Application Note

Gated Tracking Applied on an Automobile Engine Using Multichannel Analysis System Type 3550

by *H. Konstantin-Hansen, Brüel & Kjær, Denmark*

Vibrations in rotating and reciprocating machinery are caused by the acceleration of the moving parts and by impact activity in the machinery. Order tracking is applied to relate vibration to the various moving parts. Gated tracking is used to identify where in the engine cycle the vibration is generated. Gated tracking is especially interesting when dealing with reciprocating machines like combustion engines, pumps and compressors.

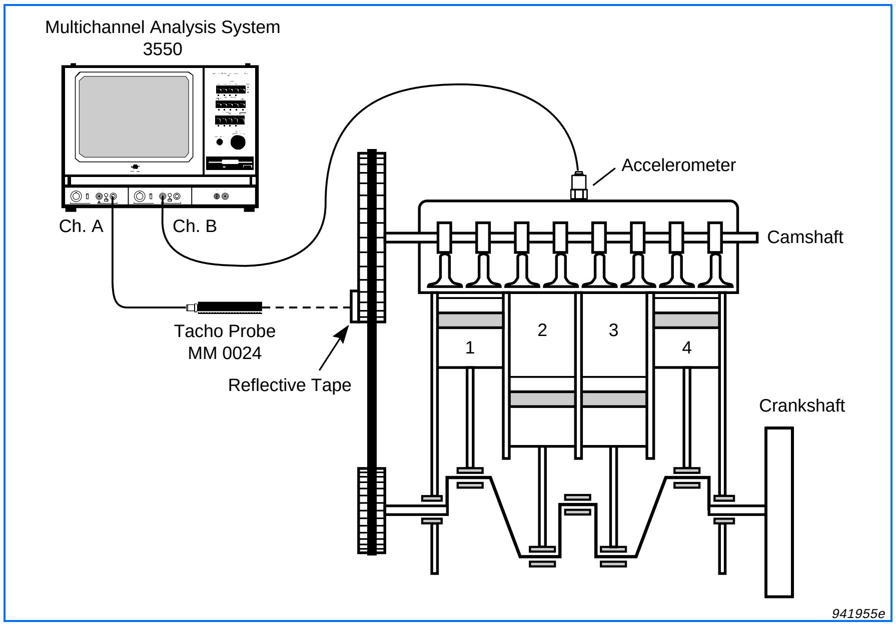

Fig. 1 Engine outline and measurement set-up

Introduction

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. The time record is now 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 and the analysis is referred to as order tracking.

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 though 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. 1, the 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

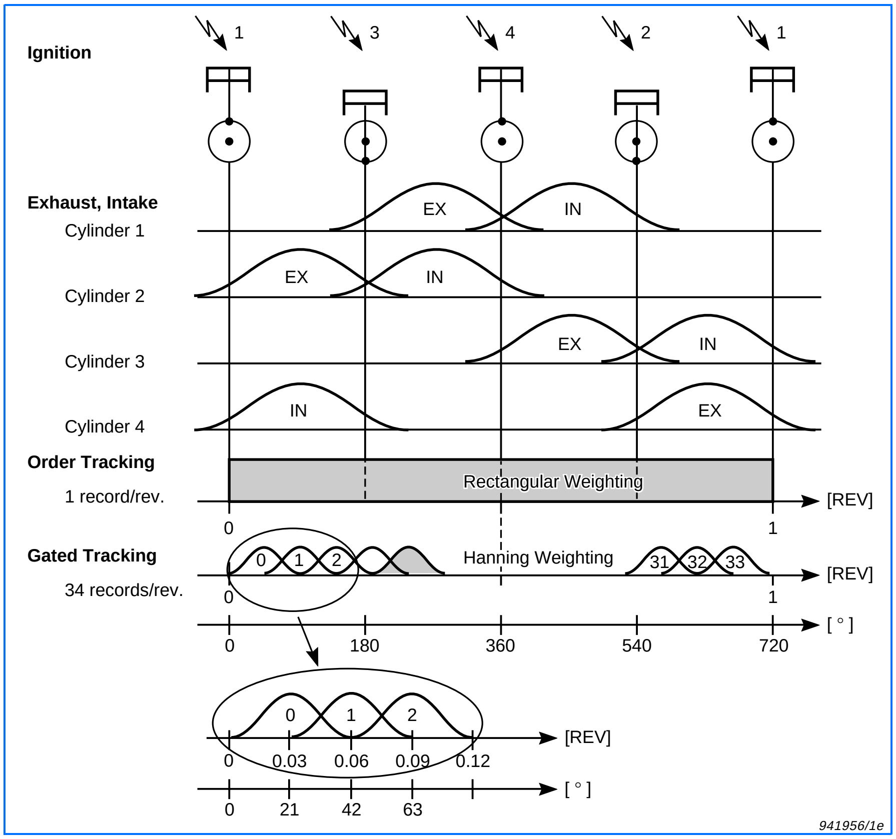

Fig. 2 Valve activity timing and record definition for order tracking and gated tracking measurements

