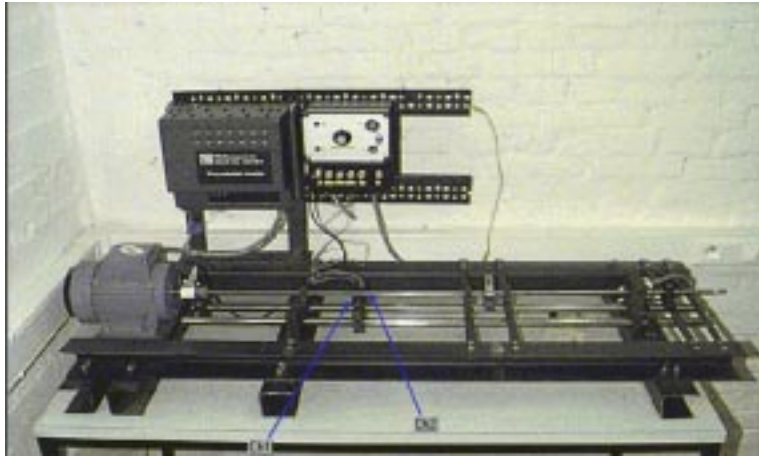


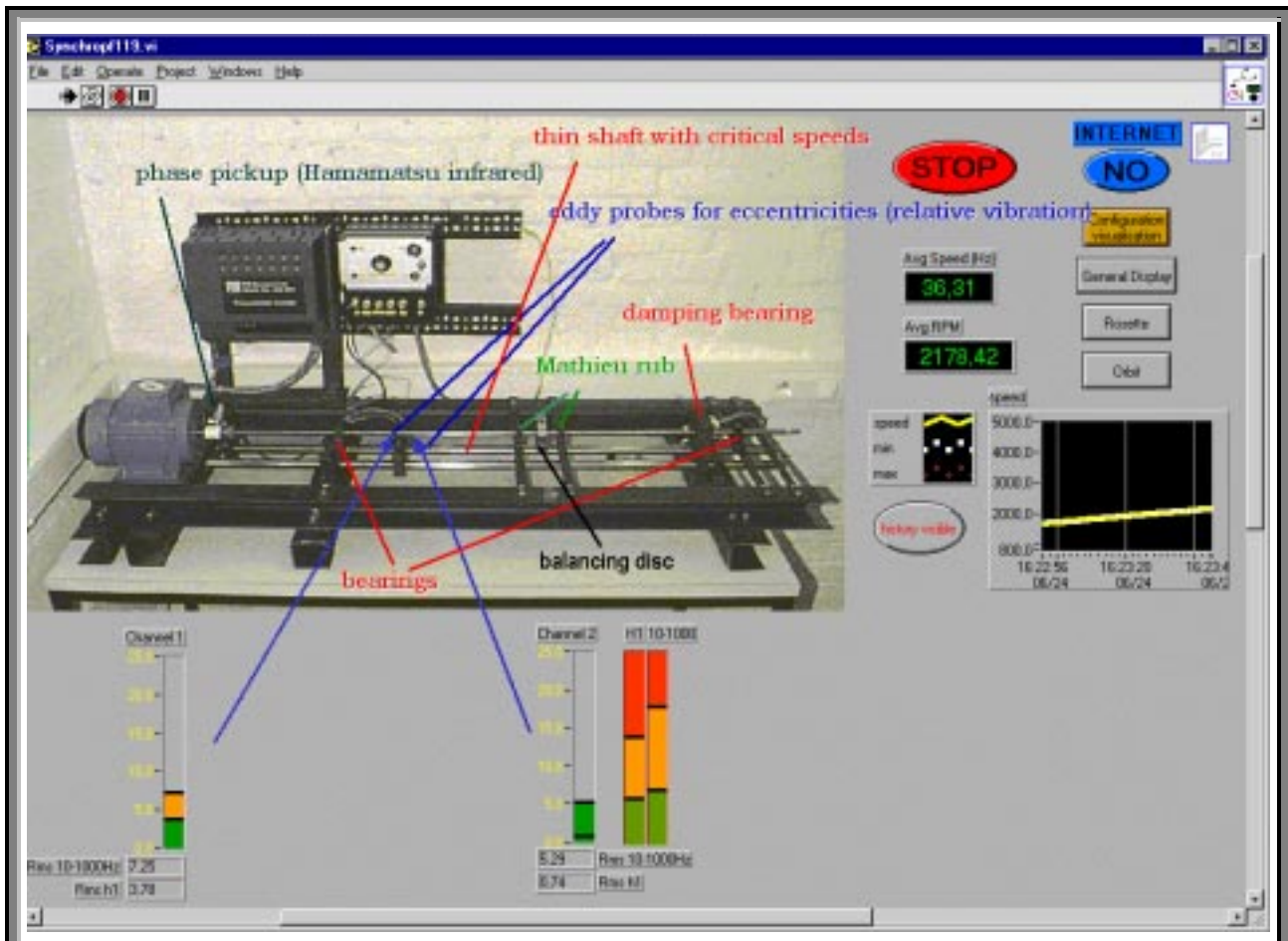
Full spectra and rotor dynamics



ULB

SMA

Test rig



Mechanical layout

The test rig consists of a variable-speed induction motor driving a flexible shaft through a flexible coupling. The shaft rests on two Glycodur (SKFTM) sleeve bearings. The thin shaft exhibits critical split speeds near 1600 rpm and near 4000 rpm. Bearings are stiffer horizontally than vertically, which explains why critical speeds split.

The shaft supports a balancing disc in at roughly mid-span. For safety reasons the shaft deflections are limited by two sleeveless bearings with ca 1.5mm radial clearances. Such auxiliary bearings are practical to simulate intermittent rub, known as Mathieu rub. One can move them upward by a mild finger pressure to bring them to slightly rub on the shaft.

In large rotating machinery, the damping of critical speeds normally originates from thick-film sleeve bearings through their oil wedge. One simulates such a damping with an additional bearing with a Glycodur sleeve supported in the pedestal through a layer of visco-elastic material.

