Automotive
Energy & Power Analysis
Field Service
Environmental
Research & Development

Order tracking

Manual

www.dewetron.com

About the content of this document

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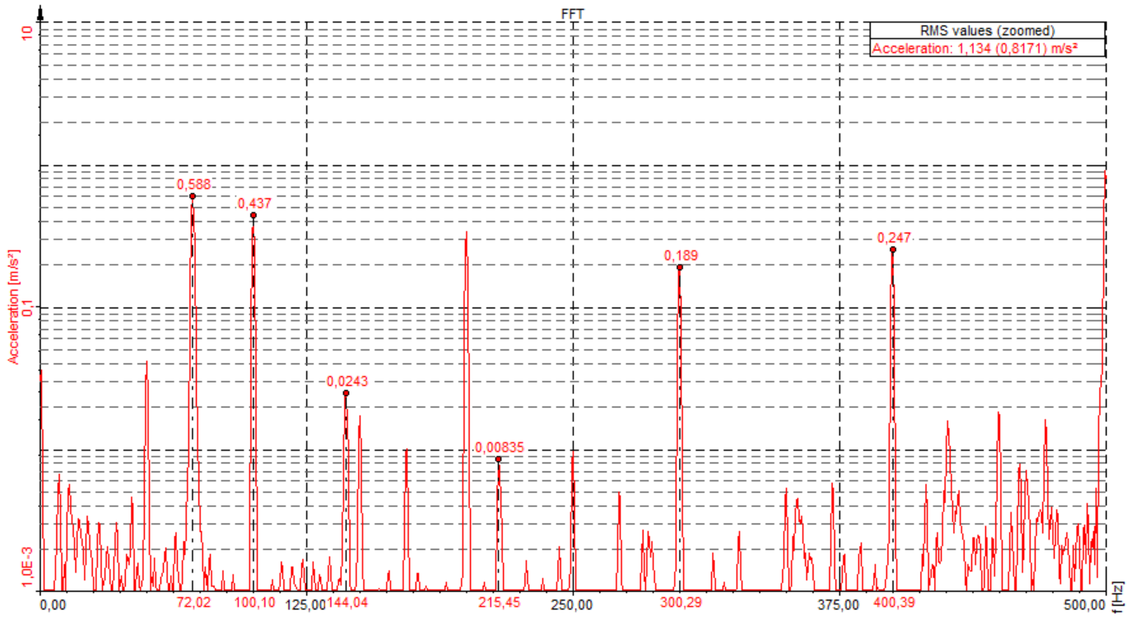
1 Introduction and Basics

Order tracking is used mainly as an analysis tool in the rotating machinery diagnostic.
Rotating machines produce vibration, which can have various reasons. Most of the time, the main vibration patterns are caused by the rotating part or parts of a machine; so belts, bearings, couplings, gear, and shafts can cause vibration.
Vibration is caused by force, which is distributed over different parts of the machine with specific transfer characteristics.
If the speed of a machine changes, also the vibration pattern will change according to the transfer curve. That's why rotating machines are checked over the full operating speed range.
As long as the frequency is stable, it would even be possible to track the frequencies with a normal FFT analysis. But this is hardly possible at run up or coast down, because the FFT spectrum is smeared. The reason why it smears is that the frequency is not stable in the analysis window used by the FFT algorithm.

That's why we have to find an analyze tool which overcomes this problem. The order tracking algorithm is designed to avoid this. So Order tracking is a tool which separates frequencies which are caused by the rotation frequency (rpm) and their multiple, even if rpm changes during analysis. These separated frequency lines, which are related to the speed of the engine, are called ORDERS.

1.1 Example manual order tracking

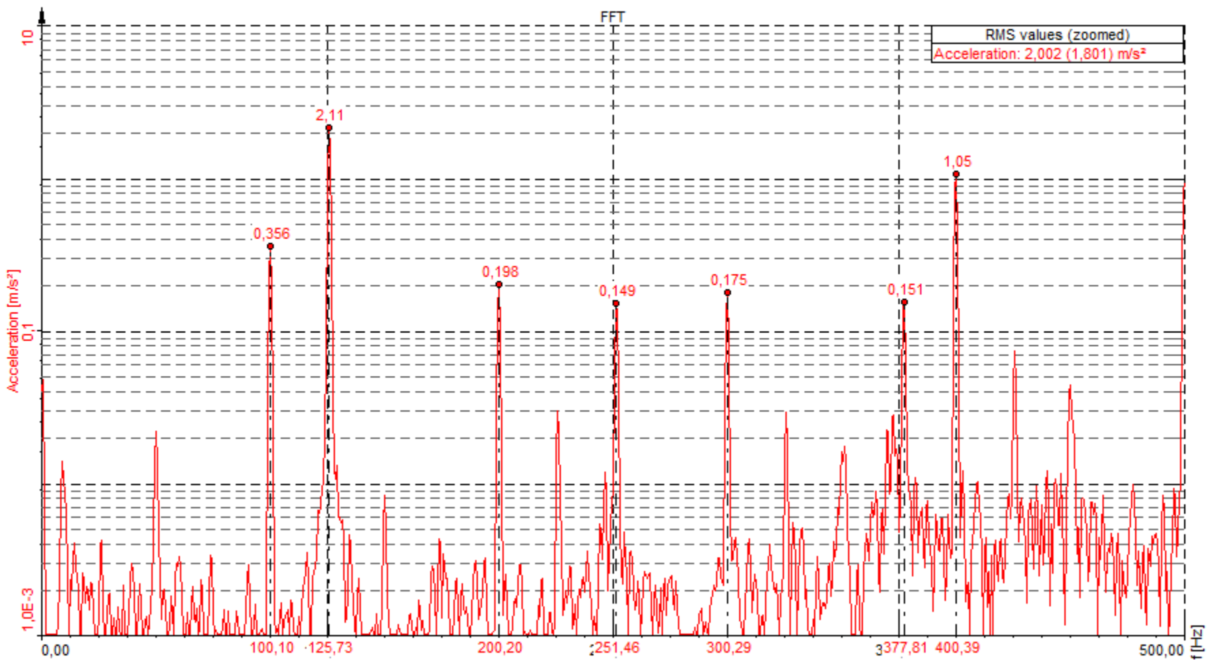
Let's assume a mixer is running with a certain speed, and we measure the vibration with an acceleration sensor.



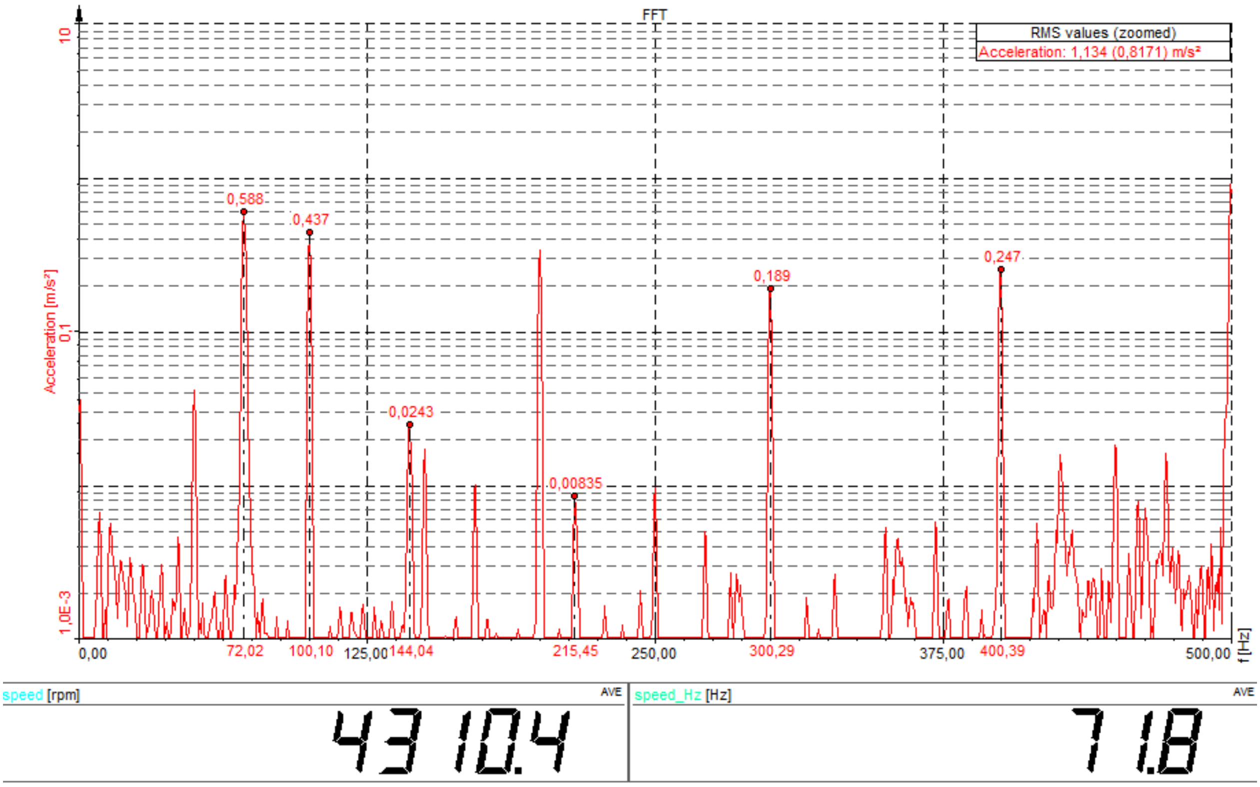
The above FFT-Spectrum is showing the vibration spectrum of the mixer.

We can see that we have significant peaks at 72.02Hz, 100.1Hz, 144Hz, … and we want to estimate where these frequencies come from?

Now let's change the speed of the mixer and let's see how the FFT spectrum changes.



In the new spectrum we can see now, that a few frequency lines disappeard (72Hz), a few did not change(100Hz), and new ones appeared (125Hz). Where does this come from?



The first spectrum was showing a peak @ 72Hz, and we would like to know where this frequency comes from, or what causes this frequency peak. If we have now a closer look to the rpm of the machine it would get much clearer.

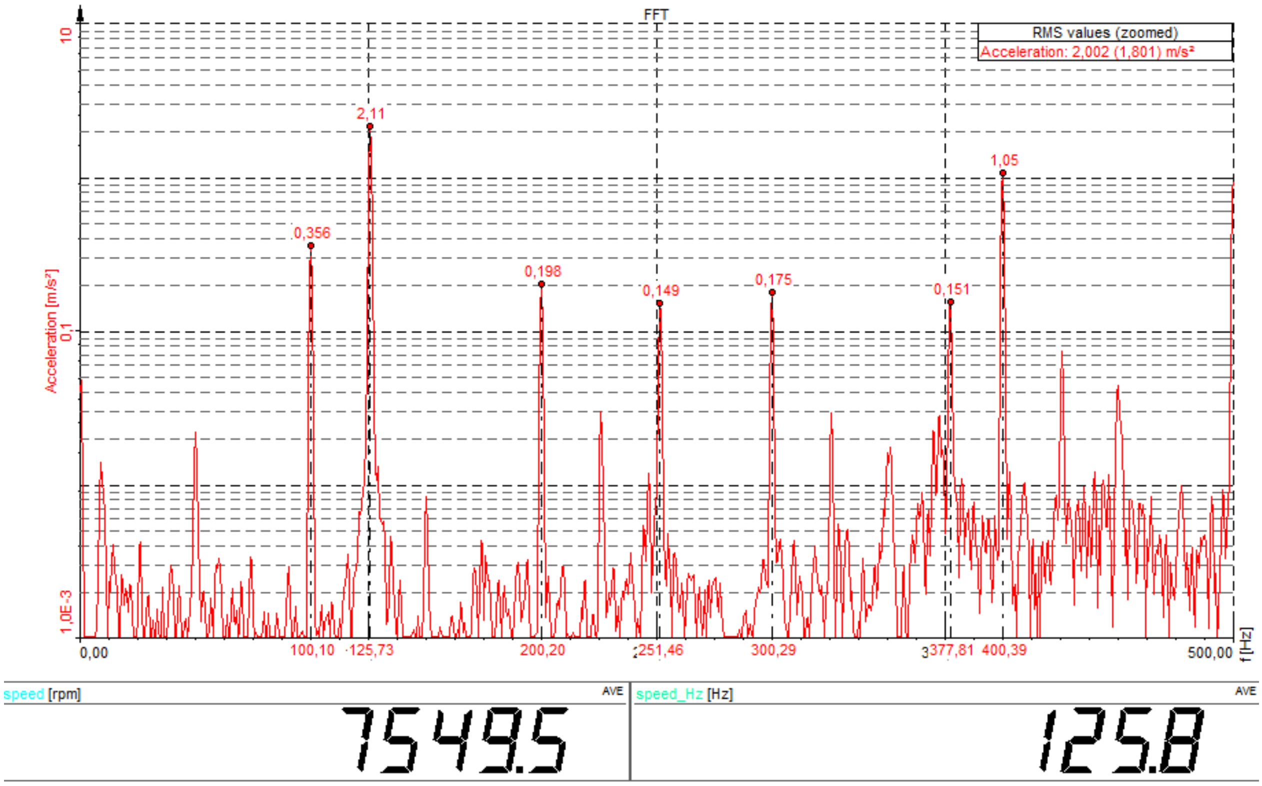
The machine is running at 4310rpm which gives a shaft frequency of 4310rpm / 60 = 71.8 rps = 71.8Hz.

rpm…..rotations per minute
rps……rotations per second

So the first peak shown here is related to the speed of the machine. So a force which runs exactly with the speed of the machine causes this vibration.

