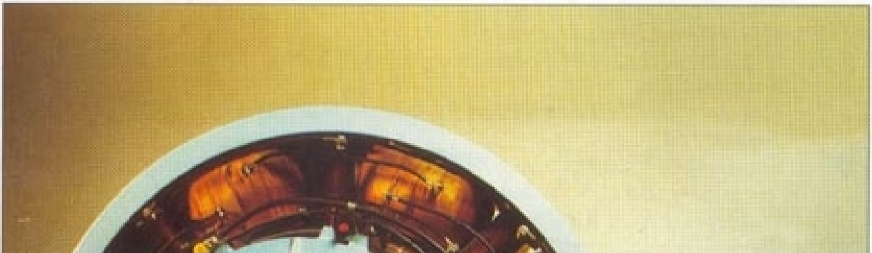
Technical Review

No.2 – 1995

Order Tracking Analysis



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Order Tracking Analysis

by S. Gade, H. Herlufsen, H. Konstantin-Hansen, N. J. Wismer

Abstract

This article introduces the theory behind digital order tracking, which is implemented by oversampling, interpolation and resampling techniques in Brüel&Kjær instrumentation. As application examples order tacking is applied to the vibration signal from a coast down of a turbogenerator from a power plant station, a run-up of a large marine diesel engine, gated measurement on an automobile engine and finally tracking is combined with time domain averaging on a single cylinder, four stroke engine.

Resume

Cet article est une introduction au principe de l'analyse d'ordre (analyse de suivi d'ordres) mis en œuvre, par suréchantillonnage, interpolation et rééchantillonnage, dans l'instrumentation Brüel&Kjær. A titre d'exemples, l'analyse d'ordre est ici appliquée au signal vibratoire généré : lors d'une descente en régime du turbogénérateur d'une centrale électrique ; lors d'une montée en régime des machines d'un navire ; lors d'une mesure fenétrée sur un moteur d'automobile. Enfin, le suivi d'ordres est combiné à un moyennage temporel sur un moteur monocylindrique à quatre temps.

Zusammenfassung

Dieser Artikel stellt die Theorie hinter der digitalen Ordnungsanalyse vor, die mittels Oversampling-, Interpolations- und Resampling-Technik in Brüel&Kjær-Geräte implementiert wurde. Anwendungsbeispiele demonstrieren Ordnungsanalyse an verschiedenen Schwingungssignalen - Auslaufen eines Kraftwerk-Turbogenerators, Hochlaufen eines großen Schinsdieselmotors, Ausschnitts-Messung an einem Automotor und schließlich die Kombination von Ordnungsanalyse und Mittelung im Zeitbereich fur einen Einzylinder-Viertaktmotor.

Introduction

Analysis of vibration or acoustic signals from rotating machines is often preffered in terms of order spectra rather than frequency spectra. An order spectrum gives the amplitude and/or the phase of the signal as a function of harmonic order of the rotation frequency. This means that a harmonic or subharmonic order component remains in the same analysis line independent of the speed of the machine. The technique is called tracking, as the rotation frequency is being tracked and used for analysis. Most of the dynamic forces exciting a machine are related to the rotation frequency so interpretation and diagnosis can thus be greatly simplified by use of order analysis.

The classical problem of smearing of the frequency components caused by speed variations of the machine is solved by using order analysis. In situations where the frequency components from a normal frequency analysis are smeared together, proper diagnosis will only be facilitated via order analysis.

Of particular interest is the analysis of the vibrations during a run-up or a coast-down of a machine in which case the structural resonances are excited by the fundamental or the harmonics of the rotational frequencies in the mechanical system. Determination of the critical speeds, where the normal modes of the rotating shaft are excited, is very important on large machines such as turbines and generators.

Use of an FFT analyzer in the normal sampling mode with a fixed sampling frequency (i.e. non-tracking) and plotting of the spectrum at certain fixed steps in rotation speed of the machine gives the so-called Campbell diagram. This is a 3-D waterfall type of plot, where vibration levels as a function of frequency are plotted against rotation speed (RPM) of the machine (plotted vertically). This means that the harmonic components appear on radial lines through the point (0 Hz, 0 RPM) while structural resonances appear on vertical straight lines (constant frequency lines). Thus such a plot can be very useful. The smearing of the components, which appears because the time window used for the individual spectra represents a certain sweep in the speed, is however, a disadvantage. The power of the components becomes spread over several lines. In particular, high frequency components in the spectrum, such as toothmesh frequencies, might be smeared so much that details in sideband structures are lost in the analysis. This is the main reason why order analysis is used instead.

For order tracking the time record is measured in revolutions [REV] rather than seconds [s] and the corresponding FFT spectrum is measured in orders [ORD] rather than frequency [Hz]. Just like the resolution, Δf [Hz], of the frequency spectrum equals 1/T, where T [s] is seconds per FFT-record, the resolution of the tracked analysis, Δord [ORD], equals 1/rev, where rev [REV] is revolutions per FFT-record. For analyses with one or more revolutions per record, the resolution of the spectrum is equal to or better than 1 ORD. The result of the analysis is a high resolution order-spectrum, where the individual orders, or fractions of orders, relate directly to the various rotating parts of the machinery. The focus is on the orders.

In general one can say that tracking analysis, by use of an FFT analyzer, is an analysis by which the harmonic pattern of the vibration signal from a rotating machine is stabilized in certain lines independent of speed variations. This means that all the power of a certain harmonic is concentrated in one line and the smearing that would result in normal analysis is avoided.

The intention of this article is, firstly, to explain the principle of order analysis (tracking) as implemented in Multichannel Analysis System Type 3550, Order Tracking Analyzer Type 2145, Multichannel Data Aquisition System Type 3551 and Multi-analyzer System Type 3560 and, secondly, to give examples of the application of this analysis.

Digital Tracking using the 3550

As the tracking is performed using digital calculations, its capabilities far surpass the traditional methods using analogue techniques.

External tracking filters and frequency multipliers with a lot of knobs to set are no longer needed.

Just supply the tacho signal directly to one of the channels (all channels have a power supply for tacho probes such as the Brüel&Kjær Types MM 0012 and MM 0024 built-in), enter the required number of orders and, if necessary, enter the tacho ratio in the measurement setup. Fig. 1 shows the measurement setup and the order spectrum for an order analysis on the Multichannel Analysis System Type 3550.

The measurement can be optimized to a run-up or a coast-down and thereby allow the tacho frequency to change up to a factor of 5.64 for each FFT record. The transform size (number of lines in the order spectrum), and thereby the analysis time, can be changed (50,100, 200, 400, 800 lines) and optimized for the application. Within a tacho frequency range up to a factor of 5.37 (in the worst case a factor of 2.69) overlap analysis can be performed, i.e. no loss of data can be obtained. The total tacho frequency range covered (i.e. max tacho frequency / min tacho frequency) is up to a factor of approximately 90.000.

The tacho frequency is measured for *each* tacho period along the record and all the following calculations are done digitally, which means that the tradi-

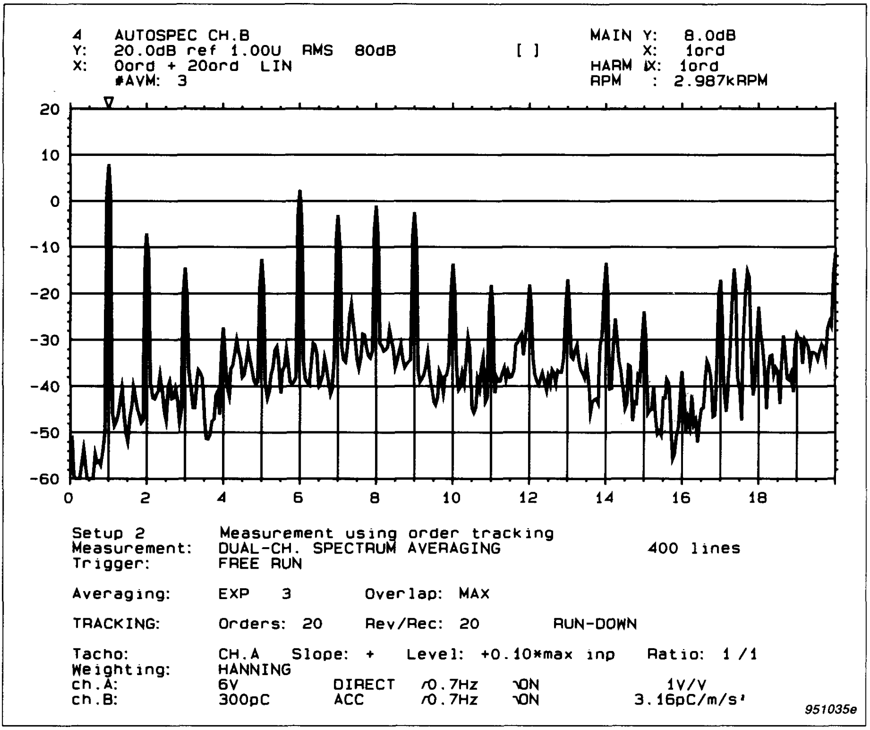

Fig. 1. Measurement setup and order spectrum for an order analysis on the 3550

tional problems of the analogue techniques, such as jitter in phase-locked loops are eliminated.

The tacho frequency is measured according to the specified tacho slope and level, and a tacho ratio in the range from 1/999 to 999/1 can automatically be compensated for in the calculations. This means that if for instance the tacho frequency is measured on the output shaft of a gearbox and the RPM should be referred to the input shaft of the gearbox, the gear ratio should be entered as a tacho ratio. If the input shaft gearwheel has 63 teeth and the output shaft gearwheel has 26 teeth, a tacho ratio of 63/26 should be used. A tacho divider can be used to compensate for several non-equidistant tacho pulses per fundamental period (revolution) and a tacho hold off, in % of the period of the tacho frequency, can be supplied in situations where only a noisy tacho signal with a lot of "ringing" is available.

Order spectra can automatically be stored as a function of tacho frequency (RPM) in dual-channel measurements where one channel is needed for tacho. Complex spectrum (i.e. Phase-assigned Autospectrum) can be used if both the magnitude of the analyzed signal as well as its phase relative to the tacho signal is needed for the analysis. This gives possibilities of 3D maps of the order spectra and plots of the magnitude and the phase of the different orders as a function of RPM (i.e. Bode plots).

Principle of digital order tracking

The key words in the digital tracking technique are: *Oversampling, interpolation* and *resampling.*

The signals are sampled at 65.536 kHz (262.144kHz in 100kHz input modules) after the analogue antialiasing filters, as in the other analysis modes. In the zoom processor, the signals are now low-pass filtered to obtain 4 times oversampling[1]. Fig.2 shows a block diagram of the sampling and zoom processing in the case where 25.6 kHz modules are used and the analyzer is in a dual-channel mode. Fig.3 visualizes the oversampling and lowpass filtering in both time and frequency domains. Notice that the sampling frequency is artificially increased by a factor of 2 by adding an extra sample with a value of zero in between the samples from the ADC. This increases the max. obtainable frequency range by a factor of 2. For order tracking analysis based on a Time History Recording (i.e. throughput to disk) the sampling frequency is increased by a factor of 4 by adding three extra samples with a value of zero between the samples from the ADC.

The low-pass filtering and decimation, D, in the zoom processor are given by the required frequency span in the analysis. In tracking mode the required frequency span is determined by the specified number of orders, the measured tacho frequency and whether it is in run-up, coast-down, "steady state" or fixed filter span mode. "Steady state" mode is used if the tacho frequency is only var-

1 Using ordinary frequency analysis a sampling frequency of 2.56 times the maximum frequency span is used in order to avoid aliasing. Thus in order tracking mode a sampling frequency of 10.24 times the maximum frequency span is used

