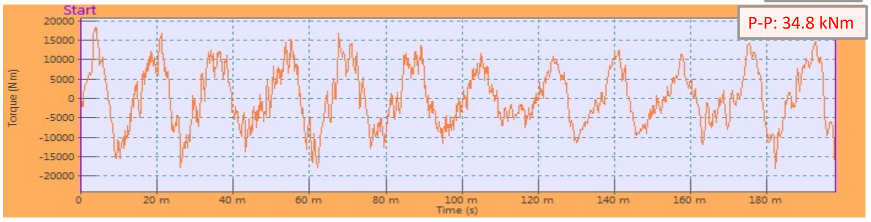
W20V32F camshaft

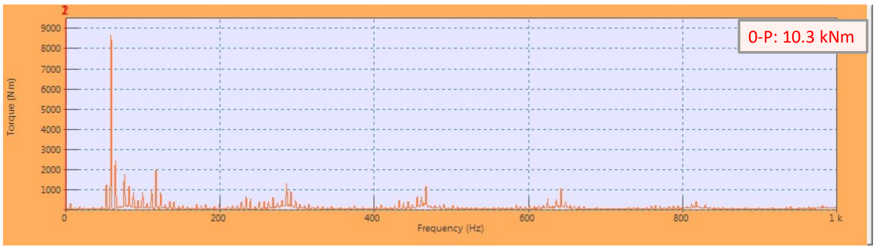
Installation: PPW20V32F Engine
Engine no: PAAE234059
Engine Type: W20V32F

Torsional Vibration Time signal & FFT

Cam shaft torque at 700 rpm at 100% load 9200kW

A-Bank





Torque measurement for W20V32F on A-bank

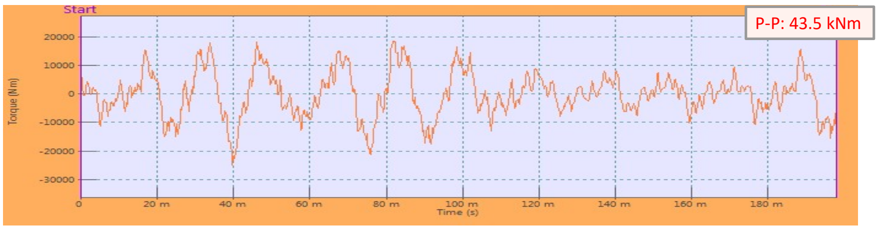
W20V32F cmashaft

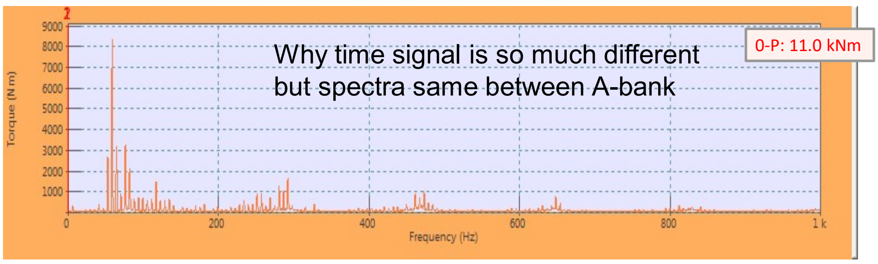
Installation: PPW20V32F Engine
Engine no: PAAE234059
Engine Type: W20V32F

Torsional Vibration Time signal & FFT

Cam shaft torque at 700 rpm at 100% load 9200kW

B-Bank





Torque measurement for W20V32F on B-bank.

Wärtsilä Vibration Standard

Aalto University Vibration Course 9-10.5.2023 / K.Saine

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Measurements

Frequency bands and measurement units

- **All components are measured in rms velocity units (mm/s) using frequency band 0 – 200 (300) Hz.**
- **Turbochargers are measured also in rms acceleration units (m/s^2) using frequency band up to the speed of the turbocharger (400 – 1000 Hz).**
- **For the electrical components velocity spectra up to 200 Hz and acceleration spectra up to 1 kHz**

Measurement video

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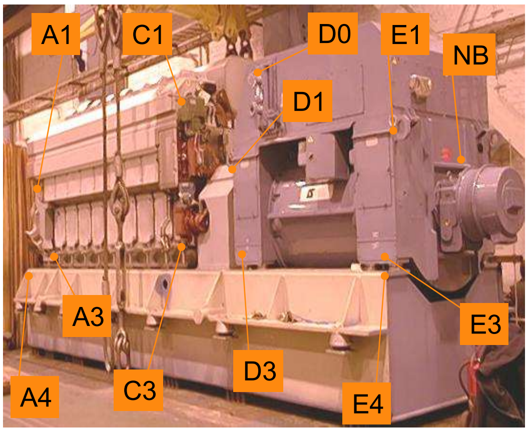
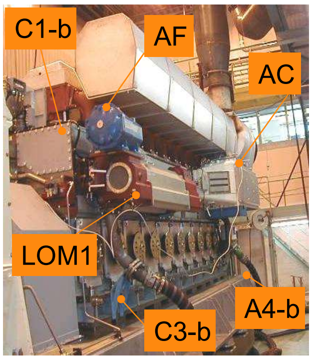
Vibration measurement points for W32





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Abbreviations

The measurement points will be formed by words' initial letters, like

TCC	TC compressor	TCT	TC turbine
TCF	TC filter	TCS	TC suction branch
TF	turbo feet	TBR	turbo bracket
ACH	air cooler housing	CAC	charge air cooler
LOM	lube oil module	AF	automatic filter
CF	centrifugal filter	Wecs	wecs
GP	gauge (instrument) panel	PLP	pre lubricating pump
CH	cylinder head	IP	injection pump
WG	waste gate		

WG-P means Waste Gate Actuator
PLP-C means Pre Lubricating Pump Control valve

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Vibration measurements

Installation: Fincantieri 6251
Engine type: W12V32D; ABB TPS 61 (AF)
Engine no.: PAAE274333

OVERALL VIBRATION LEVELS
Output 5760kW; 720rpm
Velocity data at 100% load & 720rpm

Overall RMS Velocity [mm/s], 3-200 Hz

Point	Longitudinal	Transversal	Vertical	Point	Longitudinal	Transversal	Vertical
A1	2.3	2.8	3.8	A1-b	2.3	2.8	4.3
A3	1.9	4.6	3.0	A3-b	2.2	4.6	3.4
A4	2.7	5.7	4.4	A4-b	3.3	5.7	4.8
B3	2.1	4.7	5.1	B3-b	2.6	5.8	5.3
B4	3.1	5.1	5.1	B4-b	3.0	5.9	5.0
C1	2.3	4.1	7.8	C1-b	2.7	4.1	6.7
C3	2.0	6.8	4.2	C3-b	2.6	6.6	3.6
C4	2.7	7.2	3.5	C4-b	2.6	7.0	3.7
D0	7.1	10.5	5.4	D0-b	5.7	9.9	4.7
D1+	6.3	9.7	5.0	D1+-b	4.4	9.7	4.7
D1	5.3	4.7	4.2	D1-b	4.1	4.8	4.6
D4	2.4	2.6	3.7	D4-b	2.4	2.6	3.9
E0	7.5	7.3	5.6	E0-b	6.0	7.3	4.9
E1+	6.3	7.1	5.4	E1+-b	4.3	6.9	5.1
E1	5.3	4.8	5.4	E1-b	4.4	4.4	4.4
E4	2.8	3.9	4.8	E4-b	2.4	4.2	4.0
DB	5.3	3.6	2.6	NB	6.3	4.6	3.3
LOM-a	10.8	17.4	8.0	LOM-b	9.0	17.7	8.7
Gov	9.2	10.4	8.3	TG	6.6	6.8	5.6
OMD	14.7	9.1	7.0	MC	3.5	16.7	2.9
AF	19.2	24.5	12.4	CF	24.8	21.4	18.0
WG-pos	22.8	11.8	11.5	WG-actuator	23.3	21.5	9.7
ACH	4.4	7.4	7.2	ACH-b	6.2	7.1	7.9
TCC	32.8	9.6	15.7	TCC-b	24.4	16.1	8.2
TCF	20.4	30.9	36.0	TCF-b	15.5	25.9	25.6

Engine no.: PAAE274333 Acceleration data at 100% load & 720rpm

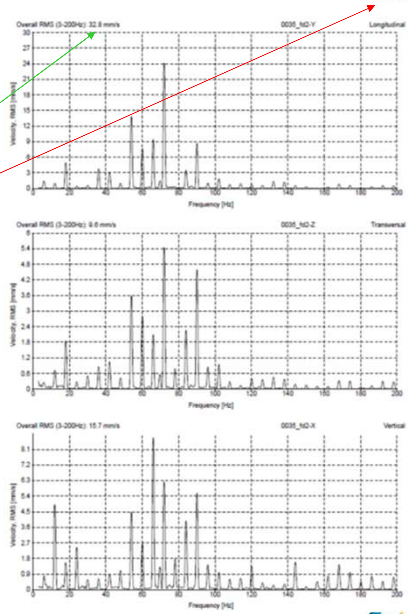
Overall RMS Acceleration [m/s²], 3-1000 Hz

Point	Longitudinal	Transversal	Vertical	Point	Longitudinal	Transversal	Vertical
TCC	17.5	5.8	10.2	TCC-b	12.1	8.3	4.6
TCF	11.7	18.1	19.4	TCF-b	9.6	14.3	13.4

Installation: Fincantieri 6251
Engine type: W12V32D; ABB TPS 61 (AF)
Engine no.: PAAE274333

VIBRATION MEASUREMENT
Output 5760kW; 720rpm
Velocity data at 100% load & 720rpm

Point TCC



Part 5 - Flexible mounting

Why flexible mounting

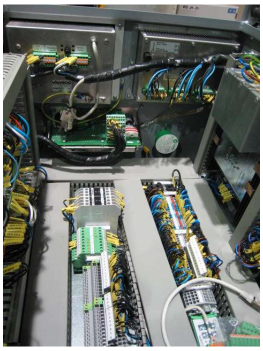
The electrical box mounted on large diesel engine contains many sophisticated components.