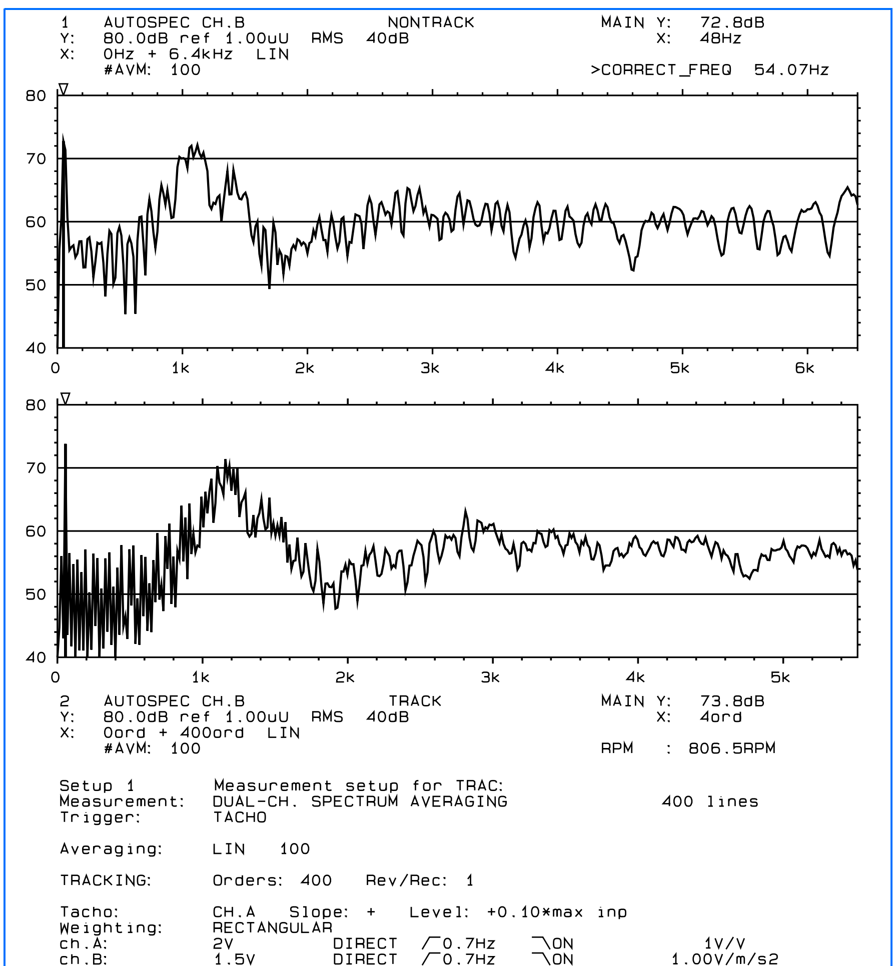

Fig. 3 Non-tracked (upper trace) and tracked (lower trace) vibration spectrum

impression of impact activities in the engine. The frequency or order spectra of the impact vibrations are wide-band spectra, which means that high frequency or order components are caused by the activation of the valves.

In the timing diagram in Fig. 2, it is shown how the valve activity is related to the angle of the camshaft. Two cycles of the crankshaft ($2 \times 360°$ = 720°) correspond to one cycle of the camshaft. 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.[1].

Order Tracking

As shown in Fig. 1, 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. 3 presents the result of two analyses of the vibrations of the engine idling at 800 RPM ± 2%. 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 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 6.4 kHz frequency analysis of the vibration signal. The 6.4 kHz span was chosen as the best match to the order analysis which covers close to 5.3 kHz (= 400×13.33 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.

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 run-down order analysis, where order related and non order related vibrations clearly separate. Ref. [2].