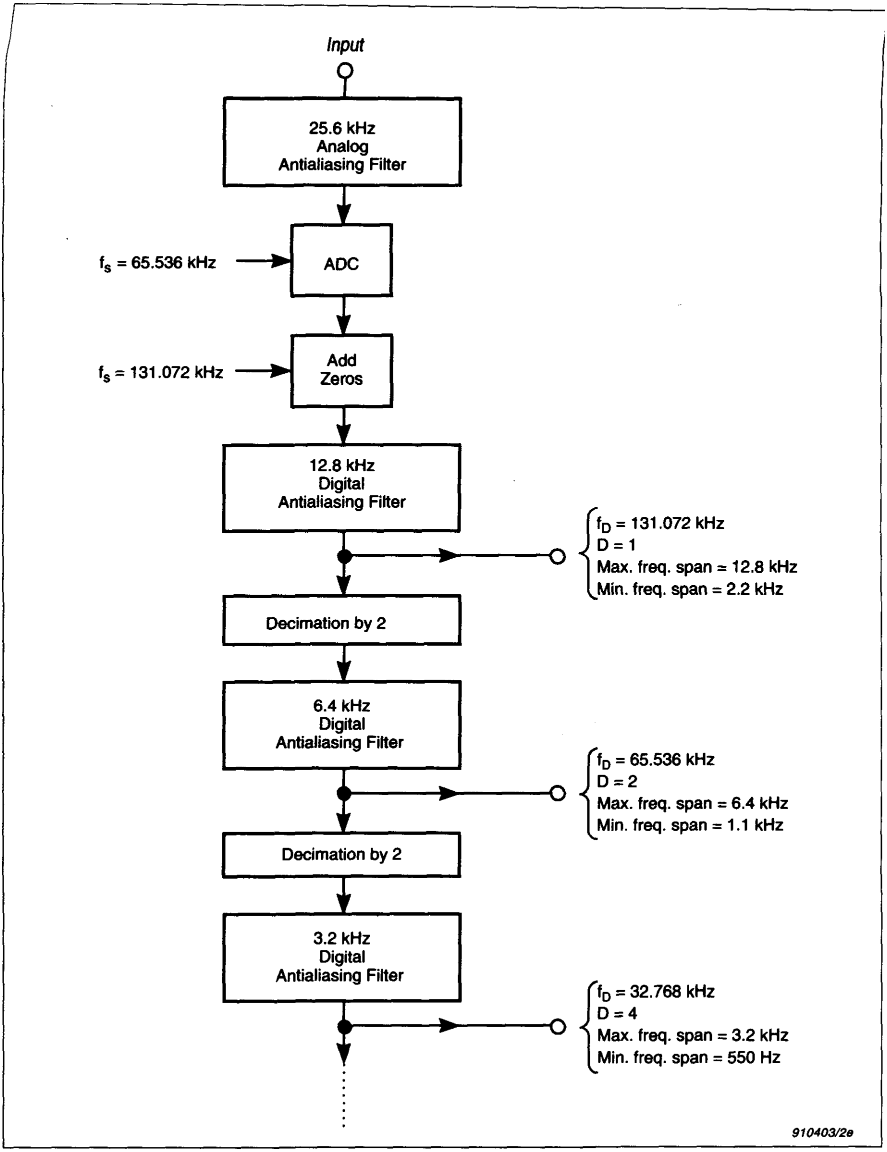

Fig. 2. Block diagram of zoom processor with decimation D, for 25kHz input modules in dual-channel configuration

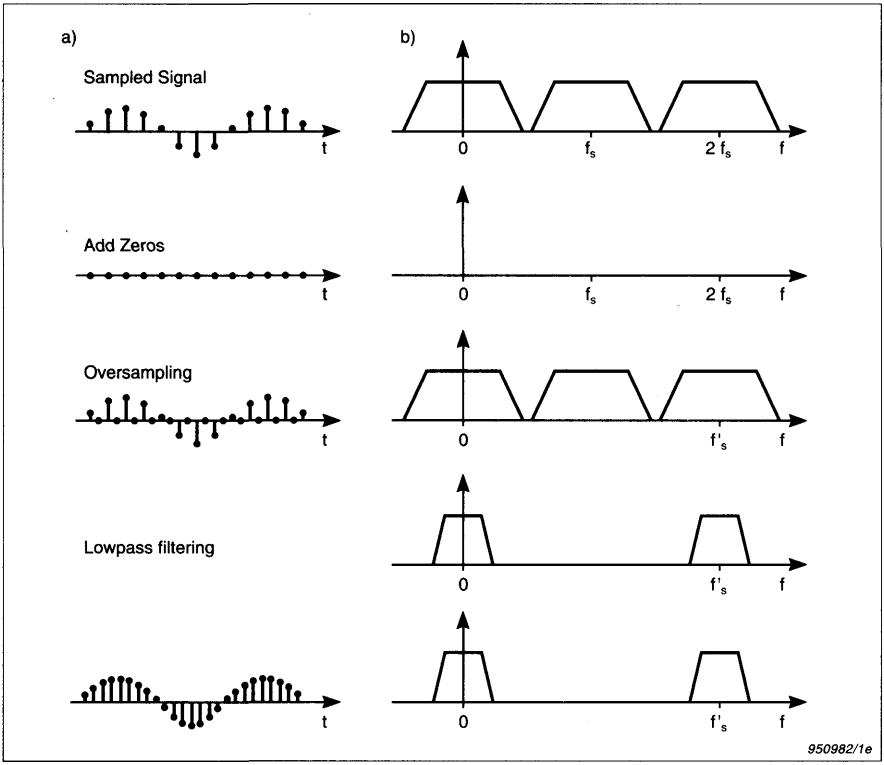

Fig. 3. Oversampling and lowpass filtering. Principle of adding zeros and lowpass filtering to achive a factor of 4 times oversampling a) time domain b) frequency domain

ying around a mean frequency. Fixed filter span mode is used to avoid shift of frequency range during the analysis.

The samples are then recorded in the memory for further "fine" decimation, d (i.e. further "fine tuning" of the sampling frequency) by interpolation and resampling. This process is controlled by the measured tacho frequency along the record and the specified number of orders. The decimation, d, can therefore vary along the record and d is a non-integer. This is illustrated in Fig.4.

Oversampling by a factor of 4 is used, allowing for a fine decimation, d, by a factor of 1 to 5.92 within each record without any aliasing problems. Fig.5a shows the low-pass filter and the sampling frequency after the D decimation

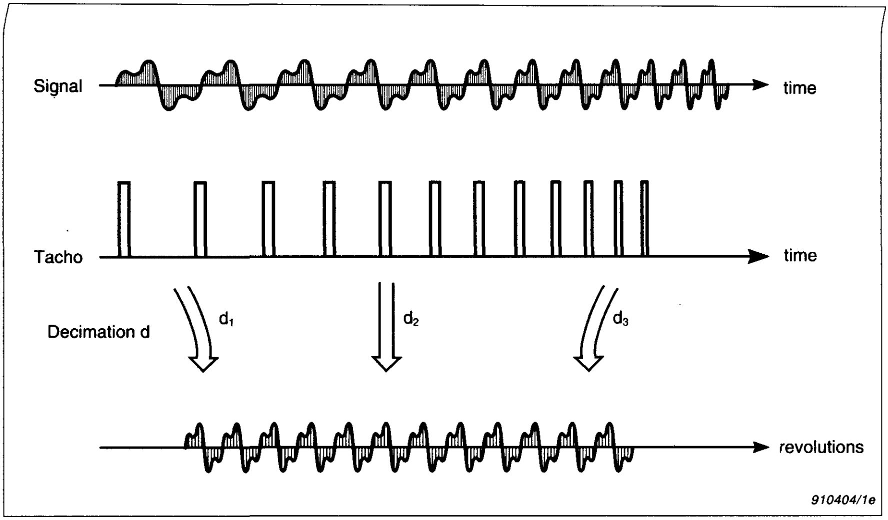

Fig. 4. Decimation d by interpolation and resampling d1 > d2 > d3

(i.e. decimation d=1) and Fig.5b illustrates the situation with maximum allowable decimation d, by a factor of 5.92, without aliasing problems in the analysis range. See Appendix A for more details.

a) In run-up mode the decimation D is selected for each new record to allow for max. tacho frequency increase in the following record. This corresponds to having a decimation d as close as possible to 5.92 in the beginning of the next record (Fig.5b). In coast-down mode the decimation D is selected for each new record to allow for max. tacho frequency decrease in the following record. This corresponds to having a decimation d as close as possible to 1 in the beginning of the next record (Fig.5a). In multifunction measurements where a measured function is stored in a multibuffer, however, the decimation D is, after the initial optimization, kept fixed as long as possible during the measurement of run-ups or coast-downs, for reasons to be explained later. A 5% margin (hysteresis) on d is used to allow for small non-monotonous changes of the tacho frequency during the run-up or the coast-down, i.e. $1.05 < d < 5.64$, which corresponds to a ratio of $5.64/1.05 = 5.37$.

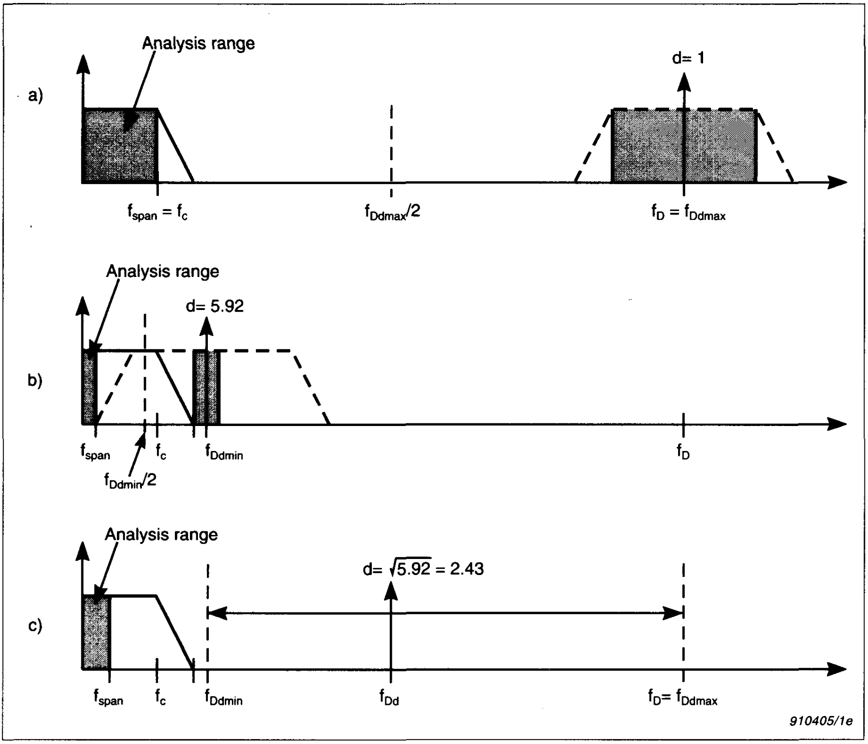

Fig. 5. Sampling frequency after decimation D in zoom processor f_D, sampling frequency after decimation d (interpolation and resampling) f_{Dd}, cutoff frequency of antialiasing filter f_c and analyzed frequency span f_{span} in the order analysis
a) no decimation d , i.e. d = 1
b) maximum decimation d without any aliasing problem in analysis span f_{span}, i.e. *d = 5.92*
c) optimal situation in "steady state" mode, i.e. d = √5.92 = 2.43, allowing a tacho frequency change, both up and down, by a factor of 2.43

In the worst case, we will have an allowable tacho frequency change of only 5.92/2 = 2.96 per record, corresponding to the steps by a factor of 2 for D.

In practice, however, much smaller speed ranges per record is required in order to get a proper measurement of the orders as a function of RPM (or frequency). This will be discussed later.

b) In "steady state" mode, the tacho frequency is supposed only to vary around a mean value. Optimization of D in this situation means that the same relative change of the tacho frequency in both directions should be possible in the following record. The maximum allowable factor of tacho frequency change (both up and down) per record is therefore $\sqrt{5.92} = 2.43$. This optimal situation is shown in Fig.5c.

c) In "fixed filter span" mode the tacho frequency may vary by a factor of 5.92 within one time record. However, it must remain within a fixed frequency range in all records. Thus the frequency span must be set equal to or higher than the maximum frequency of interest. The maximum frequency is equal to the maximum fundamental frequency times the number of orders selected.

This mode is used to avoid shift of frequency range during the analysis. A shift of frequency range from one time record to the next means that they cannot overlap. In multifunction mode it means update cannot take place within the first record after shift of frequency range, which might cause gaps in the multibuffer.

Tacho and RPM measurements

From the tacho signal Type 3550 determines the RPM or the fundamental frequency used as reference for the order-analysis. Basically the RPM is measured as the reciprocal of the time between 2 consecutive tacho pulses, but the total algorithm for the RPM determination is rather intricate.

First the tacho signal must be well conditioned by optimum input voltage, proper Tacho Accept Level, Slope, Sign and Hysteresis with respect to the signal. If there are more than 1 tacho pulse per revolution of the fundamental shaft, the Tacho Divider or the Tacho Ratio should be set accordingly. If the tacho signal is ringing or otherwise contaminated, the Tacho Hold Off should be used to prevent detection of false tacho signals. The function Monitor Signal Tacho facilitates inspection of the tacho signal for setting of the mentioned parameters. The RPM algorithm is quite demanding regarding processing power especially at lower RPMs where the tacho pulses are rare. To limit the processing load, the Tacho Lower Frequency Limit parameter specifies the lowest tacho rate the algorithm is looking for. By default this limit is set to

1 Hz. If the fundamental frequency is below 1 Hz, the limit should be set accordingly, but the lower limit should always be as high as possible.

Two properties of the RPM algorithm are noteworthy. When the tacho pulses are identified and accepted, the tacho interval is determined (by interpolation) some 50 times more accurately than indicated by the actual At. This allows for more tacho pulses per fundamental revolution without significant loss of accuracy and ensures a sufficient resolution of the fundamental frequency to be used as tracking reference. To be able to measure Phase-assigned Auto-Order-spectrum (the Autospectrum of a signal assigned the phase between the signal itself and the tacho) the tacho is subjected to the same filtering as is the signal. This means that potential fine sharp tacho pulses filter away at low RPMs. The cure against this effect is to increase the duty cycle of the tacho pulse.

When the instrument flashes "Tacho frequency under range" there are two possible reasons for that message:

In frequency analysis or run-up/down order tracking the message means, that the algorithm does not see or accept any tacho pulse. The pulse may be absent or the above mentioned parameters should be adjusted.

In order tracking with "Fixed Span" the reason may be the same or: The algorithm is able to determine the fundamental frequency, but the rotation to be tracked is too slow for the selected span. The cure is to select a lower fixed span.

