



# **Vibration guideline for large diesel engines**

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## BACHELOR'S THESIS

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### Summary

This thesis was written at Wärtsilä's engine factory in Vaasa. Wärtsilä has had several different guidelines for measuring vibrations and acceptable levels of vibration on their 20, 32 and 34 engine series. The purpose of this thesis was to locate and summarize these guidelines in one coherent text. Measurement data from vibration measurements conducted over the years was also put into one excel file.

The beginning of the thesis consists of basic vibration theory. Then the thesis deals with more advanced vibration theory needed when performing and analyzing vibration measurements. One chapter includes an overview of the gear that Wärtsilä uses. Vibration tests of different mechanical and electrical components mounted on the Wärtsilä engines are also presented.

The new guidelines need to be in agreement with valid standards from the classification societies and this was taken into consideration. But it was found out that some of the standards could not be used with Wärtsilä's guidelines. In some test procedures Wärtsilä will create a standard of their own that is stricter than the one given by the classification societies.

In the end a guideline with acceptable levels of vibration and ways of measuring vibration on not only Wärtsilä's engines but also on other large diesel engines was presented.

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## OPINNÄYTETYÖ

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### Tiivistelmä

Opinnäytetyö tehtiin Wärtsilässä Vaasan tehtaassa. Syy opinnäytetyöhön oli, että Wärtsilällä oli monia eri ohjeita värähdysmittaukseen ja sallittuja värähdystasoja heidän 20, 32 ja 34-moottorisarjaan. Työni oli kerätä ja tiivistää näitä ohjeita yhteen tekstiin. Keräsin myös mittausdataa värähtelymittauksista monelta vuodelta ja laitoin niitä Excel-tiedostoon.

Aloitin kirjoittamalla helposta värähdysteoriasta saadakseni sitä mukaan ohjeeseen. Sen jälkeen otin mukaan enemmän pitkälle kehittyntä värähdysteoriaa, jota tarvitaan, kun tehdään ja analysoidaan värähdysmittauksia. Saadaksen yleiskuvan koneelle, mitä Wärtsilä käyttää värähdysmittauksissa esitän niitä yhdessä luvussa. Wärtsilän moottoriin asennettuja mekaanisia ja sähköisiä komponentteja, joita on värähdystestattu esitellään myöskin.

Uudet ohjeet pitää olla yhteisymmärryksessä voimassa olevien standardien kanssa, joka otettiin huomioon. Todettiin, että osa näistä standardeista ei voida käyttää Wärtsilän ohjeiden kanssa. Joissakin testeissä Wärtsilä tekee omat tarkemmat standardit kuin standardiseura.

Lopussa ohje, missä löytyy sallittuja värähdystasoja ja menettelytapoja tehdä värähdysmittauksia Wärtsilän moottoreihin, mutta myöskin muihin isoihin dieselmoottoreihin.

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## EXAMENSARBETE

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### Abstrakt

Jag gjorde detta examensarbete åt Wärtsiläs fabrik i Vasa. Bakgrunden till arbetet var att Wärtsilä hade flera olika riktlinjer för vibrationsmätningar och acceptabla vibrationsnivåer på deras 20, 32 och 34 motorserie. Mitt arbete gick ut på att samla ihop dessa riktlinjer och sammanfatta dessa till en sammanhängande text. Jag samlade även ihop mätdata från vibrationsmätningar som genomförts under många år och samlade dessa i en Excel-fil.

Jag tog avstamp i enkel vibrationsteori för att få med grunderna i riktlinjen. Efter detta gick jag in på mera avancerad vibrationsteori, som behövs när man gör och analyserar vibrationsmätningar. Utrustningen som används av Wärtsilä togs upp i ett kapitel för att få en överblick av denna. Vibrationstest av olika mekaniska och elektriska komponenter som monteras på Wärtsiläs motorer presenteras även.

De nya riktlinjerna behöver vara i samförstånd med gällande standarder från klassificeringssällskapen och togs därför i beaktande. Dock konstaterades att en del av standarderna inte kunde användas i enlighet med Wärtsiläs riktlinjer. Vid en del testprocedurer kommer Wärtsilä att göra en egen strängare standard än den från klassificeringssällskapet.

I slutändan åstadkoms en riktlinje med acceptabla vibrationsnivåer samt förslag till mätning av vibrationer för Wärtsiläs motorer, men även för stora dieselmotorer överlag.

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• Språk: engelska

Nyckelord: vibrationer, riktlinjer, standard

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Appendix 1: Typical Vibrations levels on W20 and W32/34

Appendix 2: Acceptable Vibration Levels on W20 and W32/34

## **Preface**

Doing this thesis was a challenge but in the end a quite interesting one. After 5 years in Novia University of Applied Sciences, first a year and a half in electrical engineering and now finishing in mechanical- and production engineering it feels amazing! I would like to thank Mr. Kari Saine at Wärtsilä for giving me this task and also Mr. Kaj Rintanen at Novia University of Applied Sciences for helping me with the writing of this thesis. I would also like to thank Mr. Claus Paro and Mr. Manjunath Patil at Wärtsilä who have both been of great help when I needed it.

Vaasa, 4 April 2014

*Johannes Örn*

# **1 Introduction**

This thesis will be a guideline for the measurement of vibrations on Wärtsilä engines manufactured in the factory in Vasa. It will also define acceptable vibration levels on the engines and on mechanical and electrical components mounted on the engines. The thesis will be written with a base in vibration theory and vibration standards but also with the help of the knowledge existing in Wärtsilä. The thesis will be written in cooperation with Wärtsilä Powertec, at the Wärtsilä Factory in Vaasa. The factory in Vaasa manufactures the 20, 32 and 34 engine series. Today there are no updated vibration guidelines for the engines and all the knowledge is found in different documents. If an engine needs vibration testing in the field this information is not available. Also there are no updated documents on acceptable levels of vibration on the engines.

## **1.1 Wärtsilä**

Wärtsilä is a Finnish company founded in 1834 in Wärtsilä in today's Russia. Wärtsilä is divided into three major parts: Ship Power (28%), Power Plants (32%) and the largest, Services (40%). The turnover for all of Wärtsilä in 2012 was 4.7 billion euro. Wärtsilä employed 18,900 people in 70 countries in 2012. Wärtsilä provides power solutions for power plants and complete drive systems and designs for the ship industry, while services handle all the maintenance for Power Plants and Ship Power.

## **1.2 Problem definition and goal**

The problem is that there are a lot of different standards out there concerning acceptable vibration levels on engines, which can lead to confusion. Another challenge is that these standards don't give any guidelines for parts mounted on the engine, only for the main engine itself. The built-on parts are often supplied by sub-suppliers, which means that discussions should be held with these suppliers about acceptable vibrations on their components. Knowhow from experienced people should also be taken into consideration when writing these guidelines.



The goal of this thesis is to create a guideline that can be used in Wärtsilä concerning vibrations on their engines. The guideline should be used when deciding where to put sensors, how to use the measurement equipment and how to interpret the results. This guideline should be written so that a person with a non-technical background can read it and understand what vibrations are.

### **1.3 Limitations**

This thesis will be limited to making a guideline and will not go into greater depths when it comes to vibrations. The guideline will also be limited to vibration measurements on the four-stroke 20-, 32- and 34 series of engines manufactured in the Vaasa factory.

### **1.4 Outline**

The chapters in this thesis will contain the following:

- Chapter one introduces the reader to the background and the subject of this thesis. The limitations, problems and finally the goal of the thesis are also presented in the first chapter.
- Chapter two contains an introduction to vibrations, basic vibration theory as well as a short presentation of how measurements are done. The international standards used by Wärtsilä are also presented in short.
- Chapter three contains earlier research, as well as the allowed vibration levels on Wärtsilä engines and mechanical and electrical components mounted on them.
- Chapter four contains the Wärtsilä Vibration Guidelines as well as acceptable vibration levels on both mechanical and electrical components. And of course on the whole engine.
- Chapter five describes the method used when this thesis was written.
- Chapter six describes the results I've found.
- Chapter seven contains the conclusion of this thesis.

## 2 Basic vibration theory

Vibration is a form of movement of a body or a system around its point of equilibrium. Vibrations can be periodic or random. The movement of the pendulum in a grandfather's clock for example is a periodic vibration while the movement of an object travelling across an uneven surface is a random vibration. Vibrations in a machine or an engine are for the most part undesired since they can cause increased stresses, added wear, increased sound levels, material fatigue, energy losses and increased bearing loads. [1]. This can in time lead to mechanical failure and breakdown. Vibrations can be of two kinds, free vibrations and forced vibrations. The first one is the equivalent of letting go of a swing and letting it swing until it stops. Forced vibration is when a load is applied on a mechanical system causing it to vibrate, for example a washing machine with an uneven load of clothes.