Sensors

- A Hamamatsu infrared pickup faces a reflecting strip mounted upon the flexible coupling and generates one top/rev for phase referencing.
- Two eddy probes mounted horizontally and vertically measure the shaft relative vibrations (eccentricities)
- Not yet shown on the picture and soon to be installed are two miniaccelerometers mounted on the bearings to measure absolute vibrations.

Speed control

A thyristor module drives the induction motor. It can run either in Manual mode with with a rotary knob or can be driven electronically to simulate any speed variation.

Data acquisition and digital control of speed

All data acquisitions and speed controls are implemented with National Instruments general-purpose MIO card (AT MIO E-2 or 1 or, else, PCI MIO E 1) located in an ACME 200MMX lunchbox.

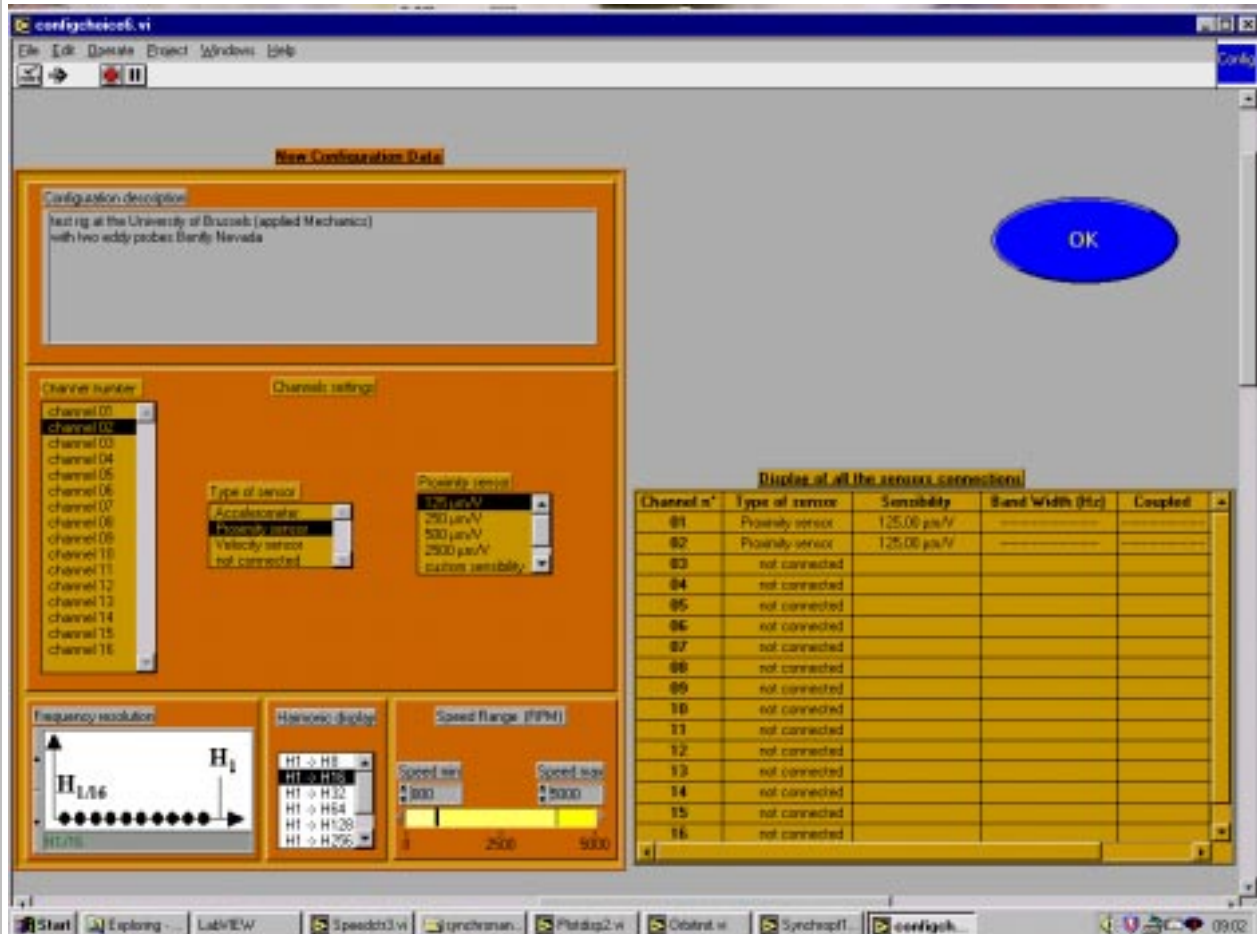
A series of dedicated real-time virtual instruments performs the following tasks:

- Synchronous sampling of the vibrations phase-locked with the phase reference
- Control of the speed
- Data processing: vector analysis, waterfalls, full spectra, orbits, single or double integration for velocity pickups and accelerometers, history charts with full spectra, speeds and ISO vibration norms, etc.

Several persons contributed to the software development: pierre.ripak@laborelec.be , gerard.dans@laborelec.be , pfontana@ulb.ac.be and axheneum@ulb.ac.be .

Sensor and data acquisition configurations

Starting the main vi prompts a configuration menu that spreads over a few forms to be filled with mouse clicks in multiple lists.



A box describes the experimental setup like shown for the test rig. It could be measurements on a pump.

Then click on channel #, then on the type of sensor, then on the standard sensitivity (otherwise click on custom sensitivity and enter the scale factor). This then automatically fills in the right-hand form to reflect changes and get an overview of the connected sensors. If a sensor has a wide frequency response and is not low-pass filtered, one must enter its bandwidth. AC DC coupling is also listed and configurable.

Mouse clicks select the resolution of the order tracking: 1/16, 1/8, 1/32 of the fundamental at the rotating frequency. Mouse drags in the "speed range" define the speed range of the machine. This automatically reserves data buffers for data acquisitions exactly.

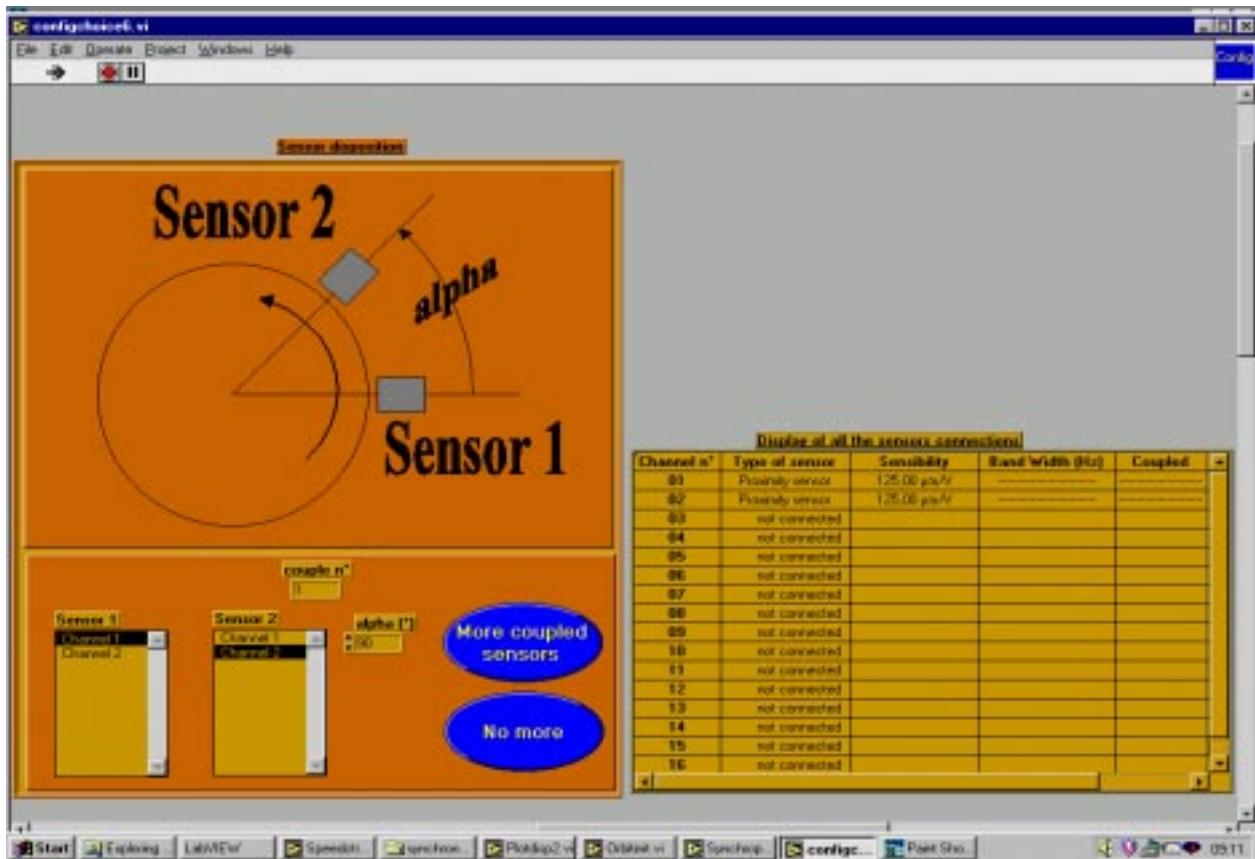
Special configuration for full spectra (1)