Especially at low tacho rates the RPM algorithm should have good working conditions, these are summarised as:

1) Optimum Input Voltage according to the output of the tacho probe
2) Tacho channel DC coupled if possible
3) Long duty cycle of the tacho signal in order to have sufficient energy after possible low pass filtering
4) Tacho Accept Level not too low but not higher than the amplitude of the low pass filtered tacho pulse
5) Tacho Lower Frequency Limit as high as possible but lower than the fundamental frequency of interest.

Frequency spans in tracking mode

The four times oversampling will restrict the max. frequency span available in tracking mode. In the dual-channel modes, the sampling frequency is therefore, as mentioned above, increased by a factor of 2 by adding zeros between the samples from the ADC followed by a lowpass filtration (see Fig.2). Order analysis can thus be performed up to 12.8kHz with 25.6kHz input modules and up to 51.2kHz with 100kHz input modules. In Time History analysis mode the full frequency range can be used as mentioned earlier.

In multichannel mode, the max. allowable frequency span in tracking mode will be given by the number of measurement channels and number of lines in the analysis. There is however no simple relation between these parameters. A few typical examples:

Analysis in 8-channel mode, i.e. up to 7 measured channels plus 1 channel for the tacho, can be performed up to max. 6.4kHz (with 100 lines).

In 16-channel mode, i.e. up to 15 measured channels plus 1 channel for the tacho, analysis will be possible up to max. 3.2kHz (with 50 lines).

With 100kHz input modules we can handle up to 3 measurement channels (apart from the tacho channel) to a max. of 12.8kHz (with 200 lines).

Time-frequency Relationship and Weighting Functions

The time-frequency relationship for FFT analysis is given by $\Delta f \cdot T = 1$, where Δf is the line spacing in the frequency domain and T is the record length in the time domain. For order tracking the line spacing is given by (Number of orders)/(No. of analysis lines) while the record length is given by the measured number of machine revolutions pr. record. Thus the time-frequency relationship for order tracking analysis is given by **No. of analysis lines = No. of orders x No. of revolutions per record.**

In the measurement setup the user can select the No. of analysis lines and the No. of orders. The resulting No. of revolutions per record, which also indicates the element number (the FFT line) where the fundamental order will appear, is then displayed in the measurement setup.

As a consequence tracking speed can be increased by decreasing the number of machine revolutions used for the calculation, i.e. by increasing the number of orders and/or decreasing the number of analysis lines in the measurement setup.

If an integer number of revolutions per record is selected, i.e. the orders are perfectly matching up with calculated FFT lines, rectangular weighting may be used since the analysis of the orders are leakage free. If there are considerable non-order related components it may be advantageous to apply Harming weighting to minimize the leakage effect of the non-order related components. Using rectangular weighting each order will appear as one FFT line, while using Hanning weighting they will appear as 3 FFT lines, Ref. [4].

Speed considerations in connection with run-up or coast-down tests

When performing run-up or coast-down tests, where order spectra are stored as a function of RPM (using multifunction mode), it is essential that the order spectra are stored with sufficiently small RPM intervals to allow for proper detection of resonances, critical speeds, etc. The change of the tacho frequency within each record should therefore be much smaller than the allowable factor of min. 2.96 (max. 5.64) per record. For analysis of fast run-ups or coast-downs as few lines as possible (e.g. 200 or 100 lines) should be used in order to get both the records (in number of revolutions of the machine) and the analysis time as short as possible.

In ch.B spectrum averaging mode, where ch.A serves as tacho input, each analysis (i.e. interpolation, resampling, FFT and averaging) of the Autospectrum in ch.B takes typically 25 ms, 30 ms, 60 ms, 125 ms and 250 ms for 50 line, 100 line, 200 line, 400 line and 800 line analysis, respectively. For averaging of Complex Spectrum ch.B (Phase-assigned Spectrum ch.B), where the phase between the tacho signal (in ch.A) and the measured signal in ch.B is calculated as well, the time for each analysis is approximately doubled. The reason for these relatively long analysis times, compared to those for normal frequency analysis, is that 4 times larger transforms are used due to the 4 times oversampling, which f.ex. means that an 8 K transform rather than a 2 K transform is used for an 800 line order spectrum analysis.

In multichannel mode, the analysis time depends upon the number of channels and number of Auto- and Cross-spectra to be calculated during the measurement.

When analysis of run-ups or coast-downs over a wide RPM range is performed, the decimation factor D in the zoom processor has to be changed at some point during the measurement. This means that the time recording has to be switched from one "tap" to another in the zoom processor (see Fig.2). This can cause gaps (i.e. missing spectra) in the multifunction measurement, as it will take a certain time before a record with the new decimation factor D is available.

In multifunction measurements of run-ups or coast-downs, the decimation factor D is optimized for each new record, as explained earlier, until the first function in the multifunction is available. After that, the decimation D is kept fixed as long as possible during the measurement in order to avoid possible gaps introduced by the change of D.

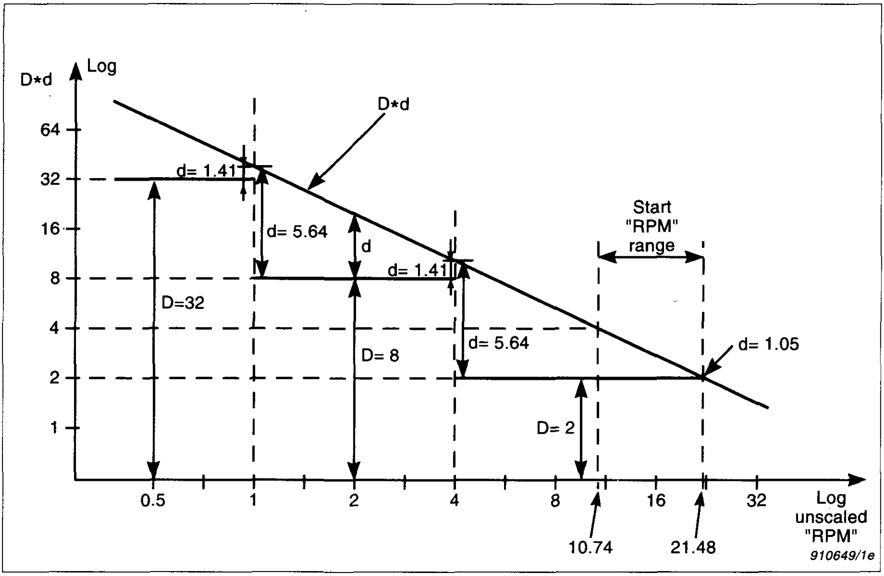

Fig. 6. Change of decimation factors D and d during a cosat-down. The start "RPM" is supposed to be between 10.74 and 21.48

Fig.6 shows how the decimation factors D and d, as well as their product D*d, change during a coast-down test using multifunction measurement mode. The log RPM axis is in unscaled numbers, called "RPM", in order to illustrate the principle rather than a specific example (which also would require specification of the number of orders in the analysis). The start "RPM" is supposed to be around 16, giving a optimal start decimation D = 2. A start decimation D = 2 is selected if the start "RPM" is max. 21.48 (corresponding to a min. allowable decimation d = 1.05) and min. 10.74 (corresponding to a max. allowable decimation d = 5.64). If the start "RPM" was higher than 21.48, D would be set to 1 and if the start "RPM" was lower than 10.74, D would be set to 4. The decimation D = 2 will not be changed before the decimation d has reached its max. value of 5.64 at "RPM" = 4. At this point D is changed to 8 and the recording has to change to another "tap" in the zoom processor (see Fig.2). A gap (i.e. a missing spectrum) could therefore appear in the multifunction at this point, if the coast-down is too fast.

At "RPM" = 1, d has again reached its max. value of 5.64 and D is now changed to 32.

The speed range obtained, before D is changed the first time during the measurement, thus depends upon the start RPM (apart from the number of orders) in the measurement. The max. speed range, without change of D (the first time), is therefore 21.48 "RPM"/4 "RPM" = (5.64/1.05) = 5.37, and the min. speed range is 10.74 "RPM"/4 "RPM" = (5.37/2) = 2.69. After the first change of D (in the example, at "RPM" = 4), D will be changed a factor of 4 for each change of RPM by a factor of 4, in the remaining part of the coast-down measurement.

For a run-up test, the considerations and the figures for speed ranges are the same.

Examples of how fast order spectra can be stored in the multifunction buffer (using multifunction mode):

Multi Autospec ch.B, 25 orders,
From: 10 Hz, To: 100 Hz, Δ: +2 Hz, N = 46

corresponding to measurements of the first 25 orders of a machine run-up from 600 RPM to 6000 RPM every 120 RPM.

Measurements without any gaps can be obtained with the sweep rates given in Table 1. The corresponding min. time between spectra is given as well.

No. of lines	50	100	200	400	800
Sweep rates	6 Hz/s (360 RPM/s)	6 Hz/s (360 RPM/s)	6 Hz/s (360 RPM/s)	3.5 Hz/s (210 RPM/s)	2.5 Hz/s (150 RPM/S)
Corresponding time between spectra	333 ms	333 ms	333 ms	570 ms	800 ms

Table 1. Max. sweep rates and corresponding min. time between spectra for the following measurement: Multi Autospec ch.B, 25 orders. From: 10 Hz To: 100 Hz Δ:- +2 Hz, N = 46

For faster run-ups (higher sweep rates) the spectrum at 32 Hz (1920 RPM) could not be measured, causing a gap at that frequency (RPM). This is due to the change of the decimation factor D, as explained above, at that frequency (RPM). Such gaps may be avoided by a recording in Time History mode, before order tracking is applied to the data.

The higher the start frequency is for a run-up (stop frequency for a coast-down), the shorter the time records will be (measured in seconds), and shorter time intervals between spectra can be obtained without gaps. Taking the example from above but changing start, stop and update criteria to:

From: 50 Hz, To: 500 Hz, Δ: +10 Hz, N = 46 allows the minimum time between spectra, i.e. measurements without gaps, to be approximately halved compared to figures given above.

Run-up or coast-down measurements over an RPM range limited to the factor of 2.69 to 5.37 (depending upon start RPM and number of orders as mentioned earlier), which means that there will be no change of D during the measurement, can be performed using multifunction mode with up to:

Approx. 25 spectra/s for 50 or 100 line analysis

Approx. 16 spectra/s for 200 line analysis

8 spectra/s for 400 line analysis

4 spectra/s for 800 line analysis

without any gaps.

Remember, however, that the run-up or coast-down time always has to be long enough to allow the system under test to respond in order to get proper measurements of resonances, critical speeds, etc. of the system under test.

Also notice that the first record in a run-up can be very long (low frequency) and therefore delay the time before the first spectrum is available.

Order Tracking Analyzer Type 2145

Portable and battery operated Order Tracking Analyzer Type 2145 (also known as Vehicle Signal Analyzer) oners the combination of simultaneous dual channel digital order tracking anaysis and real-time constant percentage bandwidth analysis (i.e. 1/3 octaves). In this case a DFT rather than FFT is performed allowing the calculation of up to 20 arbitrarily or harmonically selected orders in the order span, which can be chosen in the interval between 0,01 orders to 200,0 orders.

Type 2145 has two separate tacho inputs, rather than using an input channel for tacho and RPM calculations as implemented on Type 3550. Thus Complex Spectra are only available on Type 3550. There is internal file storage of orders for combination of both a run-up and a coast-down. Thus a 3D waterfall display of order spectra is not possible only order slices can be displayed. The advantage of using DFT rather than FFT is that the calculations are much faster when only a few orders are required. The main tacho input allows tacho frequency up to 1.800.000 RPM, i.e. 30kHz, while 3550 tacho frequencies must not exceed the frequency range of the actual input module.

Multichannel Data Acquisition System Type 3551

This Front-end system facilitates digital order tracking of up to 16 channels and uses the same input modules as the Type 3550 Analyzer. Also for this system one of the input channels is used for the tacho signal and RPM calculation, thus permitting calculation of complex orders (i.e. both magnitude and phase).

Up to 16 arbitrarily chosen orders (integers as well as non-integers) can be calculated, with simultaneous real-time calculation of overall level, overall A-weighted level and overall level in a user-definable frequency span independent of the order tracking span. Order tracking using Type 3551 is supported by the LMS CADA-X Signature Monitor, which provides the necessary tools for further analysis and display of waterfall spectra, order slices, frequency cuts etc.

Multi-analyzer System Type 3560

Multi-analyzer System Type 3560 combines the possibility of having separate tacho channels with a user-definable frequency range for the RPM measurement, using for example multiple tacho pulses per machine revolution from a shaft encoder, and simultaneously being able of measuring Phase-assigned Order Spectra with a phase reference of a once per revolution tacho (Key Phasor).

Type 3560 is a PC/ Front-end based system, which runs under MS Windows ™ NT. The system has scaleable real-time performance by use of multiple DSPs and can be configured up to 32 measurement channels in version 1. The signals can be replicated for individual analysis by the use of multiple analyzer concept (up to 8 instruments in one PC). Thus true multi-analysis can be performed, for example, two simultaneous Order Tracking Analyses referenced to two different tacho signals, FFT Frequency Analysis and Constant Percentage Analysis (e.g. 1/3 octaves). This can be for the same or different frequency/order ranges and/or resolution, and can be simultaneous baseband and zoom analyses. The measurement data from the different analyzers can be stored in multibuffers for waterfall, contour, slice plots etc.