If we now take a closer look, we could even detect frequencies which are 2 or 3 times the base frequency.

71.8Hz * 2 = 143.6Hz
71.8Hz * 3 = 215.4Hz and if we would mark more peaks we would even find more frequency lines which are multiples of 71.8Hz → 4308rpm.



Now the rpm of the machine was changed and as mentioned above a few lines dissapeared, like the 71.8Hz, a few lines did not move 100Hz, and new one came up like the 125Hz.

But if we again have a look to the actual speed of the engine this become much more clear. The machine is running with 7500rpm.

7500rpm / 60 = 125 rps = 125Hz. So the actual shaft frequency is 125Hz.

If we now look closer, we will also find multiples of 125Hz, like 250Hz, 375Hz.

1.2 Conclusion

What we have done now in the above example is **manual order tracking**. So we checked the frequency spectrum at certain speeds of the machine, and manually tracked the frequencies which are related to the speed of the engine and multiples of those, and frequencies which are not related to the speed of the machine. A few frequency lines are always present, indpented from the engine spped. In the upper example the 50Hz 100Hz 200Hz 300Hz and even 400 Hz are always present. In this case this is coming from the electrical engine inside. So 50 Hz and its harmonics cause vibration, as the engine is a universal motor, which is speed controlled over voltage.

1.3 Definition

Frequencies which are related to the speed of the engines are called ORDERS.

So there is a normalisation done to the speed of the engine.

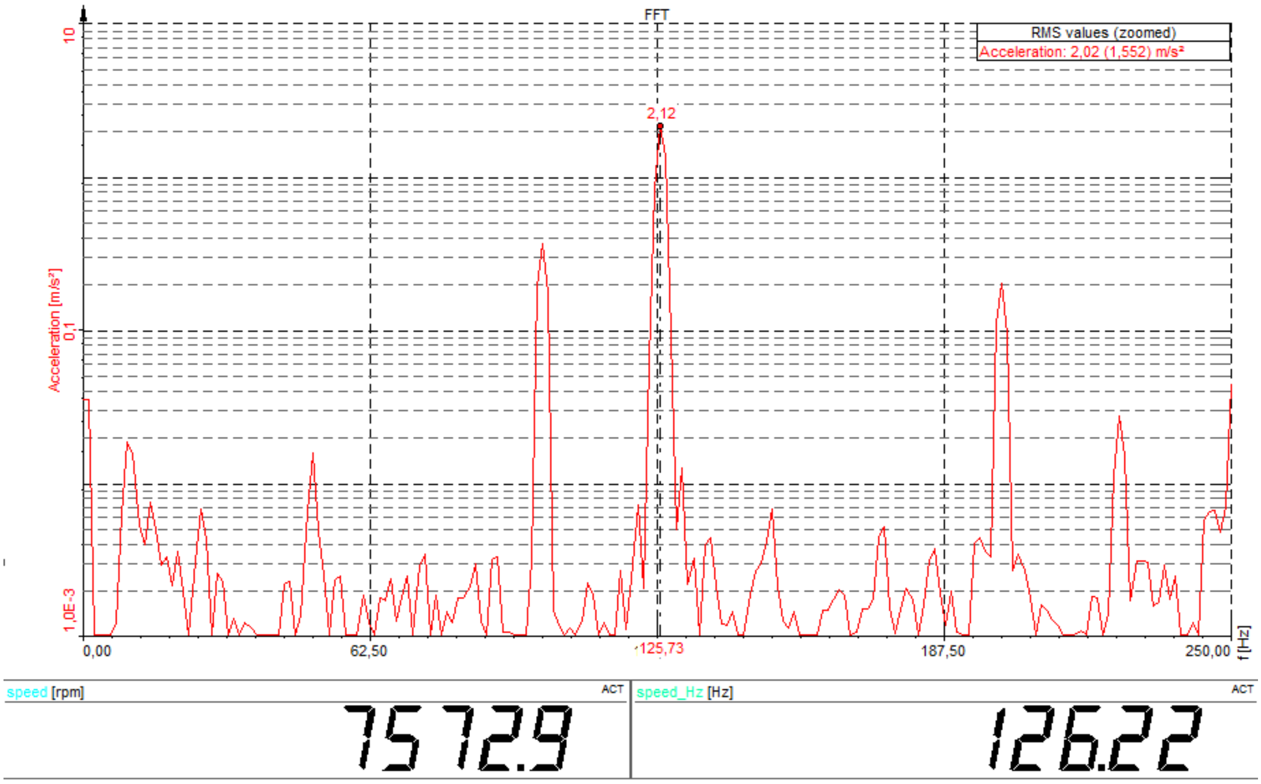
The first order of a machine is always	speed(rpm)/60 * 1
The second order of a machine is always	speed(rpm)/60 * 2 , ….

Ordertracking is used to separate frequencies which are related to the engine speed and multiples of them, and those which are related to the structure.

1.4 Why can't we use FFT

The previous examples gave us a clue what order tracking is. Now the question is why can't we use simple FFT, and track the harmonics out of FFT. The only additional signal that we need is the rpm of the engine.

In principle this is right and could be done, so at stationary speed, like we have seen in the examples above this could be done. But even there, if we have a closer look it will happen that Frequency line will not fall exactly on a FFT line. So therefore the amplitude will drop because the energy is distributed also into the neighbouring FFT lines.



So the peak of the first harmonic is located in the FFT @ 125.73Hz, but the actual engine speed is 7572rpm or 126,22Hz. So the amplitude of the first harmonic (1 Order) is not exact, because the frequency does not fall exactly on an FFT line.

If the machine would run with 125,73Hz * 60 = 7543,8 rpm, the frequency of the first order will exactly fall on an FFT line and the amplitude would be correct.

Now we could say, this error is so small, we could change the line resolution of the FFT to get 0,5 or even 0,2Hz and the error is negligible.

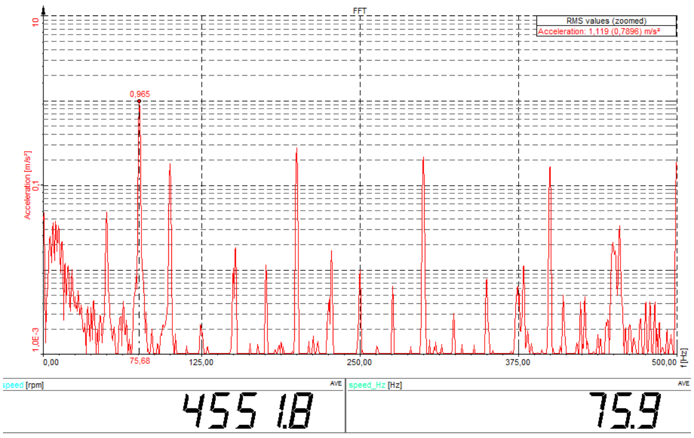
This is true and could be done @ stationary speed.

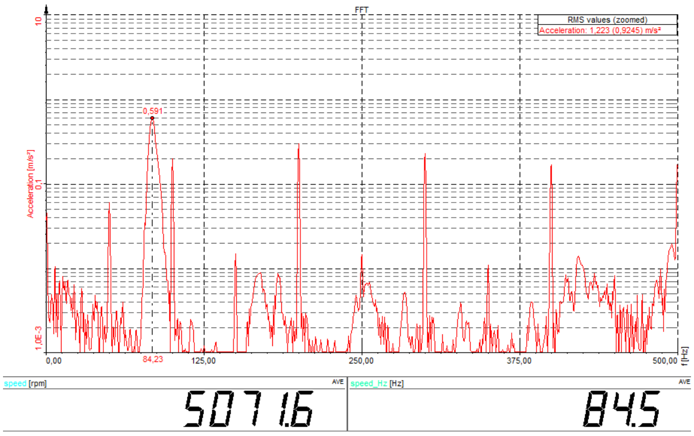
Engineers would like to get several orders 2, 4, 5, … at different speeds of the engine.
We did manual order tracking @ 2 different speeds above. But in practise it is common to track the orders in steps of 25, 50, 100 rpm, or any other step. Imagine a cars diesel engine, the speed range would be from 700rpm up to 5000rpm, if we do Order tracking of the first harmonic every 100rpm this would give us

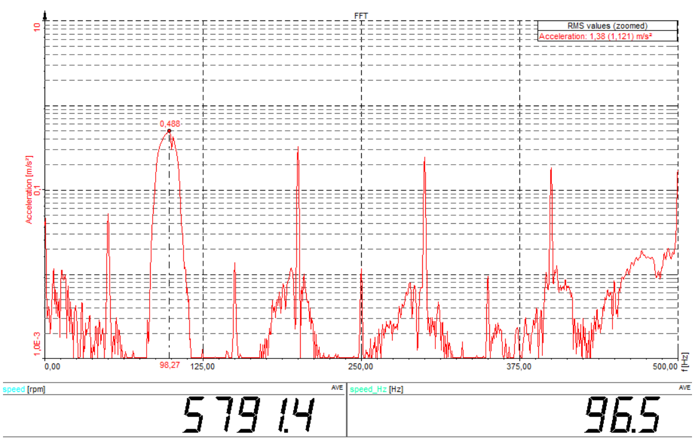
(5000rpm – 700rpm) / 100rpm= 43 points in the speed range.

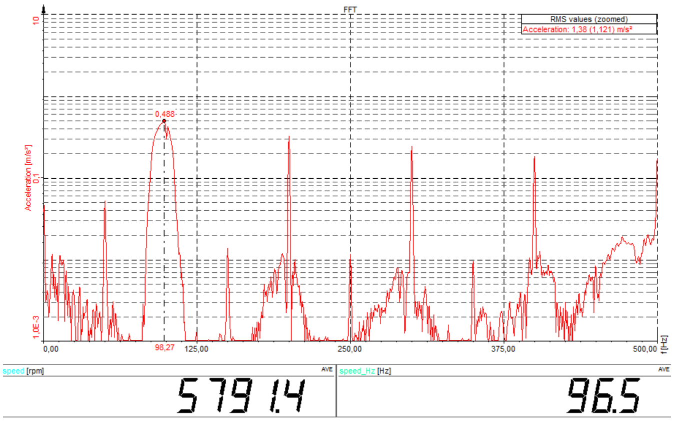
So we have to run the engine @ 700, 800, 900, 1000,…rpm and do the manual order tracking. This would take so much time that nobody would do it.

So in practise the machine is running up from 700rpm to 5000rpm in a reasonable time, and out of that the orders are calculated.







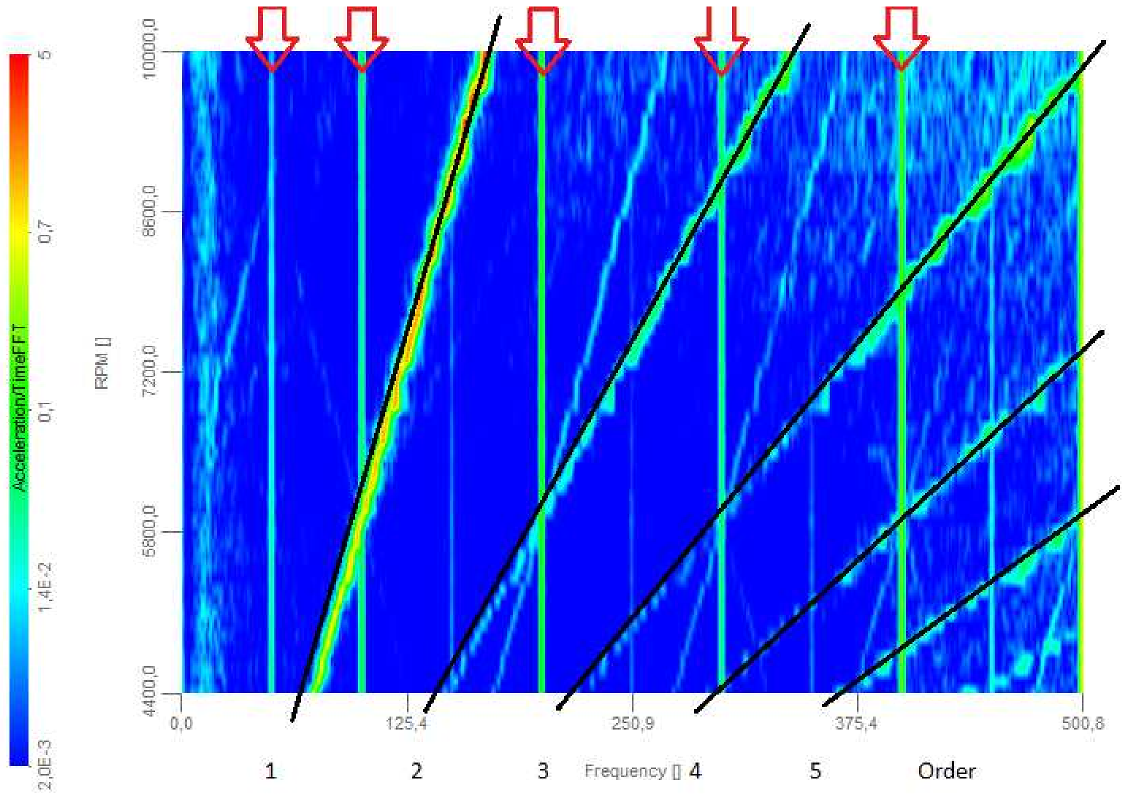


The FFT spectra above will give an example how it would look like if we do Order tracking out of FFT during a run up. At the first picture the machine is at constant speed, we could see very narrow FFT lines and could extract the orders. But during run up the peak is moving and gets smaller and wider. This is caused by continuously changing engine speed during FFT analysis. So that's an other reason why FFT is not useful to do Order tracking.

