APPLICATION NOTE

Order Tracking of a Coast-down of a Large Turbogenerator

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In this application note, it is demonstrated how to use the order tracking facility of PULSE™, the Multi-analyzer System Type 3560. The data to be analysed is a coast-down of a large turbogenerator in a power station. Critical speeds were confirmed during the measurement. In addition, the 37th order component (and multiples thereof) were identified, caused by loose blades in the cooling fan system.

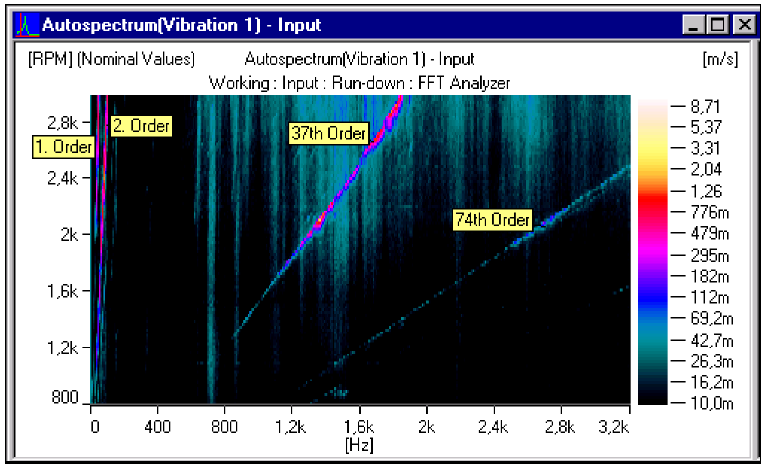
Introduction

Analysis of vibration or acoustic signals from rotating machines is often preferred 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 sub-harmonic 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.

Fig. 1
Contour plot of coast-down using ordinary FFT analysis



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 (Fig. 1). 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 stabilised 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.

Order Tracking of a Coast-down of a Large Turbogenerator

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 Photoelectric Tachometer Probe Type MM 0012 giving the rotation frequency of the shaft.

The coast-down lasted nearly 10 minutes and was therefore suitable for order tracking analysis. The lowest 20 harmonics of the vibration signal are analysed during the coast-down. The PULSE setup is shown below and the order spectrum at 2513 RPM in Fig. 2.