When an internal combustion engine is running it is creating several sorts of excitations. Despite being balanced there are always vibrations from rotating engine parts, gas pressures and the firing of the engine. Therefore it is important to design the engine so that none of these vibrations are close to the natural frequency of the engine. If the vibrations of the running engine are close its natural frequency, they will amplify each other leading to higher forces and early breakdown.

The natural frequency of the engine can be found through a FEM calculation or measurement of the engine. Accelerometers are used when the overall vibration of the running engine is measured; these accelerometers measure movement in three directions, longitudinal, transversal and vertical movement along the axis. Vibration levels can be different on different parts of the engine and because of this there need to be a grid of predefined points where to put the accelerometers when measuring. The results of the measurements must also have a "normal" value for each point on the engine but also for each point on each engine type. Excess of this value means that there is too much vibration and the cause of this needs to be found.

Vibrations can be both problematic and helpful. Vibrations in an engine are never good but cannot be avoided, while we need vibrations in compactors, eccentric grinders and in the vibrators in our mobile phones among other things.

## 2.1 Basic theory

A simple vibration system consists of three parts: a spring for storing potential energy, a mass or inertia for storing kinetic energy and a damper through energy is gradually lost. When a system is vibrating, its energy is alternating between its kinetic and potential form. A damped system loses energy each during cycle if it is not maintained through an external source. [2]

In a translational (linear) vibration system we have three components, a spring, a mass and a damper. The change in the length of the **spring** is proportional to the force acting along it, giving us this formula:

$$F = k(x - u)$$

Where  $k$  is the strength of the spring and  $x$  and  $u$  is the difference in length after the spring has been compressed. This is the formula for an ideal spring so it's considered to have no mass.

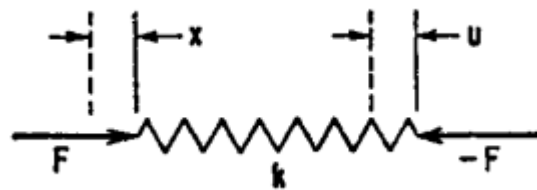


Figure 1. A linear spring [2]

The **mass** in the system is considered a rigid body that according to Newton's second law has an acceleration that is proportional to the resultant of all forces acting on it giving us the formula:

$$F = m\ddot{x}$$

where  $m$  is the mass of the body and  $\ddot{x}$  is the acceleration.

The **damper** in the system is affected by an applied force that is proportional to the relative velocity of the connection points of the damper, giving us:

$$F = c(\dot{x} - \dot{u})$$

where  $c$  is the damping coefficient and  $\dot{x}$  and  $\dot{u}$  are the velocity of the fastening points of the damper. The damper is ideal and is considered to have no mass so the force is equal but opposite at each end. [3]

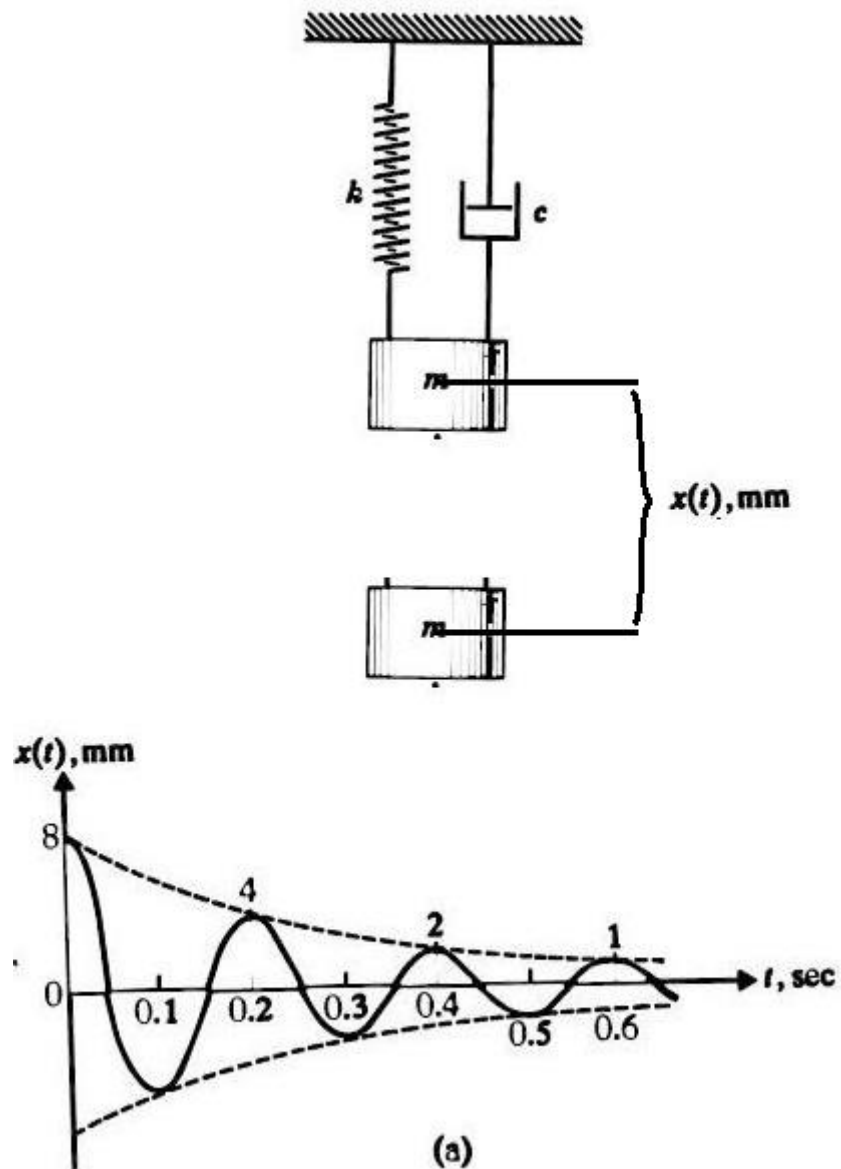


Figure 2. Movement of a damped simple system. The amplitude of the damped mass decreases with every vibration cycle. [11]

## Frequency

Simply put the frequency is the repetition of the vibration. The amount of times a system repeats one cycle in one second is the same as frequency. The unit of frequency is Hz. The formula is:

$$f = \frac{1}{T} = 1 \text{ hertz}$$

T is the period and is usually measured in seconds. [12]

## Orders

To get the first order of the engine in Hz you divide the running speed of the engine by 60, so for an engine running at 720 rpm the first order is  $720/60 = 12\text{Hz}$ . So if there is a clear peak at 24Hz (2x12 Hz), it is at the engine's 2<sup>nd</sup> order and so on. The firing order on a Wärtsilä engine is for an inline engine the number of cylinders divided by 2, or for a V-engine the number of cylinders on one cylinder bank divided by 2.

## Amplitude, displacement

Amplitude is the amount of vibration or the maximum value of a sinus curve. [13]. In a continuous sinus curve the amplitude is always the same:

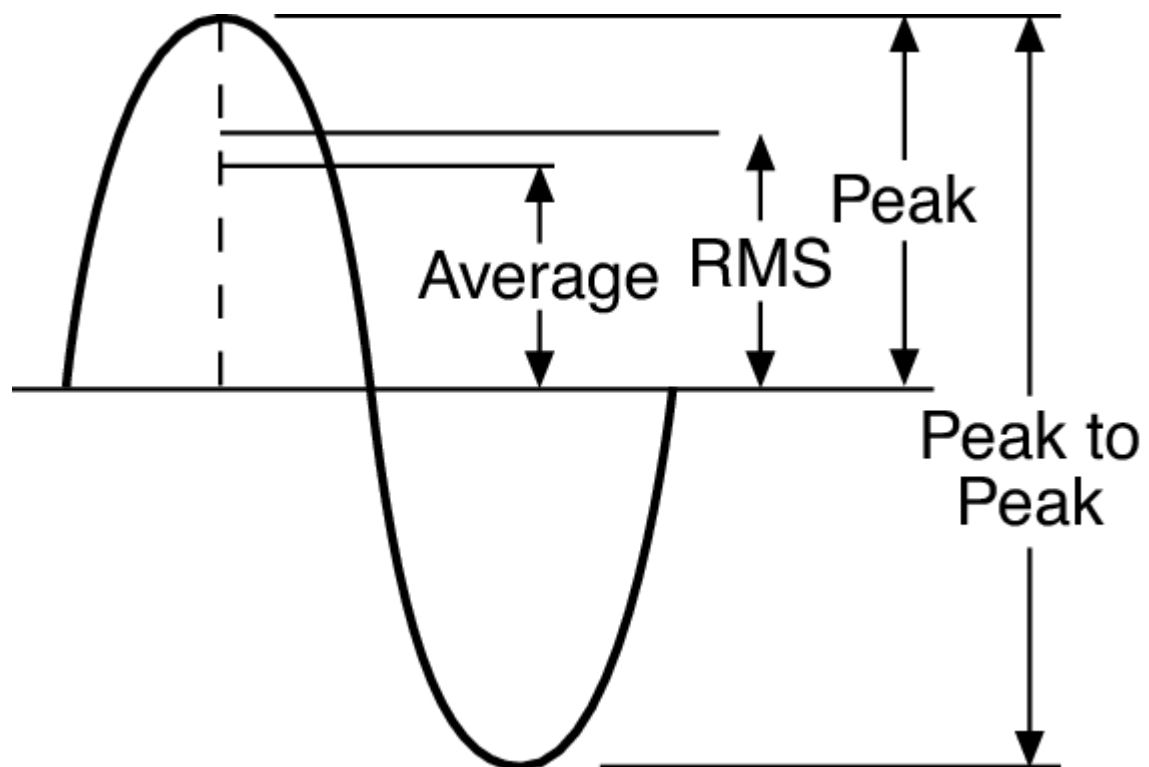


Figure 3. Peak, peak to peak, RMS and average values of a sinus curve [15]

## Peak

Peak is the maximum value of a vibration in a given interval, usually the maximum deviation from the mean value in that vibration. [14]. In a vibration spectrum the peak value is always the highest value.