1.5 Order tracking basic displays

As described above, order tracking is done during a run up or coast down of a machine.
So the engineer would like to see the vibration spectrum in frequency domain, over the engine speed, and also extract specific orders over RPM.

1.5.1 Time FFT Waterfall diagram



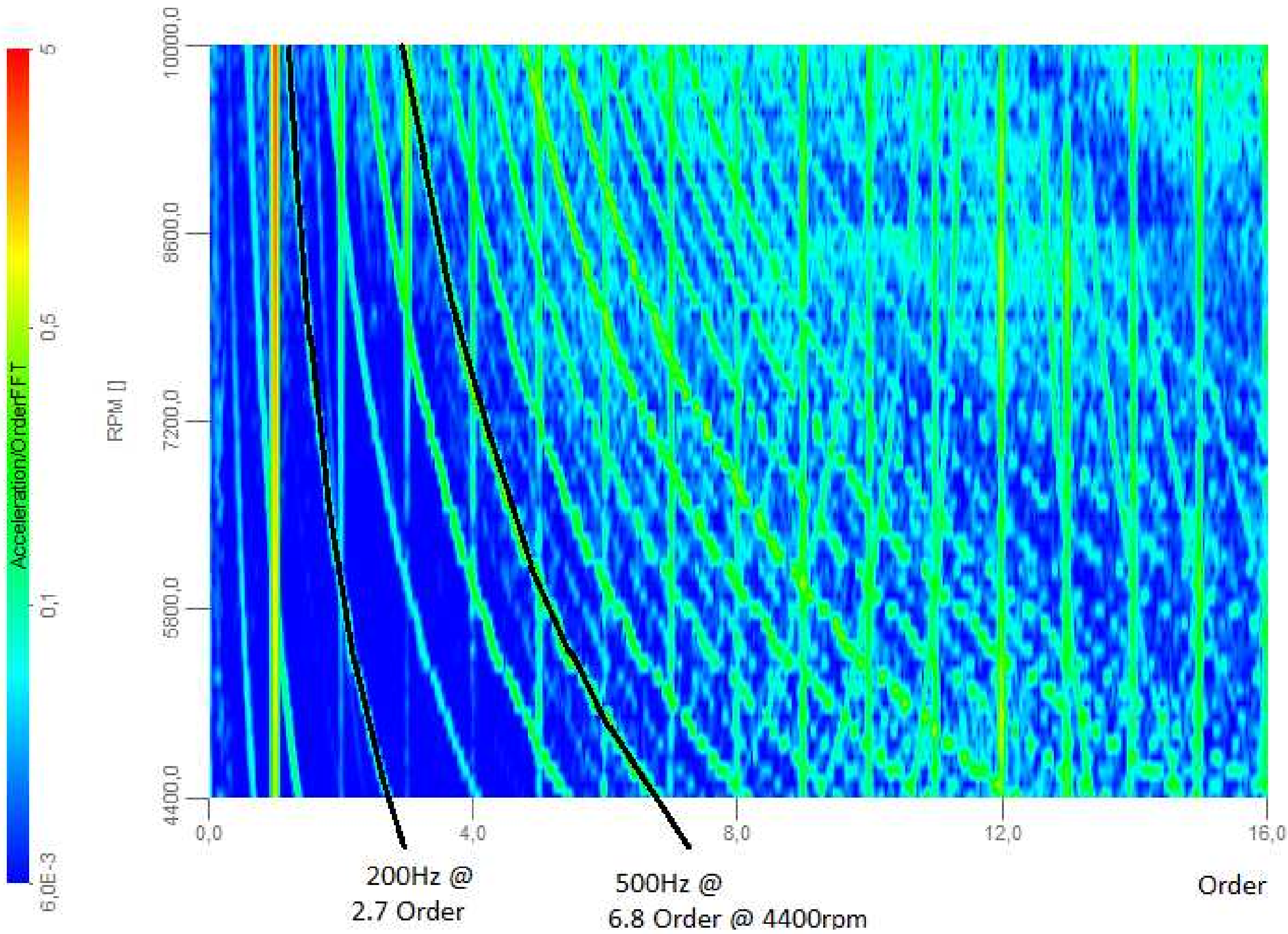
The above picture is the waterfall diagram of our mixer.
In a waterfall diagram an FFT Spectrum is drawn over rpm.
So we can see in the Z direction the rpm, in X direction the frequency and in Y direction the amplitude, which is indicated as a colour map (so the colour indicates the amplitude).

In this diagram we can now separate frequencies, which are related to engine speed (Orders), and frequencies which are related to structure or other sources.

The fixed frequencies will appear parallel to the z axis (in vertical lines, indicated with the red arrow), whereas the orders appear as rays (indicated by numbered black lines).

The fixed frequencies could be either resonances, or fixed vibration sources on electrical machines, where magnetic vibration of the electric field (50/60Hz) is the reason for the vibration. Also picked up noise, or ground loops could cause that.

1.5.2 Order FFT Waterfall diagram



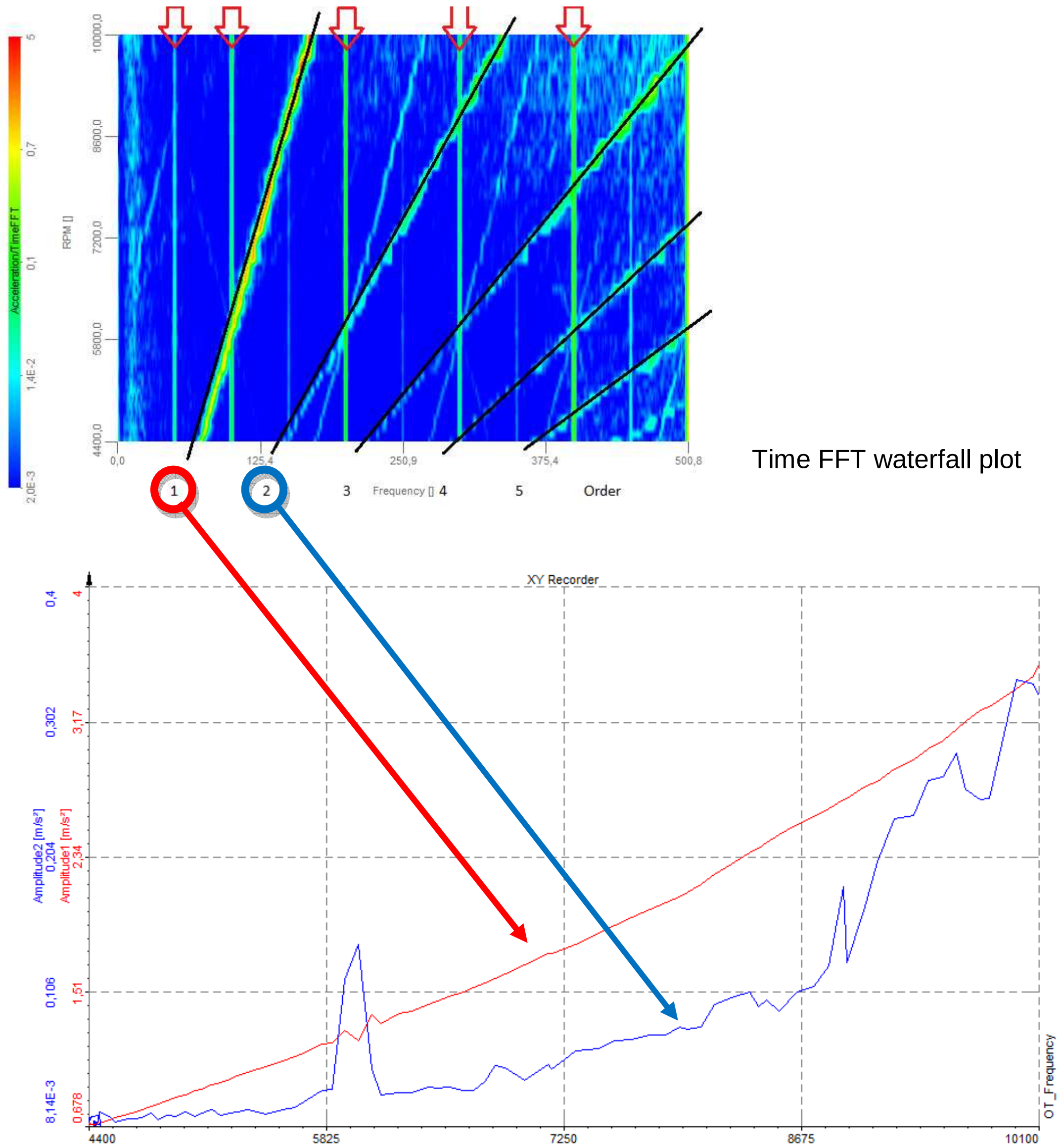
Instead of showing the frequency over rpm, we could also show the Orders over rpm.
So we get the same waterfall diagram, Z direction is still rpm, Y direction is amplitude, and X direction will become orders instead of frequency.

So the order lines run in parallel to the Z axis, where fixed frequencies will appear as hyperbolic functions. This is because each rpm will give a different frequency at the same order.

At 4400rpm the first order will have a frequency of 4400rpm/60= 73.3Hz
At 6000rom the first order will have a frequency of 6000tpm/60= 100Hz.

So a 200Hz frequency will appear at the 2.7 Order, and 500Hz at 6.8 Order when the machine is running at 4400rpm. If the machine will run @ 8800rpm they will appear @ 1.35 and 3.4 Order.

1.5.3 Specific order and phase over rpm



Another diagram which is used almost every time in order tracking is the one shown above. Here specific orders are printed over rpm. So the first, second or any other order line in the time FFT waterfall, or order FFT waterfall is extracted and displayed over rpm.

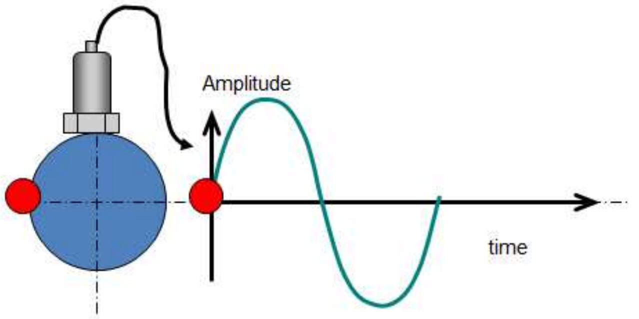
This way it is much easier to examine the amplitude and phase (phase not shown yet) over rpm. Also amplitude values are much easier to check, because individual scaling can be used.

1.6 What does the 2nd 3rd xxth Order mean

Now we know how to extract orders and how to show them in various diagrams. But why do we need to observe them, and what does a 1st or 2nd Order mean.

1.6.4 1st Order = Imbalance

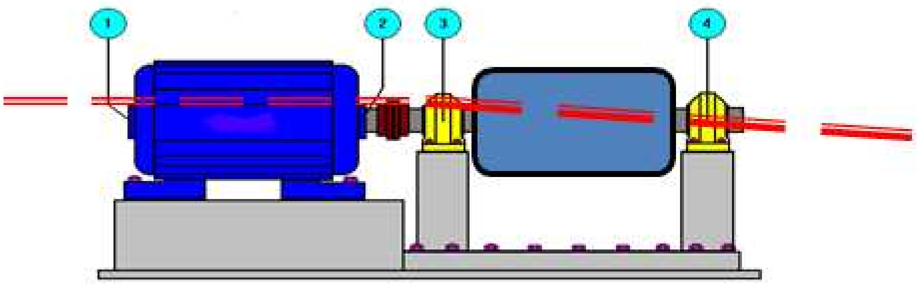
The first order is the shaft frequency, so if the first order is the main reason for high vibration, this is related to an unbalanced shaft or blade.



Imagine a blade or a shaft or any rotating part has a higher weight at one side. This weight will rotate with exactly the rotation speed (1 order) and create a force and therefore a vibration frequency which is exactly the roation speed or first order.

So high amplitude of first orders indicate an unbalanced system!