Coast-down of a large turbogenerator

(First application example)

The vibration signals (acceleration) at the bearings of the generator and the turbine were recorded at the same time as was the tacho signal from a Photo-electric Tachometer Probe Type MM 0012 giving the rotation frequency of the shaft.

The coast-down lasted nearly 15 minutes and was therefore suitable for order tracking analysis. The lowest 20 harmonics of the vibration signal are analysed during the coast-down Ref. [1]. Fig.7 shows the 3550 measurement setup and the order spectrum at 2503 RPM.

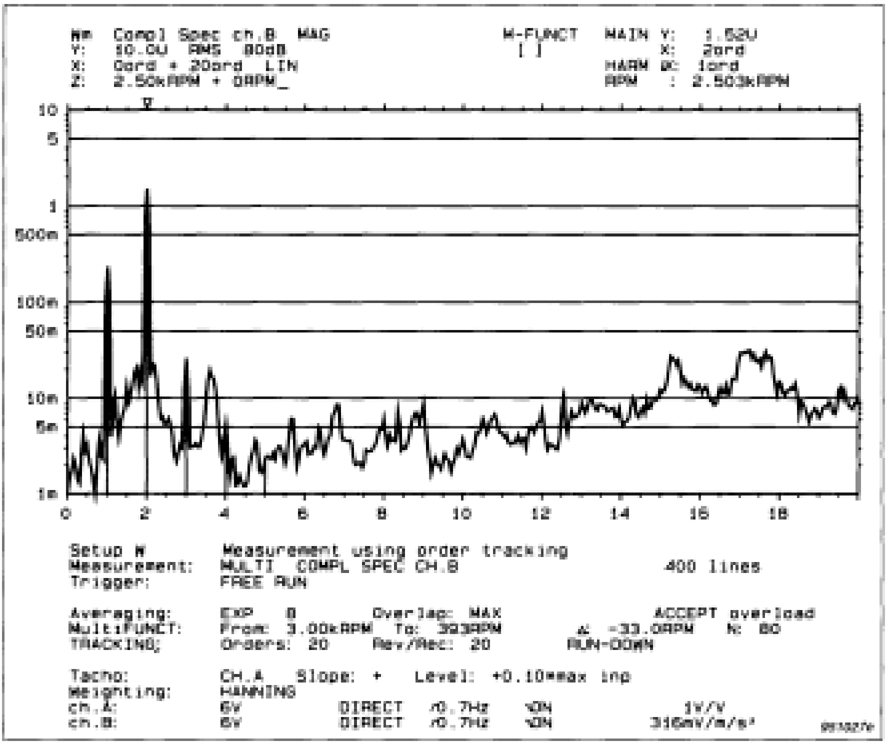

Fig. 7. Order spectrum at 2503 RPM and the measurement setup. Notice only 3 significant orders are seen

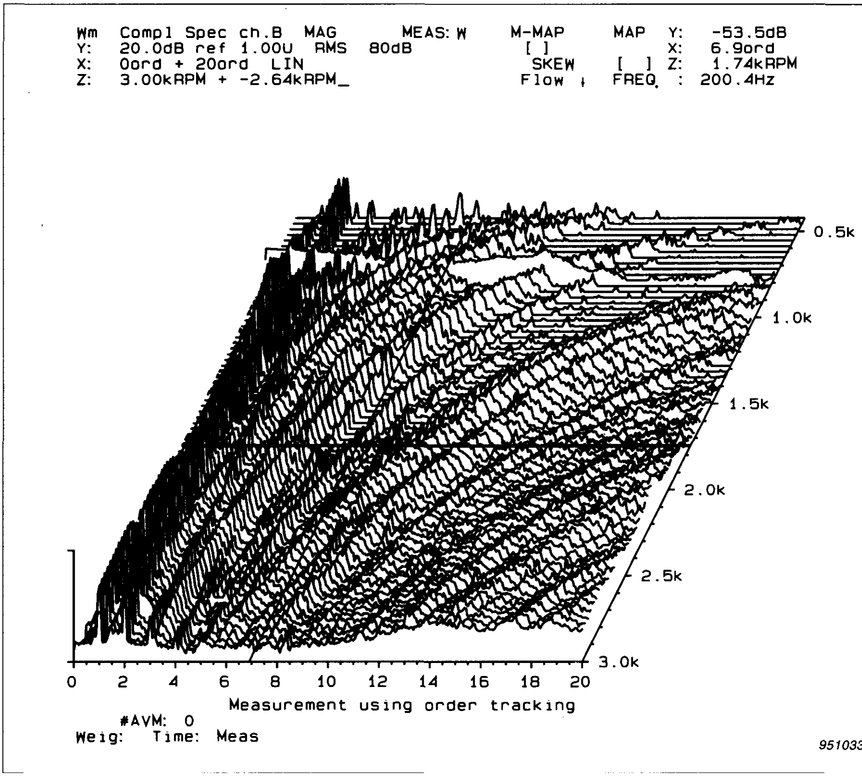

Fig. 8. Order analysis of lower harmonics of generator vibration signal during coast down

A 3-dimensional plot of the stored spectra of the vertical vibration signal at the generator bearings is shown in Fig.8. The first 3 harmonics are significant in level and show characteristic resonances. For example, a resonance is seen in the fundamental between 950 RPM and 1050 RPM which evidently is also excited by the second harmonic between 475 RPM and 525 RPM. The constant frequency components, presumably vibrations from other machines transmitted through the foundations, show up on hyperbolic curves in the rotation speed - harmonic order plane. The curves are given by c x n = f x 60, where c is speed in RPM, n is harmonic order and f is the frequency in Hz. Fig. 9 shows some examples of constant frequency curves. The curve for the 200 Hz component is indicated by the x- and z- cursors in Fig.8. Notice the smearing of the constant frequency components. As an overall view of all the related components this plot is very useful.

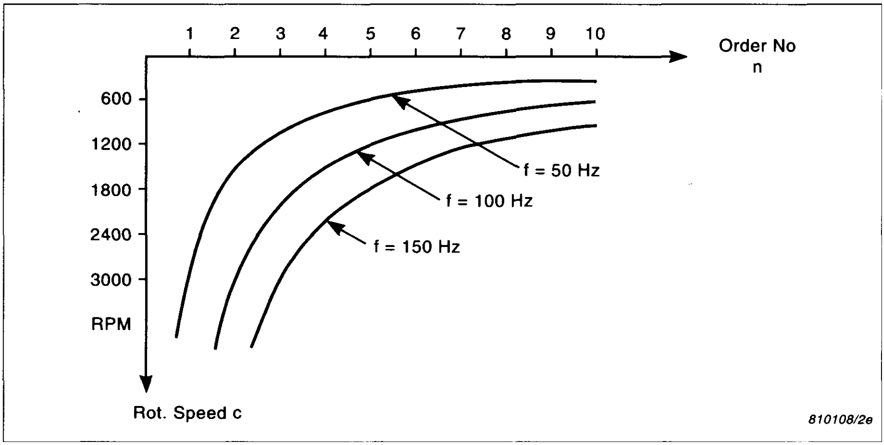

Fig. 9. Constant frequency curves

Using a slice cut (order cut) as shown in Fig. 10 a) and b) the resonances can be displayed in more detail. It is seen that the resonance around 1000 RPM actually has its peak at 16,9 Hz and is excited by both the fundamental and second harmonic. The broad resonance shape around 1700 RPM in the fundamental is also discernible in the second harmonic. The increased level at 2700 RPM in the fundamental corresponds to a critical speed stated by the manufacturer to be at 45,8 Hz. This resonance is not seen in the second harmonic. In the 1500 - 3000 RPM range of the second harmonic at least four resonance peaks are seen. Some of these might be combinations of more than one resonance.

As mentioned earlier, acceleration was measured in this example. Acceleration is the vibration quantity which puts emphasis on the high frequencies and is thus preferable if it is wanted to raise the higher harmonics relative to the dominating first harmonics. If, however, a measure of the energy in the vibration is desired the velocity should be measured (by integration of acceleration), as the kinetic energy is proportional to velocity squared.

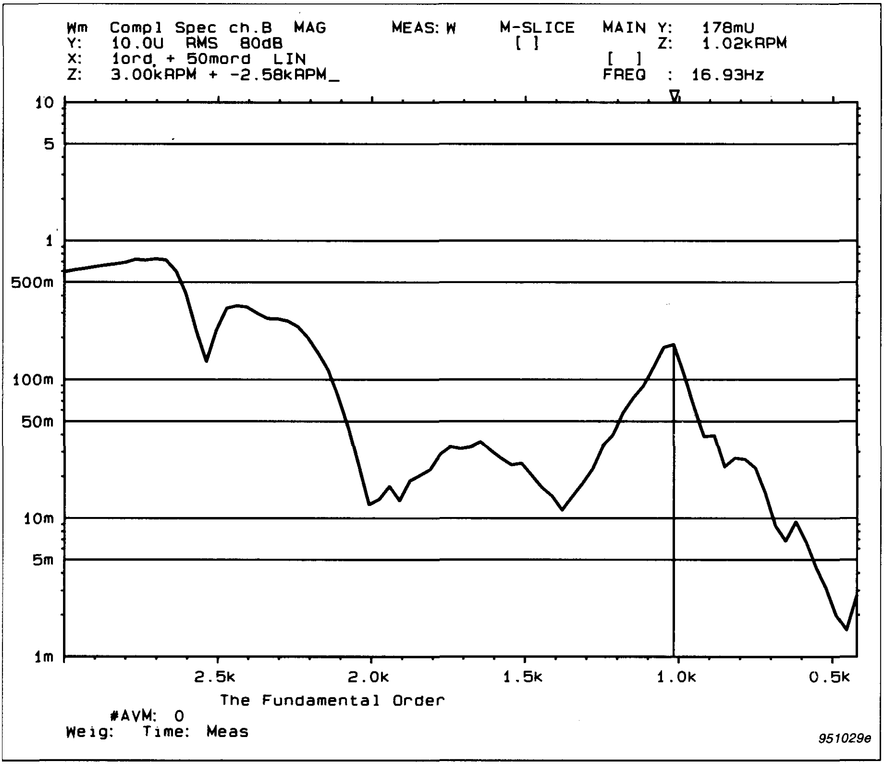

Fig. 10 a) Fundamental of generator vibration during coast down

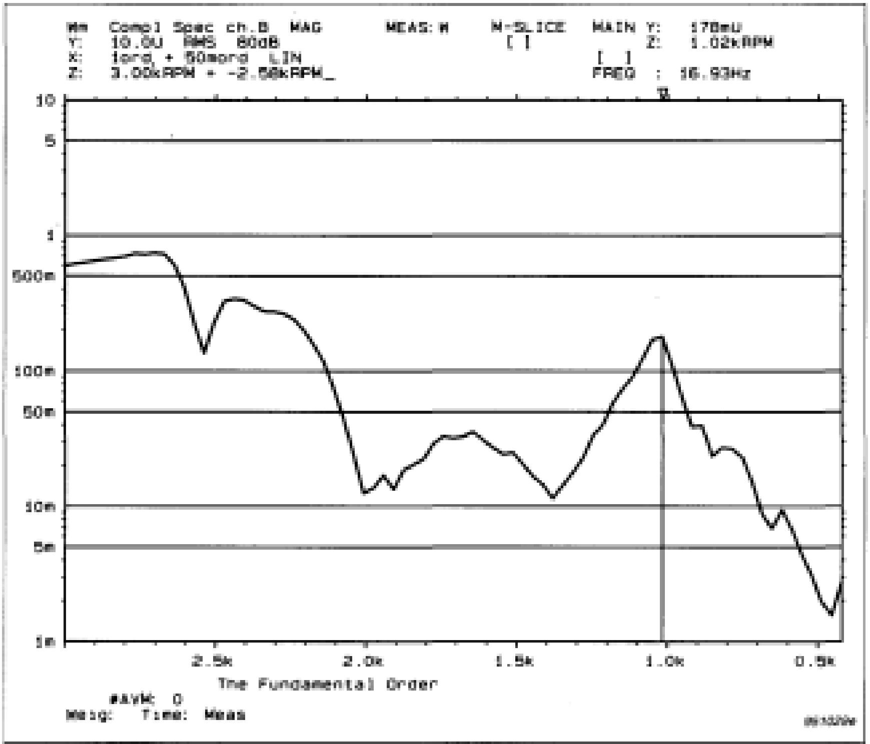

Fig. 10 b) Second order of generator vibration during coast down

Since complex spectra (see Fig. 7) have been stored in the multibuffer it is possible to show not only magnitude of orders as a function of RPM but also phase, Bode plots and Nyquist plots. Fig. 11 shows the fundamental order as a Nyquist plot. The cursor is positioned to the same RPM as indicated in Fig. 10a. Both real, imaginary and magnitude cursor values are indicated.