## RMS

Vibration amplitude values are given as RMS values in the spectrum. RMS is relevant because it takes into account both the time history of the wave and gives an amplitude value, which is important because the amplitude gives the energy of the vibration and that is how destructive the vibration is. The formula for RMS is:

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

## Phase

In a system of vibrations you have many different vibrations working at the same time. The relationship between these vibrations is the phase. [5]

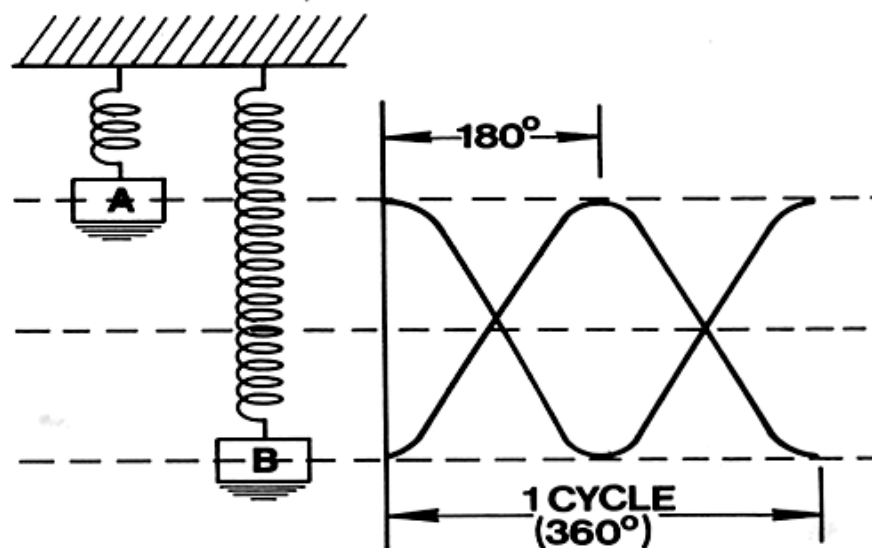


Figure 4. The difference between the vibrations is the phase. [16]

Think of the weights A and B in the figure above as different points on the engine. They are never moving in the same direction and are because of this not in phase. The resulting vibration of these two vibrations is zero because the vibrations are out of phase by  $180^\circ$ .

## Damping

The **damper** in the system is affected by an applied force that is proportional to the relative velocity of the connection points of the damper, giving us:

$$F = c(\dot{x} - \dot{u})$$

where  $c$  is the damping coefficient and  $\dot{x}$  and  $\dot{u}$  are the velocity of the fastening points of the damper. The damper is ideal and is considered to have no mass so the force is equal but opposite at each end. [3]

## Natural frequency

The natural frequency of a system is the frequency at which it will continue to vibrate if excited. For example, the frequency of the A string on a guitar is tuned to 440Hz, becoming its natural frequency, and will continue to vibrate at that frequency for a long time after the string has been picked.

The natural frequency of a system is determined by a series of expressions. In an undamped system we get the expression:

$$m\ddot{x} + kx = 0$$

$X=0$  equalizes the equilibrium position of the system's mass. When breaking out  $x$  from the previous formula we get:

$$x = A \sin \sqrt{\frac{k}{m}} t + B \cos \sqrt{\frac{k}{m}} t$$

The term  $\sqrt{\frac{k}{m}}$  is the angular natural frequency of the system which is defined by:

$$\omega = \sqrt{\frac{k}{m}} \quad \text{which is in radians/second.}$$

The time it takes to complete one cycle is called the period:

$$\tau = \frac{2\pi}{\omega_n}$$

When combining these definitions you get the expression for the natural frequency,  $fn$

$$fn = \frac{1}{\tau} = \frac{\omega_n}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

## Rigid body

A flexibly mounted structure has six ways of moving. There are three translational modes: movement along the longitudinal, transversal and vertical axes. There are also three rotational modes: pitching, yawing and rolling around the axes. In these six modes there is no deformation and the structure moves as a rigid body. [5][10]. For each order of the natural frequency of the structure there is a specific movement. When a body is flexibly mounted you can isolate it from the vibrations with springs or rubber mounts.

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

The operation mode shape or the operational deflection shape is the combined movement of these six modes for all their frequencies and all orders when the engine is running. Basically it is the way the engine is moving at running speed. [Discussion with Mr. Claus Paro and Mr. Manjunath Patil]

## Elastic body

An elastic body has many ways of moving but the three simplest ways of moving are 1<sup>st</sup> bending, 1<sup>st</sup> torsion and 1<sup>st</sup> order vertical bending. Each peak in the spectrum represents a different way of moving, so an elastic body has infinitive body modes. [5][10]

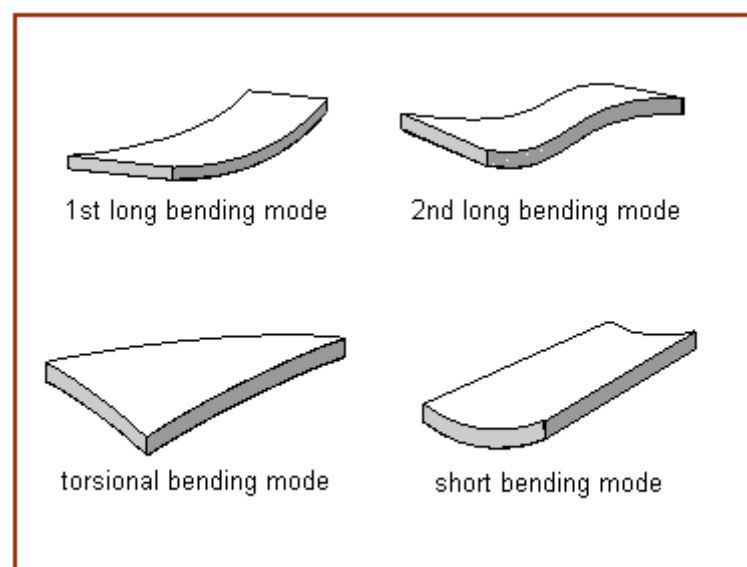


Figure 5. The different bending modes of a steel plate, 1<sup>st</sup> Order [20]



## Forced vibration

Forced vibrations are the movements that are the result of a continuously applied force that causes the system to vibrate. This force can be a strict force on the system, or the movement of the system foundation. If the mass of an undamped single degree of freedom system is excited by a force, the results are either the amplitude of the motion of the mass called *motion response* or the applied force that is transmitted through the system to the foundation of the system called *force transmissibility*.

If it is the foundation that is moving, the resulting motion is usually a result of the amplitude of the motion of the mass compared to the amplitude of the motion of the foundation. This is called the system's *motion transmissibility*. [4]

## Resonance

If an excitation is the same as or close to a natural frequency, the amplitudes will grow and amplify each other, or resonate, creating a dangerous situation since high amplitudes can damage the structure. How much the amplitudes grow is dependent on the damping of the system, the higher the damping the less the amplification. When a structure resonates it is vibrating in its natural frequency or in a frequency very close to it. [8]. The tone you hear when you hit a metal object is the dominant resonance frequency of that structure.