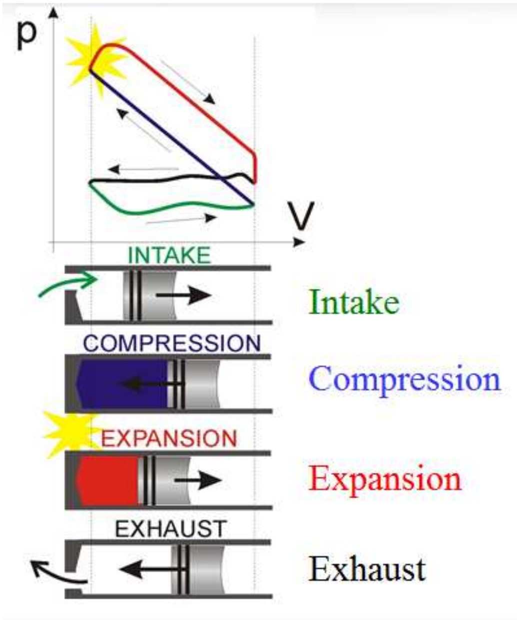
1.6.5 1 & 2 Order = Misalignment



If a high second order is observed in a spectrum of a machine, it often indicates a misalignment of two coupled engines. So two times per revolution (2nd Order) the shaft is bent and causes a vibration force, which is transmitted over the housing and creates vibration.

1.6.6 Diesel and Gasoline engines

At diesel and gasoline engines we can observe that 2nd, or 3rd, or 6th order are almost every time the highest, why?



It now depends on the cylinder count of the engine. Let's assume we have a 4 cylinder 4 stroke diesel or gasoline engine, which one does not matter.
A 4 stroke engine's cylinder is fired every 2 revolutions, so we would get 0,5 order vibration if we would have a one cylinder engine.

At a four cylinder engine the firing of the four cylinders is distributed over 2 revolutions,
2rev/4 =0,5rev so one of the 4 cylinders will fire every 0,5 revolutions.
So at one revolution 2 cylinders are fired, which will cause the second order to contribute a significant part of the total vibration.

A 6 cylinder 4 stroke engine will produce high 2rev/6 = 0,33rev = 3rd Order.

2 Measurement

In chapter 1 the fundamentals of Ordertracking are explainined and its usage is described. The second part will guide in detail trough a measurement from sensor to the result.

The unit which is tested is an electrical engine mounted on a table. During run up from 0 to 6000rpm, high noise and vibration is observed at certain speed. Order tracking should help to understand why and where this comes from.

2.1 What do we need for Order tracking

The main channel is the channels which should be analysed. Most of the time this is an acceleration channel or a microphone, but any other signal (analogue) can be used to determine the included orders. Here, depending on the application, one or several signals could be analysed.

2.1.1 Analogue signals to analyse:

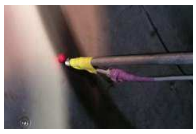
- acceleration channels (seat, steering wheel,
- microphone (driver side left- right ear, co driver,…)
- pressure (pressure fluctuation of power steering,)
- rotational vibration (rpm deviation)

(only a few examples)

Because Order tracking needs to know the rpm, we also need one tacho or rpm input channel. Depending on the tacho probe, it is either connected to analogue input or counter input.

2.1.2 RPM probes

- Tacho probe → analogue input



- Encoder → connected to counter input

- RIE- 360/720 CDM Sensor → Connected to counter input

- Any other digital or analogue signal which reflects the rpm of the machine

In general it does not matter which rpm probe is used to acquire the rpm. Tacho probes are used very often because a simple colour mark, flute or screw head deliver one (one more) pulse(s) per revolution, which can be used to acquire the speed of the engine. Sensor adaption is very fast and uncritical in comparison to an encoder or RIE sensor.

HINT: If machines with high rpm dynamic, or with a high rotational vibration (big rpm deviations during one revolution) are estimated, and also high orders should be extracted, an encoder or a tacho probe with more than one pulse/rev. (180p/rev or higher) is recommended, to get higher accuracy.

Reason: The order tracking algorithm resamples the time domain data into angle domain. If we get more information from the tacho probe, we have more pulses per revolution and the resampling to angle domain will be much more accurate!

2.2 The setup

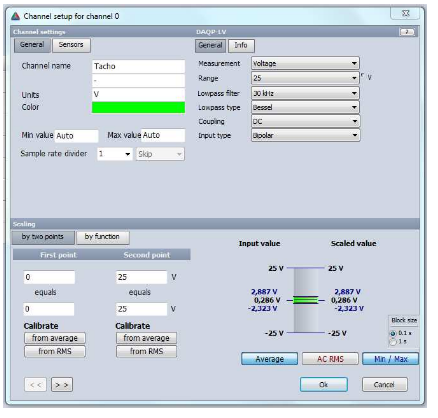
For this measurement an analogue tacho probe and one acceleration sensor is used.

2.2.3 Analogue Setup

0	Used	Store		Tacho	**DAQP-LV** 50 V .. 300 kHz (BE)
1	Used	Store		acceleration	**DAQP-ACC-A** 5000 mV .. 300 kHz; Exc 4 mA

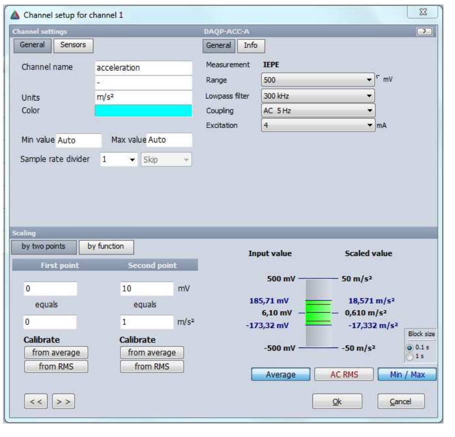
Analogue Trigger probe is connected to a voltage amplifier DAQP-LV of channel 0.
The acceleration input is connected to an DAQP-ACC-A modul.

2.2.3.1 Channel 0 Tacho Input



The volatge input of the tacho probe is set to 25V, tacho probe's power supply is 12 V, so the maximum signal we get will be about 11V. Therefore 25V Range is suitable for it. Filter is set to 30kHz. There is no scaling needed , trigger probe output is voltage which will be later used to get the speed of the machine.

2.2.3.2 Channel 1 Acceleration Input

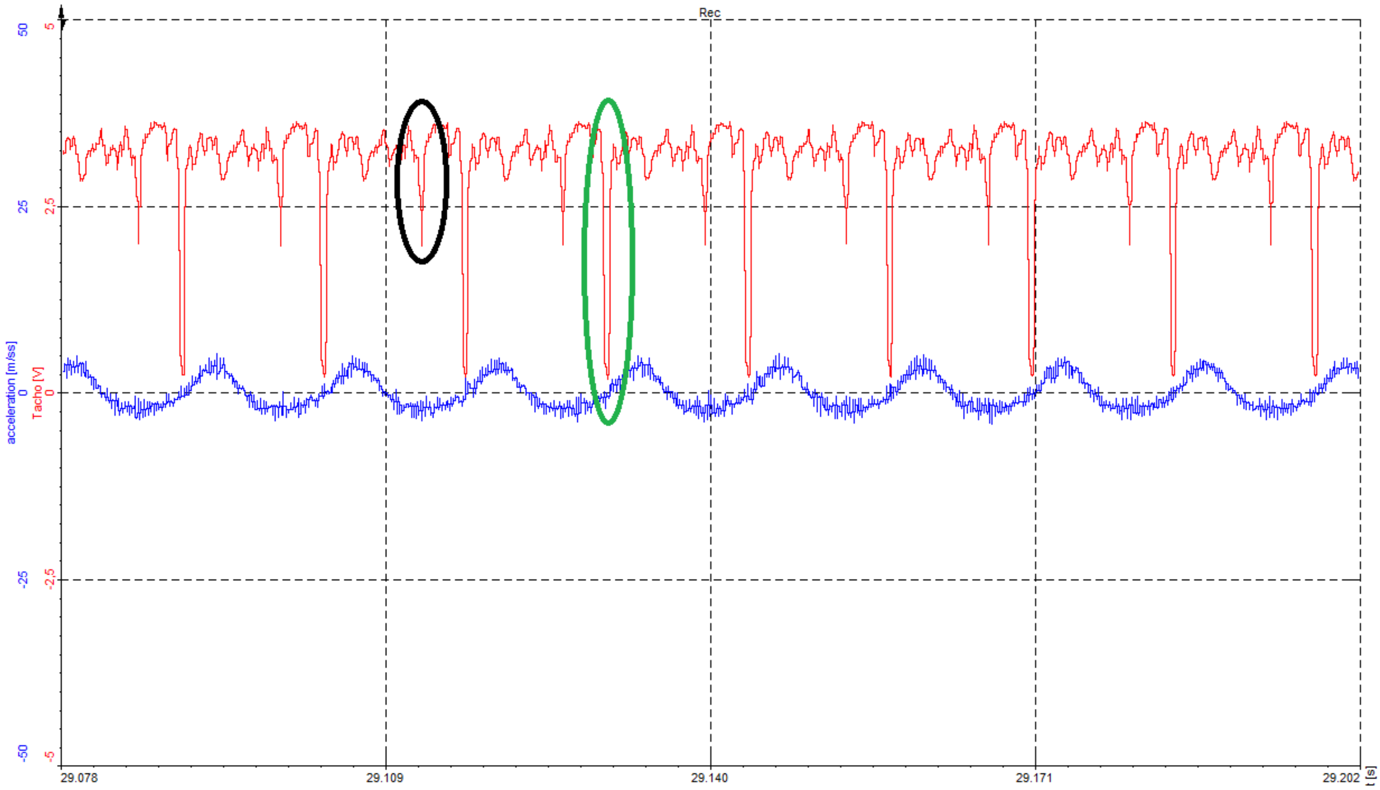


The acceleration sensor is connected to the DAQP-ACC-A input of the Dewetron System. Range is set to 500mV and filter is set to 300kHz, because a 24bit Orion card with antialiasing filters is used here for the measurement.

Sensor Scaling is set to 10mV/m/s², which will give us an input range of 50m/s² at 500mV input range.

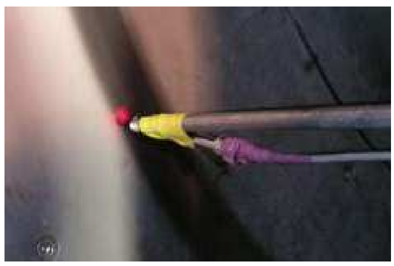
2.2.4 Let’s check the signals

Before order tracking algorithm is applied, first the trigger signal and also the acceleration signals should be checked in a recorder.



Above the acceleration and the trigger signal are shown. On the shaft of the engine a black tape is used to create the trigger pulse. So every time the black tape passes, the reflection decreases, and therefore the voltage output of the trigger probe drops. We could see a nice triggere signal which will give us a volatge drop every revolution(green). But we can also observe a small drop between (black) which is caused from an other part on the shaft which decreases the reflection like dirt or rust.
But this will not disturb, because it is very small compared to the main signal, so if we set the right trigger level (1.2V) for the rpm detection we will get a nice signal.

In case the trigger level is not high enough or is burried under noise, the probe must be readjusted to get a clear trigger per revolution.



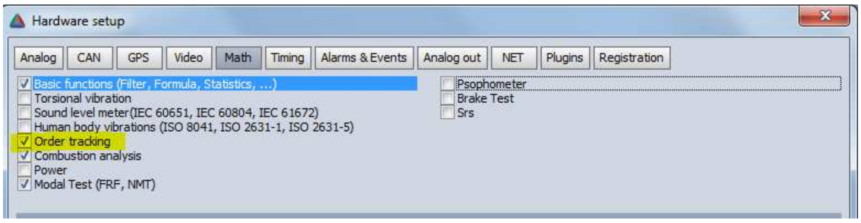
2.2.5 Order tracking setup

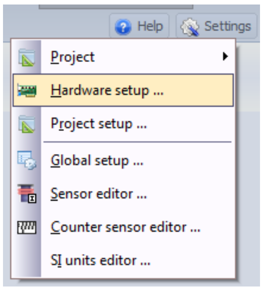
All signals are checked now and we can add the order tracking mathematic module.
This will appear beside the analoge and Math icon. In case it is not shown in the menu it has to be activated in the Hardware setup of DEWESoft.