Excitations from engine have many strong frequency components that may destroy the electric box.

Hence it must be isolated from the engine excitations.

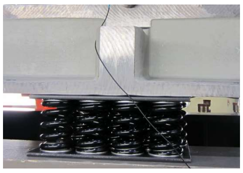
it is very important to select the right isolator for an application.

Main cabinet in resonance



Flexible mounted aggregate or main engine

- The purpose of flexible elements either steel springs or rubber elements is to minimize the energy transmissions from engine to surrounding but ALSO vice versus (earthquake).
- This means that the ground can be desinged according to statical load.
- It is very important that all the outcoming pipelines have installed with flexible elements



Vibration Isolation

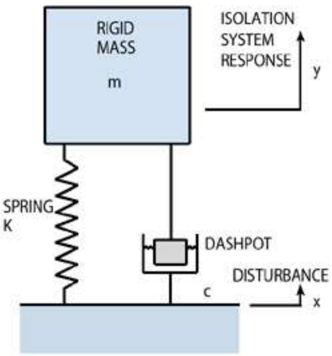
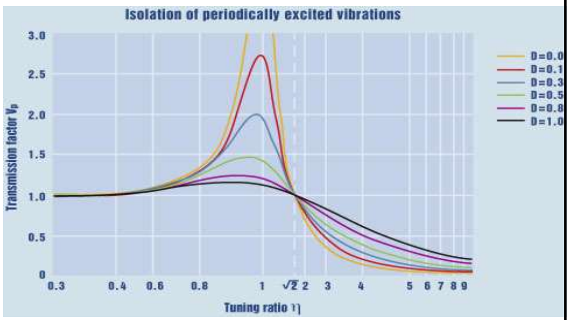


FIGURE 42.1
Typical Isolator Represented as a Mass, Spring and Dashpot



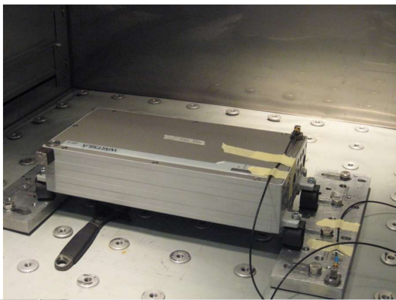
Tuning ratio = Excitation Freq/ Natural Freq

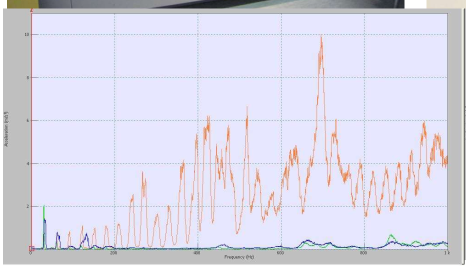
Transmission Factor = Amplitude of mass/ Amplitude of frame

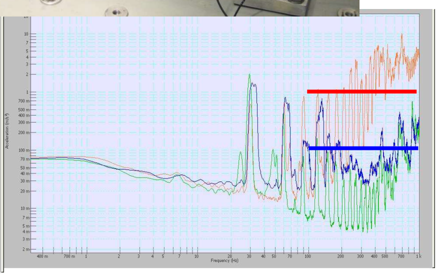
Natural Frequency = $\sqrt{\dfrac{k}{m}}$

Isolation Parameters = Stiffness of isolator, mass of box, engine excitation and damping

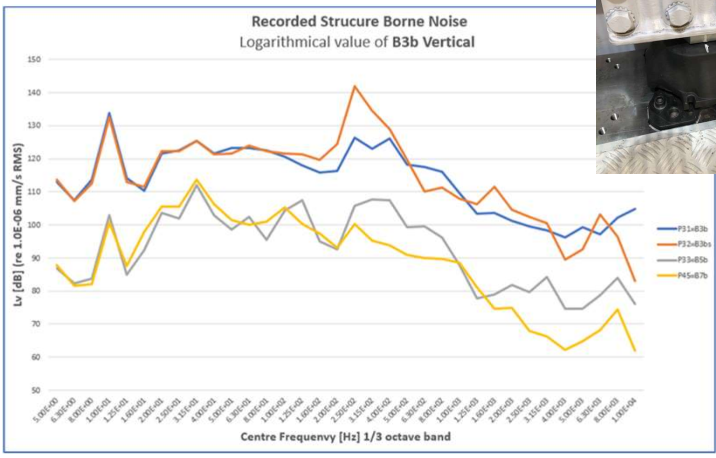
Flexible mounting – Halt test







Structure Borne Noise



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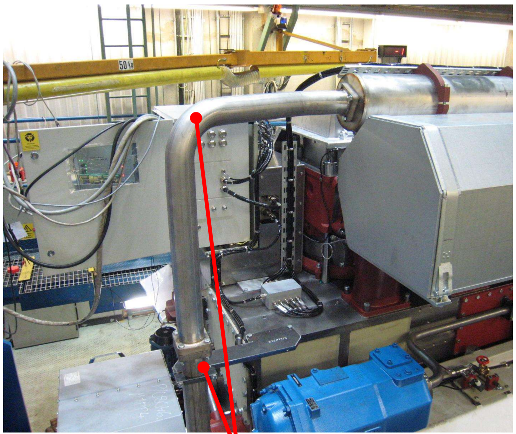
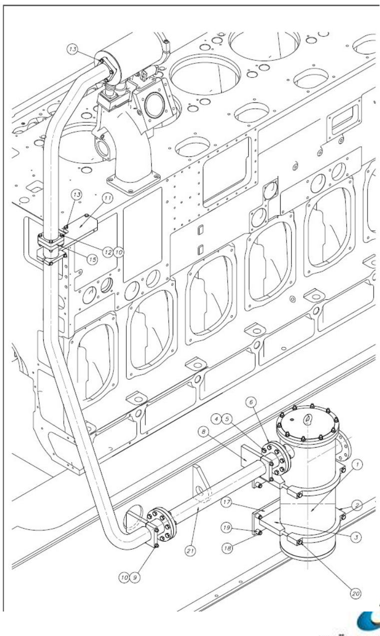
Gas pipe



Measurement points

Vibration spectra



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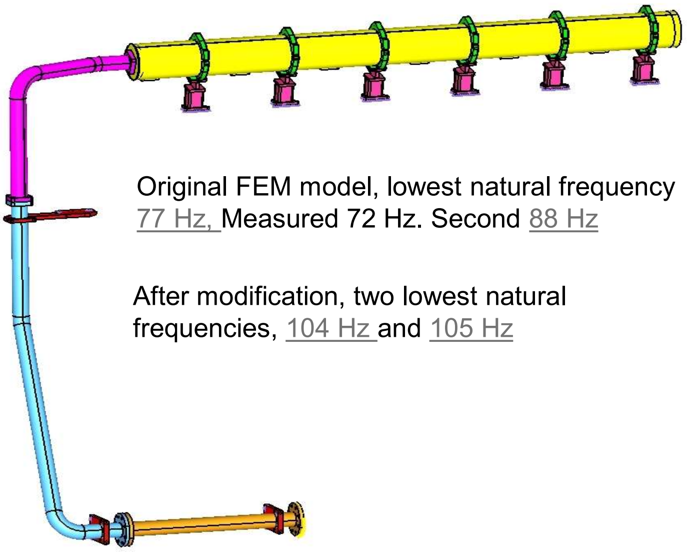
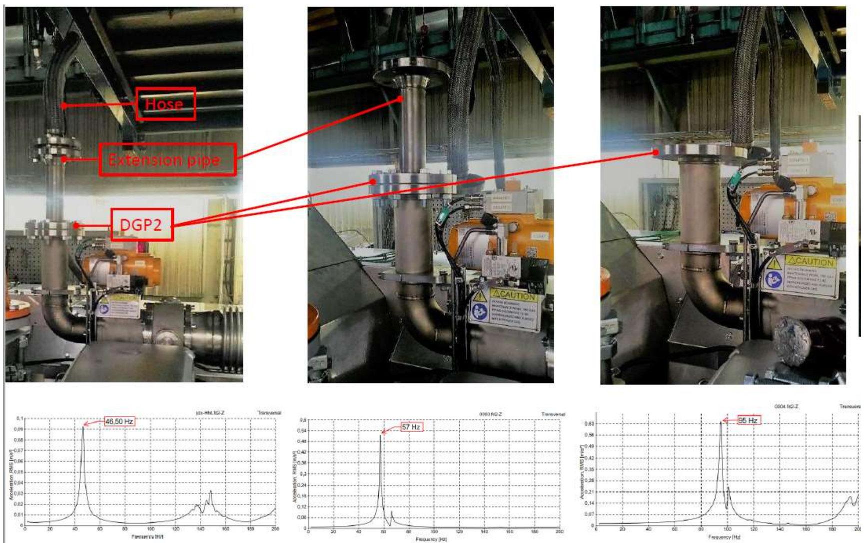
Gas pipe - FEM