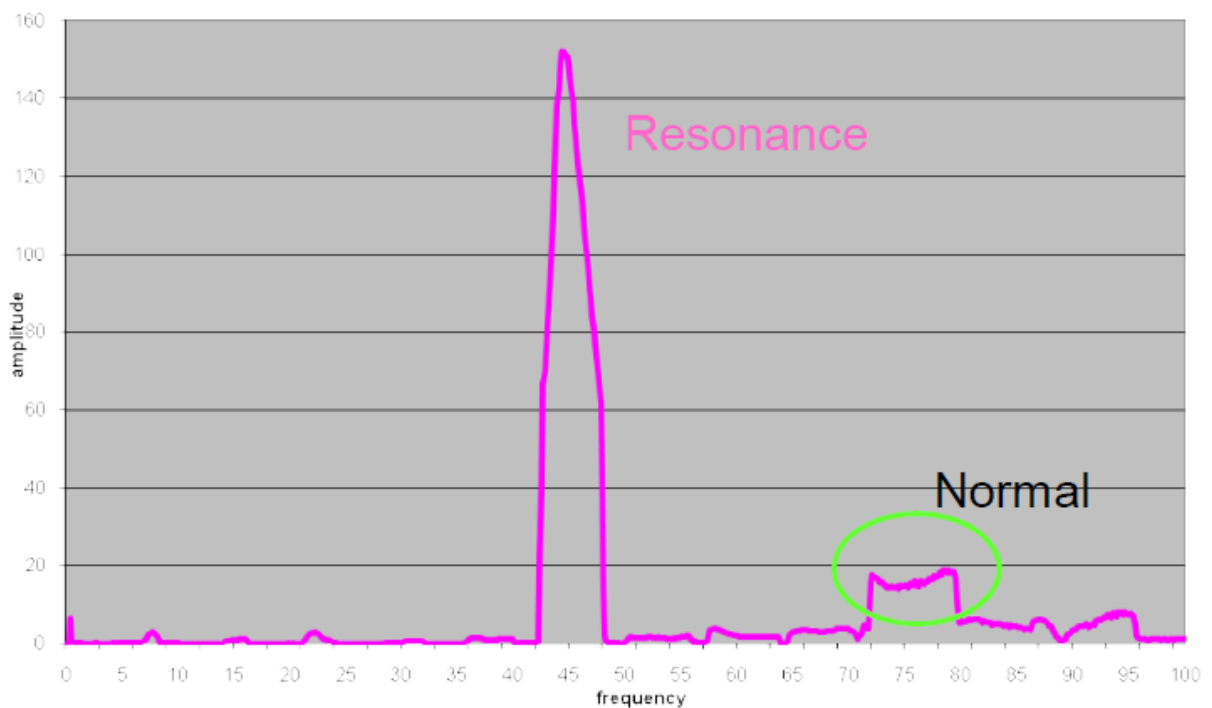


Figure 6. The resonance frequency can be clearly seen as a high peak in the spectrum. [5]

## 2.2 Vibration parameters

When measuring vibrations different vibration parameters could be used. *Displacement* measured in mm should be used when the frequency is low, 30 Hz and below. This is good if you want to know how much the structure is moving. *Velocity* measured in mm/s should be used when the frequency is 10-300 Hz. When measuring velocity the low and high frequencies correspond to a given energy level meaning that the frequencies are equally weighted from a vibration energy point of view. This is the recommended way of measuring vibrations on a Wärtsilä engine. *Acceleration* measured in mm/s<sup>2</sup> should be used when the frequency is 100 Hz and up. These measurements are weighted towards measurements on high frequency components. On a Wärtsilä engine the vibrations of the turbos are measured in acceleration. [5]

The mathematical relationship between displacement  $x(t)$ , velocity  $v(t)$  and acceleration  $a(t)$  is described by the following formulas:

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

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

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

It can also be more simply defined by:

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

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

[5]

## 2.3 Time signal versus spectrum

Measurements are always done as a time signal. It does not matter whether you are measuring displacement, velocity or acceleration; they are all measured as time signals. The time domain or the time history does not give us much of value and is hard to read. We do, however, get the peak-to-peak value of the vibration from the time history. If we further analyze the time signal (or history), we get a spectrum consisting of sinusoid peaks with their own amplitude and phase.

Jean-Baptiste Fourier developed the Fourier analysis in 1807. This gives us the mathematical connection between time and frequency and, if given a time signal, allows for calculation of the spectra.

The Fast Fourier Transform (FFT, 1967) is a fast way to calculate the Discrete Fourier Transform (DFT). Analyzers using FFT are widely used in vibration analysis.

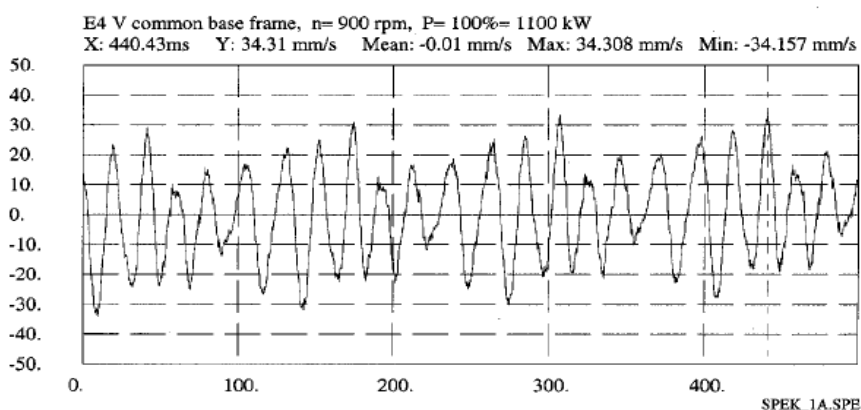


Figure 7. Time signal of point E4 before FFT analysis [5]

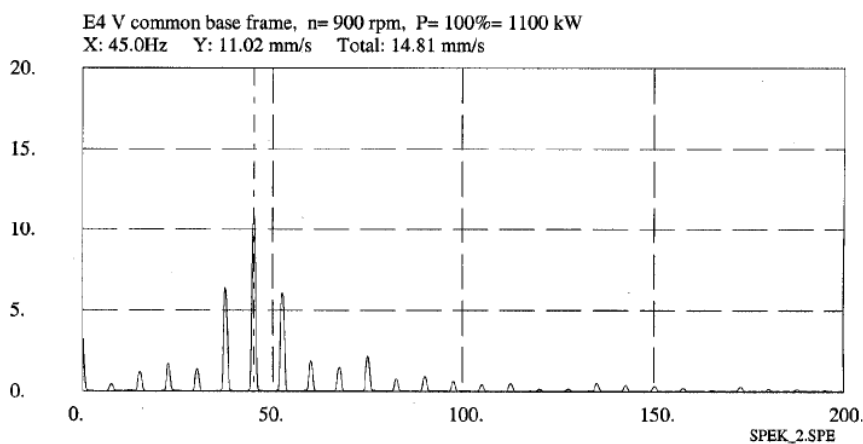


Figure 8. After the time signal has gone through the FFT analyzer we get this spectrum of point E4 [5]

## 2.4 International standards

The standards mainly used by Wärtsilä are **ISO 8528-9** (measurement and evaluation of mechanical vibrations), **ISO 10816-6** (reciprocating machines with power rating above 100kW) and **ISO 6954-2000** (guidelines for the measurement, reporting and evaluation of vibration with regard to habitability on passenger and merchant ships).

**ISO 8528-9** gives us basic knowledge about how and where to measure the engine. Measurements should be taken in the x, y and z axis of the engine, and at measurement points at top front and back and bottom front and back of the engine as well as at the base of the generator. The bearings of the generator should also be measured. The standards also state that measurements should be taken at the operating temperature at both zero and rated power. Vibration levels on an RIC engine (Reciprocating Internal Combustion) should be between 2Hz and 300Hz but, when considering the whole system of the genset, it should be measured in 2Hz to 1000Hz. Wärtsilä gensets are mostly arranged in the A.3 configuration of this standard, meaning that the engine and generator are rigidly mounted on a resiliently mounted base frame, connected with a flexible coupling. [6]

**ISO 10816-6** applies to engines above 100 kW, but not to engines in road vehicles such as passenger cars, trucks and tractors etc. This standard also states that vibrations should be measured in the range from 2Hz to 1000Hz. The result of the measurement should be given as an RMS value of displacement, velocity and acceleration with an accuracy of  $\pm 10\%$  over the range from 10Hz to 1000Hz and the accuracy of  $\pm 10\%$  over the range from 2Hz to 10Hz. The vibrations should be measured in the x, y and z axis and on several points on both sides of the engine. The first point should be on the base level of the engine block, the second on the same level as the crankshaft and one on top of the engine block. This should be repeated on the coupling end of the engine, in the middle of the engine and on the free end of the engine. When the measurements are being taken the engine should be at operating temperature. The severity of the vibrations should be measured as overall (broadband) RMS values of displacement, velocity and acceleration. The severity grade for each of the highest overall RMS values for displacement, velocity and acceleration shall be obtained. The highest of these values is the vibration severity grade of the machine. [7]

**ISO 6954-2000** deals with the effects of vibrations on ships on humans. Measurements shall be done in enough places so you get an idea of the vibration levels in the whole ship. Measurements are required in all three directions and on at least two places on each deck with a frequency range from 1Hz to 80Hz. Each measurement must last at least one minute, two minutes if there are significant frequencies below 2Hz. The results must be given in RMS values. [9]

### 3 Measurements

The measurements are performed on different points on the engine. The engine block, the generator and the common base frame have specific measurement points. The auxiliary equipment on the engine, pumps, filters etc. are also measured. When measuring the engine the crankshaft of the engine shall always be in the longitudinal direction, but when measuring on the turbocharger the TC shaft shall be used as the longitudinal direction.