2.2.5.1 Activation of Ordertracking

The Order tracking mathematic is enabled in the hardware setup of DeweSoft, section MATH.
To enable the Order tracking mathematic

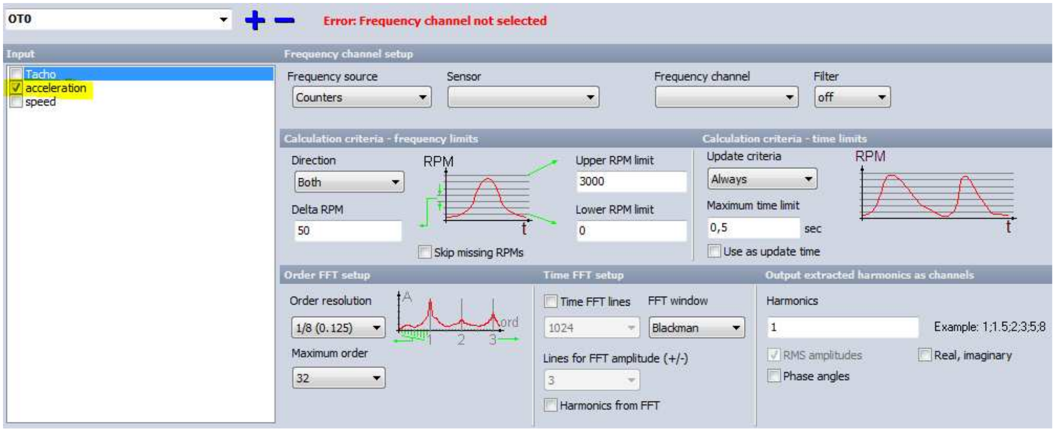
- Settings , Hardware setup
- Math, enable Ordertracking



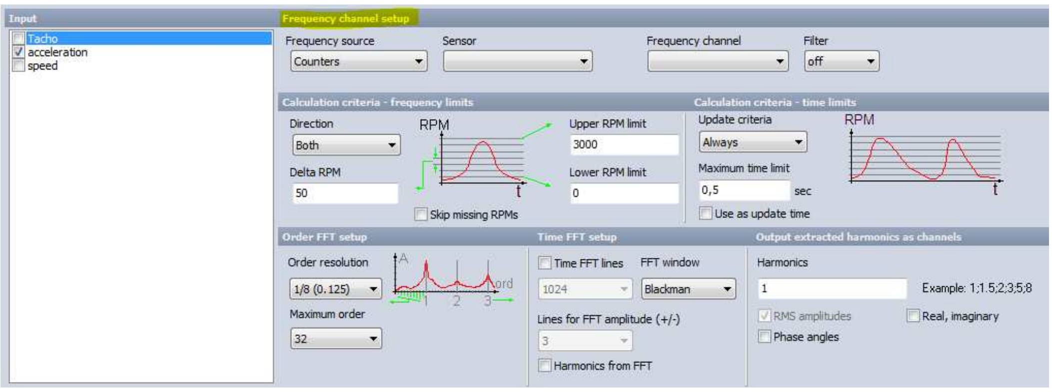


INFO: To enable Ordertracking, licence DSA, or Option Order tracking must be activated.

Add New Order tracking math to setup.

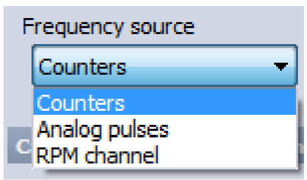


On the left side we have to select the channel which should be analysed. In our cause this is the Acceleration channel. In case more channels have to be analysed, they simply have to be checked in the input list.



Now the engine speed channel has to be selected. First we have to hoose the frequency source, which could be:

- Counters
- Analogue Pulses
- RPM channel

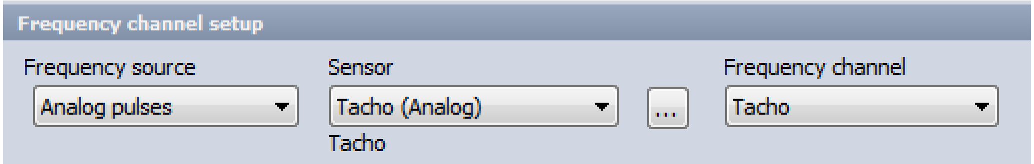


So depending on rpm sensor we have to select the right input source.

Counters: Is used if RPM probe is an encoder, CDM or Trigger probe with digital output connected to counter input of a Dewetron Instrument. For more details check online help in DEWESoft. (**Press F1)**

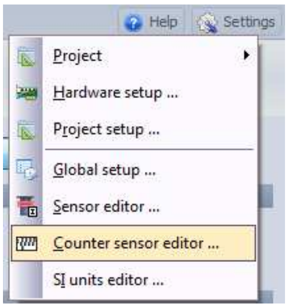
RPM Channel: RPM channel is used if an analogue input voltage (0 to 10V = 0 to 6000rpm) is availble for engine speed. For more details check online help in DEWESoft. (**Press F1**)

Analogue Pulses: Our Tacho probe delivers a pulse per revolution, out of that the ordertracking module will calculate the rpm. So we will select Analogue Pulses as input source.

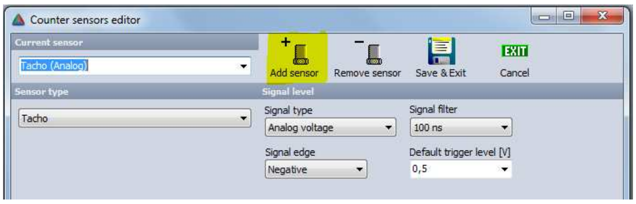


Because tacho channels could have various pulses, we have to define the sensor. In our case this is an analogue Tacho pulse. If this is not available, we have to create this sensor in the counter sensor editor of DEWESoft.

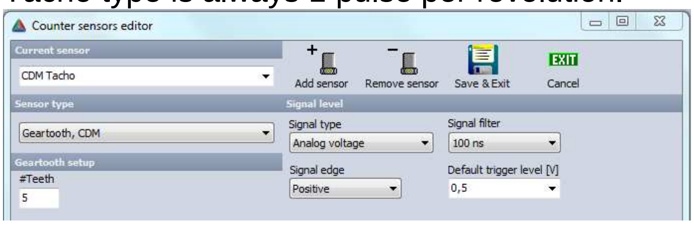
2.2.5.2 Create Analog Tacho Counter Sensor



Settings, Counter sensor editor will open the counter sensor editor.



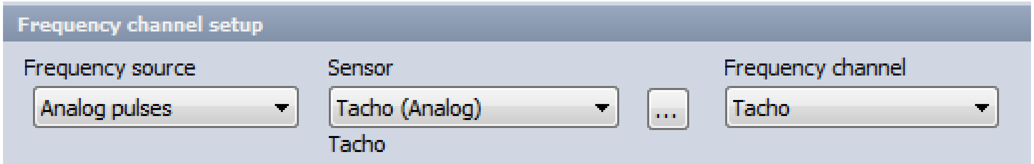
In the editor we create a new sensor called Tacho (Analog) and select Tacho for sensor Type. Tacho type is always 1 pulse per revolution.



If we get more pulses from the analogue trigger probe, because we are looking to the screw head of a flange where 5 screws are used, we have to use the Geartooth ,CDM sensor type.

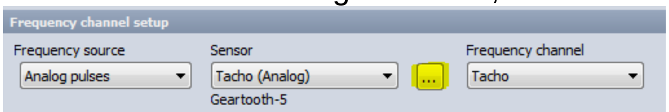
Signal type indicates which type of signal we get from the probe. In our case we get an analog voltage, so we have to set this to Analog voltage. Signal filter is used if tacho signal has noise on it, so it has to be at least for the duration of 100ns high or low to be counted. Signal edge predefines if pos. or neg. slope is used for trigger, and also a default trigger level can be set.

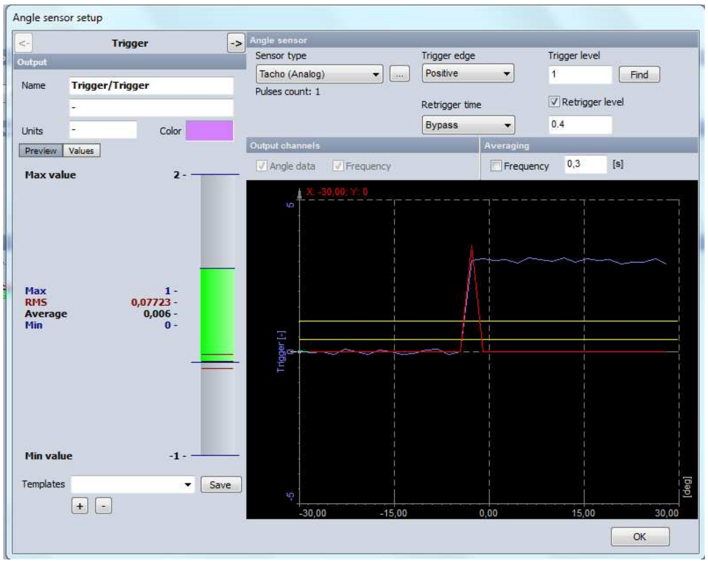
INFO: Signal type is used for filtering the sensor, so if Digital (TTL) is selected instead of analogue it will not appear in the Sensor list of Ordertracking if Analogue Pulses is used as source.
The same if Counter sensor is set up as analogue sensor, and should be used when "Counter" is selected as frequency source in Ordertracking.



Now we have to selct the Freqency input channel which is the analogue input channel called Tacho.

Because this is a analogue sensor, we have to set or adjust the trigger level.

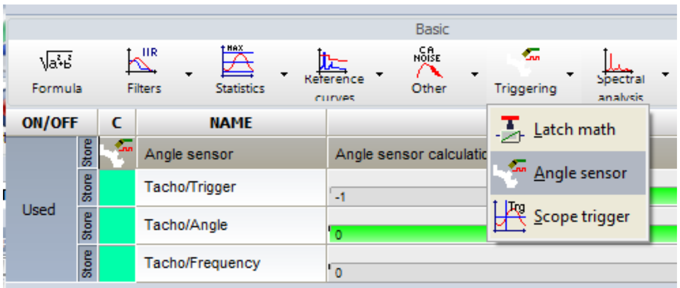


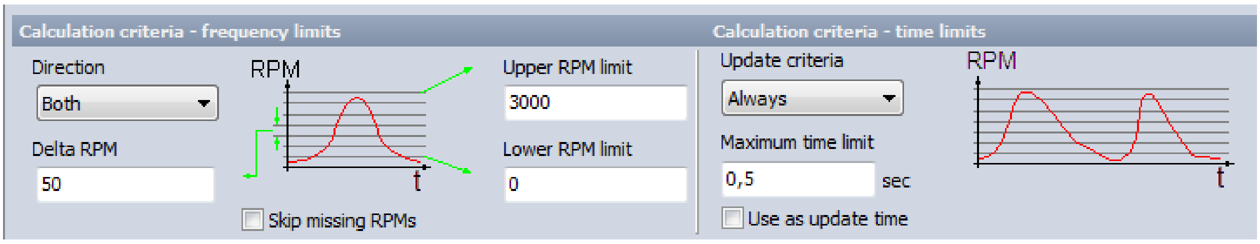


Now the machine must run that we see the tacho signal live. After that we can set the Trigger and Retrigger level to get the right rpm of the machine. Retrigger level is recommended to avoid double trigger caused by noise.

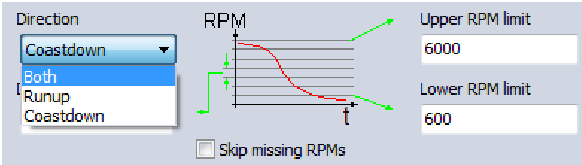
Retrigger works like this: After a trigger is detected (1V) a new trigger will be only detected if Retrigger value is crossed before. So if signal is noisy around trigge level, a double trigger could appear if retrigger is not used.

Info: For analogue Tacho or CDM sensor in Math the angle sensor mathematic is used from the ordertracking module and created in Math section automatically. So the settings are controlled out of Ordertracking module, and are looked in Math of DeweSoft.





The next settings are related to operation mode of the Order tracking calulation.

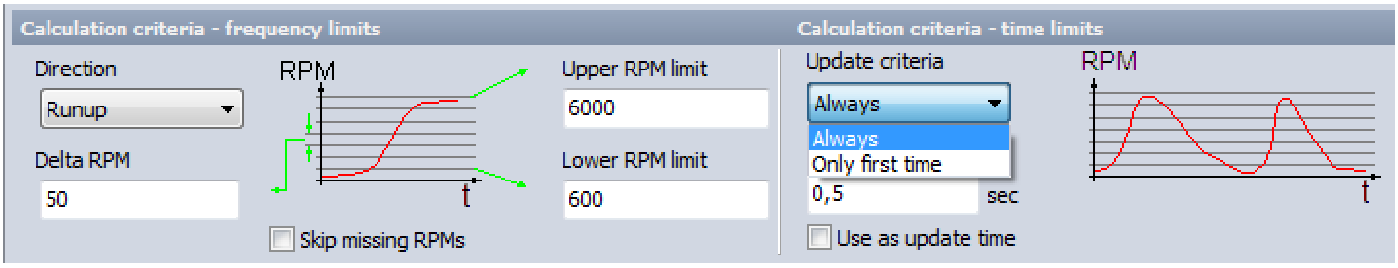


Direction will define when the calulation should be done, either at runup, coastdown, or on both.
So if we select runup, the waterfall spectrum and the order extraction will only be calculated at runup.

Upper and Lower RPM limit define the range of the waterfall Z axis, and are also used to set the right samplingrate depending on max orders extracted.

Delta RPM will define when a new update of the waterfall spectrum and also the extracted order should be calculated. In case the rpm is not changing the calculation is performed after the **Maximum time limit** setting.

Skip missing RPMs is used if runup is very fast and not all rpm points can be calculated.



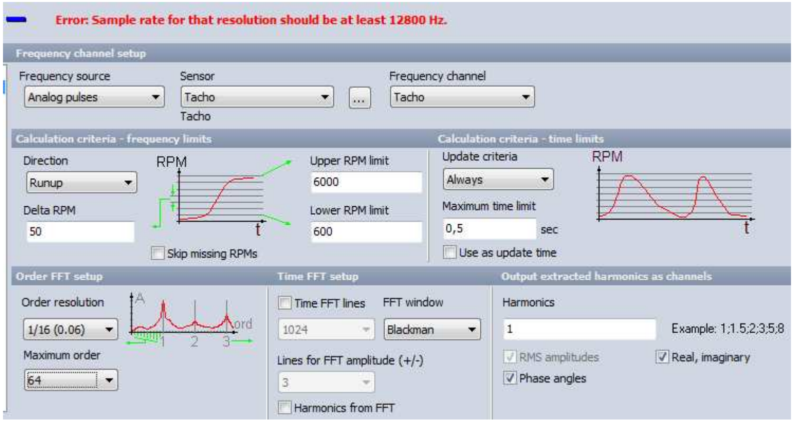
Update criteria defines if waterfall should be updated always or only the first time.
So if you have more runup or coast downs, only the first run will be used, if selected.