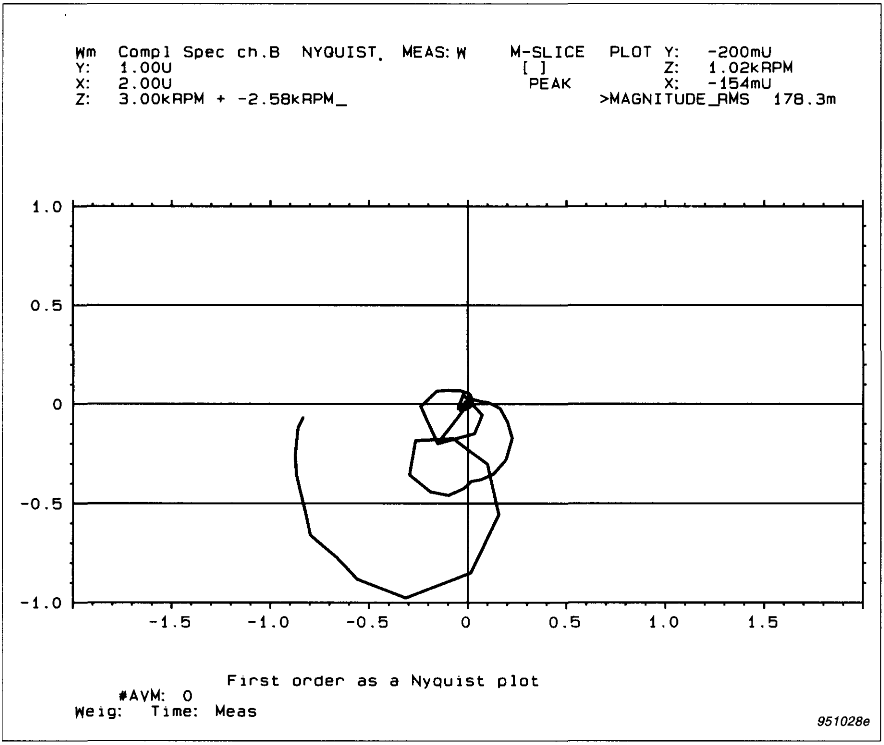

Fig. 11 Nyquist plot of the fundamental of generator vibration during coast down

The vibration signal at the generator bearing contained among other components a significant 37th harmonic and harmonics of this. A 3-dimensional plot of a 400 line zoomed order analysis around this 37th harmonic during coast-down is shown in Fig. 12. This component was found to be caused by a fan with 37 blades in the generator cooling system. Some peaks are easily seen. No sideband structure is seen around this component, indicating that it is a rather pure blade-passing frequency without modulation. The fundamental is plotted versus rotation speed in Fig. 13. Peaks showed up in the higher harmonics at nearly the same rotation speeds as in the fundamental. This indicates that the increases are not due to structural resonances, but might be caused by increased turbulence in the blower at different speeds.

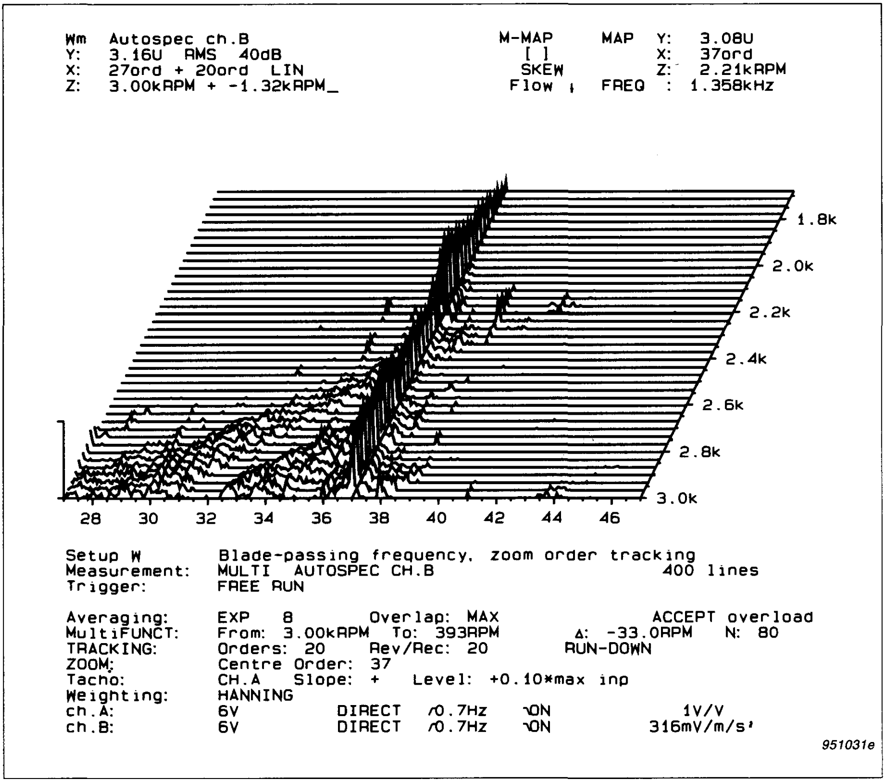

Fig. 12 Blade-passing frequency (i.e. 37th order) of fan during coast down

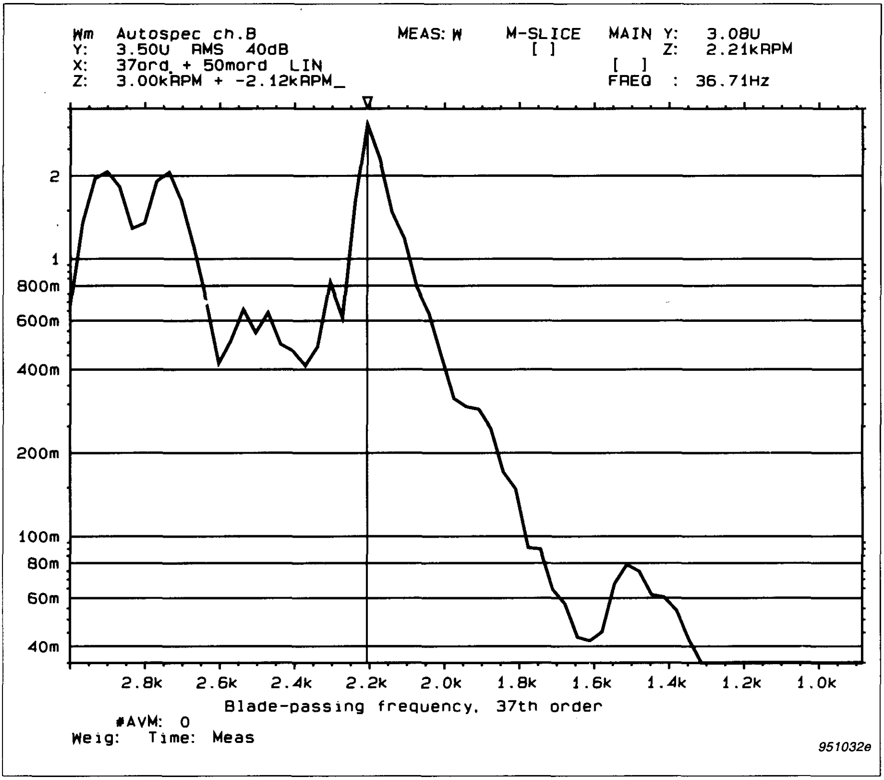

Fig. 13 Zoomed order tracking analysis around 37th order

Run-up Order Analysis of Axial Vibrations in a 2190 kW, MAN B & W, Marine Engine

(Second application example)

When designing marine engines, vibration control is of great importance. Excessive vibration levels may damage the engine/ship and create an annoying human environment.

The propulsion shafting, i.e. the crankshaft, the propeller shaft and the propeller are subject to dynamic torsional deformation as well as dynamic axial displacement, both causing axial vibration. In the design of the propulsion shafting, the vibration caused by the torsional deformation is controlled by tuning the torsional natural frequency (1-node) to an appropriate cpm (cycles per minute). The vibration caused by the dynamic displacement of the propulsion shafting is controlled by the presence of a viscous axial vibration damper (A/V damper). Apart from damping the displacement vibration completely, the A/V damper also dampens the axial vibration caused by the torsional deformation.

The engine under test was designed by MAN B & W Diesel A/S, Denmark. The verification test of the design comprises axial as well as torsional vibration measurements. Only the axial vibration measurements are presented here.

Propulsion Shafting Model and Instrumentation

The engine is a MAN B&W 6S26MC, a six cylinder, two stroke, 2190 kW engine with a maximum continuous RPM of 250. Due to the alternating compression/power strokes and the load of the propeller, the propulsion shafting is subject to dynamic torsional deformation. The torsional deformation causes

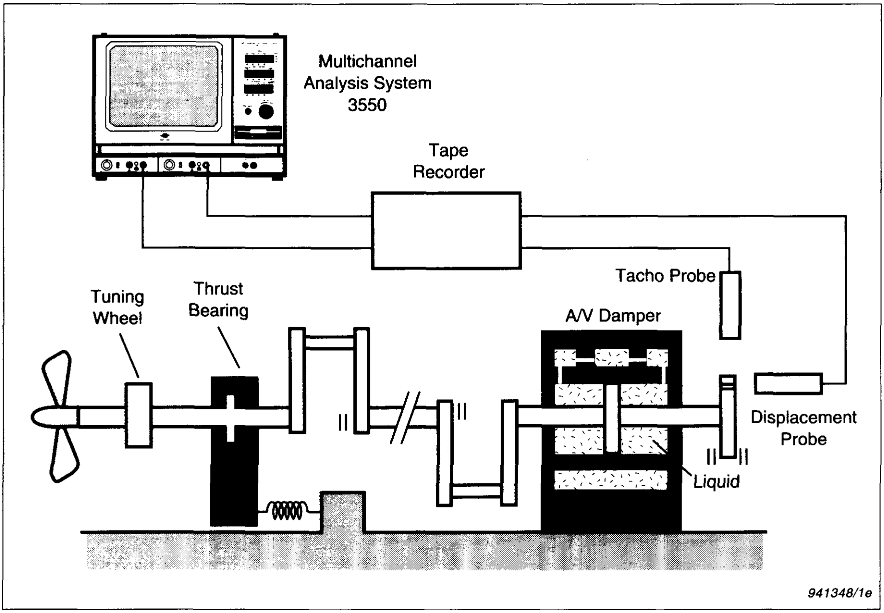

Fig. 14 Propulsion shafting model and instrumentation set-up

changes in the length of the crankshaft which is seen as axial vibration at the free end of the crankshaft. See Fig. 14. The torsional vibration also causes the propeller to rotate with varying speed, which in turn gives a varying thrust. The varying thrust excites the propulsion shafting axially, which also causes axial vibration to be seen at the free end of the crankshaft. The modal model of the propulsion shafting is a rather complex model comprising torsional and axial DOFs. The model predicts that the coupled 1-node torsional mode and the 0-node axial mode, when excited, are the major contributors to the axial vibration.

The torsional 1-node natural frequency was tuned to 847.5 cpm (≈14.1 Hz) by proper selection of length and diameter of the propeller shaft, and by introduction of a tuning wheel. The resulting mass made the calculated axial, 0-node, natural frequency appear at 992.6 cpm (≈16.5Hz).

Since the engine is a 6 cylinder, 2 stroke engine, the critical speeds are expected to be the speeds where the 6th order of the speed coincides with the natural frequencies. Other orders excite the natural frequencies at other speeds, but the 6th order excitations are expected to be predominant. Table 2 presents the calculated and measured critical speeds and displacements for the two important natural frequencies.

The free end of the crankshaft is fitted with a coupling flange. The deflection signal together with a tacho signal (1 per revolution) were measured on this flange. The measurement was performed in situ, i.e. the engine was in full operation at sea. Two measurements were made. One with the damper disa-

A/V-damper	**Passive**		**Active**		
	Calculated	**Measured**	**Calculated**	**Measured**	**Units**
1-node torsional nat. freq.	847.5	861.0*	847.5	852.0*	cpm
6th order critical speed	141.3	143.5	141.3	142.8	RPM
6th order A/V amplitude	2.19	1.53	0.40	0.52	mm
0-node axial natural freq.	992.6	1009.2	no	no	cpm
6th order critical speed	165.4	168.2	no	no	RPM
6th order A/V amplitude	1.99	1.23	no	no	mm
Max. continuous speed	250.0	250.0	250.0	250.0	RPM
6th order A/V amplitude	0.13	0.113	0.10	0.12	mm

* The measurement is not a direct measurement of the torsional natural frequency, but a measurement of the axial deformation caused by the torsional deformation. This can explain the deviations in the results

Table 2. Calculated and measured critical RPM and A/V amplitude

bled and another with the damper active. Over a 25 minute period of time the speed was gradually increased from 100 RPM to the maximum continuous 250 RPM, at all times with maximal propeller pitch corresponding to maximal thrust. The tacho and displacement signals were recorded on an FM tape recorder for later analysis.

The Measurement Set-up

The subject of the analysis is to determine the critical speeds of the engine, and to measure the corresponding worst case deflection of the free end of the crankshaft. Since the excitation of the propulsion shafting is a function of the rotating shaft itself, order analysis (no smearing and no leakage) is the tool that gives the best determination of the critical frequencies and the max.