Original FEM model, lowest natural frequency 77 Hz, Measured 72 Hz. Second 88 Hz

After modification, two lowest natural frequencies, 104 Hz and 105 Hz

De-gassing pipe – influence of extra mass (pieces)



Point DGP2 (Hort hit)-1
with both extension pipe + hose

Point DGP2 (Hort hit)-2
with only extension pipe

Point DGP2 (Hort hit)-3
no external connection (free condition)

Influence 10 Hz

Influence of 8 kg from 57 Hz to 95 Hz

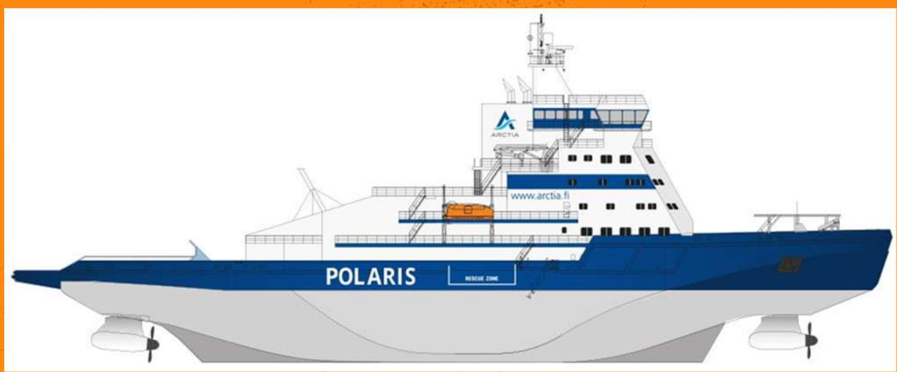
Standards

- ISO 6954 — Mechanical vibration-Guidelines for measurement, reporting …
- ISO 8528-9 — Reciprocating internal combustion engine driven alternating generating set
- ISO 10816-6 — Mechanical vibration-Evaluation of machine vibration by measurements of nonrotating parts
- ISO 1940-1 — Mechanical vibration-Balance quality requirements for rotors …
- ISO 11342 — Mechanical vibration-Methods and criteria for the mechanical balancing of flexible rotors

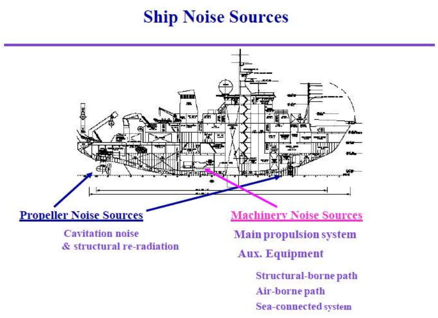
- IEC 60068-2-6 — Environment testing: Vibration
- IEC 60068-2-27 — Environment testing: Shock
- IEC 60068-2-64 — Environment testing: Vibration, broadband random and guidance

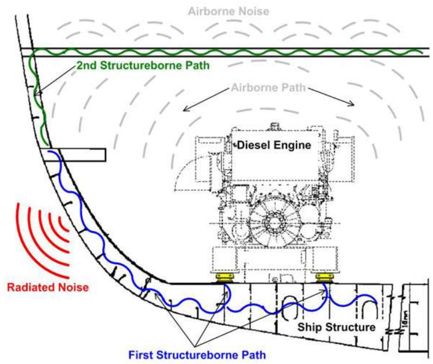
- etc.

Vibration at ships



Ship excitations

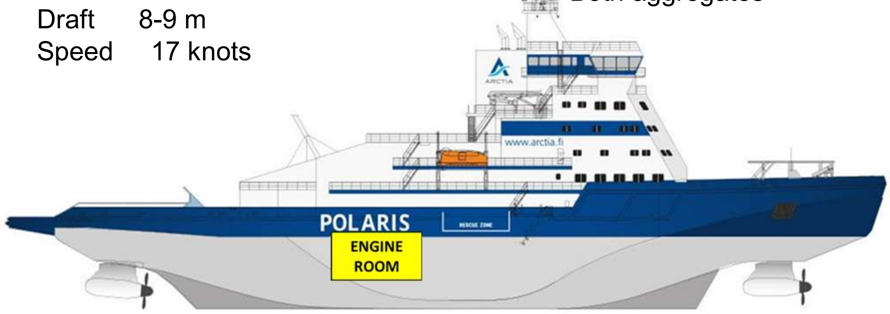




Icebreaker Polaris

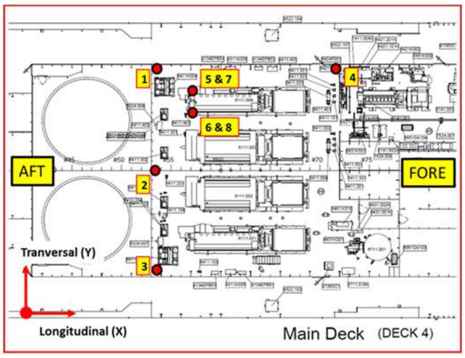
Lenght 110 m
Width 25 m
Draft 8-9 m
Speed 17 knots

2 * W9L34DF (4500 kW)
2 * W12V34DF (6000 kW)
Both aggregates



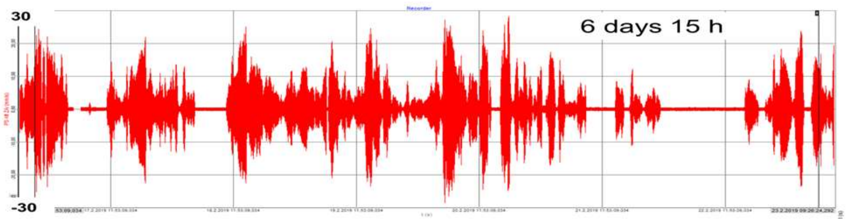
Vibration measurements during winter time to clarify how engines will behave in ice conditions, what will be acceleration levels of ship hull.

Icebreaker Polaris

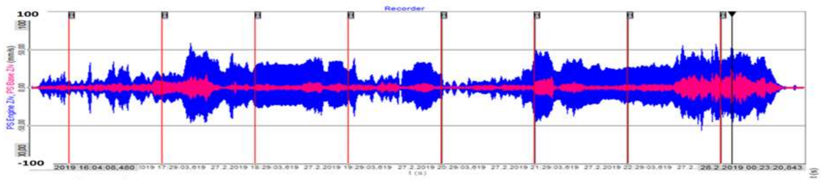


- Vibration measurements were carried out during winter time, from February to May 2019 at Bay of Bothnian. The purpose was clarified what is happend during icebreaking. 8 pieces 3D-accelerometers were used, 4 in ship frames and 4 on aggregates.

Icebreaker Polaris

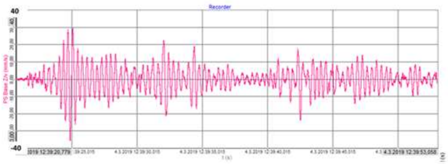


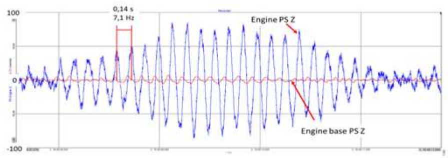
- Long-term measurements during icebreaking. Very high vibartion levels could be measured both on ship hull and on aggregates.
- Normal vibartion levels outside icebreaking.



- Icebreaking 27.2.2019 16:00 – 28.2.2019 00:20
- Red curve Base Z (Mp 5)
- Blue curve Engine Vertical Z (Mp 7)

Icebreaker Polaris

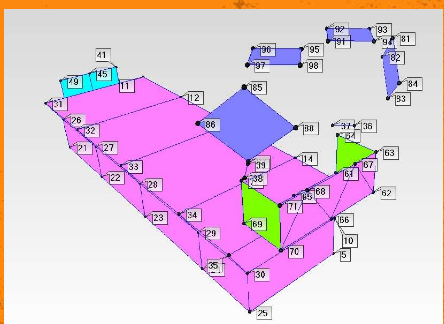


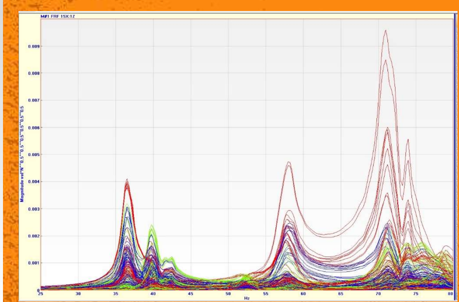


- On ship hull could be found following natural frequencies
- 2.8 Hz 30 mm/s=2.8 mm
- 5.6 Hz
- 8.2 Hz
- 7.1 Hz   7 mm/s=0.16 mm
- This 7.1 Hz frequency is very close to rigid body natural frequency of aggregate and that is why whole aggregete is jumping with amplitude 70 mm/s=1.6 mm