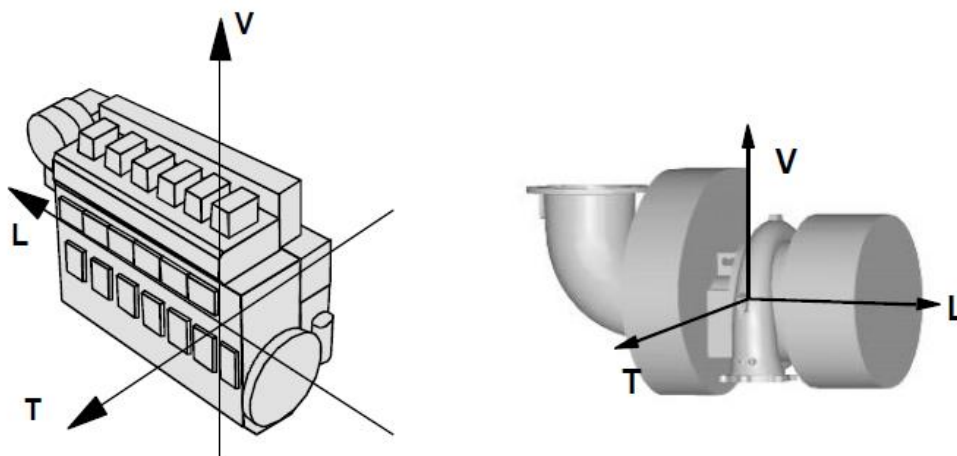


Figure 9. Longitudinal, transverse and vertical directions on the engine and the turbocharger [5]

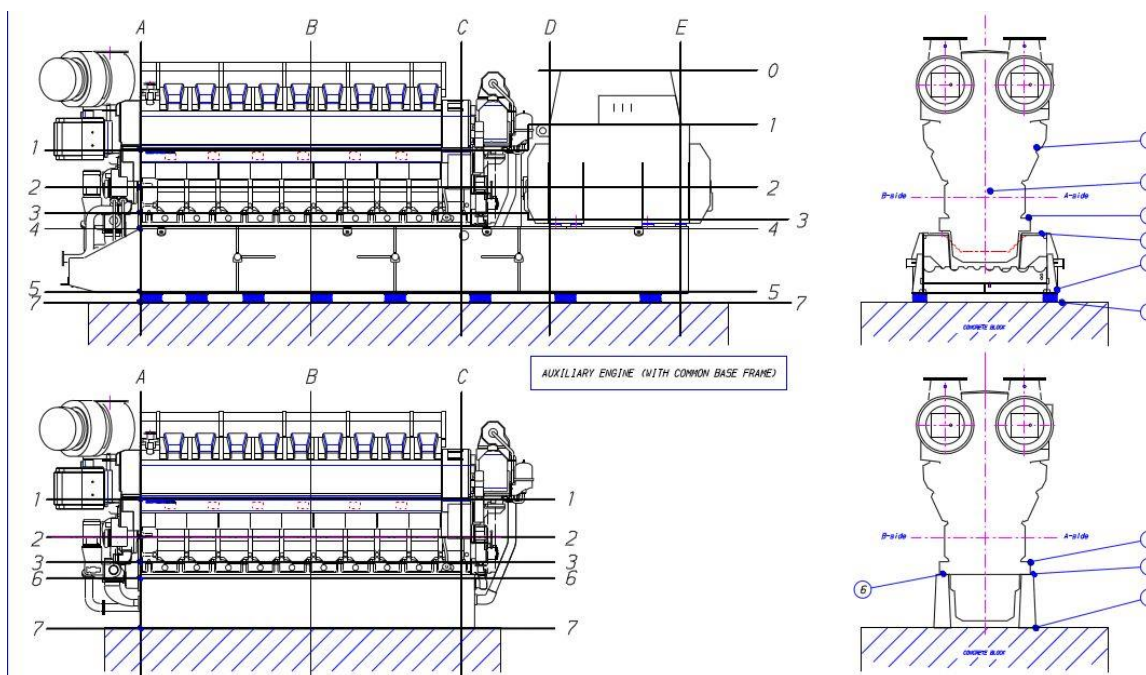


Figure 10. Measurement points on a W32/34 V-engine. [22]

### 3.1 Accelerometer

Accelerometers are used to pick up the vibrations from the object that is being measured. They can be simple hand-held accelerometers that only measure in one direction or more complicated accelerometers measuring in all three directions.

Depending on the frequency there are a couple of different ways to mount the accelerometers onto the object of measurement. The accelerometers can be stud mounted, which can handle vibrations of up to 50 kHz. [17]. They can be glued to the object and can then be used for vibrations of up to 2-5 kHz depending on the glue frequency [5]. Wärtsilä usually uses magnetically mounted accelerometers when performing measurements. If the surface that is being measured isn't magnetic, a small piece of metal is glued to the surface so that the magnet can stick on. Magnetically mounted accelerometers can be accurately used up to 2-3 kHz. [5]. The last way of mounting the accelerometer is by hand. This isn't very accurate and one can only measure frequencies of up to 1 kHz. [5]



*Accelerometers used by Wärtsilä. The two in the front row measure vibrations in all three directions, the ones in the back row only measure one direction. The one at the back to the right needs an amplifier. All accelerometers in the picture are mounted onto magnets.*

### 3.2 Analyzer

Wärtsilä uses the OROS 34 multichannel FFT analyzer and a Benstone portable analyzer. These are used to analyze the time signal from the measurements. The Oros 34 must be connected to a computer while the Benstone can be used as it is. The Oros has eight channels and an output channel while the Benstone has four channels. Both are used to record data that later can be analyzed, but with the Oros you can analyze in real time on the computer while the measurements are being done. The Benstone is more like a recorder. You can see an FFT spectrum on the screen but you cannot modify anything. The Benstone is good for doing simple and quick vibration measurements because it's hand-held.



*Figure 11. Oros 34 Multichannel FFT analyzer [18]*

**Impaq**  
4 Channel Dynamic Signal Analyzer

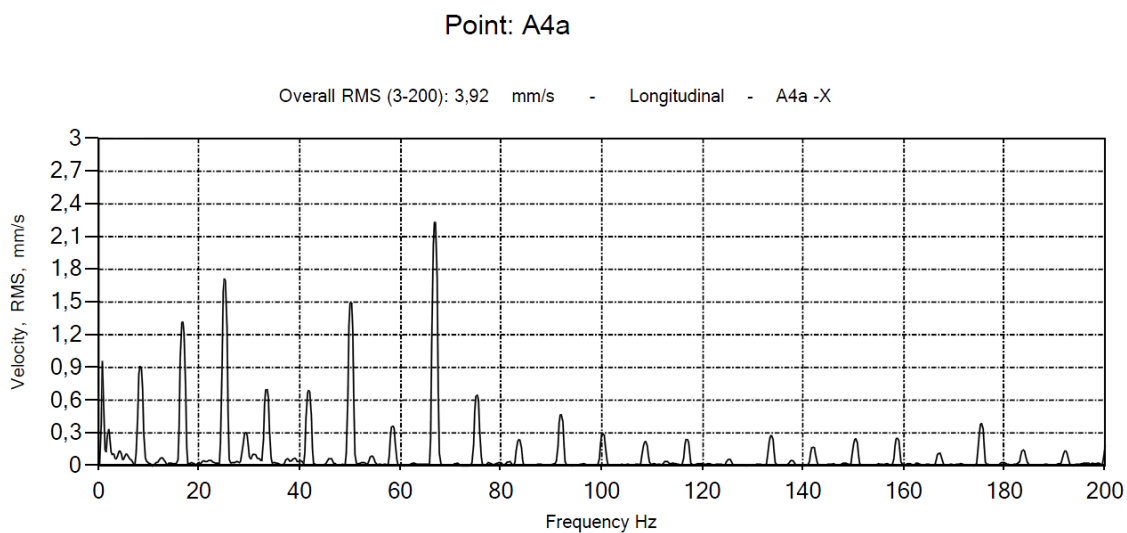


*Figure 12. Benstone Impaq portable FFT analyzer [19]*



### 3.3 Spectrum

The spectrum is the analyzed time signal in frequency level after the FFT analysis. The spectrum shows the amplitudes and frequencies of the vibrations. The values are shown either as RMS values or Peak values. In the spectrum you can see where you have the highest amplitudes and at what frequency. Every peak in the spectrum is an excitation from the engine. If one frequency is very dominant it normally means the structure is resonating at this frequency. If you have high vibration levels on an engine it is very important to know the frequencies. The frequencies will give information about the engines and help you understand how the structure is moving, and then you can solve the problem. [25]



*Figure 13. Spectrum at 100% load at measuring point A4a on the engine.*

### 3.4 Sweep

Sweeping is done to find both the low and the high natural frequencies on different engine speeds and loads. With a sweep you can make sure that there are no resonance frequencies close to the different orders of the engine. Different vibrations can have different peaks that are not in phase with each other; the spectrum then only shows the dominant amplitude. With a sweep or waterfall you can see all the peaks. Sweeping is performed by raising or lowering the speed and the load of the engine gradually. This needs to be done to find all the critical frequencies of the system. [5]. When all the critical frequencies have been found they must be checked so that they are not close to or the same as other excitation frequencies of the engine, e.g. the firing order.