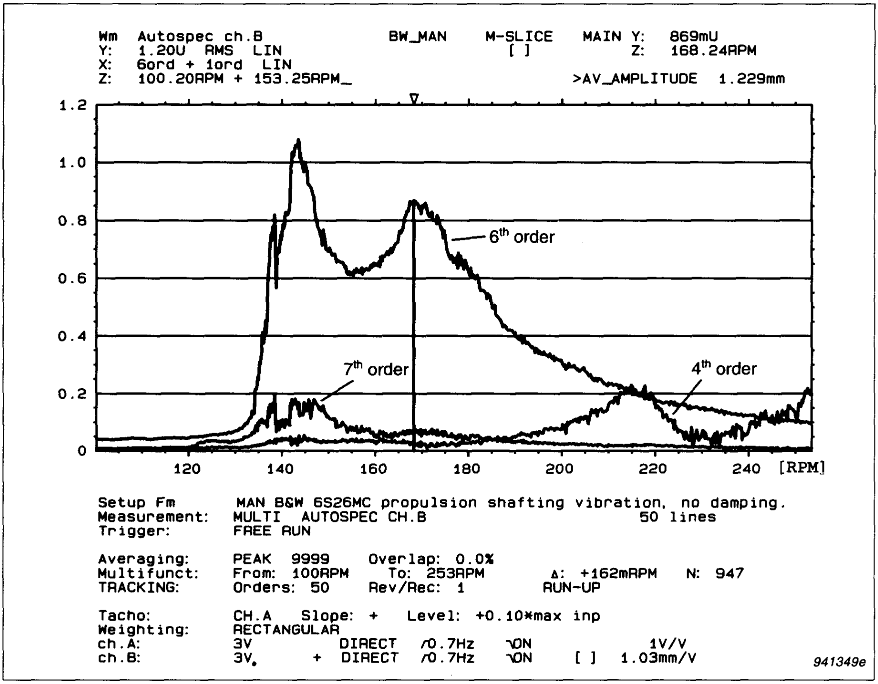

Fig. 15 Measurement set-up and analysis of undamped vibrations

deflection. The critical frequencies are found by inspecting the dynamic displacement pictured as a function of RPM for the various orders, also called order slices.

The MULTIfunction is selected to be AUTOSPEC CH.B, and from 100 RPM to 253 RPM a record is registered in the multibuffer whenever the RPM has increased by 0.162 RPM. Since critical speed and maximum displacement are the objectives, the records should be as short and as many as possible. The update criteria 0.162 RPM is the smallest possible increment for the wanted RPM range corresponding to the maximum number of records in the multibuffer. The selection of 50 lines spectra and 1 revolution per record give the shortest record obtainable for this application. The analysis results in a multibuffer containing 947 order spectra as a function of RPM, each spectrum being the maximum displacement as a function of orders from 1 to 50. The averag-

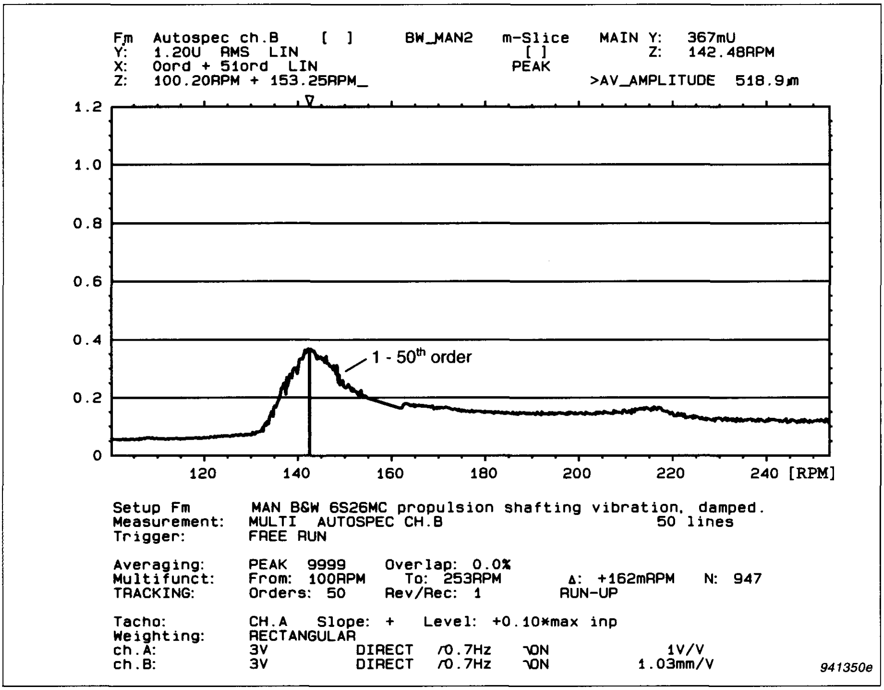

Fig. 16 Analysis of damped vibrations

ing option PEAK is selected to register the maximum value seen by the individual records in the multibuffer. The measurement setup is shown in Fig. 15 and Fig. 16.

Displaying the Results

Looking first at the analysis of the run-up with the A/V-damper disabled: As expected, the 6th order excites the natural frequencies most seriously. Fig. 15 shows the 6th order SLICE where two critical speeds are identified. 143.5 RPM excites the 1-node torsional natural frequency, and 168.2 RPM excites the 0-node axial natural frequency. The deflection is scaled to RMS. By defining a very simple User-defined Auxiliary Information (UDAI) named AV_AMPLITUDE, the cursor reading is also given as peak millimetres. The measured values are given in Table 2 for comparison with the calculated values.

Fig. 15 also shows other order slices. The 4th order excites the two natural frequencies at 215 RPM and 253 RPM, respectively, and the 7th order excites the axial natural frequency at 144 RPM. The corresponding resonance displacements are considerably smaller than those caused by the 6th order excitation. The remaining orders, not shown, hardly excite the natural frequencies.

Fig. 16 shows the result of the analysis with the A/V damper activated. The figure does not show a particular order slice but a Δ-slice containing the PEAK value of all the orders from 1 to 50. It is seen that maximum deflection still is at the 1-node torsional natural frequency, but that has been considerably damped. Inspecting the orders one by one, it can be seen that the axial resonance has been effectively damped. The maximum deflection is acceptable and the damper works as expected. See also Ref. [5].

Gated Tracking Applied on an Automobile Engine
(Third application example)

The vibration signal from reciprocating machinery is in a double sense a non-stationary signal. The vibrations are caused by the moving parts of the engine, so if the speed of the engine varies, the vibrations vary accordingly. Tracking analysis transforms the non-stationary vibration signal into a stationary one.

Although order tracked, the vibration signal is still non-stationary. Within one cycle, the vibration signal is to be considered as a transient and should be treated as such. A useful tool is the STFT (Short Time Fourier Transform), where a set of short records are placed consecutively to cover one engine cycle. Each short record is locked on to a particular angular fraction of the cycle and carries only information about the vibration related to that fraction. The shorter the record the more accurately the vibration can be related to where in the cycle it arises, at the expense of coarse order resolution. The focus is on where in the engine cycle, or where in the revolution the vibration arises, and the analysis may be referred to as revolution tracking or gated tracking.

The 4-Cylinder, 4-Stroke Engine (Toyota Carina)

All noise and vibration found in and around the engine is generated by the rotating and reciprocating parts of the engine itself. Referring to Fig. 17, the

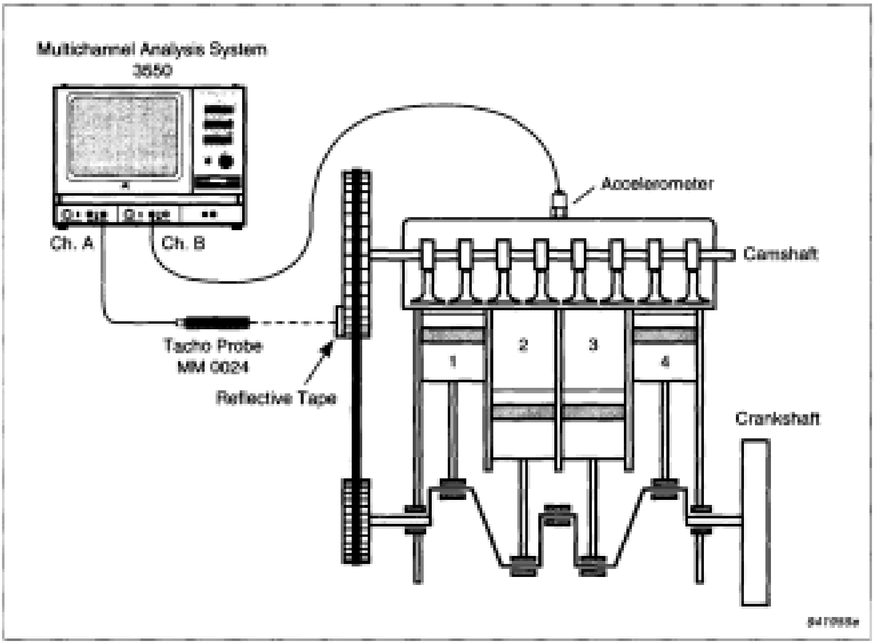

Fig. 17 Engine outline and measurement set-up

rotating parts are the crankshaft and the camshaft. The reciprocating parts are the pistons and the valves. The rotating parts and the pistons are well balanced and move very harmonically. The vibrations generated by these parts are therefore low harmonics of the rotating speed of the engine. As opposed to the pistons the valves are excited in a transient-like way. Most of the sound emitted by the engine is the clicking or clanging noise generated by the operation of the valves. Monitoring the vibrations using an amplified accelerometer signal and a loudspeaker enhances the impression of impact activities in the

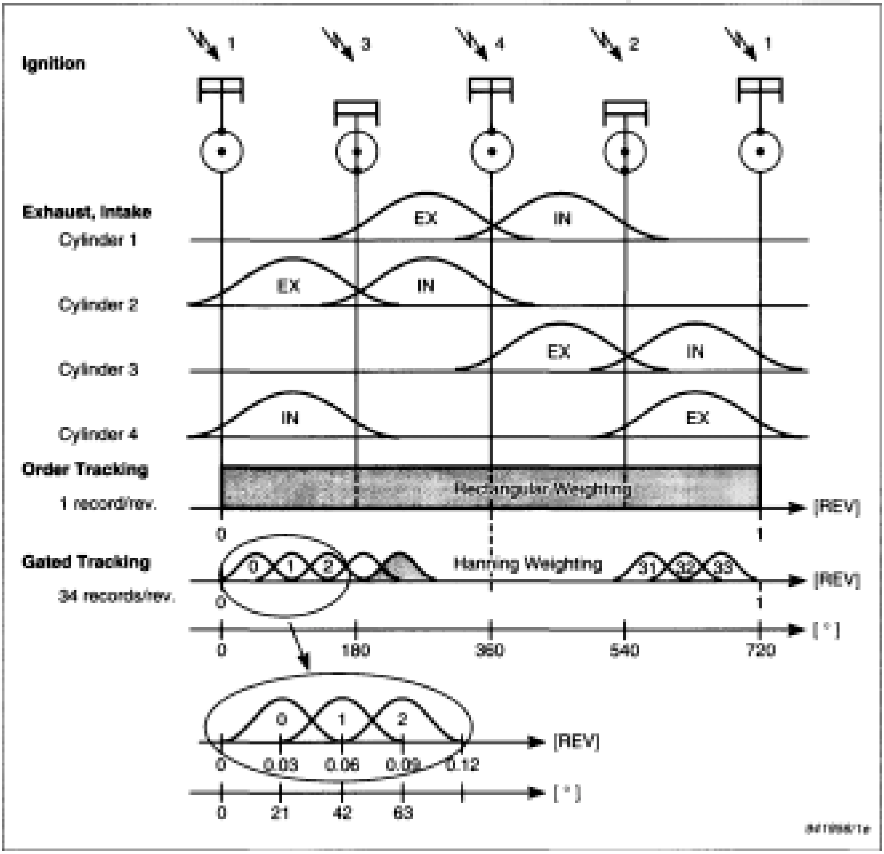

Fig. 18 Value activity timing and record definition for order tracking and gated tracking measurements. The revolution is referred to the camshaft

engine. The frequency or order spectra of the impact vibrations are wideband spectra, which means that high frequency or high order components are caused by the activation of the valves.

In the timing diagram in Fig. 18, it is shown how the valve activity is related to the angle of the camshaft. Two revolutions of the crankshaft (2 x 360° = 720°) correspond to one revolution of the camshaft i.e. one cycle of the engine. The small figures in the diagram indicate the Top Dead Center (TDC) and Bottom Dead Center (BDC) of piston 1. Ignition of the individual cylinders occurs some 10° to 15° before the TDCs; the firing order is indicated on top of the figures. As shown on the diagram the opening and closing of the valves are located to the vicinity of Dead Centers (DC). The valve activation starts and stops slightly before and after the DCs, but the maximum acceleration of the valves actually takes place very close to the DCs. Ref. [3].

Order Tracking Measurement

As shown in Fig. 17, two signals are measured and used in the following analyses by the Type 3550. Channel B measures the vibration signal picked up by the accelerometer placed on top of the engine. Channel A picks up the tacho signal generated by the tacho probe and a piece of reflective tape placed on the camshaft. The tacho pulse is a once per camshaft revolution pulse or a once per engine cycle (720°) pulse.