Gated Tracking

Regarding the wideband spectrum at higher frequencies, the order analysis gives no better information than does the frequency analysis. 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. 4, the measurement is set up as follows:

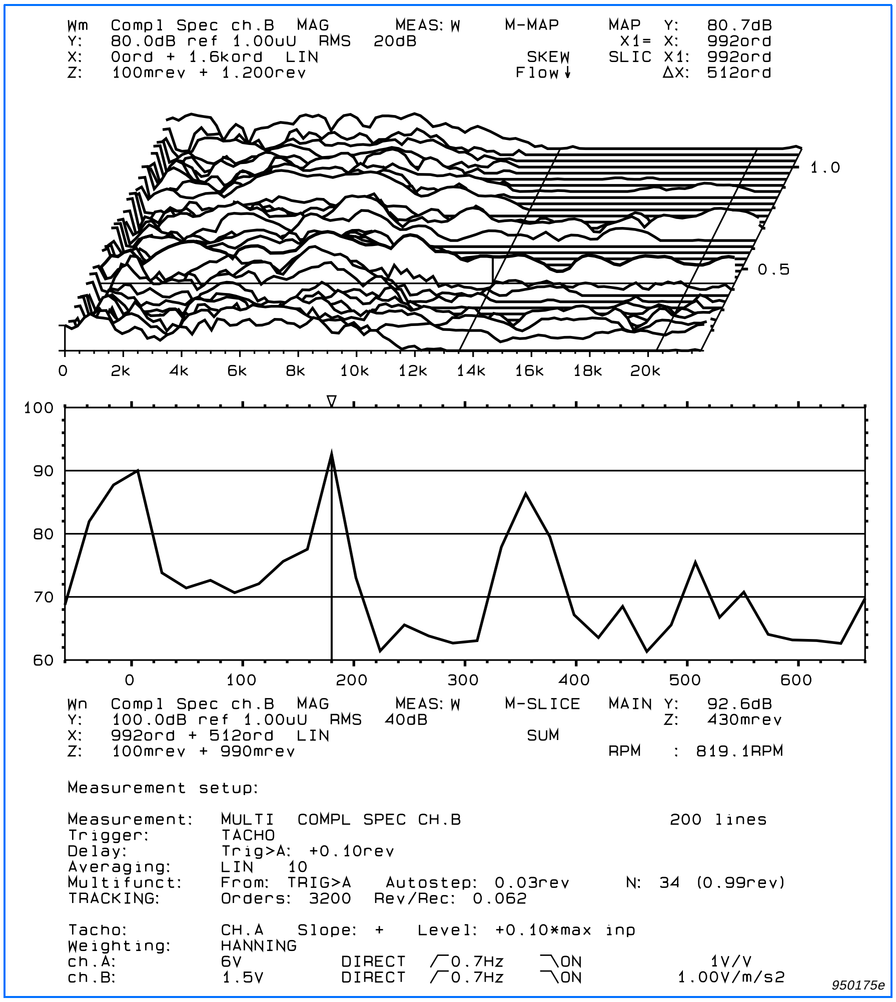

Fig.4 Order Spectrum MAP and Δ-SLICE of the gated, tracked vibration spectrum

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*.

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. 2.

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.

* The record covers 0.0625 revolutions which together with the 200 FFT lines corresponds to 3200 orders (no. of orders × 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) × (fundamental frequency), in this case 3200 × 806.5/60Hz = 43 kHz. The maximum bandwidth determines the minimum length of the record!

Displaying Results

The result may be displayed for interpretation in various ways. The most important presentations are the MAP of the Order Spectrum, which shows all the data as a function of revolution, and the SLICE which is a particular order, or range of orders, shown as function of angle. Fig. 4 shows the two. The top trace 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.

For extraction of detailed information, the MAP is equipped with various cursor tools. The cursor selected here is the SLICE-indicator, which defines a Δ-cut in the MAP. The cursor associates directly to the lower trace where the indicated Δ-slice is shown. The SLICE-indicator in the

MAP may be locked onto the X-start and X-width specifications in the SLICE, so that when the SLICE-indicator is moved, the SLICE is updated accordingly. In turn the SLICE has its own selection of cursor tools for extraction of information from the slice. Note that the horizontal scale of the SLICE has been redefined from 1 REV to 720°.

Interpretations

Referring again to Fig. 4, the MAP shows the vibration spectrum from 0 Hz to 21.5 kHz (0 ORD to 1600 ORD) over 1 engine cycle. The order resolution is 16 ORD, which means that the 0 order FFT-line contains the predominant vibration power related to the 4th order as seen in Fig. 3. Up to 13 kHz, this analysis does not give much information about where in the cycle the vibrations arise. The spectrum as function of angle looks quite uniform, though there is a tendency for the vibration power to be concentrated around 8 particular angles in the cycle. This can be revealed by making slices or Δ-slices in the 0 Hz to 13 kHz range.