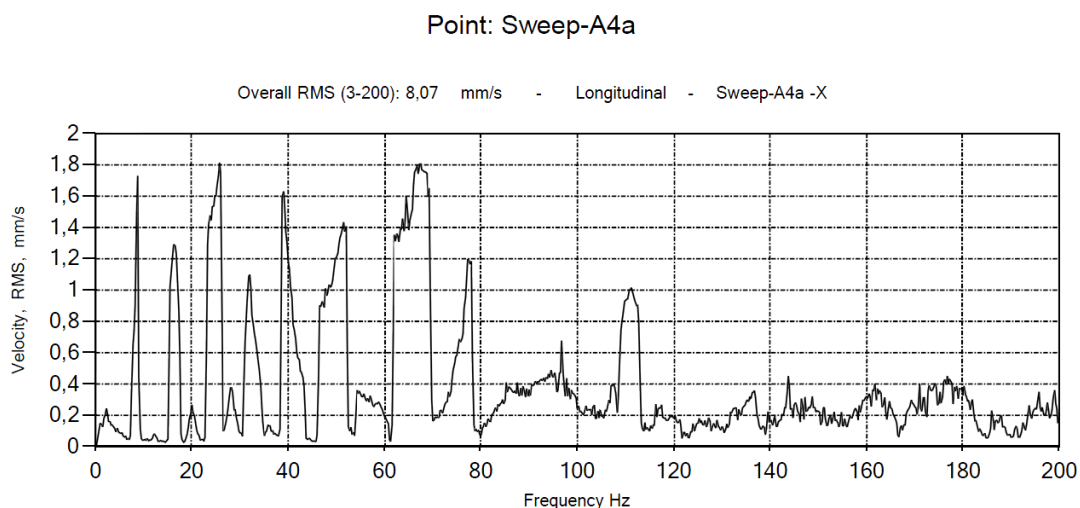


Figure 14. Sweep from 930 to 1050 rpm at 85% load at measuring point A4a on the engine

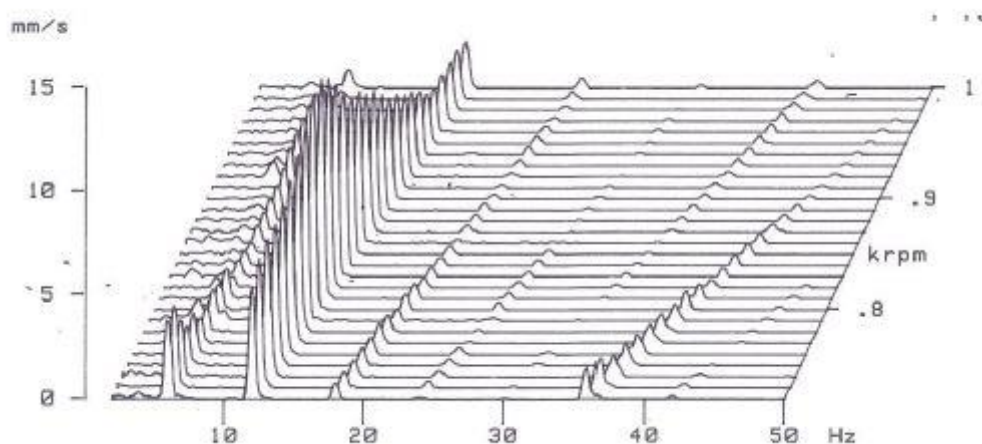


Figure 15. Waterfall spectrum of a sweep measurement [5]

### **3.5 Operation deflection shape**

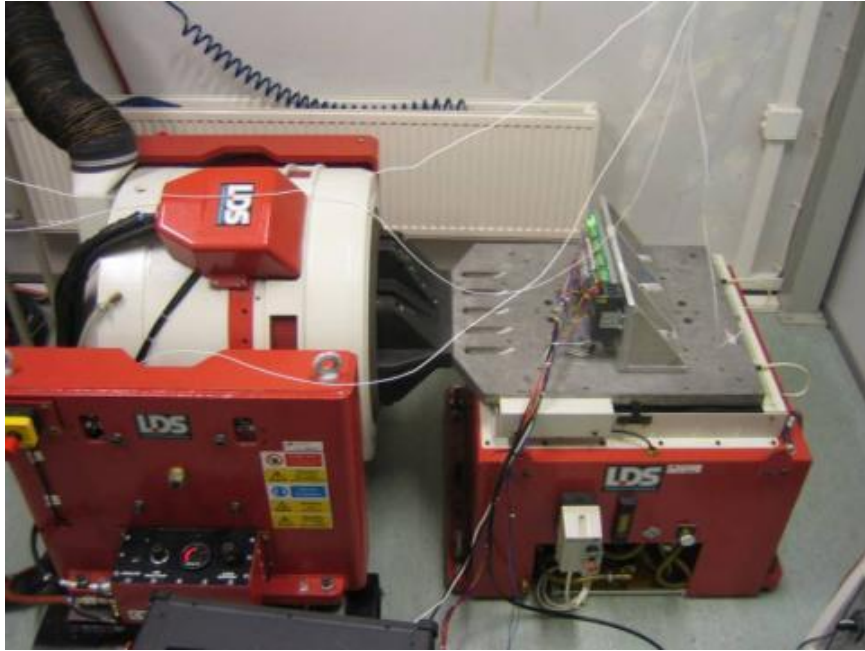
Operation Deflection Shape (ODS) is the way a structure is moving during operation, or how different parts of the structure are moving compared to each other. With ODS you can find out if the structure is moving as a rigid body or if it's moving as an elastic body. When you know how the structure is moving in the actual frequency range, it is much easier to find a remedy for any problem. The measurements from the different points on the engine can then be made into a simple model of how the engine is moving during operation. [5]

### **3.6 Modal**

The modal measurement is performed to find the natural frequencies and mode shapes of the engine. The modal measurement is performed by placing a sensor on the object being measured and hitting the object with a hammer also connected to a sensor. This gives you an impact force from the hammer and a response on the structure. It's a quick way to find the natural frequency of a structure. [21]

### 3.7 Shaker

The purpose of a shaker measurement is to find the natural frequency of a component or even the whole engine. If it is a small component it can be placed on a shaker table. When performing a shaker test on a whole engine a hydraulic cylinder is attached to the engine and is made to vibrate randomly. This is very similar to the modal test but will give you a better result.



*Figure 16. Component on a shaker table. [5]*



*Figure 17. Shaker test of a complete Genset, using a hydraulic shaker [5]*

## **4 Wärtsilä vibration guidelines**

In this chapter I will go through the acceptable vibration levels on different mechanical and electrical parts of the engine. These levels originate in the many years of experience of their engines found at Wärtsilä, but also in the acceptable levels stated in the ISO standards. The chapter also includes a short summary of previous research in the subject.

### **4.1 Earlier research**

You can say that Wärtsilä has been researching vibrations ever since the sixties when they started measuring vibrations on the engines. In the eighties Wärtsilä started analyzing the vibrations.

In 2009, Mr. Mohd Afzal wrote his Master of Science thesis in sound and vibration at Kungliga Tekniska Högskolan, KTH in Stockholm, Sweden. The thesis entitled “Flexible Mounting System Design, Theory and Practice” was done on behalf of Wärtsilä. The focus of his thesis was on finding suitable vibration isolators and a good way to isolate the electronic box from the engine excitations. The electrical box contains critical control systems needed when running the engine.

### **4.2 Wärtsilä standard/acceptable vibration levels**

The maximum allowed vibration level on a Wärtsilä engine complies with ISO 10816-6. According to the ISO 10816-6 vibration severity grade 18, the overall vibrations of the engine should be kept under the values mentioned in severity grade 18. Severity grade 18 states that overall vibrations should be kept under 283  $\mu\text{m}$  (RMS) displacement, 17.8 mm/s (RMS) velocity and 27.9  $\text{m/s}^2$  (RMS) acceleration. These severity grades must be used in the frequency range of 2Hz to 1000 Hz. [Email Discussion 30.1.2014]

The typical overall vibration level on the engine block of a W20 engine is 15 mm/s, on a W32/34SG L-engine it is 12 mm/s and on a W32/34SG V-engine 10 mm/s (RMS: 3-200Hz).