In this mode the update is done if rpm changes for value of Delta RPM or if Maximum Time limit is reached.

Sometimes it is also necesaary that ordertacking calculation is done in a fixed time intervall, independent of the rpm, for example car is driving a defined track, machine is operated and observed during a workin cycle.

If this is needed, **USE as update time** must be checked, so the calulation will be updated independently from rpm every 0,5s.

2.2.6 Order resolution max. Order and samplingrate



In the order FFT setup, we can define the order resolution and the maximum order that the alogrithm should extract.
Depending on Upper RPM limit and maximum Order, the Order tracking modul will inform you that the sampling rate has to be set higher. (picture above)!

In this setup the sampling rate is set to 10kHz, and the Order tracking module require a sampling rate of 12.8kHz. So we should set it to 15kHz or better to 20kHz.

But why does the ordertracking module need this.

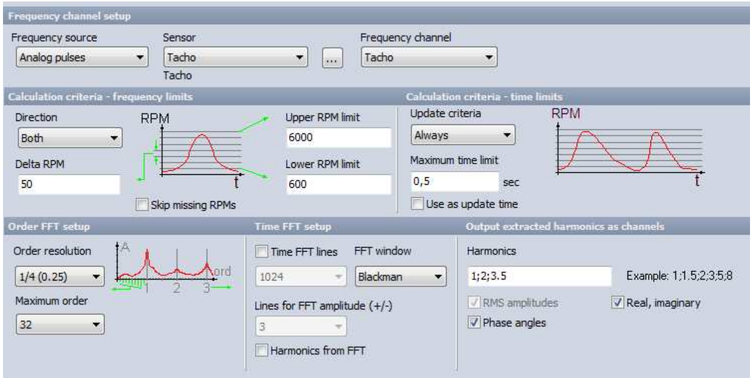
We set 6000rpm as upper limit, this would be 6000rpm/60= 100rps = 100Hz.
So the first order @ 6000 rpm is 100Hz, therefore the 64th order would be 100Hz * 64 = 6400Hz.!
And because the Orderalgorithm is still FFT based we need at least 2 times higher sampling rate.
That's why Ordertracking module requires 12.8kHz sampling rate.

Maximum Order defines the maximum order which should be extracted. If the 64th order should be extracted we have to measure at least 128 times per revolution, which gives us 100Hz*128=12.8kHz samplingrate. So it is similar to time domain, if 2kHz should be measured in FFT we have to sample at least @ 4kHz. Order is related to revolutions as frequency is related to time.

Order resolution defines how many order lines should be calculated between two orders.
We can picture this smilar to FFT resolution. So if we have 0.1Hz we would get 10 lines between 1Hz and 2Hz in the FFT spectrum. The same with Orderspectrum . So in the Order waterfall diagram we would get 10 lines between 1st and 2nd order. So if we want to know the 3.4 order exactly, the resolution has to be set to 0.1 orders.

It is maybe known from FFT, that if line resolution is 0,5Hz the required data window must be 2s. The same with Orderresolution, if the resolution is set to 0,25 orders 4 revolutions are required for one data block.

Output extracted harmonic will extract specific orders from the Order waterfall plot to be used as channels. So it would be possible to draw a specific order over time, or over engine speed.

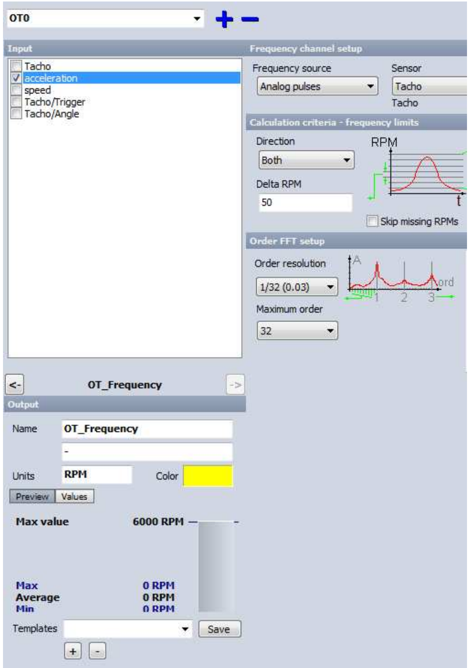


To extrac the order we enter the number and separate it with [;].
In the example on the right 1st, 2nd 3.5th is extracted.

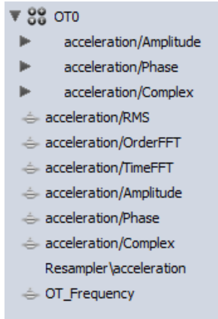
If extracted order falls between discrete order resolution steps, the closest fitting resolution will be taken.
So if resolution is 1 Order and 1.8 is extracted 2nd order will be used.

In the lower left corner, the result channels are provided.
With the ←, → we can change between the result channels, like Time FFT, Order FFT, OT_Frequency, … also renaming of channel(s) can be done.

If the engine is running OT_frequency channel should already indicate the right rpm. Otherwise trigger level of Tacho has to be adjusted.



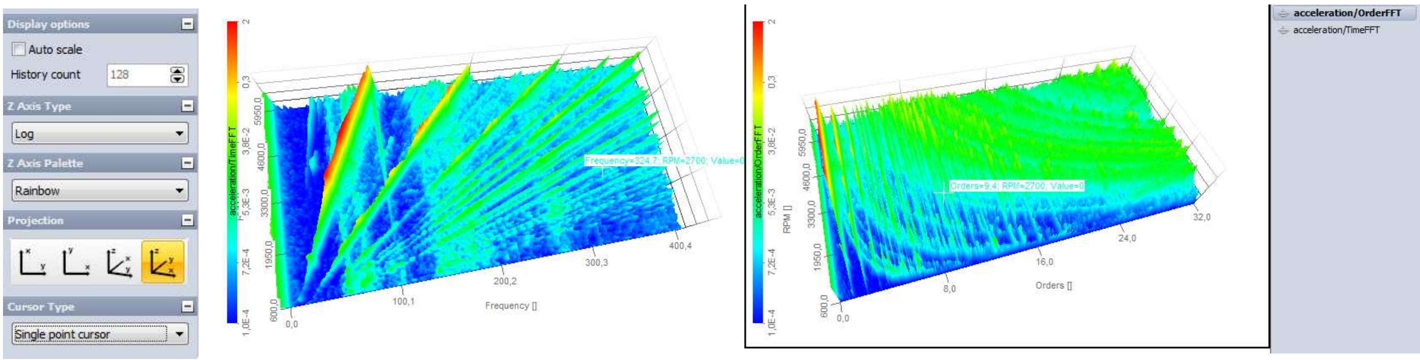
2.3 Creating the Display setup



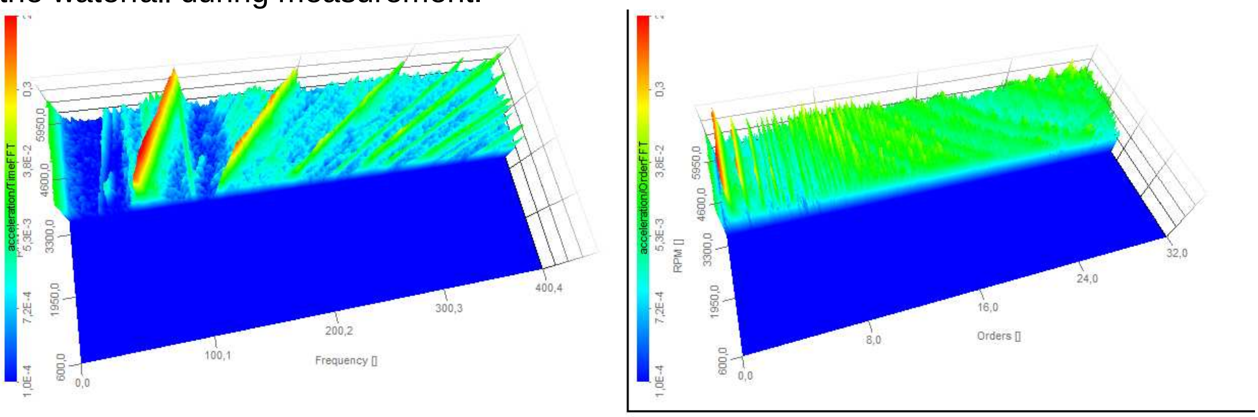
If we change to measure, we have to create and arrange the displays. If we do not select any display we can already see the result channels of the order tracking Module.

2.3.7 Create Time- Order FFT water fall

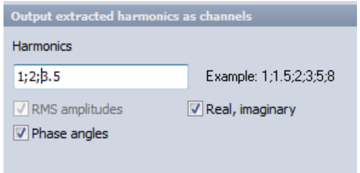
For that we have to use the 3D graph.
If it is selected, the channel selector will only show the channels which can be applied to a 3D graph; in our case the Order FFT and Time FFT waterfall diagram. To the left, display properties like projection, lin. or log. scaling can be set according to needs.



The picture above will already show the end result of a run up or coast down. During run up or coast down the waterfall diagramm will grow with the speed of the engine. The picture illustrates the waterfall during measurement.

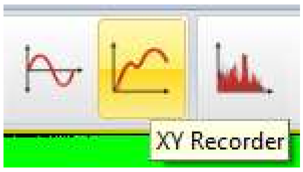


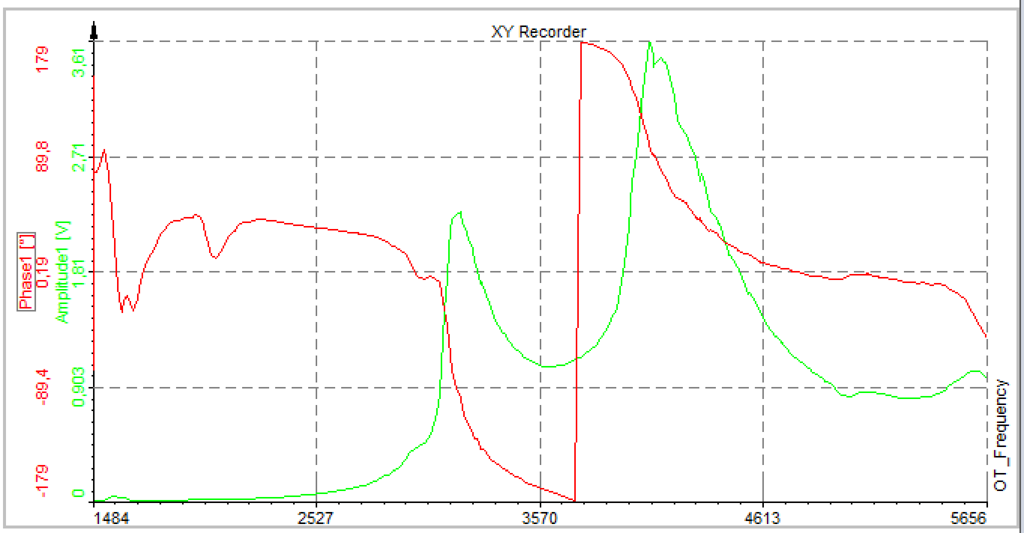
2.3.8 Draw specific orders over RPM (Bode Plot)

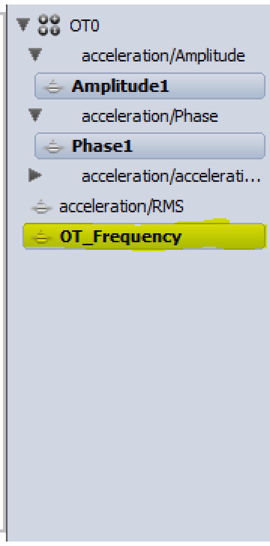


Now we would like to draw the extracted order(s) and their phase over the engine speed. To also get the phase extracted, **Phase angles** has to be checked in the Order tracking module.

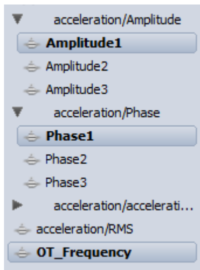
To draw order and phase over rpm, the XY Plot in DEWESoft has to be used.







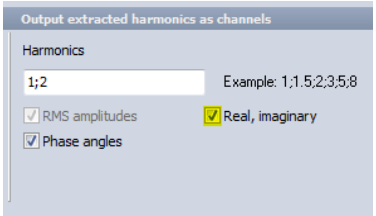
After that we have to apply the channels to the XY diagram. So first we apply the OT-Frequency channel, which reflects the rpm, and after that the Amplitude and Phase of the specific order. Amplitude1 and Phase1, corresponding to 1st order. In case 2nd and 3rd order of amplitude and phase is also extracted, Amplitude2, Amplitude3, and also Phase2, Phase3 will be available.



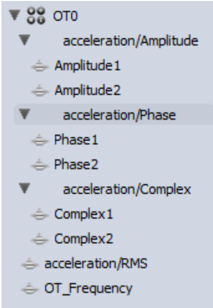
INFO: The first channel applied to the XY diagram is always used for the X channel.
All the following channels are used as Y values.