Advanced Vibration Course

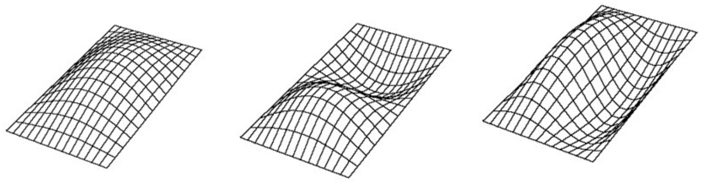
Part 2 - Natural frequencies



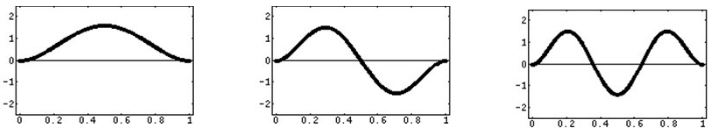


Natural frequency

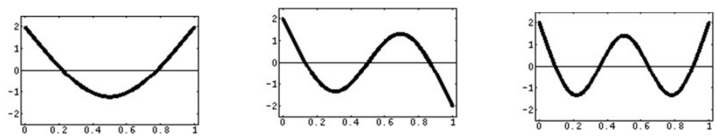
- **At different natural frequencies system oscillates in different shape that is called the mode shape or mode of vibration. Modes are inherent properties of structure. They don't depend on the force or loads acting on the structure. Modes will change only if material properties (mass, stiffness, damping properties) or boundary condition (mounting) of the structure change. The most well-known natural frequencies correspond to the first bending and torsion mode shapes.**



Natural frequencies and shapes



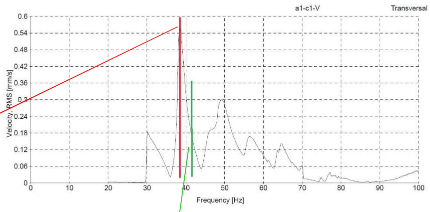
1st bending 2nd bending 3rd bending

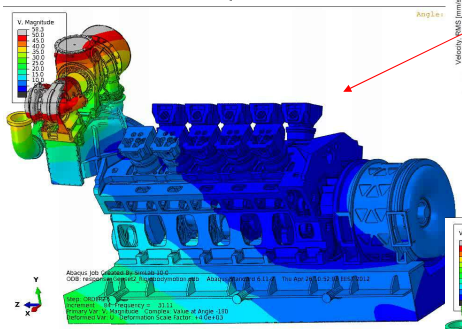


Plates Mode shapes

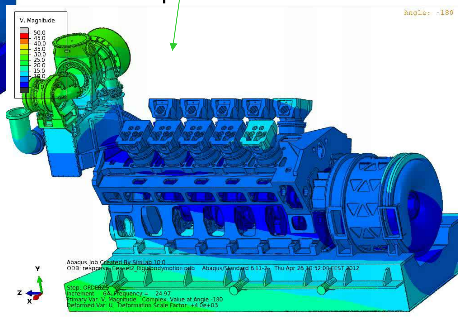
Resonance

Mode shape of resonance





Mode shape outside of resonance



resonance

Most easiest way to solve the resonances is using FEM (klowledges are needed)

Outside of resonance

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The mode shapes of the natural frequencies

Rigid body frequencies

Longitudinal, transversal, vertical
Pitching, yawing, rolling

Elastic natural frequencies

1st torsio
1st bending
1st horizontal bending
2nd …

- All real structures have multiple natural frequencies. Modes or resonances are inherent properties of a structure. Modes are determined by the material properties (mass, stiffness, and damping properties), and boundary conditions of the structure. The amplitudes at resonances are manly depending on damping values of the stucture (multi body sturctures)
- Modes are further characterized as either ***rigid body*** or ***flexible body*** modes. All flexible mounted structures have up to ***six rigid body*** modes, three translational modes and three rotational modes. The structure moves as a rigid body, no deformation.

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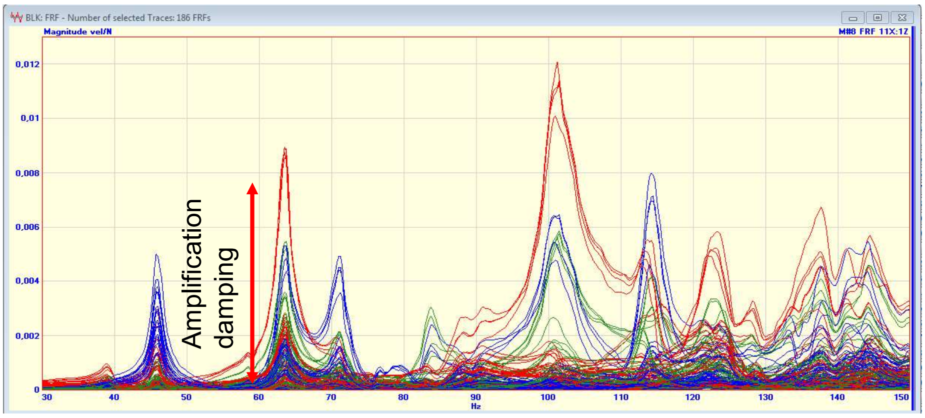
FRF natural frequencies



- **FRF (Frequency Response Function)** is a characteristic of a system that has a measured **response** resulting from a known applied input, every peaks means the natural frequencies of the structures of different components; local or global

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Part 3 - Measurements

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Measurements

- Standard linear vibration measurements
- Sweeping measurements (3D or water fall measurements = change the engine speed)
- ODS (Operational Deflection Shape = how the structure is moving)

- Hydraulic shaker measurements with random or sinusoidal excitation (natural frequencies of the stucture)
- Modal (Hammer) measurements

- Shaker table measurements

- Weighing engine and gravity point

- Stress measurements

Measurements

- Standard vibration measurements 5.20
- Laser measurements 2.30
- Shaker table measurements 3.20
- Shock test 2.45
- Hydraulic shaker measurements 5.40
- Weighing 2.05
- Rigid body measurements
- Stress measurements 7.10
- Earthquake test 1.00

Vibration measurements

Installation: Fincantieri 6251
Engine type: W12V32D; ABB TPS 61 (AF)
Engine no.: PAAE274333

OVERALL VIBRATION LEVELS
Output 5760kW; 720rpm
Velocity data at 100% load & 720rpm

Overall RMS Velocity [mm/s], 3-200 Hz

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B3	2.1	4.7	5.1	B3-b	2.6	5.8	5.3
B4	3.1	5.1	5.1	B4-b	3.0	5.9	5.0
C1	2.3	4.1	7.8	C1-b	2.7	4.1	6.7
C3	2.0	6.8	4.2	C3-b	2.6	6.6	3.6
C4	2.7	7.2	3.5	C4-b	2.6	7.0	3.7
D0	7.1	10.5	5.4	D0-b	5.7	9.9	4.7
D1+	6.3	9.7	5.0	D1+-b	4.4	9.7	4.7
D1	5.3	4.7	4.2	D1-b	4.1	4.8	4.6
D4	2.4	2.6	3.7	D4-b	2.4	2.6	3.9
E0	7.5	7.3	5.6	E0-b	6.0	7.3	4.9
E1+	6.3	7.1	5.4	E1+-b	4.3	6.9	5.1
E1	5.3	4.8	5.4	E1-b	4.4	4.4	4.4
E4	2.8	3.9	4.8	E4-b	2.4	4.2	4.0
DB	5.3	3.6	2.6	NB	6.3	4.6	3.3
LOM-a	10.8	17.4	8.0	LOM-b	9.0	17.7	8.7
Gov	9.2	10.4	8.3	TG	6.6	6.8	5.6
OMD	14.7	9.1	7.0	MC	3.5	16.7	2.9
AF	19.2	24.5	12.4	CF	24.8	21.4	18.0
WG-pos	22.8	11.8	11.5	WG-actuator	23.3	21.5	9.7
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TCC	32.8	9.6	15.7	TCC-b	24.4	16.1	8.2
TCF	20.4	30.9	36.0	TCF-b	15.5	25.9	25.6

Engine no.: PAAE274333

Acceleration data at 100% load & 720rpm

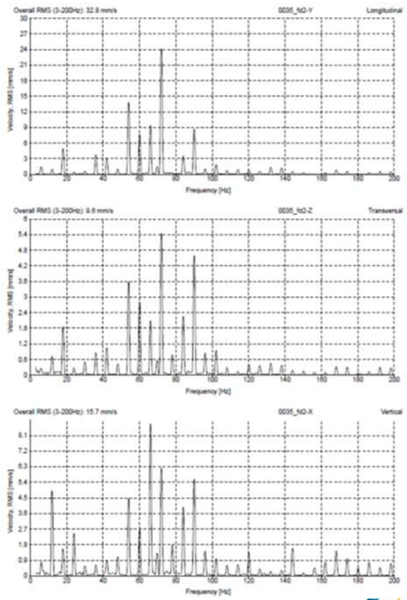
Overall RMS Acceleration [m/s²], 3-1000 Hz

Point	Longitudinal	Transversal	Vertical	Point	Longitudinal	Transversal	Vertical
TCC	17.5	5.8	10.2	TCC-b	12.1	8.3	4.6
TCF	11.7	18.1	19.4	TCF-b	9.6	14.3	13.4

Installation: Fincantieri 6251
Engine type: W12V32D; ABB TPS 61 (AF)
Engine no.: PAAE274333

VIBRATION MEASUREMENT
Output 5760kW; 720rpm
Velocity data at 100% load & 720rpm

Point TCC



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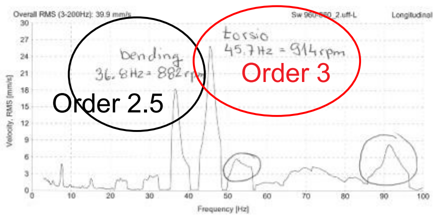
Sweeping measurements

Installation: M/V Resolution (re-eng)
Engine type: W6L20
Engine no.: PAAE092554

VIBRATION MEASUREMENT
P=1110kW 900rpm =100%
Sweeps 960->860rpm P=1110kW

Appendix 1 12

Point D1 Sweep

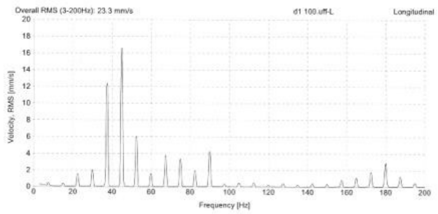


Installation: M/V Resolution (re-eng)
Engine type: W6L20
Engine no.: PAAE092554

VIBRATION MEASUREMENT
P=1110kW 900rpm =100%
Sweeps 960->860rpm P=1110kW

Appendix 1

Point D1 100%



The sweeping measurements, where the engine speed will change, are carried out normally with constant output.