The typical overall vibration level on the common base frame of a W20 engine is 12 mm/s, on a W32/34SG L-engine it is 12mm/s and on a W32/34SG V-engine 10 mm/s (RMS: 3-200Hz). See Appendices 1 and 2

#### **4.2.1 Mechanical components**

The ISO standard 10816-6 gives acceptable vibration levels for a few components mounted on the engine, but, for the ones not listed in the standard, Wartsila has some typical overall vibration levels for different mechanical and electrical components mounted on the engines. See appendices 1 and 2

##### **4.2.1.1 Turbo charger and filter/suction**

The turbocharger and filters are measured in both acceleration and velocity, acceleration in the 3-1000Hz range and velocity in the 3-200Hz range. The accepted vibration level on the turbo charger filter is for the W20 and W32/34 engines 75 mm/s (RMS) velocity and 4g acceleration. The accepted vibration level on the turbo charger itself for the W20 and W32/34 engines is 55 mm/s (RMS) velocity and 4g acceleration. If a turbocharger has a higher acceleration value than 4g, it states that the turbocharger is unbalanced. The typical vibration levels for both the W20 and W32/34 engines are well below these values. See appendices 1 and 2

#### **4.2.1.2 Other mechanical components**

The vibration levels on these components are measured in mm/s velocity in the 3-200Hz range. The acceptable vibration level on the lube oil module (LOM) and on the air cooler housing (ACH) on the W20 and W32/34 engines is 35mm/s (RMS). The acceptable vibration level of pumps, filters and low-pressure pipes is for the W20 and the W32/34 engines 55 mm/s (RMS). The acceptable vibration level on high-pressure pipes on the W20 and the W32/34 engines are 80mm/s (RMS). For non specified components on the engines the acceptable vibration level is 80 mm/s (RMS). The vibration levels on the W20 and W32/34 engines are below these values. See appendices 1 and 2

However, when measuring pipes the measurement could be done in the velocity range of 3-300Hz. Before Wärtsilä started using high-pressure common-rail systems the range of 3-200 Hz was good, but because of the high-pressure common-rail systems you can have excitations in higher frequencies than 200 Hz. [Discussion with Mr. Claus Paro]

#### 4.2.2 Electrical components

The different electrical parts mounted on the engine are of course vibrating with the engine at different amplitudes and frequencies. Wärtsilä has many years of experience of vibrations on their engines and has set some vibration levels adjoining with ISO 10816-6 that used to be considered acceptable vibration levels. The displacement level in the 2-10 Hz range is for an Isolated Electrical Component (IEC) 0.5mm (RMS), and for a non-IEC 1.1mm (RMS). The upper velocity allowed in the frequency range of up to 200 Hz is 30mm/s (RMS) for an IEC and for a non-IEC 80mm/s (RMS). The highest acceleration value for an IEC in the 200Hz to 1 kHz range is 3g (RMS) and for a non-IEC 10g (RMS). However, any single frequency component exceeding 75% of the RMS value isn't allowed. The maximum limit for a single acceleration component is 2.5g in the range from 0.2 to 0.5 kHz, and 5g in the range from 0.5 to 1 kHz and 10g in the range from 1 kHz to 2 kHz. See appendix 2.

However, these levels may need to be reconsidered as Mr. Afzal states in a report written after a shaker test on a pressure sensor performed at Technobotnia on 25-26 February 2013.

Typical vibration levels for an IEC on the W20, V and L W32/34SG is 25 mm/s (RMS), for a non-IEC on the W20 35mm/s (RMS) and on the V and L W32/34SG 40 mm/s (RMS). See appendix 1.



### 4.3 Natural frequencies of different components

The natural frequencies of different components can be mathematically found with a FEM analysis, or with a shaker test or a modal, hammer, test. The natural frequency of a single component is needed to make sure it is not close to one of the orders of the engine. When you know the natural frequency of a component you can more easily choose the correct damper for the component. As a rule of thumb the natural frequencies of the different parts must be above the firing order of the worst engines or above 75Hz; in most cases this will be on the safe side.

For example the order for the firing frequency of a W20V32 is the number of cylinders on one bank divided by 2, or 5 in this case. So depending on if the engine is running at 720rpm, 12Hz, or 750 rpm, 12.5Hz, the natural frequency of the component must be above  $5 \cdot 12\text{Hz} = 60\text{ Hz}$  or  $5 \cdot 12.5\text{Hz} = 62.5\text{ Hz}$ . But 75Hz is the number to use. [Discussion with Mr. Kari Saine]

#### 4.4 Test components/shaker table test

When performing a shaker test Wärtsilä has a few demands that need to be fulfilled. The shaker test must consist of two tests. The first one should consist of a sine sweep from 10Hz to 140 Hz, 10 minutes per sweep for a total of six hours. This must be done in all three directions. At different frequencies different velocities and accelerations must be used.

Table 1. Test levels of velocity and acceleration at different frequencies

Frequency, Hz	Velocity, mm/s (rms)	Acceleration, m/s <sup>2</sup> (peak)
10	20	0,18
40	40	1,3
100	40	3,54
140	10	1,24

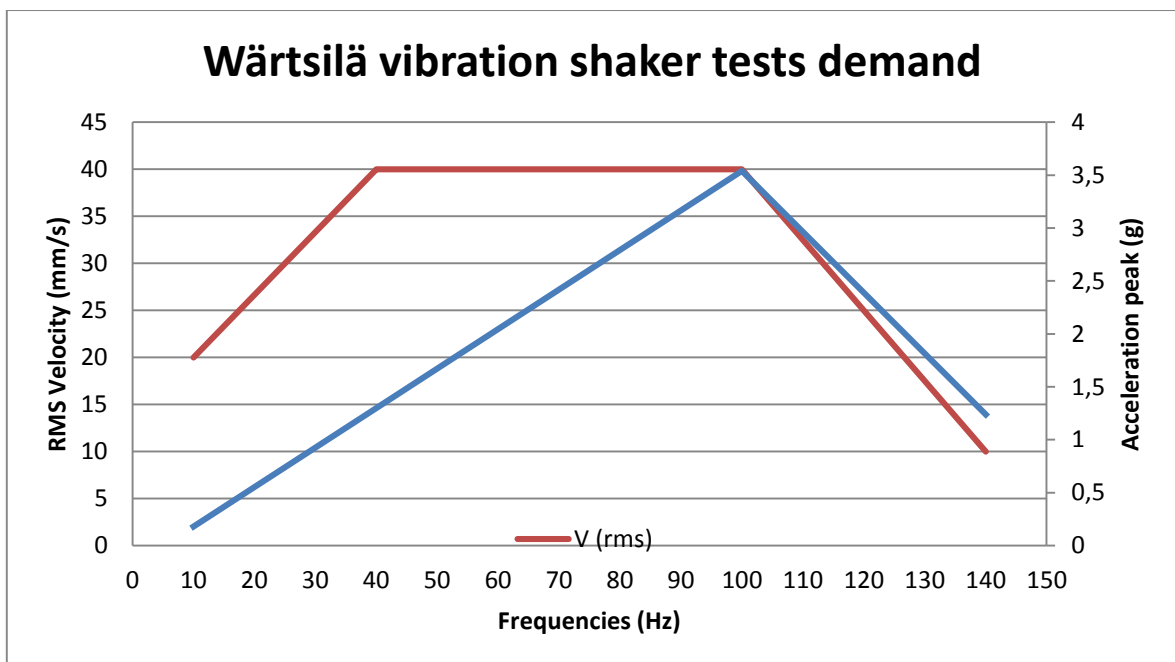
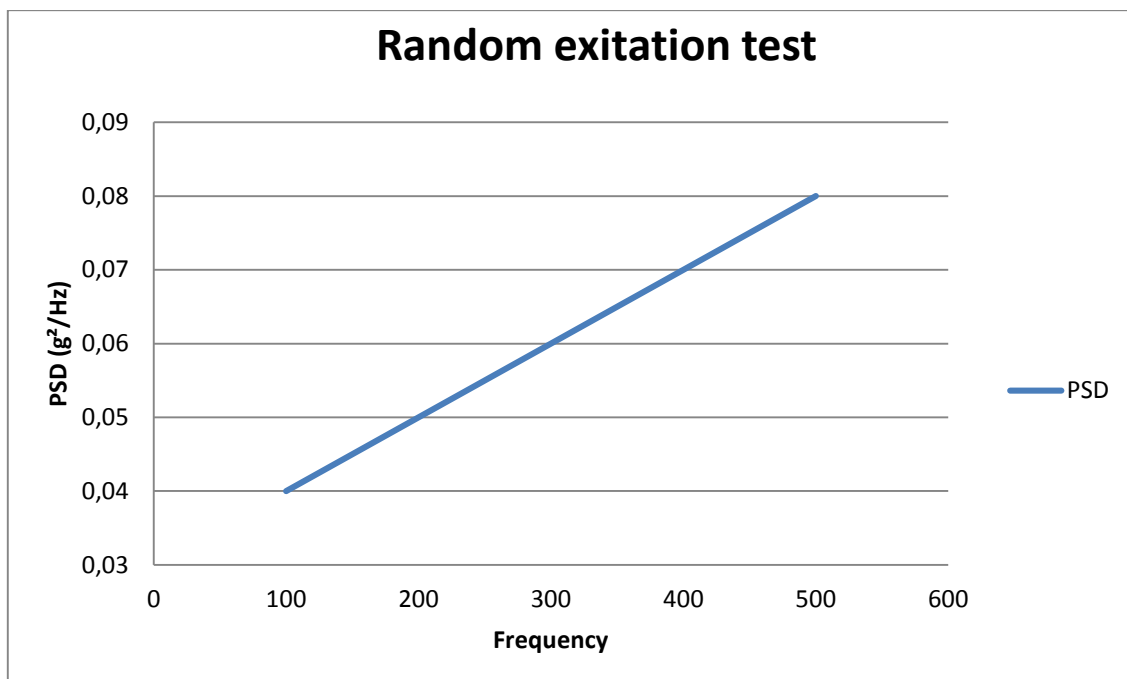


Figure 18. Test curve of the values given in table 1.