The screenshot shows a software window titled 'config'. The main area is orange and contains a diagram of two sensors, 'Sensor 1' and 'Sensor 2', with a circular path around them. Below the diagram are two lists of channels for 'Sensor 1' and 'Sensor 2', and an 'Alpha [1]' input field. Two blue buttons are labeled 'More coupled sensors' and 'No more'. A dialog box is open, asking 'Do you have coupled sensors for the full spectrum analysis?' with two options: 'Yes, I have coupled sensors in one or more planes.' and 'No, I do not have it.' To the right, a table titled 'Display of all the sensors connections' lists 16 channels. The first two channels (01 and 02) are 'Pressure sensor' with a sensitivity of '125.00 ps/P'. The remaining channels (03-16) are all 'not connected'.

Channel n°	Type of sensor	Sensitivity	Band Width (Hz)	Coupled
01	Pressure sensor	125.00 ps/P		
02	Pressure sensor	125.00 ps/P		
03	not connected			
04	not connected			
05	not connected			
06	not connected			
07	not connected			
08	not connected			
09	not connected			
10	not connected			
11	not connected			
12	not connected			
13	not connected			
14	not connected			
15	not connected			
16	not connected			

If the configuration detects more than 2 eddy probes, it asks whether some are coupled. Answering yes prompts the following series of dialog panels, whereby one selects pairs of channels corresponding to eddy probes in a single transverse plane that can be analyzed according to the [full spectrum technique](#).

Special configuration for full spectra (2)



Clicking in the first list box ("Sensor1") selects the first channel of the pair made of a second channel that one selects by clicking into the second list box ("Sensor 2"). Then one types the angle at which both sensors target the shaft according to the above picture reminder where the direction of shaft rotation is clearly shown. In a future release, one will also show the angular position of the phase pickup to streamline balancing procedures by means of specialized vi's.

The angle generally differs from 90°. In this case, one must reconstruct the complex-valued shaft orbit prior to applying a complex Fourier transform to it. This involves linear operations upon the time-domain signals, based on cosine projections in space. Actually one first performs real-valued FFT on the original signals (they are used elsewhere in the vi) and then combines the FFT linearly to get the complex-valued FFT of the orbit.

Special configuration for full spectra (3)