The results show the location of the natural frequencies and their's amplitudes (safety margin)

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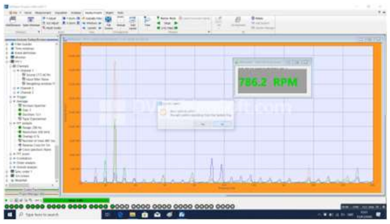
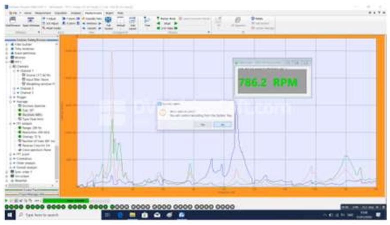
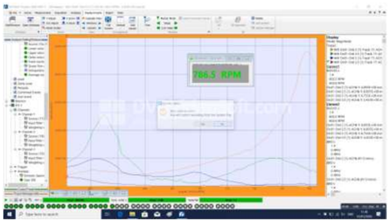
Sweeping measurements



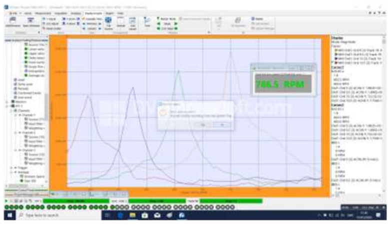
Sweeping n= 600->800 rpm with exp average



Sweeping n= 600->800 rpm with peak hold



Order tracking n= 600->800 rpm



Order tracking n= 600->800 rpm

Sweeping measurements

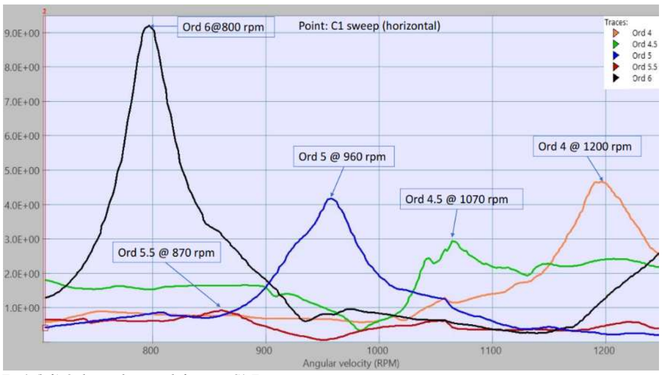
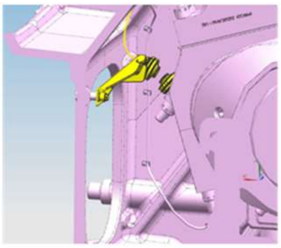


Fig 3:(left) Order tracking result for point C1-T

- W9L20 engine block torsion is located at 80 Hz
- With speed from 700 rpm to 1280 rpm different orders will pass this torsion. Order 6 at speed 600 rpm, order 5 (960 rpm), order 4.5 (1070 rpm) firing frequency and order 4 (1200 rpm)

Influence of low damping



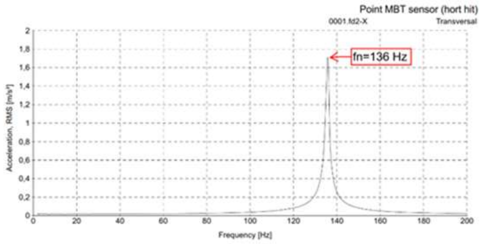
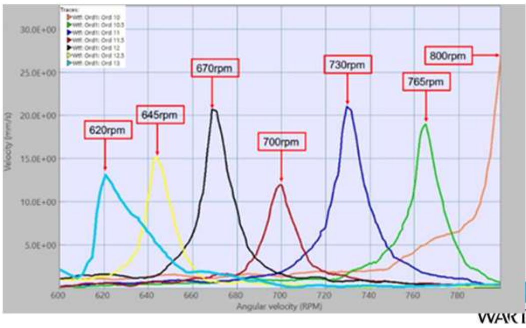


Fig 5: W20V34DF, MBT sensor (left) location drawing (right) ***modal result*** *for MBT sensor bracket at cylinder A4*

MBT sensor and higher excitation orders,

sweep 600 -> 800 rpm



Hydraulic shaker measurements

- With hydraulic shaker measurements could be created high random or sinusoil force from 10 Hz up to 200 Hz.
- Structure is isolated from ground with flexible elements
- The force is measured with force transducer.
- This measurement system is quite easy to perform here in Vaasa
- Normally is used 60-120 measurement points from the structure.

Hydraulic shaker measurements

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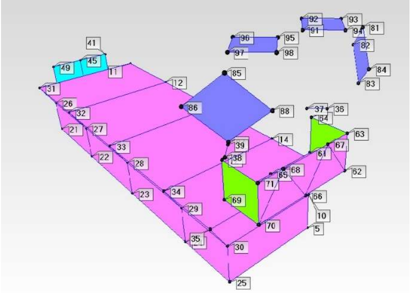
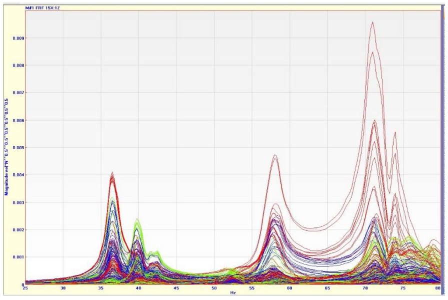
Hydraulic shaker measurements





- **FRF (Frequency Response Function)** is a characteristic of a system that has a measured **response** resulting from a known applied input, means the natural frequencies of the structures of different components
- Mode shapes of the natural frequencies will tell the movements of the structure. It is very important to understand how different part moves each other.
- That is why it is very important to have as many points as possible. Normally is used 60-140 measurement points.

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Mode shapes

- Turbo bracket 39 Hz with AFS
- Turbo bracket 39 Hz WITHOUT AFS
- Engine block 50 Hz torsion
- LOM 64 Hz vertical

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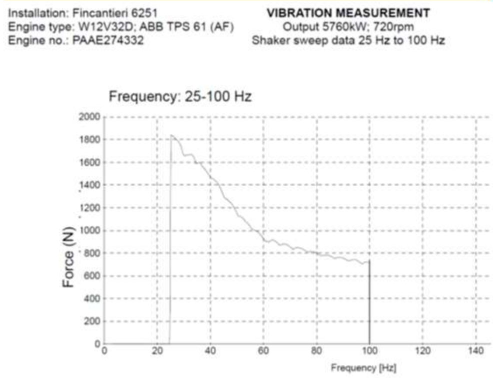
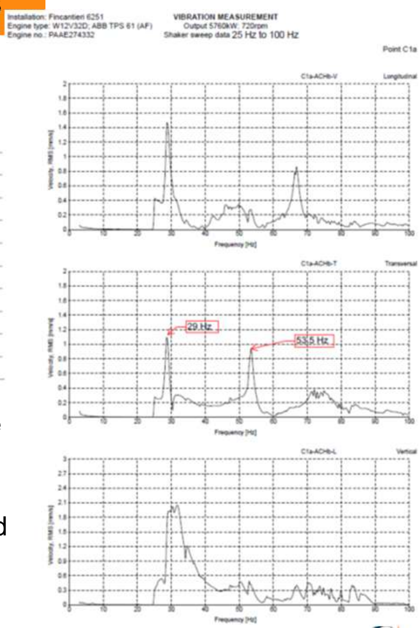
Hydraulic sweep measurements





- In resonance situations the amplitude of whole aggregate could be as high as 10 to 20 mm/s with force 1000 N.
- With known sinusoid excitations could be improved our FEM models.