Fig. 19 presents the result of two analyses of the vibrations of the engine idling at 800 ± 2% RPM. The bottom trace is an order analysis (400 orders) where the record length exactly tracks one engine cycle. Since the vibrations are generated by the rotating parts of the engine, rectangular weighting of the vibration signal is leakage free for the order components and gives the best order resolution (Δord = 1 order). For comparison the X-axis has been rescaled to Hz, using 800 RPM = 13.33 Hz as the mean frequency of the 1st order.

The top trace is an ordinary 6.4kHz frequency analysis of the vibration signal. The 6.4kHz span was chosen as the best match to the order analysis which covers close to 5.3kHz (= 400 x 13.33 Hz). In this analysis the harmonic vibration signals do not match the record length and Hanning weighting was used to control (minimize) the leakage.

Comparison of the two measurements reveals the benefits of the order analysis. The order analysis shows clearly vibration at the 4th order. Vibration at the 4th order corresponds to events taking place 4 times per engine cycle. This vibration is mainly caused by the smooth movements of the shafts and the pistons and the 4 times per cycle combustion.

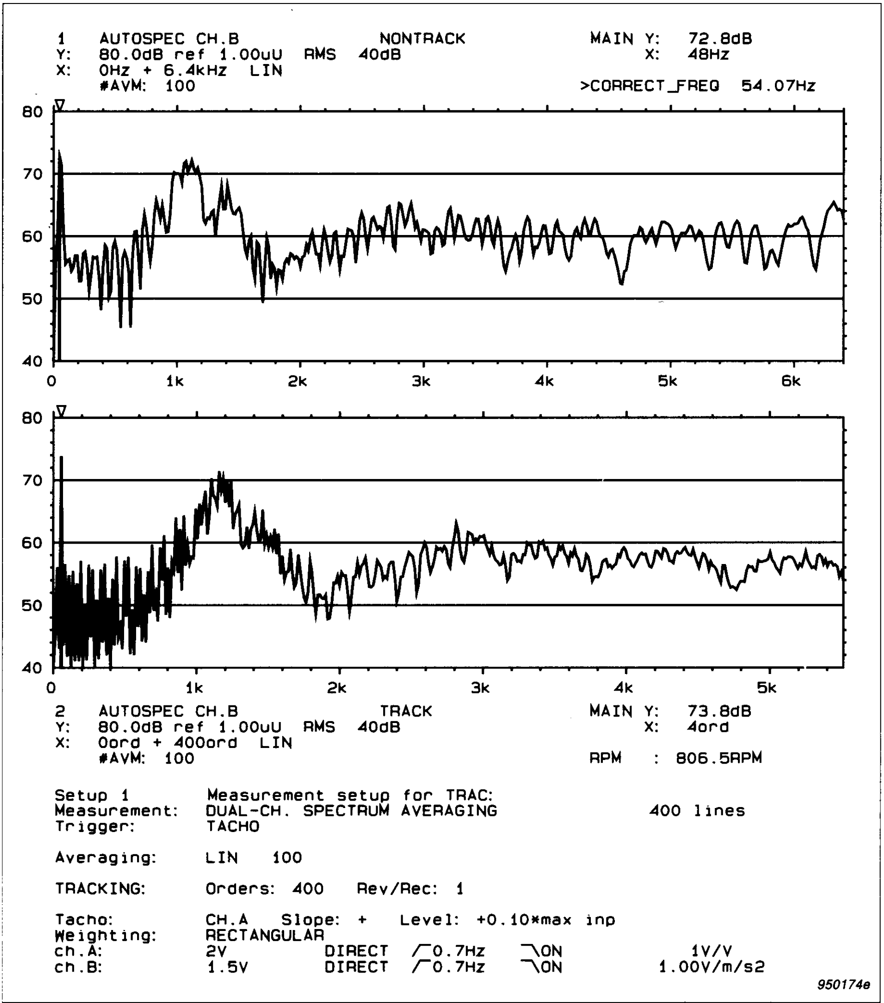

Fig. 19 Non-tracked (upper trace) and tracked (lower trace) vibration spectrum. Measurement setup for the order tracking analysis is also shown

The order analysis also shows very good selectivity. At the lower end of the spectrum, the order analysis shows that the vibration mainly consists of even orders which is not evident in the frequency analysis. Also, the order analysis gives a better estimate of the vibration level. Due to the leakage and smearing in the frequency analysis, the 4th and predominant order is underestimated by 1 dB, as shown by the cursor readings. The frequency analysis finds the 4th order vibration at 48 Hz (Δf = 16 Hz). Applying a simple User-Defined Auxiliary Reading, CORRECT_FREQ, the 4th order frequency is calculated to be 54.07 Hz and hence the fundamental frequency 54.07/4 Hz = 13.52 Hz. In the order analysis the mean speed is measured to be 806.5 RPM, which means that the fundamental frequency is measured to 806.5/60 = 13.44 Hz.

The higher vibration level around 1.1 kHz is due to a structural resonance in the engine block excited by the vibrations caused by the moving parts. This was shown by conducting a coast-down order analysis, where order related and non order related vibrations clearly separate. Ref. [1].

Gated Tracking Measurement

Regarding the wideband spectrum at higher frequencies, the order analysis gives no better information than the frequency analysis does. The claim was that the wideband vibration was caused by the impact operation of the valves. The goal is now to measure where in the engine cycle this wideband vibration arises.

The Type 3550 system contains all the tools needed to obtain this "where in the cycle" information or in other words, to perform the gated tracking analysis. Referring to Fig. 20, the measurement is set up as follows:

Using the Multifunction measurement mode, Type 3550 is set up to measure 34 records of 200 lines order spectra of the vibration signal, each record covering 0.06 engine cycle[2].

2 The record covers 0.0625 revolutions which together with the 200 FFT lines corresponds to 3200 orders (no. of orders x revolution/cycle = no. of FFT lines). The number of orders is of minor interest here. Note that the resolution is 3200/200 ORD = 16 ORD (times 1.5 due to the Hanning weighting). Also note that the bandwidth required for the analysis is (no. of orders) x (fundamental frequency), in this case 3200 x 806.5/60Hz = 43kHz. The maximum bandwidth determines the minimum length of the record!

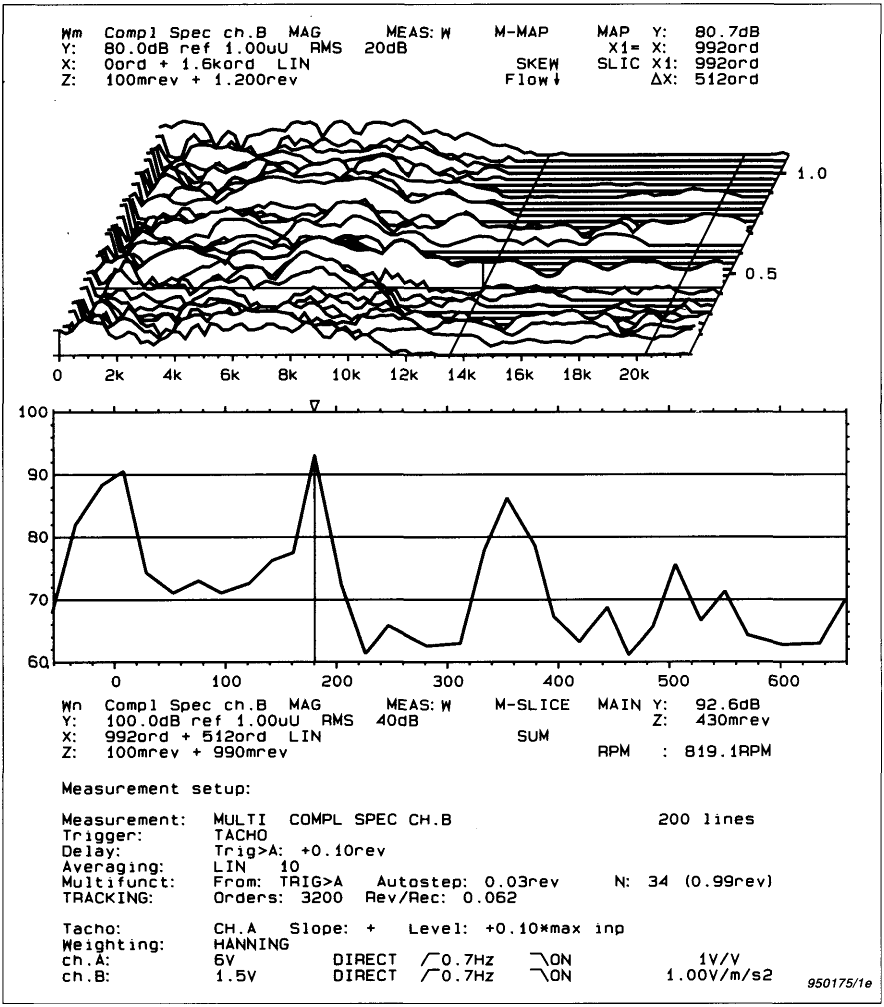

Fig. 20 Order Spectrum MAP and Δ-SLICE of the gated, tracked vibration spectrum

The Hanning weighting is chosen to control the leakage introduced into the analysis by looking at only a fraction of the transient signal. Ref. [4]. The weighting effectively throws away more than half of the signal. To compensate for that loss, the shift between the individual records is set to Autostep = 0.03 REV, which means the records overlap by approximately 50% , see Fig. 18.

Very important for the confidence of the analysis, and unique for Type 3550, the system offers averaging of the data collected in the individual records. Here the averaging is set to 10 linear averages.

Displaying Gated Tracking Results

The top trace of Fig. 20 is the MAP where the X-axis order scale has been redefined to the corresponding mean frequency scale [kHz]. The Z-axis is the angular revolution axis. Note that the horizontal scale of the SLICE in the lower trace has been redefined from 1 REV to 720°. The MAP shows the vibration spectrum from 0 Hz to 21.5kHz (0 ORD to 1600 ORD) over 1 engine cycle. From 13kHz to 20kHz, the vibration power clearly is located at 4 particular angles. This is already seen in the MAP, and more clearly in the SLICE. The slice shows the power of the 512 orders from order 992 (13.5kHz to 20.4kHz) as a function of cycle angle. The vibration power concentrates at 0°, 180°, 360° and to some extent at 540°. Referring to Fig. 17, it is seen that 4 out of the 8 valves are activated (deactivated) at the same time, so it is a kind of a puzzle to relate the effect of the individual valves to the 4 angles. One interpretation could be that the valves of the 2nd cylinder cause most of the vibration. They are both activated around 180°, where the vibration level is highest, and neither of them is activated at 540°, where the level is lowest. See also Ref. [6].

3 For full compensation, i.e. to obtain equal analysis weighting of all data either $GG^2/3$ or 75% overlap must be selected

Time Domain Averaging
(Fourth application example)

The most common method of acquiring frequency information is to use spectrum averaging, i.e. averaging is performed in the frequency domain. This method has a number of advantages, the principal one being that it is a very easy method to use, and that it can be applied to any type of signal.

But if we have some a priori knowledge about the signal under investigation, and if the signal of interest is periodic, then the (synchronous) time domain averaging method, or signal enhancement can be used. As opposed to frequency spectrum averaging, signal enhancement requires a trigger signal synchronous with the periodic signal of interest. Its principal advantage is that the signal components uncorrelated with the trigger signal average to zero as the number of averages increases towards infinity. This is not the case when using spectrum averaging.

An obvious target for time domain averaging is measurements on rotating machinery (turbines, internal-combustion engines, pumps, etc.), or machinery that exhibit cyclic patterns (hydraulic or pneumatic equipment, presses, etc.).

Some of these are very stable, and the use of time domain averaging is unproblematic. Others are less stable, making the signal enhancement method a little more problematic. Changes in rotational speed while the measurement is in progress will cause smearing of the time signal and its frequency components. This smearing can be eliminated by the use of order tracking.

Combining Time Domain Averaging and Tracking

When measuring on rotating machinery, time domain averaging can often be combined with order tracking. The reasons for using order tracking are twofold. First, the rotational speed of many types of machinery is usually not extremely stable. Second, there are very often speed variations within one cycle, this variation can also change during the measurement.

Time domain averaging using order tracking can therefore be split up in these two cases:

1) One tacho pulse per engine cycle, meaning that the RPM is only calculated once per cycle. In this case the order tracking will compensate for slow changes in the engine RPM, changes which take place over many cycles, but not for changes within one cycle.
2) Several tacho pulses per revolution, meaning that the angular velocity is calculated for many angles during the engine cycle. In this case order

tracking will compensate for speed variations within one engine cycle. *With* this method those signals that are synchronous with the engine rotation angle are kept, the rest is averaged out.

The first of these methods is the easiest to use. It only requires one combined trigger and tacho source. The second requires independent trigger and tacho sources, since many tacho pulses are needed per revolution.

Test Set-up, Instrumentation and Measurement Results

To show the differences between the different methods, a test set-up consisting of an electric motor driving a small single cylinder, four-stroke engine was used (see Fig. 21).