2.3.9 Draw Polar diagram / Nyquist Diagram

Another way of plotting the extracted order and phase will be the polar diagram.
The polar diagram is mainly used at stationary engine speed, where one order is tracked with amplitude an phase. In the polar diagram the amplitude is indicated by the length of the vector and angle reflects the phase. The Polar plot is often used to visible the imbalance of a rotor.
Both, Polar and Bode plot describe the Amplitude and Phase relation during speed change of an engine. The Bode Plot reflects a better view over rpm, where the Polar plot is more sensitive to phase changes.

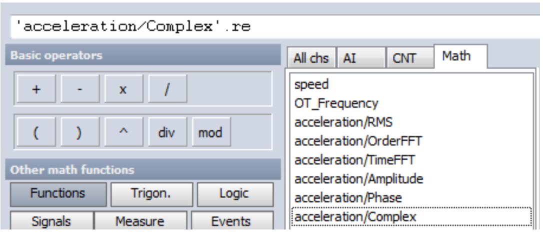


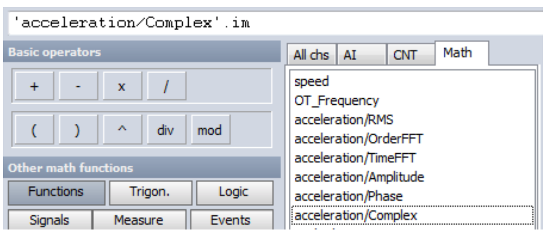
To show a Polar Plot we use XY diagram.
To show the vector in the XY diagram we have to get Real and Imag. part out of the signal.
So if Real, Imaginary option is checked in Order tracking, a Complex channel will be available.



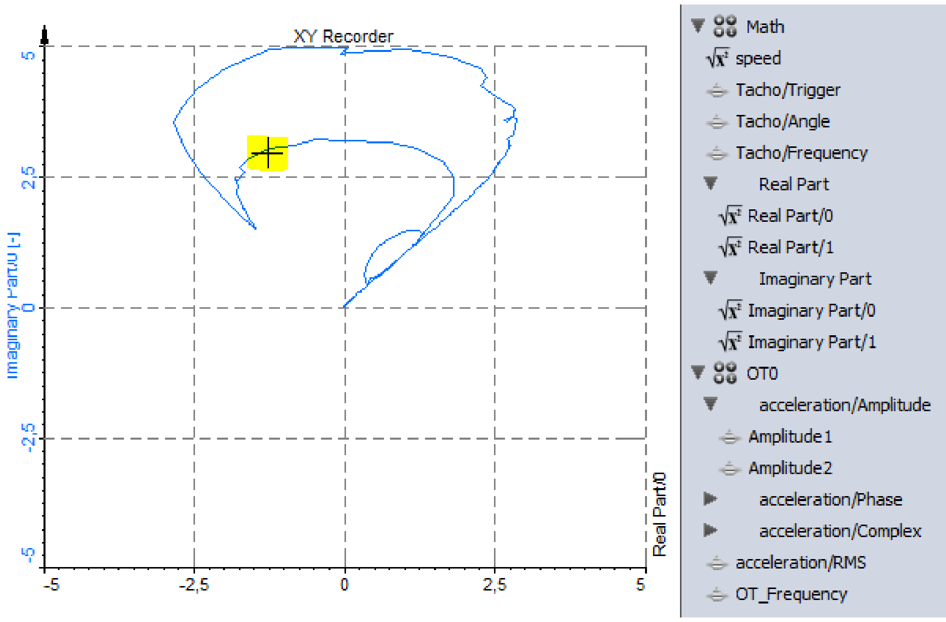
These channels Complex1 and Complex2 hold the complex results for the 1st and 2nd order. To separate such a channel into real and imaginary part we have to use math function.

The real part is extracted with <u>CHANNELNAME.**re**</u> and
the imaginary part is extracted with <u>CHANNELNAME.**im**</u> in the formula of DEWESoft.





After that the XY diagram must be added into the measure screen. 



Real part and imaginary part are now available in the math section of the channel selector. Real Part/0, Imaginary Part/0 reflect now the 1st Order where Real Part/1, Imaginary Part/1 reflect the 2nd Order in this case. Now the REAL Part/0 has to by applied to XY digramm first, and after that Imaginary Part/0 .

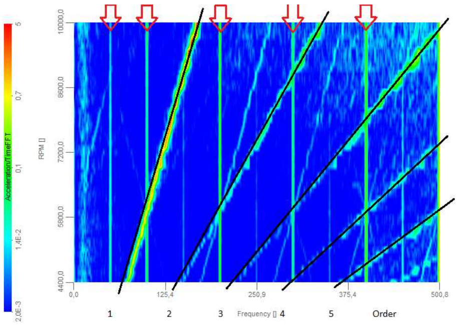
To get a Polar plot, the X and Y axis has to be manually scaled to the same range. Otherwiese the cursor (yellow) does not show the exact phase angle, because of graph scaling.

INFO: When this manual was written Polar plot which could directly handle the complex result from Order tracking was under construction. If this is available, the manual will be updated.

2.4 Time FFT Setup in Order tracking module

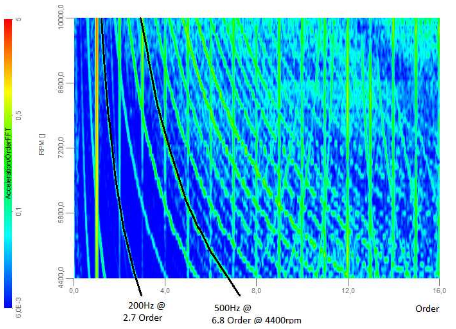
2.4.10 Calculation background

Order tracking module is creating a waterfall plot out of rpm change. So every time the rpm changes for the defined delta rpm, a data block is cut out. FFT is calculated for this data block and the result is shown over rpm, which is the Waterfall diagram in Time FFT. (remember picture on the right)



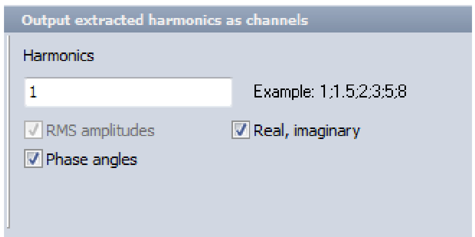
The FFT resolution here and the data block length are automatically calculated out of sampling rate, Order resolution, and maximum order.

At the same time, this data block is fed into a special mathematic algorithm, which resamples the data that we get exactly 2^x values during one revolution. Out of that we can get the order and phase spectrum without any leakage of FFT values. So FFT lines (= Orders) will have exact amplitude (no smearing) and phase, almost no matter how fast we change the engine speed.



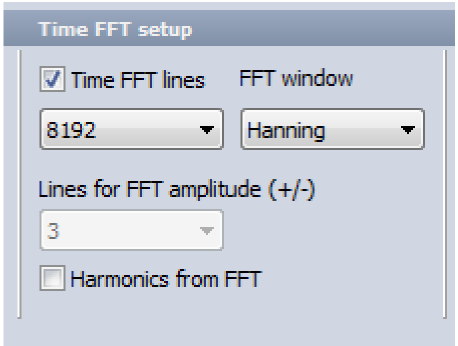
The maximum Order and the resolution is set in the Order tracking user interface.

Extracted Orders and Phase will be taken out of the resampled Order FFT waterfall and shown over rpm, or with a Bode or Nyquist plot.



As mentioned in point 2.4.10, the FFT lines in the Time FFT waterfall diagram will be set automatically.

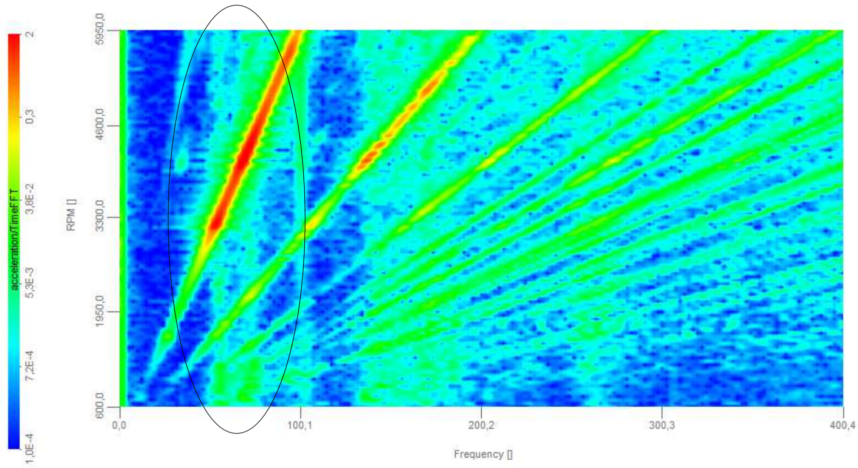
If **TIME FFT lines** is checked, the Time FFT waterfall diagramm will have 8192 lines for one rpm shot. So we can influence the FFT resolution in the FFT waterfall diagramm with this setting.

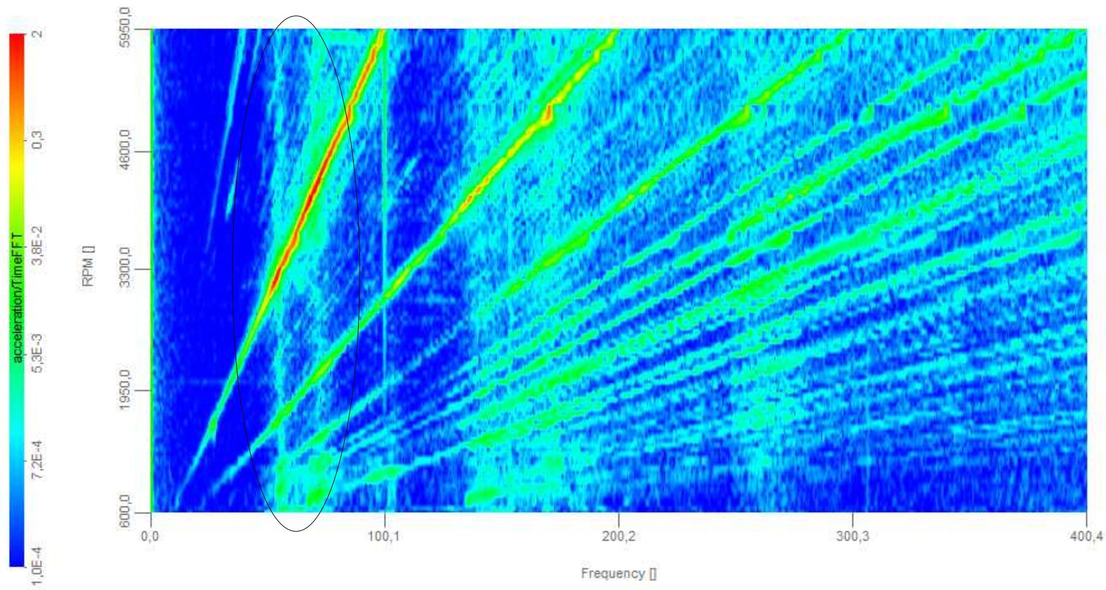


The two waterfall digrams below are illustrating the difference.

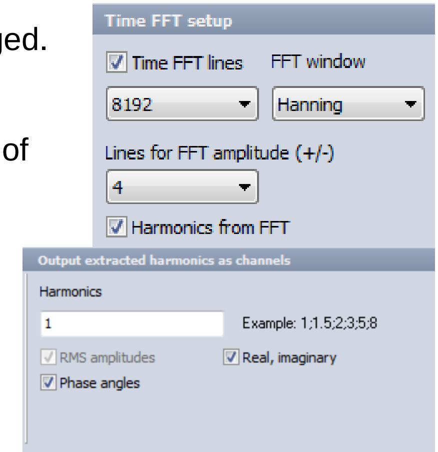
At the right, **Time FFT line option** was **not** checked, and we get a frequency resolution of about 2 Hz.

Below **Time FFT line option** was checked and set to 8192 lines, which gives at 10kHz a line resolution of 10/2=5kHz/8192= 0,6Hz.





In the second picture orders appear sharper (not so wide) and also separated much clearer into fixed frequencies or resonance frequencies.



But that is not the only reason why Time FFT lines can be changed.

If **Harmonics from FFT** is checked, the extracted Orders (Harmonics) are calculated out of the FFT spectrum and not out of the resampled data.

The LINES for FFT amplitude(+/-) will define, how many lines are taken around the centre frequency of the actual order extracted to calculate the Amplitude.

Example: Sampling rate is set to 8192Hz, resolution is set to 8192, this will give
a frequency resolution of 8192/2/8192=0.5Hz

If the machine is now running with 3180rpm/60= 53Hz, the algorithm will find the 53Hz line (1st Order) in the FFT spectrum and calculate the amplitude out of +-4 frequency lines.

Starts at 53Hz – 0,5Hz*4 = 51Hz
Stops at 53Hz+ 0,5Hz*4 = 55Hz so these lines are used to calculate the Amplitude.

If second order is extracted, the centre frequency is 53Hz *2 = 106Hz, so also here +-2Hz (+,- 4 frequency lines) are used to calculated the amplitude of the 2nd Order.