From 13 kHz to 20 kHz, 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 (13.5 kHz to 20.4 kHz) as a function of cycle angle. The vibration power concentrates at 0°, 180°, 360° and to some extent at 540°. Referring to Fig. 2, 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 are activated at 540°, where the level is lowest.

This interpretation may be backed up by further measurements involving running the engine at other RPMs and applying other record lengths and overlaps.

This single analysis shows that the vibrations above 13 kHz come from the valve activity, and that an ordinary FFT analysis in that frequency range informs about vibration and noise caused by the valves alone.

Improvements and Features

The tracking analysis was based on a once per revolution tacho, which means that the analysis is unable to track speed variations occurring *within* the engine cycle. To track these variation, more tacho pulses per camshaft revolution must be generated (*equidistant!*). Ref.[3].

Referring to the measurement setup in Fig. 4, the analysis is concerned with the *complex* Autospectrum of the vibration signal. The phase embedded in this spectrum, also referred to as Phase Assigned Autospectrum (PAS), is the phase between the tacho signal and the vibration signal. The Phase Assigned Autospectrum is essential in run-up/coast-down measurements for determination of natural frequencies of rotating shafts. The function also opens for determination of Operational Deflection Shapes (ODS), frequency or order related.

The measurements described in this note were actually recorded on a DAT Recorder and then in turn analysed using Type 3550. Having the data on tape makes it possible to analyse the same data over and over again in different ways. Keeping track of the calibration of a recorded measurement may turn out to be a task in itself. In Type 3550 it is possible to calibrate the measurement before or after the analysis using a built-in automatic calibration procedure.

Instrument list

Analyzer

Multichannel Analysis System Type 3550 configured as follows:

- Signal Analyzer Unit Type 2035
- 100kHz/Multichannel Zoom Processor Type 3157
- 2×100kHz Input Module Type 3020
- Sampling Module Type 3018
- Dual-channel Analysis Software Type 7649
- Tracking Analysis Software Type 7670
- Signal Analysis Software Type 7671

Transducers

- Delta Shear Accelerometer Type 4384
- Tacho Probe MM 0024

Recorder and Transducer Supply (if recording is wanted)

- 8-channel Deltatron Accelerometer Supply Type 5963 + Charge Accelerometer
- 8-channel Charge Amplifier Type 5974 + Deltatron Accelerometer
- SONY PC 208A DAT Recorder
- SONY TCD-D3 DAT Recorder

References

[1] Automotive Handbook (3rd Ed.), BOSCH, ISBN 1-65091-372-X

[2] Henrik Herlufsen, "*Order Analysis Using Zoom FFT*", Brüel & Kjær Application Note (012-81)

[3] N. Johan Wismer, "*Time Domain Averaging Combined with Order Tracking*", Brüel & Kjær Application Note (BO 0420-11)

[4] S. Gade & H. Herlufsen, "*Use of Weighting Functions in DFT/FFT Analysis*", Brüel & Kjær Technical Reviews Nos. 3 & 4, 1987

Brüel & Kjær

WORLD HEADQUARTERS:
DK-2850 Naerum · Denmark · Telephone: +45 45 80 05 00 · Fax: +45 45 80 14 05 · Internet: http://www.bk.dk · e-mail: info@bk.dk

Australia (02) 9450-2066 · Austria 00 43-1-865 74 00 · Belgium 016/44 92 25 · Brazil (011) 246-8166 · Canada: (514) 695-8225 · China 10 6841 9625 / 10 6843 7426
Czech Republic 02-67 021100 · Finland 90-229 3021 · France (01) 69 90 69 00 · Germany 0610 3/908-5 · Holland (0)30 6039994 · Hong Kong 254 8 7486
Hungary (1) 215 83 05 · Italy (02) 57 60 4141 · Japan 03-3779-8671 · Republic of Korea (02) 3473-0605 · Norway 66 90 4410 · Poland (0-22) 40 93 92 · Portugal (1) 47114 53
Singapore (65) 275-8816 · Slovak Republic 07-37 6181 · Spain (91) 36810 00 · Sweden (08) 71127 30 · Switzerland 01/94 0 09 09 · Taiwan (02) 713 9303
United Kingdom and Ireland (0181) 954-236 6 · USA 1 - 800 - 332 - 2040
Local representatives and service organisations worldwide

BO 0444 – 11