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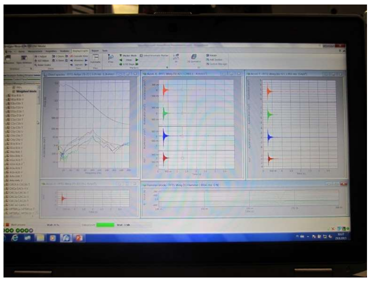
Modal measurement with hammer



\+ fast

\- weak excitation

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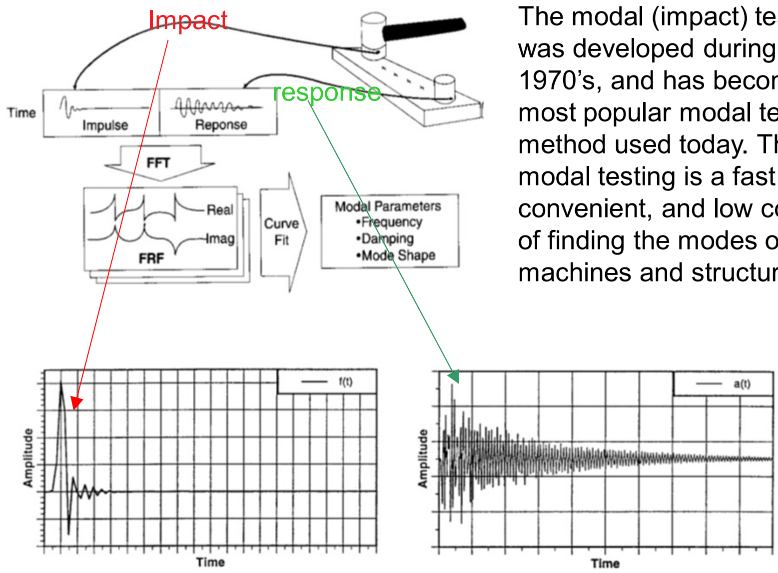
Modal measurements



The modal (impact) testing was developed during the late 1970's, and has become the most popular modal testing method used today. The modal testing is a fast, convenient, and low cost way of finding the modes of machines and structures.

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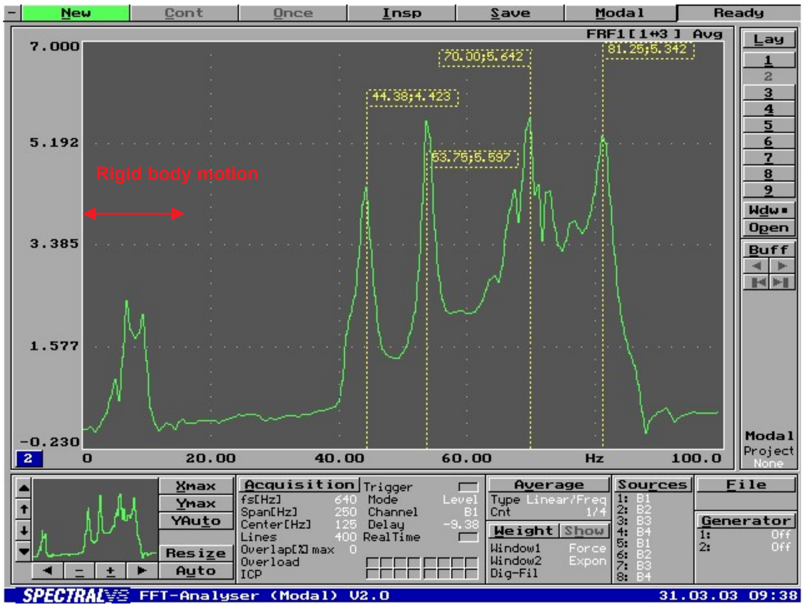
Frequency Response Function



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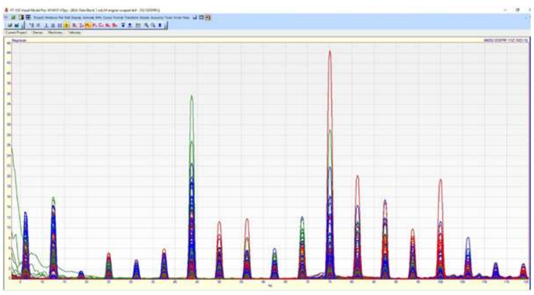
Running conditions Operation Deflection Shape

- Normally measurements will carry out with nominal engine speed and full load.
- The ODS movements are relativ movements, the amplitudes must be taken from real spectra



- ODS order 0,5 yawing
- ODS order 1 vertical and bending
- ODS order 3 firing frequency TCF
- ODS order 4,5 LOM

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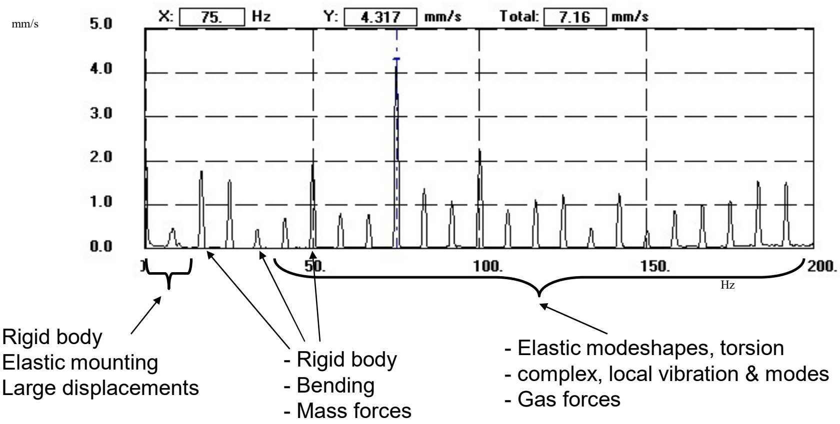
Time domain and frequency domain

FREQUENCY DOMAIN A typical vibration spectrum measured from a diesel engine



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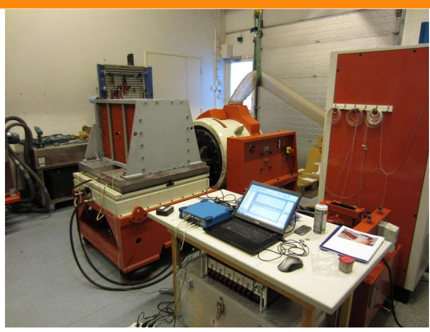
Electrical shaker table test



- The reliablity of differents engine components could be easy way to test with electrical shaker table.
- With shaker table could be excited different structures up to 2 kHz with very high excitations.
- The test mass could be as high as 500 kg
- All new components must be tested according to Wärtsilä standard

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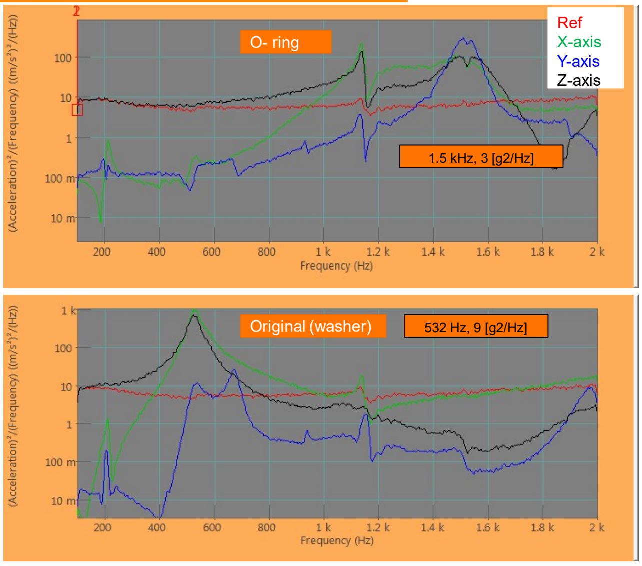
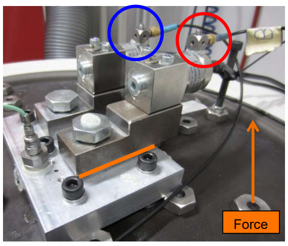
Electrical shaker table test

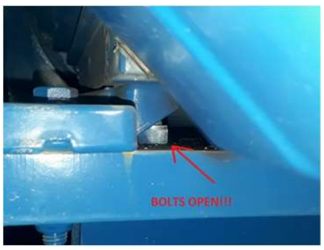
Modified O-ring fixture
Original washer fixture

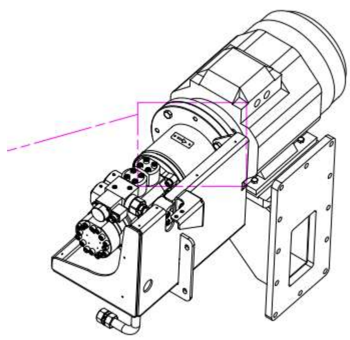




When is used washer the contact area is area of washer. And with O-rings the contact area is whole mounting structure.