Setup
System Analysis Bandwidth : Auto

Order Analyzer
Lines : 400

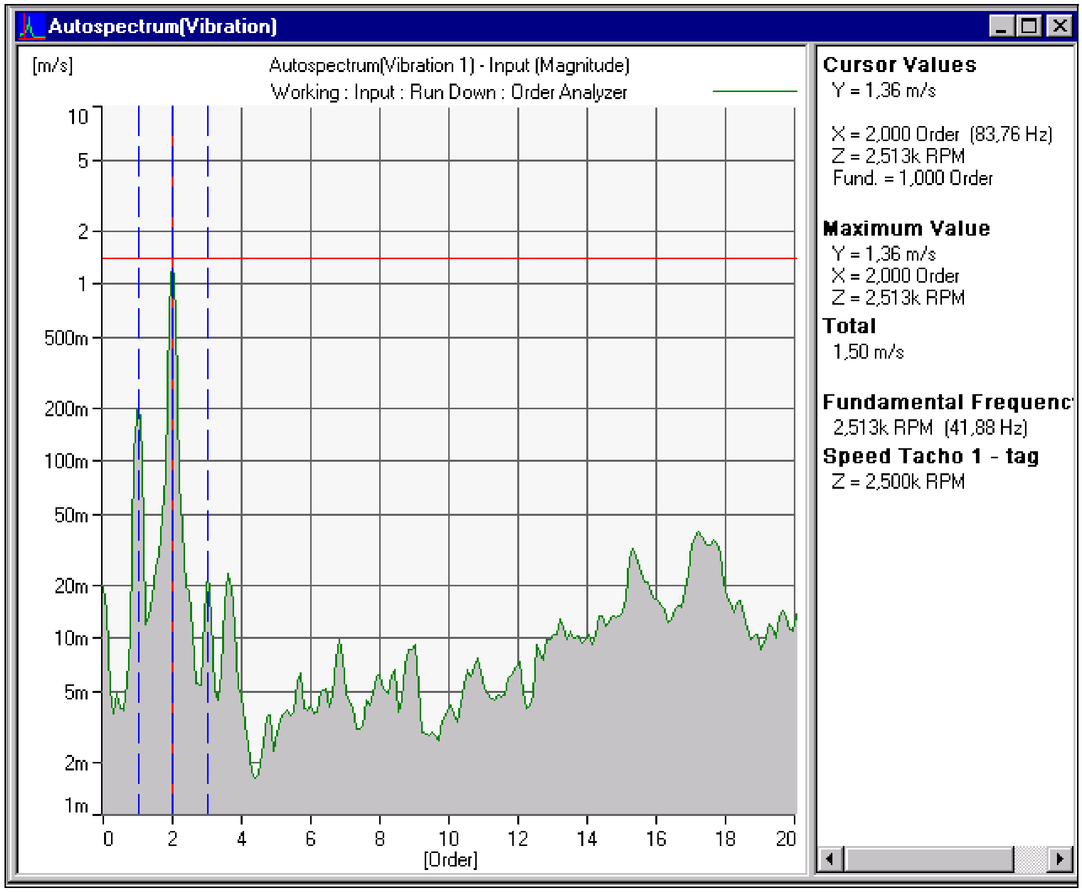


Fig. 2
Order spectrum at 2513 RPM and the measurement setup. Notice only 3 significant orders are seen

Order Span: 40 Order dOrder : 100m Order
Record Size: 10 Rev/Rec

Trigger: Free Run
Overlap: 66.67 %
Averaging:
Average Update: New Record
Exponential Averaging 20
Tracking:
Tracking Mode: Auto
Frequency Range: 25.6k Hz
Fundamental Frequency Limits: 0 -- 38.4k RPM (0 -- 640 Hz)
Tachometer: Tachometer
Tacho Signal: Speed (Tacho 1)

Vibration 1
Window: Hanning
Weighting: None
Integration - differentiation: None
Channel 1
Gain Adjust: 1
Max Input: 5 V (6.667 m/s)

Tachometer

Tacho 1
Tacho Detection
Slope: Positive
Level: -20 % of max input
Hysteresis: 20 % of max input
Hold Off: 1u sec 40 % of interval
Divider: 1 pulses
Averager: 5 pulses

Tacho Gearing
Gearing Select: Ratio

Ratio: $\frac{1}{1} \times \frac{1}{1} \times \frac{1}{1} \times \frac{1}{1} = 1$

Factor: 1
Combined: 1
Sensitivity: 1 V/V
Gain Adjust: 1
Max Input: 5 V (6.667 V)

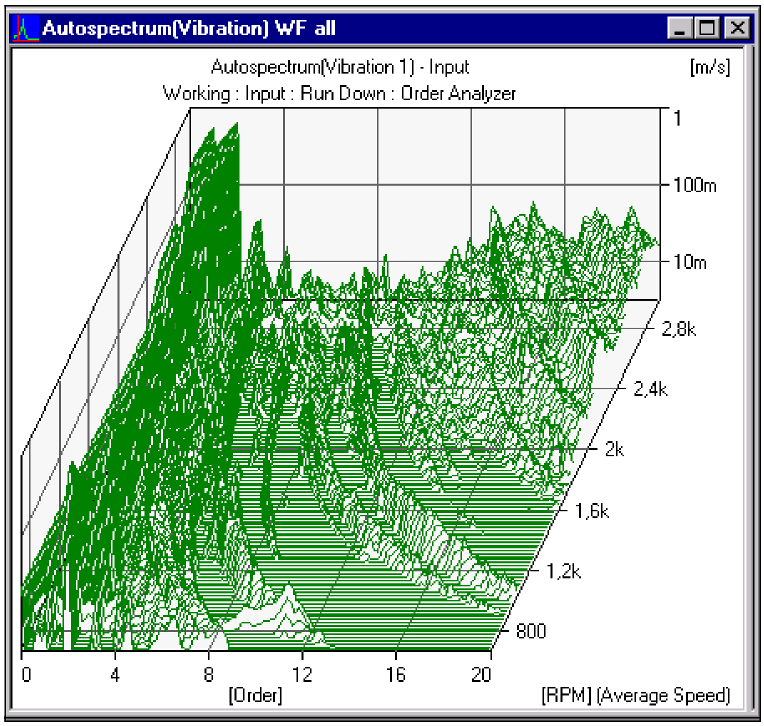


Fig. 3
Order analysis of lower harmonics of generator vibration signal during coast-down

A 3-dimensional waterfall plot of the stored spectra of the vertical vibration signal at the generator bearings is shown in Fig. 3. 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 $c \times n = f \times 60$, where c is speed in RPM, n is harmonic order and f is the frequency in Hz. Fig. 4 shows some examples of constant frequency curves. Notice the smearing of the constant frequency components. As an overall view of all the related components this plot is very useful.