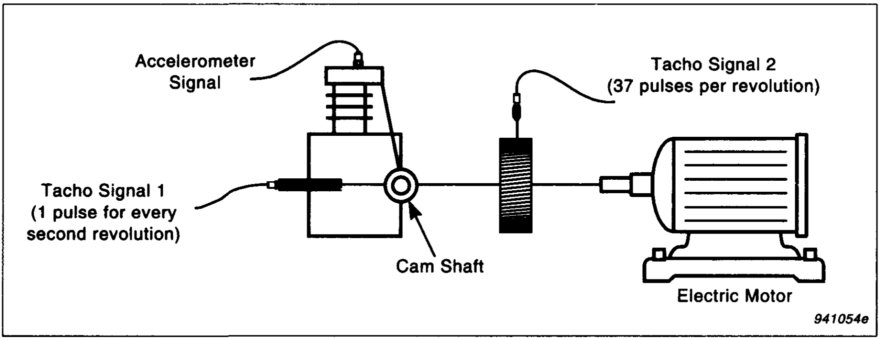

Fig. 21 Test set-up. Tacho signal 1 used to trigger time records and for order tracking Tacho signal 2 used for order tracking only

Three signals were measured:

1) Tacho signal 1 measured with a Photoelectric Probe MM 0024. One pulse for every cam shaft revolution, i.e. once for every second engine revolution. This signal was used to trigger the time records, and also for tracking with one pulse per engine cycle.
2) Tacho signal 2 measured with a Photoelectric Probe MM 0012.37 pulses per engine revolution (crank shaft revolution). This signal was used for order tracking with many pulses per engine cycle.

3) Vibration signal measured with an Accelerometer Type 4393. The accelerometer was close to the cylinder inlet and exhaust valves.

Three different measurements were performed:

1) Signal enhancement, no order tracking.
2) Signal enhancement, order tracking using tacho signal 1.
3) Signal enhancement, order tracking using tacho signal 2.

As can be seen in the cursor set-up (upper right corner of Fig.22), the motor rotational speed was 16 revolutions per second. One engine cycle takes two motor cycles, each engine cycle therefore takes 125ms. This is equal to the record time, which can be seen in the measurement set-up (below the graph).

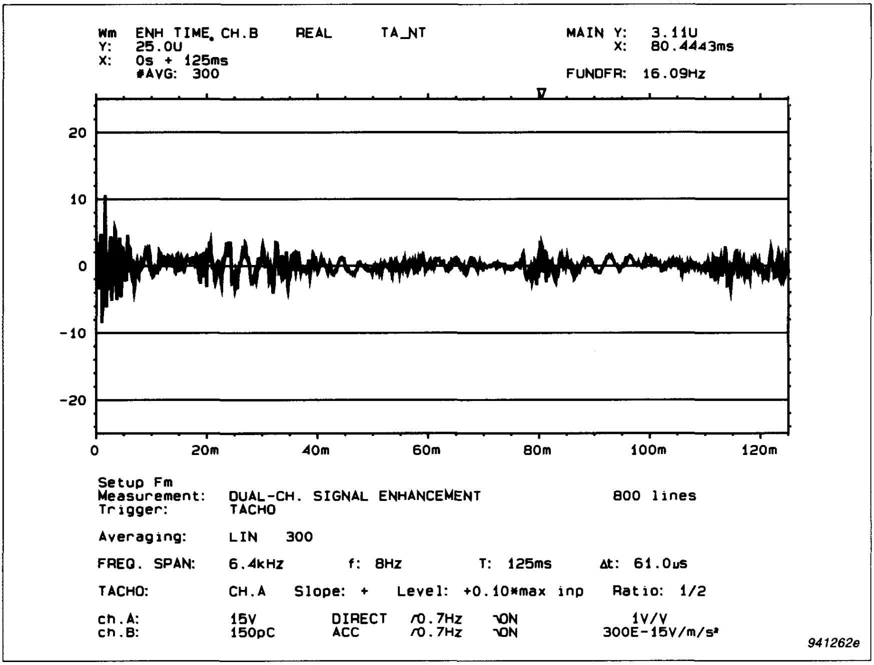

Fig. 22 Signal enhancement, no order tracking

Fig.22 shows the time averaged accelerometer signal. There is a tendency that the signal amplitude at the end of the record is lower than at the start of the record. This smearing of the time data is due to small changes in the RPM during measurement (300 averages).

The x-axis in Figs. 23 and 24 has been re-scaled from revolutions (0 to 2), to crank shaft angle (0° to 720°).

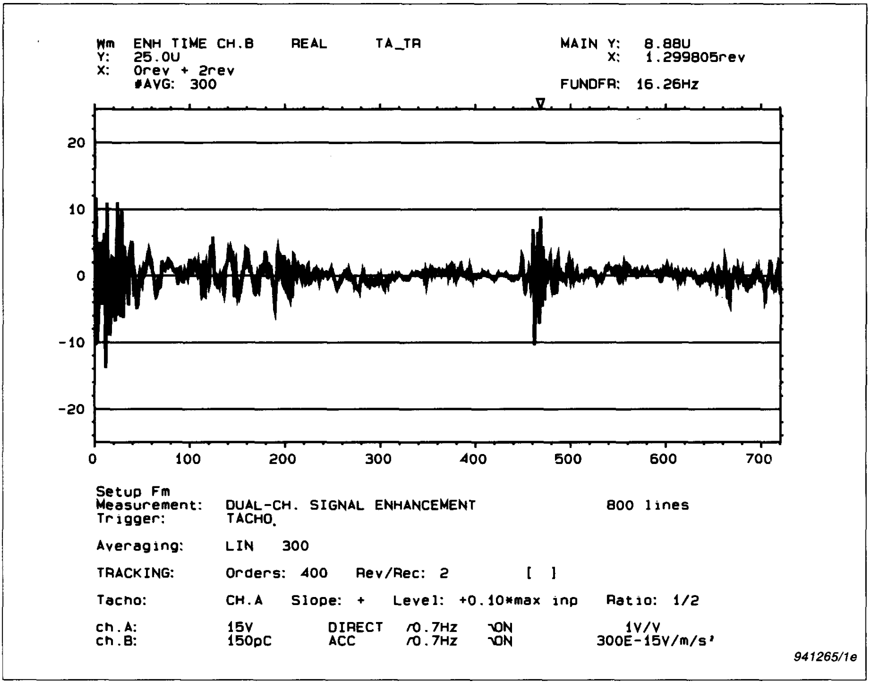

Fig. 23 Signal enhancement, tracking using tacho 1 (one pulse per camshaft revolution)

Notice that the amplitude of the signal is different and more correct in the record for the tracking measurement shown in Fig. 23 than for the non-tracking measurement shown in Fig. 22; it does not fall off at the end of the record. This is due to the fact that order tracking compensates for RPM changes during the measurement.

Still, this measurement does not take into account changes in angular velocity within one engine cycle which are significant in this case.

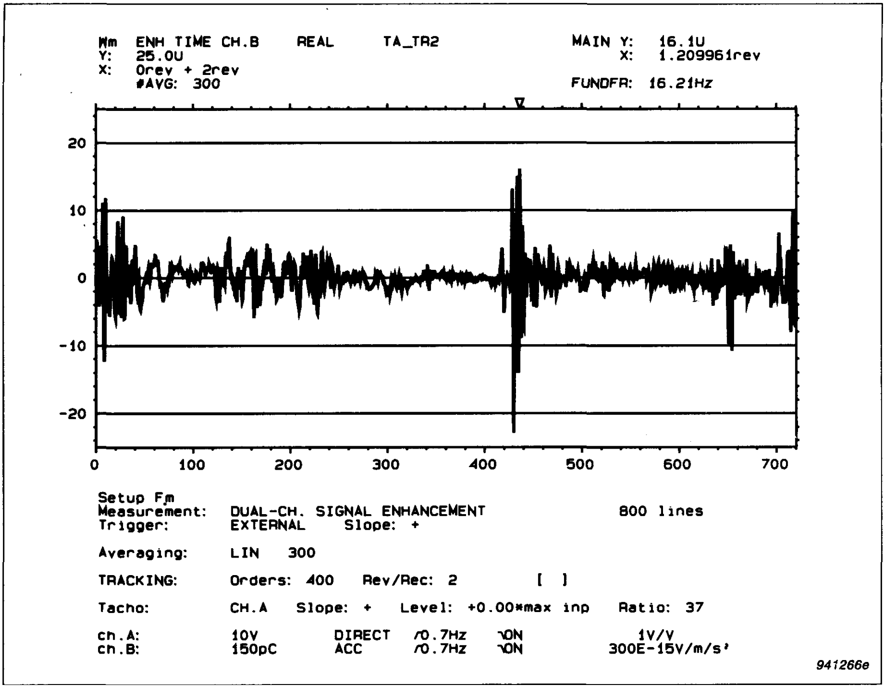

Fig. 24 Signal enhancement, tracking using tacho 2 (37 pulses per engine revolution)

The measurement shown in Fig. 24, which used order tracking with many pulses per engine revolution, gives the most correct picture of the vibration signal within one engine cycle. Comparison of this measurement (Fig.24), with those in Figs. 22 and 23, it is seen that more features are visible in the enhanced time signal, but more important the re-scaled x-axis (in degrees) was only approximate in Fig. 23, but is much more accurate in Fig. 24.

This is because in the case shown in Fig. 23, with one tacho pulse per engine cycle, the crank angle rotation was assumed to be uniform during the engine cycle, whereas it is measured and corrected 74 times per engine cycle in this case shown in Fig. 24. This means that certain portions of the signal shown in Fig. 23 have been compressed in the x-direction, other portions have been stretched. For example, the exhaust valve opening is shown at around 460° in Fig. 23 while in Fig.24 the same event more accurately seems to have taken place at about 430° . See also Ref. [7].

Appendix A

Explanation of the max. decimation d = 5.92 within each record.

In order to prove and understand the available range of 1 to 5.92 for the decimation d within each record, we need the relation between the different frequencies given in Fig. Al. Fig.A1a and Fig. A1b correspond to Fig.5a and Fig.5b with the inclusion of the frequency of 80 dB attenuation, f_{80}, of the antialiasing filter (with cutoff frequency f_c).

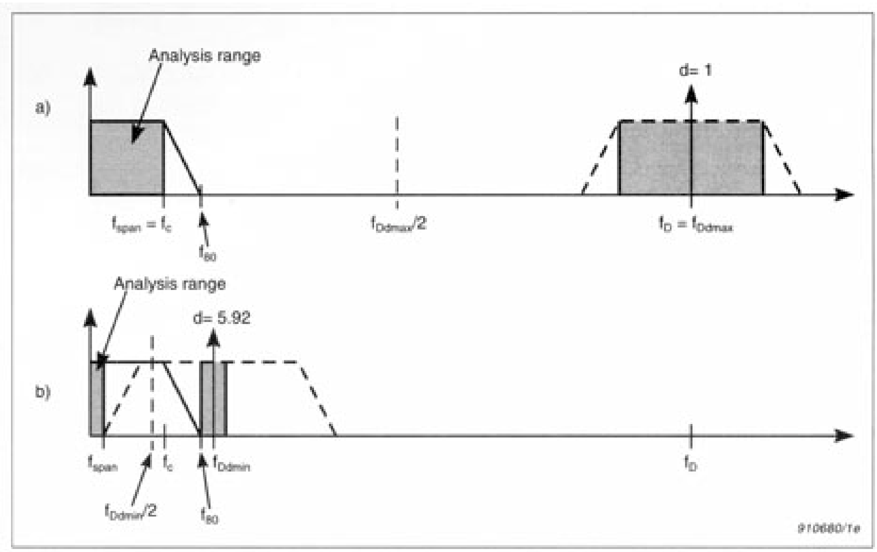

Fig. A1 Max. obtainable decimation d + f_{Ddmax} / f_{Ddmin} *+ 5.92*

For these filters we have

f_{80}=1.56 x f_c

In normal frequency analysis mode we have a ratio between the sampling frequency, f_s, and frequency span, f_{span}, of

f_s/f_{span} = (65.536kHz /25.6 kHz) = 2.56

In tracking mode, where 4 times oversampling is used, we have a ratio between sampling frequency after decimation D, f_D, and max. frequency span in the order spectrum, $f_{span\ max}$, of

$$f_D/f_{span\ max} = f_{Dd\ min}/\ f_{span\ min} = (131.072kHz/12.8kHz) = 10.24 \qquad (A1)$$

From Fig.A1a we have
$f_{Dd\ max} = f_D = 10.24 \times f_{span\ max} = 10.24 \times f_c$

From Fig.A1b we have
$f_{Dd\ min} = f_{80} + f_{span\ min} = 1{,}56x\ f_c + f_{Dd\ min}/10.24$

or

$$f_{Dd\ min} \times (1 - 1/10.24) = 1.56 \times f_c \qquad (A2)$$

From (A1) and (A2) we get
$f_{Dd\ max}/f_{Dd\ min} = (1-1/10.24) \times (10.24 \times f\ c) /(1.56 \times f_c)$

or

$$f_{Dd\ max} / f_{Dd\ min} = (0.9023 \times 10.24) /1.56 = 5.92 \qquad (A3)$$

Equation (A3) shows that within each record we have a max. tacho frequency range i.e. a max. decimation d range of 5.92.

Conclusion

In this article the theory behind digital order tracking as implemented in Brüel&Kjær instrumentation has been presented.

Through different application examples the use of order tracking when analyzing the vibration signals from rotating machinery has also been demonstrated. Main applications are run-up coast-down test for identification of structural resonances, critical frequencies etc. and measurement on machines with varying speed. It was also demonstrated how analysis techniques such as gated measurement, and time domain averaging can be improved by applying order tracking.

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