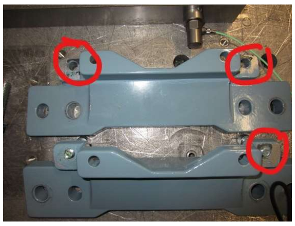
Pilot fuel pump

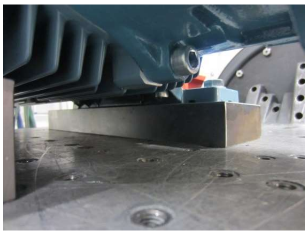




From field was gotton information for broken bolts on el-motor

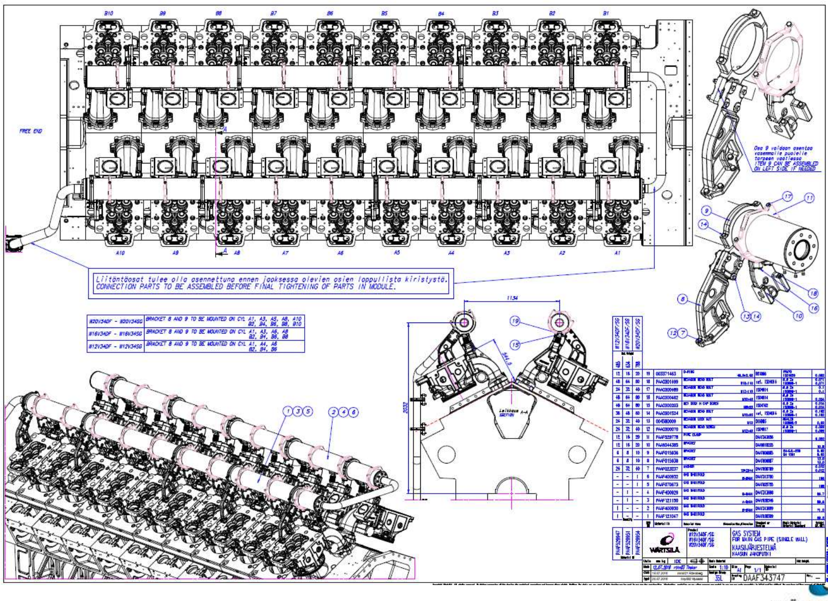
Electrcal shaker table test





- On field some challanges with broken bolts
- With random excitation these bolts were opened or broken after 2-3 hours

Single wall gas pipe



Single wall gas pipe

- During year 2019 Wärtsilä got claims from cracking single wall gas pipes. Only common was that cracks seem to start on same place, immediately after clamps, different cylinders

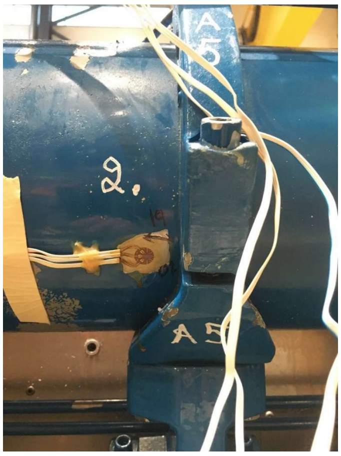
Single wall gas pipe

- Low vibration levels were measured around gas pipelines of different engine configurations. Also mode shapes seem to normal. Vibration can't be a reason for cracks.
- FEM calculation showed also that stress levels should be acceptable.
- Many trial and errors were carried out with satisfactory results.
- Finally was decided to do some special tests with W16V34DF engine at Vaasa.

Single wall gas pipe

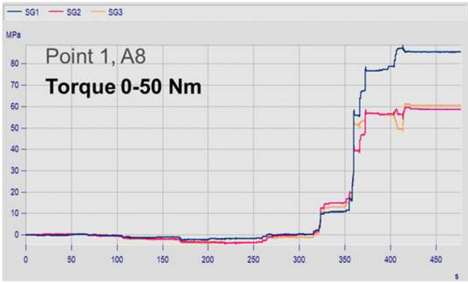
Overall view from aggregate

Single wall gas pipe



Just before measurements was decided to add strain gages on both side at cylinders A1, A5 and A8

Stress measurements



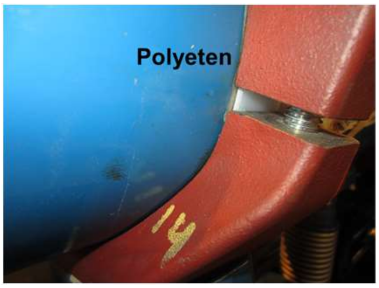
Stress levels on gas pipe with tightening torque

Static surface tension at different torque

Steel		A8			A5			A1	
A-bank	1	2	3	1	2	3	1	2	2
Torque test	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
50 Nm	85	58	60	54	56	42	38	35	65
85 Nm	113	98	78	67	83	48	42	53	82
Dev	+28	+40	+18	+27	+27	+6	+4	+18	+17
@100% load	*150*	*146*	*108*	*97*	*125*	*93*	*63*	*62*	*97*

Steel		B8			B5			B1	
B-bank	1	2	3	1	2	3	1	2	3
Torque test	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
50 Nm	27	12	34	80	72	80	42	70	42
85 Nm	31	12	38	115	82	115	73	107	70
Dev	+4	-	+4	+35	+10	+35	+31	+35	+28
@100% load	80	75	90	144	135	172	81	129	68

Stress measurements



Static surface tension between materials using different clamping torque

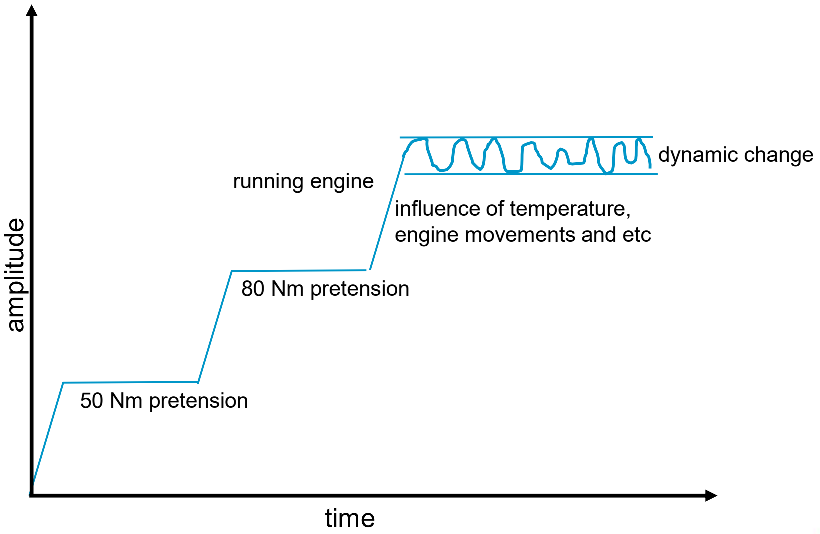
Steel		B1	
B-bank	1	2	2
Torque test	MPa	MPa	MPa
50 Nm	42	70	42
85 Nm	73	107	70
Dev	+31	+35	+28

NBR-rubber		B1	
B-bank	1	2	3
Torque test	MPa	MPa	MPa
50 Nm	65	42	56
85 Nm	74	70	75
Dev	+9	+28	+19

BA-S, fiber		B1	
B-bank	1	2	3
Torque test	MPa	MPa	MPa
50 Nm	30	45	40
85 Nm	45	80	60
Dev	+15	+35	+20

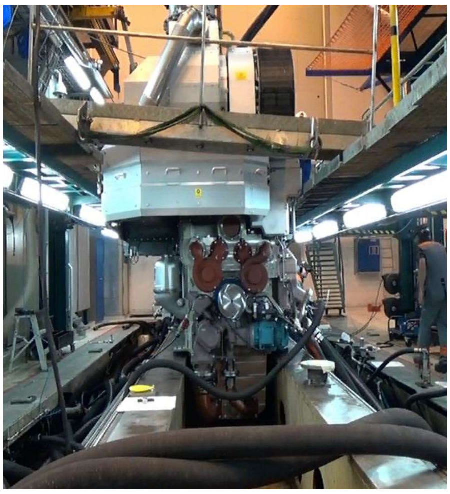
PE, polythene		B1	
B-bank	1	2	3
Torque test	MPa	MPa	MPa
50 Nm	30	45	40
85 Nm	45	80	60
Dev	+15	+35	+20

Static and dynamic amplitudes

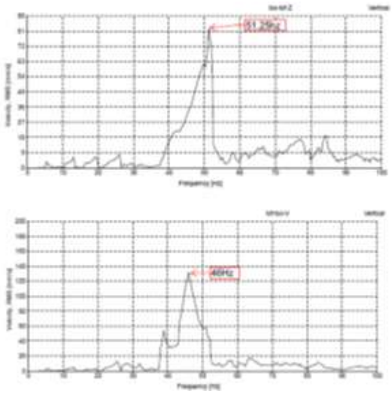


Case study – fixing rails of test run

- Very high vibration levels have been measured on rigidly mounted main engines of W8L32 at 50 Hz (firing frequency)
- Why this can be accepted?
- Spectra and mode shape

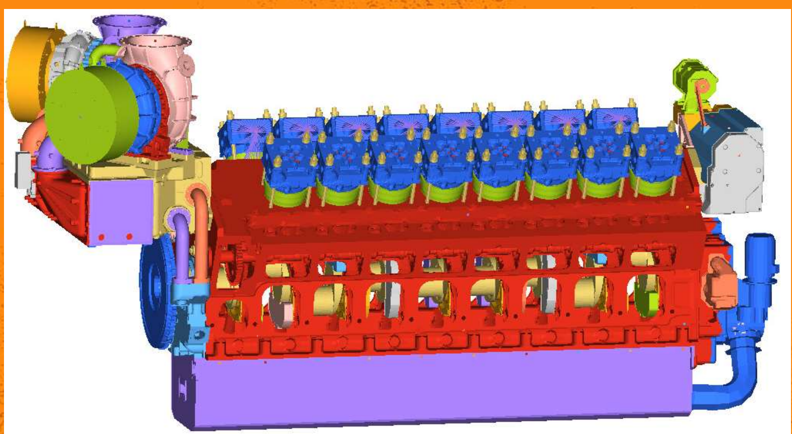


Case study – badly supported exhaust pipe after turbo



Sweeping spectra on TCF on vertical direction. On top badly support exhaust pipe and below on right way supported exhaust pipe.

Part 6 - Theoretical calculations with FE models



Gas Manifold Pipe

- During year 2021 were reported cracks on W20DF gas manifold pipes.
- Why suddendly?