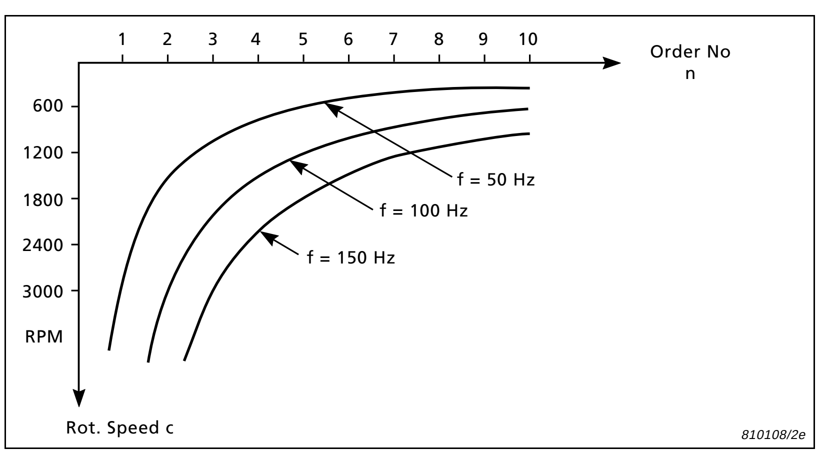


Fig. 4
Constant frequency curves

Using a slice cut (order cut) as shown in Fig. 5 the resonances can be displayed in more detail. It is seen that the resonance around 1000 RPM actually has its peak at 17.44 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.

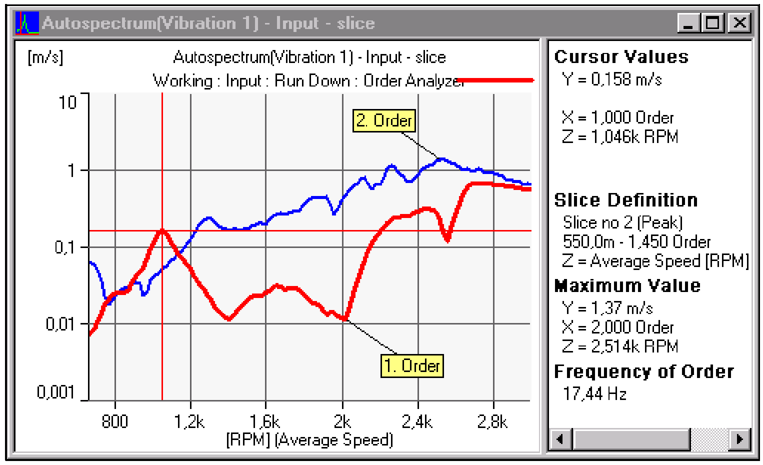


Fig. 5
Fundamental and second order of generator vibration during coast-down

Acceleration was measured in this example but integrated to velocity. 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.