The second test should consist of a random excitation test from 100 Hz to 500 Hz. One direction should be tested for six hours and all three directions should be tested.

*Table 2. PSD values at different frequencies.*

Frequency	PSD ( $\text{g}^2/\text{Hz}$ )
100 Hz	0,04
500 Hz	0,08



*Figure 19. Test curve of values given in table 2.*

#### 4.5 Testing of electrical/automation components

According to a report written by Mr. Afzal, the standard IEC 60068 used today for deciding acceptable vibration levels on automation parts by Wärtsilä is not good for measuring automation parts on four-stroke diesel engines. The measurement frequencies mentioned in IEC 60068 are very low, only up to 100Hz. Wartsila has found that when an electrical or automation part breaks it is at significantly higher frequencies, at about 400 to 500 Hz. This statement was removed in a later revision of the report. In the future electrical and automation parts should be tested according to chapter 4.4 in this guideline.

## **5 Method**

This chapter describes the realization of the project and my working process writing the thesis.

In September 2013, I was given the task of writing a simple guideline for measuring vibrations on Wärtsilä engines. I was also to give clear vibration limits on the engines.

### **5.1 The Excel sheets**

I started by filling in two Excel sheets, one with the Wärtsilä W20 engines and one with the Wärtsilä W32/34 engines. Wärtsilä has conducted a lot of measurements on their engines so there are a lot of vibration data available. To fill out the excel sheet I took a measurement report, typed in the engine name, the serial number, the power rating and how it was mounted. For each measurement point on the engine there are three vibration values, longitudinal, transverse and vertical vibrations. These were filled into the Excel sheet for every measured point on the engine. When there are enough measurement data for a point on an engine, Excel calculates the mean value and the standard deviation.

These values will be used as a reference to what can be considered normal vibration levels for each point on each type of engine.

### **5.2 The theory**

When I started writing I began with the theory. After discussions with my supervisor at Wärtsilä, Mr. Kari Saine, I got an idea as to which vibration theory needed to be included in the thesis. The theory needed to contain the absolutely basic vibration theory like amplitude, frequency and phase, but also some more advanced theory about measurements and the analysis of the results. I had found some of the theory from the internet, from the manufacturers of the measuring devices but mostly from the book “Harris shock and vibration handbook, fifth edition” by Cyril M. Harris and Alan G. Piersol. The guidelines must also follow the ISO standards to some extent. Wärtsilä mainly uses ISO-10816-6, ISO-6954 and ISO-8528-9. However, some of the levels in the ISO standards could not be directly applied on the Wärtsilä Vibration Guidelines.

### 5.3 ISO standards

On the engine itself Wärtsilä uses the vibration severity grade 18 from ISO 10816-6 as an acceptable vibration level, but since ISO 10816-6 mostly covers vibrations on the engine block only, all mechanical and electrical components mounted on the engine need to have an acceptable vibration level of their own. Wärtsilä has made a table of which components on the engines belong to which vibration severity grade adjoining ISO-10816-6, e.g. the turbocharger has an acceptable vibration severity grade of 71 while the common base frame uses grade 18. The standards fulfill most of Wärtsilä's demands but not all of them, so in some areas Wärtsilä needs to come up with their own standards. Electrical components used to be classified under grades 28 and 71 depending on if they were isolated from vibrations or not, but Mr. Afzal came to the conclusion that Wärtsilä needs to come up with their own vibration levels for the electrical components. This is the only case that differs from the ISO standards.

## 6 Results

The result of this thesis is basically the thesis itself as it will be used as the guideline. I have collected the number of guides that were already available at Wärtsilä into one document, which was the purpose of the thesis from the beginning. In this thesis I have gathered basic vibration theory to get a basis for the guideline and some more advanced theory needed when analyzing a vibration measurement. The equipment used by Wärtsilä when performing vibration measurements is also presented in the thesis. The acceptable vibration levels needed to have a base in the standards given by the different classification societies. The standards mainly used by Wärtsilä for their engines are ISO 8528-9, ISO 10816-6 and ISO 6954-2000 and I found that they work well with the demands made by Wärtsilä. However, it was found out that when testing automation components for the engines, the testing standard IEC 60068 was not good enough for Wärtsilä's demands so Wärtsilä will write their own standards for testing automation components. The acceptable vibration levels for a Wärtsilä engine adjoining ISO 10816-6 can be found in appendix 2 and the typical vibration levels on Wärtsilä engines based on years of vibration measurements can be found in appendix 1.

## 7 Conclusions

The goal of this thesis was to write an updated guideline where Wärtsilä's knowledge of vibrations was to be collected in one document. The typical vibration levels on the engines have been gathered as well as the critical levels. The vibration levels in ISO 10816-6 are still acceptable for the mechanical components on the engine. We have found that the old way of performing shaker tests according to standard IEC 60068, on electrical and automation components is not good enough for Wärtsilä's use and Wärtsilä has come up with a new way of testing these components. See chapter 4.4. This will lead to new demands being made on subcontractors. In some cases when measuring pipes it is necessary to increase the range of the spectra from 3-200Hz to 3-300Hz. This is needed because of the relatively new common-rail fuel-injection systems that can have excitations in higher frequencies. It has also become clear that today's international standards do not fulfill all of Wärtsilä's demands. Because of this Wärtsilä will have to make their own standard for acceptable vibration levels on their 4-stroke diesel and gas engines. Hopefully this guideline will come to good use in Wärtsilä in the future.

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Appendix 1: Typical overall vibration level (RMS:3-200 Hz) on Wärtsilä 4-stroke engines in mm/s														
Engine Type	W20/A20		W26		W32/34 SG		W38		W46		W50		W64	
	L-engine	V-engine	L-engine	V-engine	L-engine	V-engine	L-engine	V-engine	L-engine	V-engine	L-engine	V-engine	L-engine	V-engine
Engine block	15	-			12	10								
Common base frame	12	-			12	10								
Alternator	18	-			20	20								
Turbo charger filter/suction	45/2g*	-			50/2g*	45/1.6g*								
Turbo charger compressor	35/1.8g*	-			35/1.5g*	30/1.3g*								
Isolated Automation part	25	-			25	25								
Non-Isolated automation part	35	-			40	40								
Air cooler housing	20	-			18	15								
Lube oil module	25	-			30	20								
Pipes/Pumps/Filter	40	-			40	40								

\* represents acceleration level [3-1000 Hz] in m/s<sup>2</sup>.

<b>Appendix2 Wärtsilä standard for acceptable vibration levels on 4-stroke engines- adjoining ISO 10816-6</b>					
<b>Component name</b>	<b>Displacement [2-10 Hz] mm (r.m.s)</b>	<b>Velocity [10-200 Hz] mm/s (r.m.s)</b>	<b>Acceleration [200-1000 Hz] m/s<sup>2</sup> (r.m.s)</b>	<b>Vibration severity grade ISO 10816-6</b>	
Common base frame (CBF), Bearing	0,3	20	2g	18	
Engine block, Alternator & IEC	0,5	30	3g	28	
LOM and ACH	0,6	35	3g	45	
TCC,pumps, Filter & Low pressure pipe	0,9	55	4g	71	
Turbo charger filter	1,2	75	4g	71	
High pressure pipe, Automation part & Non-IEC	1,1	80	10g	71	
Non-specified components	1,1	70	8g	71	
Abbreviation: LOM=Lube oil module, ACH=Air cooler housing, TC=Turbo charger compressor, IEC=Isolated electrical component					
Note: a) Any single frequency component exceeding 75% of the r.m.s limit isn't acceptable.					
b) Max limit for single frequency acceleration component is 2.5g in the frequency range of 0.2-0.5 KHz, 5g in the frequency range of 0.5-1 KHz					