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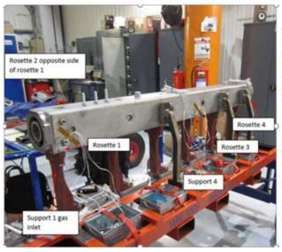
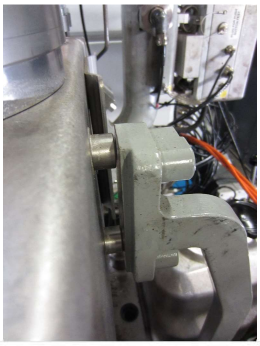
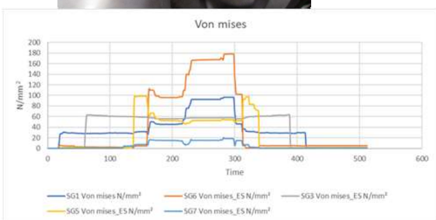
Gas Manifold Pipes





- Very high stress levels were measured on mounting area when side supports were tightened on gas pipes
- Same results were reported also on sites.



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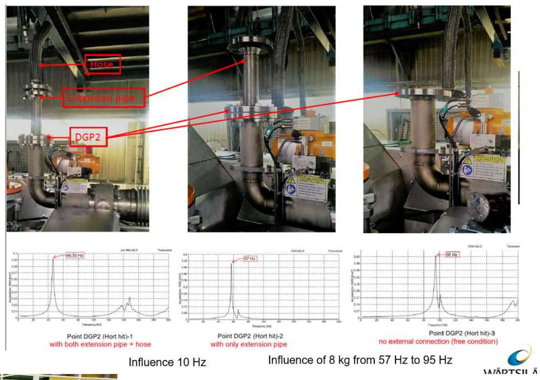
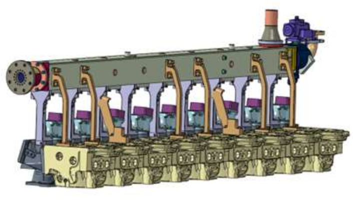
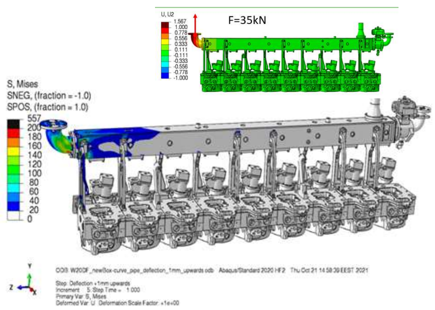
Gas Manifold Pipes

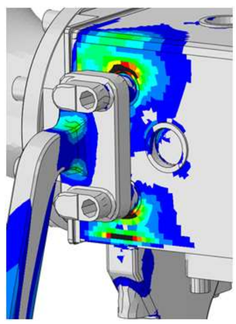


Gas Manifold Pipes - FEM

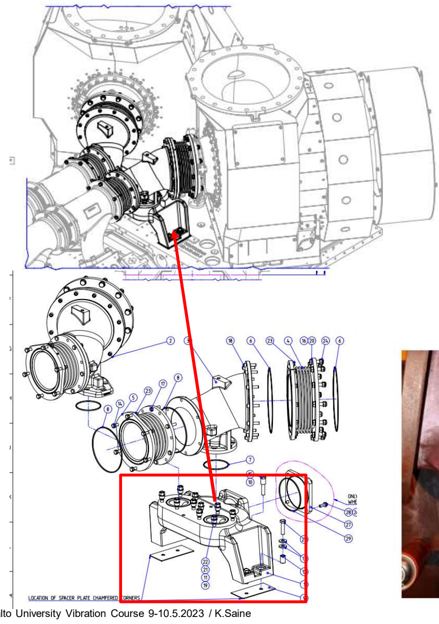




With many different calculations could be easy way to show the stress levels on gas pipes, like pressure load, terminal stresses, engine block bend, CH firing movements, feeding pipe deflections, etc



Turbo exhaust pipe bracket ’Jakkara’



During 2019 was reported cracks from many sites on this jakkara, especially Peaker type of Power Plants.

Many different type solutions were tried to solve these challanges without any luck.

Finally is was decided to carry out validation measurements in Vaasa.

Exhaust temperature is 500° and engine block 70°

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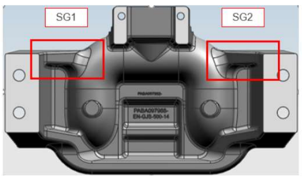
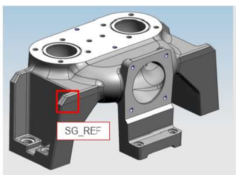
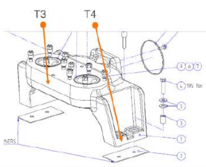
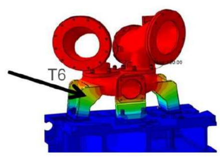
Turbo exhaust pipe bracket ’Jakkara’









T1: Temp. inlet flange
T2: Temp. outlet flange
T3: Temp. connection piece body middle
T4: Temp. connection piece foot bottom
T5: Temp. of turbocharger bracket top surface
T6: Temp. connection piece foot top

Based on FEM calculations it was expetected that main reason for cracks must be movement of feet. It was expected that temperature will influence the movement of feet or in worst case will prevent this movements

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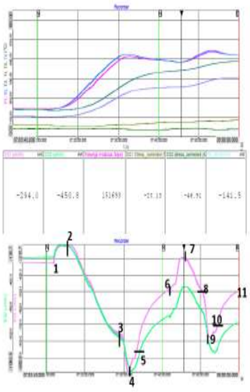
Turbo exhaust pipe bracket ’Jakkara’



Original legs
1= engine started
1-2= idle load
2-3= increase load to 100% 12 min
3-4= dropped load to idle, 2 min
4-5= engine idle 1min
5= engine stopped
5-6= engine cooling, 15 min
6-7= engine started and load to 50%, 3 min
7-8= increase load 50%-100%, 3 min
8-9= load dropped 100% to idle
9-10= idle load 2 min
10= engine stopped
10-11 engine cooling

Figure 3: Engine start and stopping with original feet. The lower picture stress levels. The unit in Y-axis is strain (µm). The stress levels are strain multiply with Young’s module which is about 160 MPa. Upper picture are temperatures at different places.

First measurement indicated something strange. When engine load increased (step 2-3) the stress levels increased normally to about 110 MPa. After that, the load was dropped back to idle (step 3-4) in 2 minutes and the stress levels increased suddenly again about 25 MPa. How this is possible, idle load and stress levels increased?

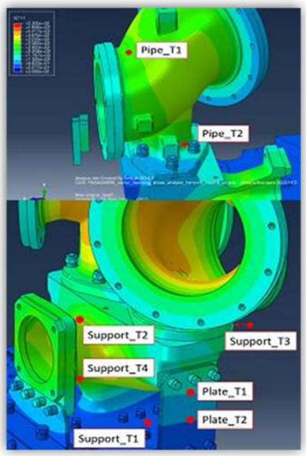
When engine started again (step 6), the stress levels decreased (step 6-7) until at 50% engine load the stress levels started to increase again. All the time the temperatures increased on jakkara. After 100% load (step 8) the load dropped to idle and again stress level started to increase (step 8-9), like in previous stop, but now maximum stress (peak to peak) is about 95 MPa when in first starts it was about 135 MPa.

All three different jakkara behave same way

Turbo exhaust pipe bracket ’Jakkara’ - FEM

- COLD START

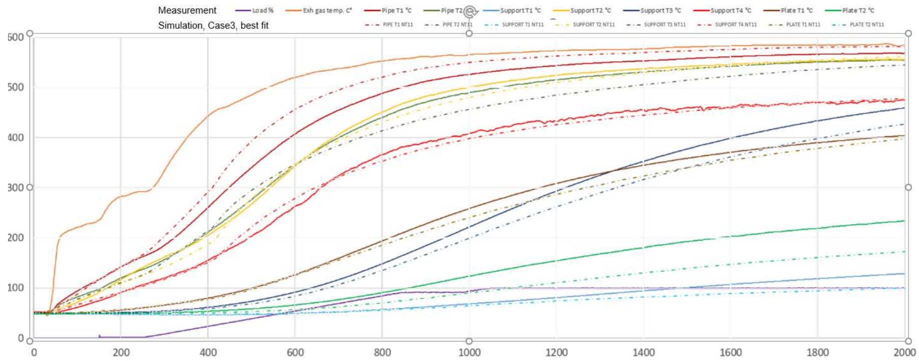
- Fours simulation of the same FEM model but with different boundary conditions were compared to measurement
- Original simulation, under estimated exhaust temperatures, HTC=300W/m2k for low load, HTC=600W/m2k for high load
- Simulation Case1 (Constant HTC), exhaust temperature according the measurement, constant HTC=300W/m2k
- Simulation Case2 (Extreme case), exhaust temperature according the measurement, HTC 150-300 for idling and 600W/m2k for power ramp
- Simulation Case3 (Best fit), exhaust temperature according the measurement, HTC 150-300 for idling and 450W/m2k for power ramp



Turbo exhaust pipe bracket ’Jakkara’ - FEM

COLD START, SIMULATION CASE3

- Simulation case3, best fit to measurement
- HTC values were chosen so that the simulated temperature and temperature gradient close to critical location(Pipe T2, SupportT2,T4) at the most critcal point of time(600s-1000s) are close to measured values



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