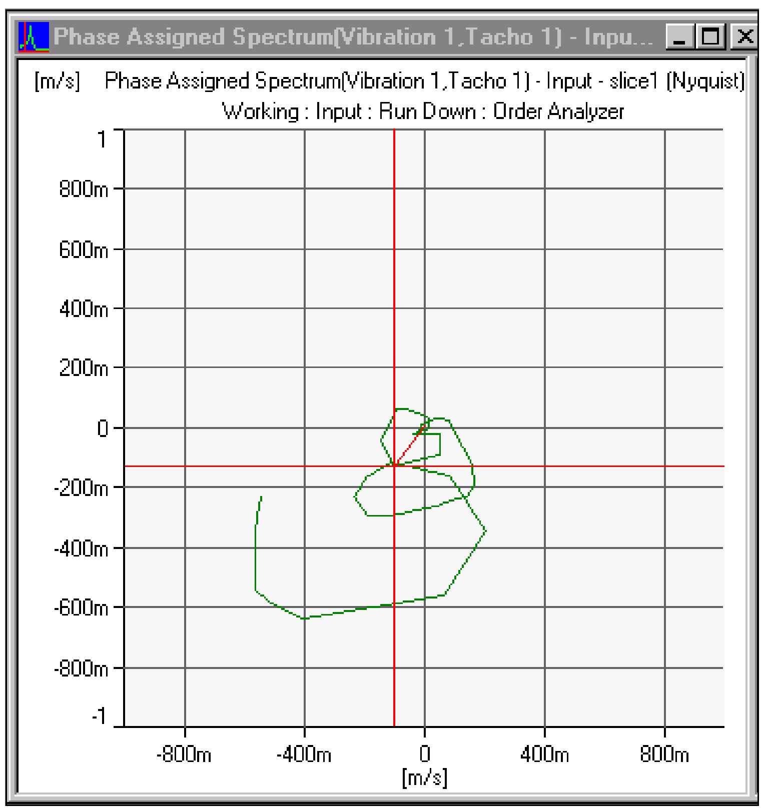
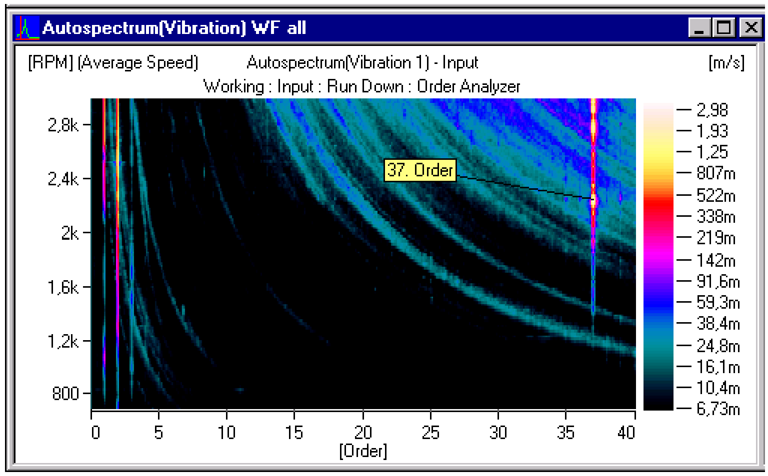


Fig. 6
Nyquist plot of the fundamental of generator vibration during coast-down

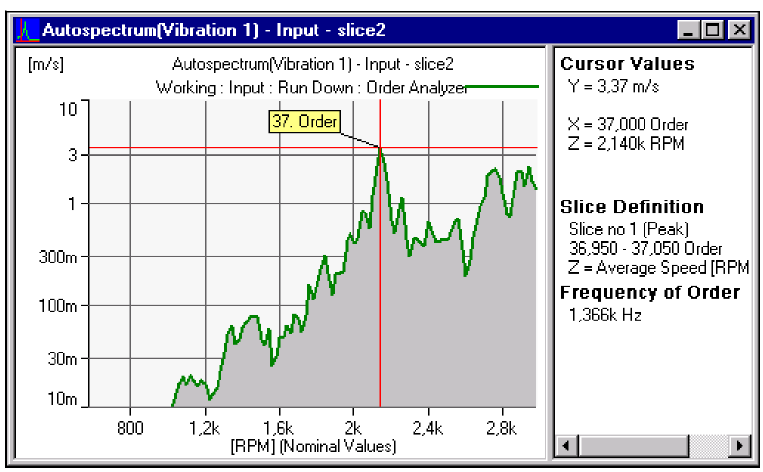
Since phase assigned order spectra have been stored in the multi-buffer it is possible to show not only magnitude of orders as a function of RPM but also phase, Bode plots and Nyquist plots. Fig. 6 shows the fundamental order as a Nyquist plot. The cursor is positioned to the same RPM as indicated in Fig. 5. Both real, imaginary and magnitude cursor values can be shown.

Fig. 7
Order tracking analysis including 37th order



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 order analysis up to the 40th harmonic during coast-down is shown in Fig. 7. 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. 8. 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. 8
Blade-passing frequency (i.e., 37th order) of fan during coast-down



Conclusion

PULSE, the Multi-analyzer System Type 3560, offers three methods for order analysis:

- Frequency-based order analysis
- Order tracking analysis
- Order tracking filtering

The first two methods are in real-time, while the third is a post-processing method. All the methods offer phase assigned orders as output.