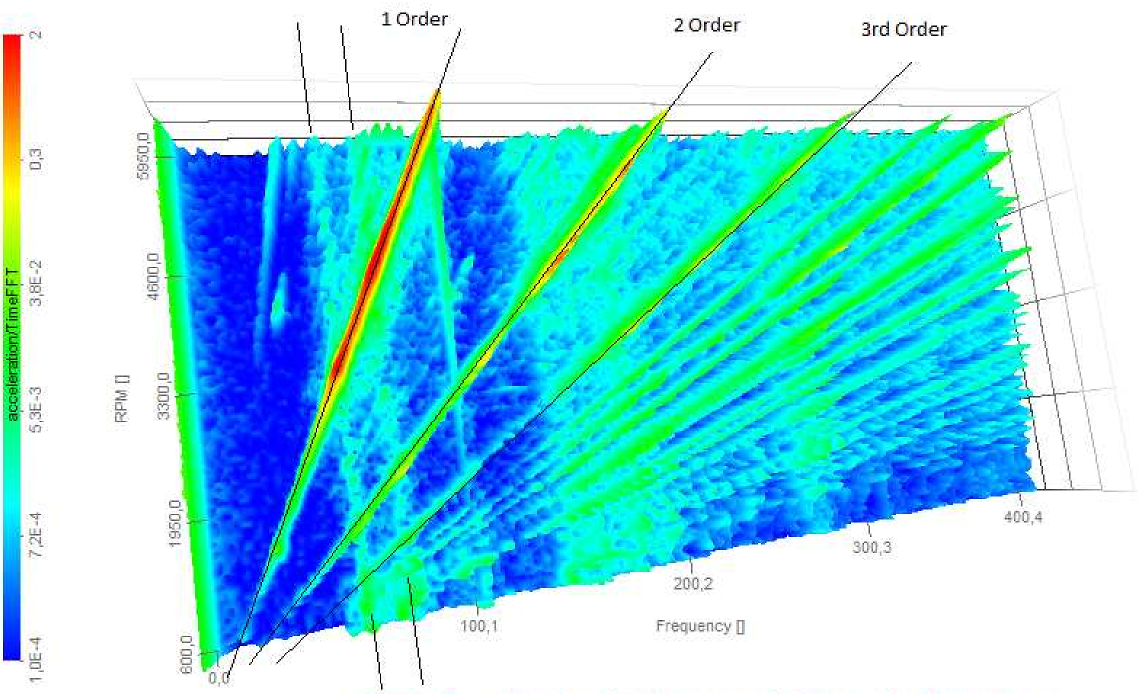
So amplitude is not calculated out of resampled data, it is calculated out of FFT data with a defined band around the centre frequency of specific order. So a smeared FFT with the right band around centre frequency will give also reliable results.

3 Interpretation of Data

3.1 Demo Engine

On the demo engine mounted on the table we can observe high vibration and noise during run up or coast down. The high vibration and noise only appears on certain rpm points. After passing these critical speeds, noise and vibration is reduced tremendously.

Before Order tracking was used to investigate where this comes from, a rpm measurement was already indicating that the high vibration and noise only appeared around 3200 -3400 rpm, and also around 4200 to 4400 rpm. Above and below there was still vibration, but reasonable amounts.



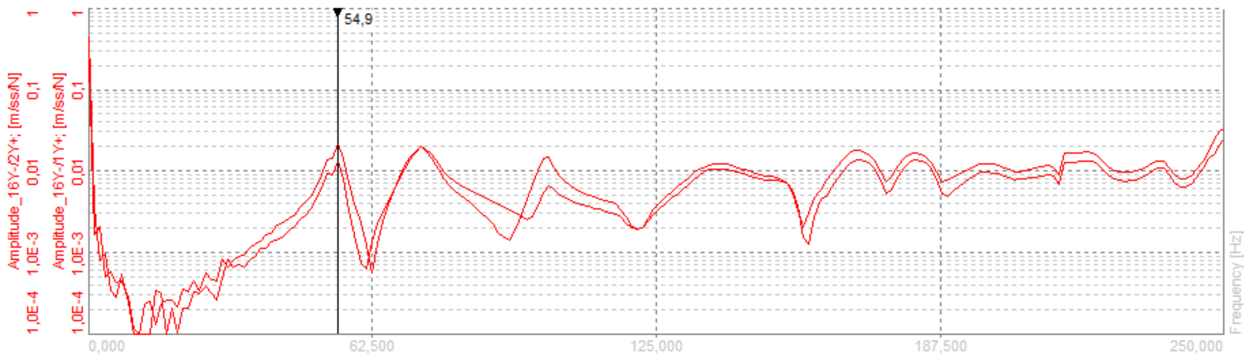
55Hz 72Hz are not related to engine speed, they are related to structure,...

In the Time waterfall diagram we can already see a little what causes the vibration on certain speeds. At the run up of the engine we can see the distinctive Orders. 1^{st} and 2^{nd} are the highest. If first order is very dominant, this is a sign for an unbalanced shaft. But why is the vibration so high around 3300rpm and 4400rpm if shaft is unbalanced we should have the vibration across the whole speed range? If we take a closer look we can see a frequency line, which is always available (constant) over the whole rpm range. These frequencies (55Hz and 72Hz) are independent of engine speed. And if the engine passes that frequency, we get the high vibration and noise. This parallel vertical lines indicate a resonance of the structure.

3.1.1 Resonance frequency

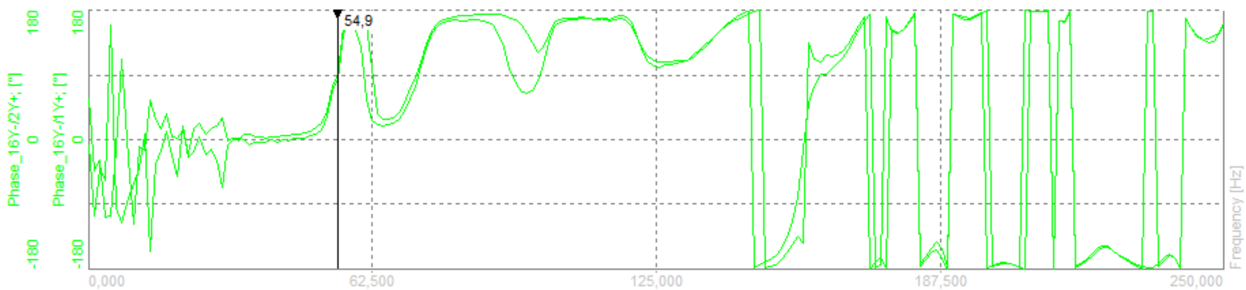
A vibration on a structure is always caused from a force. So if we have no force which excites the structure, it will never vibrate. So if a force is applied to a structure with a frequency x, the structure will respond with a certain vibration level and frequency x. The vibration level of response depends on the structure. This relation between force and response is called transfer function.
Let's assume we always use the same force, and excite a structure over a certain frequency range. The output vibration level will be different on almost every frequency.
This relation is called transfer function, and is the result of Modal Analysis.

The transfer curve of the engine table is shown in the picture below. (measured with the frequency response function of DEWESoft).



So we can see very clearly that at certain frequencies 55Hz and 72Hz we get significantly higher vibration responses at the same force. Out of the shape, we could already interpret that this is a resonance.

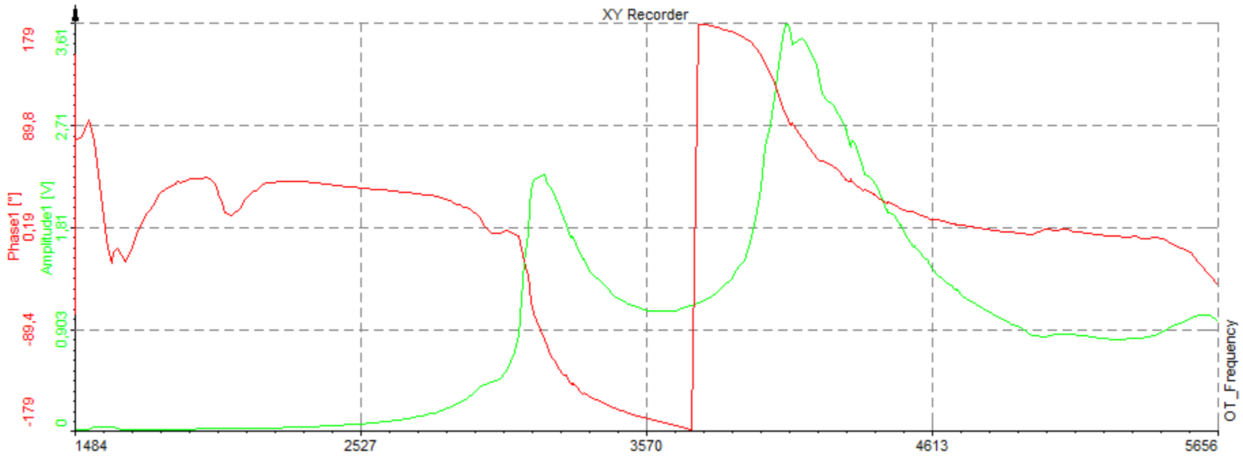
This is proved if we take a look to the Phase.
At a resonance the phase is changing for 180degs.
We can clearly see this on the phase spectrum below. So 55Hz and 72Hz are structural resonances of the engine table, because phase is changing for 180deg at these frequencies.



So at a resonance a small force causes high vibration. We could see that out of the transfer characteristic (red curve).

In the waterfall diagram we can see these resonance frequencies, too. They are significantly higher than all the other frequencies. And if we pass these resonance frequencies (@ 55Hz*60= 3300rpm and 72Hz *60= 4300rpm), the excitation force (which is reflects the unbalance of the machine) excites the structure. Because it is a resonance frequency, the small force is enough to cause high vibration at those speeds.

Bode Plot 1st Order Amplitude and Phase



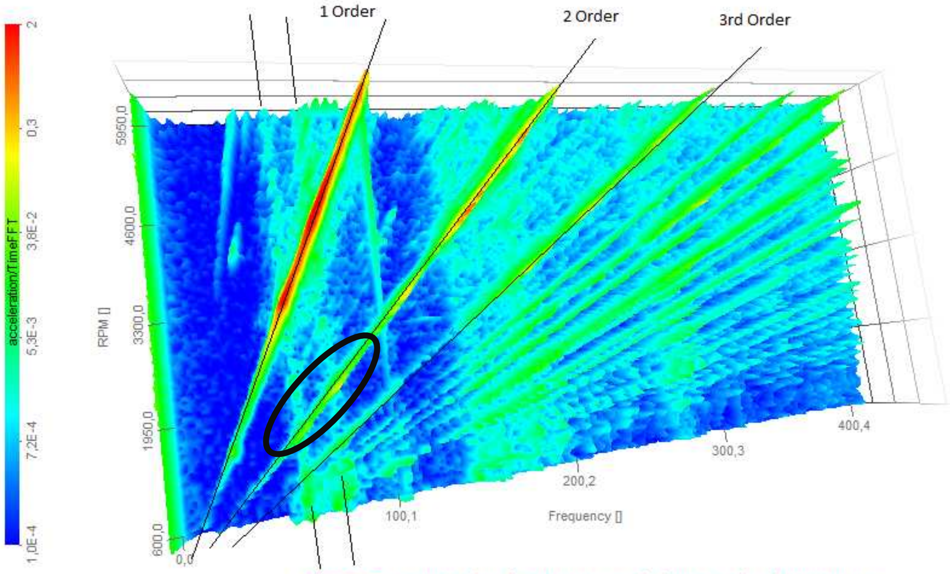
As mentioned, we could already see that we have a structural resonance frequency @ 55Hz and 72Hz and therefore get high vibration when the engine speed hits these frequencies.

If we now determine amplitude and phase of the first order in the Bode Plot, the whole theory is confirmed. At 3300 and 4300 rpm the vibration amplitude suddenly gets higher and falls off after passing this range. Also, the phase flips over by 180 deg in that area, which clearly indicates that we have passed a structural resonance.

3.2 Conclusion

In the waterfall diagram and also in the Bode diagram we can see clearly that we passed a structural resonance. We can also see (black mark in waterfall) that the 2nd order also passes these resonance frequencies much earlier, but this does not increase the vibration so much. But if first order passes these frequencies, we get high vibration.

Because first order is so high and it is related to unbalance, we should first try to balance the shaft and check if vibration decreases.



55Hz 72Hz are not related to engine speed, they are related to structure,...

If the shaft was balanced, it would produce less vibration force and therefore the resonance of the structure will not be excited that much. Maybe that already solves the vibration problem.

If that does not solve the problem, the only way to avoid this is to

- avoid to operate the engine in that frequency range (speed)
- pass that frequency as fast as possible
- change mechanical construction so that resonance frequency is shifted
- isolate engine from structure with damping material (rubber dampers,..)

3.3 Combustion engine

Also Diesel and Gasoline engines produce Orders depending mainly on the cylinder count.
So also on these machines Order tracking is used. A 4 stroke engine with 4 Cylinders shows the 2nd and 4th order and a few others very dominantly. So at a run up of the engine we can track these orders, and check their levels, as dampers, parts of drivetrain will see this orders and it could be considered that a damper, or any other part of the machine is optimized for that specific orders (damping) to reduce overall vibration and noise.