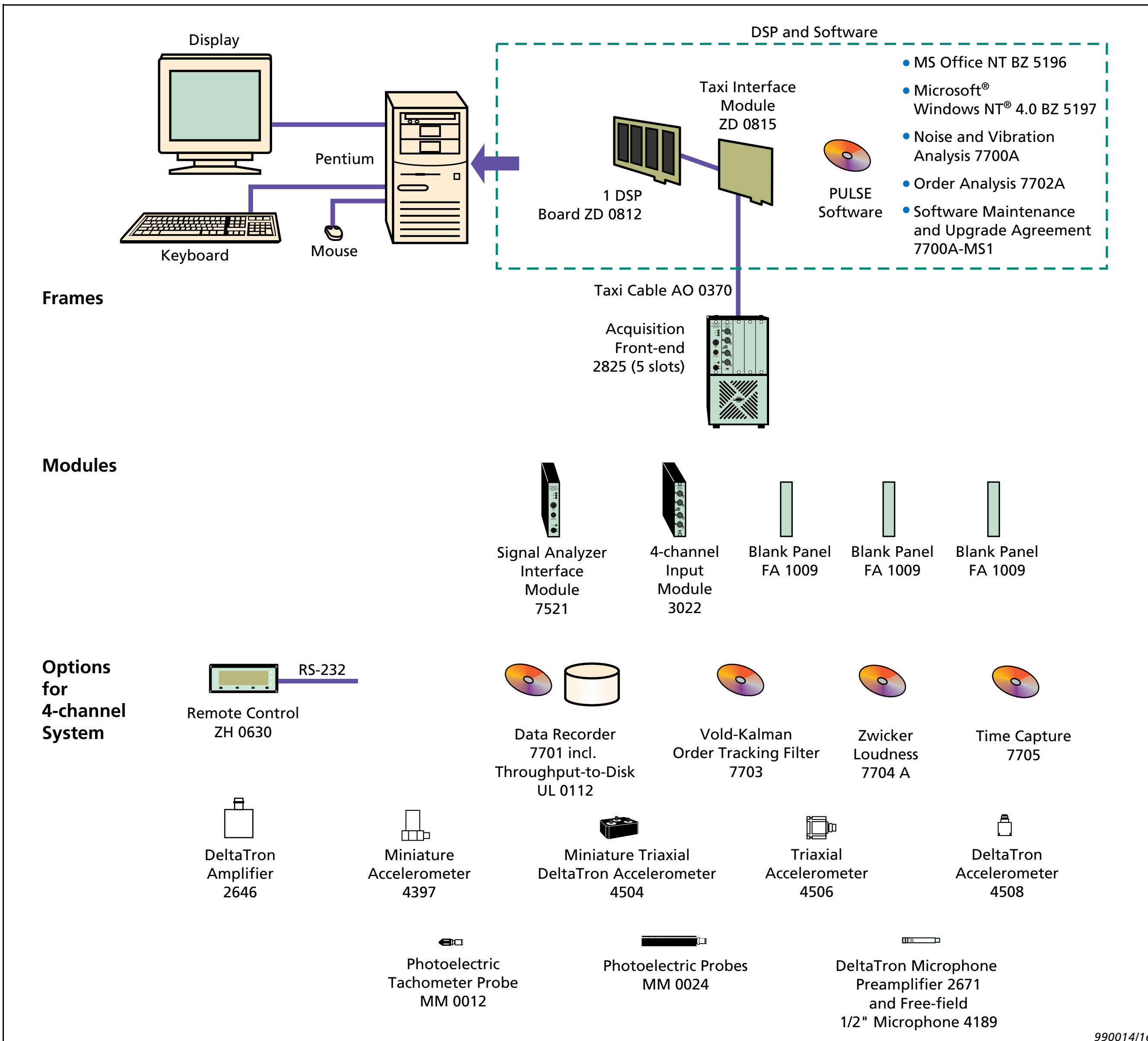
Frequency-based order analysis using fixed sampling frequency has the advantage of being fast and easy to implement, but it can only be used over a limited RPM range and cannot be used for the accurate extraction of higher orders due to smearing.

Order tracking analysis, which uses resampling techniques, is free of smearing and can thus be used for extracting high orders. Implementation is slower due to the more complex calculations involved.

PULSE also offers Vold-Kalman order tracking as post-processing on time data. The main advantages of this technique are that there are no slew rate limitations including gear shifts and decoupling of close and crossing orders. Since this is a time-domain based technique, the Vold-Kalman technique also produces order waveform extraction with no time delay, which is very useful for sound quality synthesis and editing.

An overview of a complete PULSE-based order analysis system is shown in Fig. 9.

Fig. 9 Overview of a 4-channel PULSE system for order analysis



References

[1] S. Gade, H. Herlufsen, H. Konstantin-Hansen, N.J. Wismer, "Order Tracking Analysis", Brüel & Kjær Technical Review No. 2, 1995

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