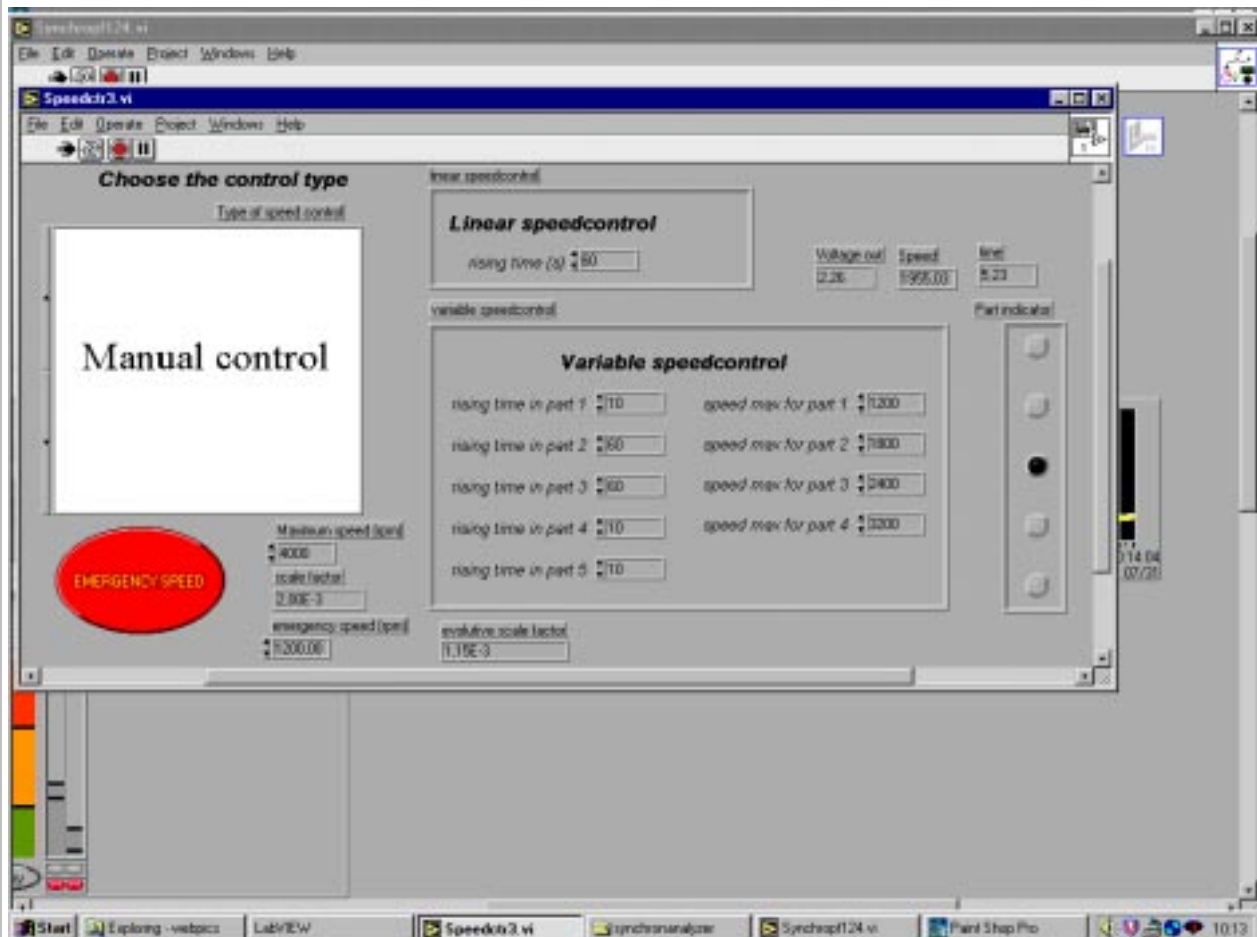
The screenshot shows a software window titled 'config.exe, v1'. The main area is divided into several sections:

- Sensor description:** A diagram showing two sensors, Sensor 1 and Sensor 2, positioned around a central point. An angle α is indicated between the line connecting the sensors and a reference line. Below this are two vertical panels for 'Sensor 1' and 'Sensor 2', each with 'Channel 1' and 'Channel 2' dropdowns. A 'couple n°' field is set to '1'. There are two blue buttons: 'More coupled sensors' and 'No more'.
- Configuration controls:** A list box 'Names of the new configuration' contains 'Configuration not recorded', 'Configuration 1', 'Configuration 2', 'Configuration 3', 'Configuration 4', and 'Configuration 5'. A yellow button 'View of the selected configuration description' and a blue button 'Configuration completed' are also present.
- Sensors connections table:** A table titled 'Display of all the sensors connections' with columns: Channel n°, Type of sensor, Sensibility, Band width (Hz), and Coupled. The first two rows are populated with 'Proximity sensor' and '125.00 µs/V', while the rest are 'not connected'.

Channel n°	Type of sensor	Sensibility	Band width (Hz)	Coupled
01	Proximity sensor	125.00 µs/V		with 2 of 31°
02	Proximity sensor	125.00 µs/V		with 1 of 31°
03	not connected			
04	not connected			
05	not connected			
06	not connected			
07	not connected			
08	not connected			
09	not connected			
10	not connected			
11	not connected			
12	not connected			
13	not connected			
14	not connected			
15	not connected			
16	not connected			

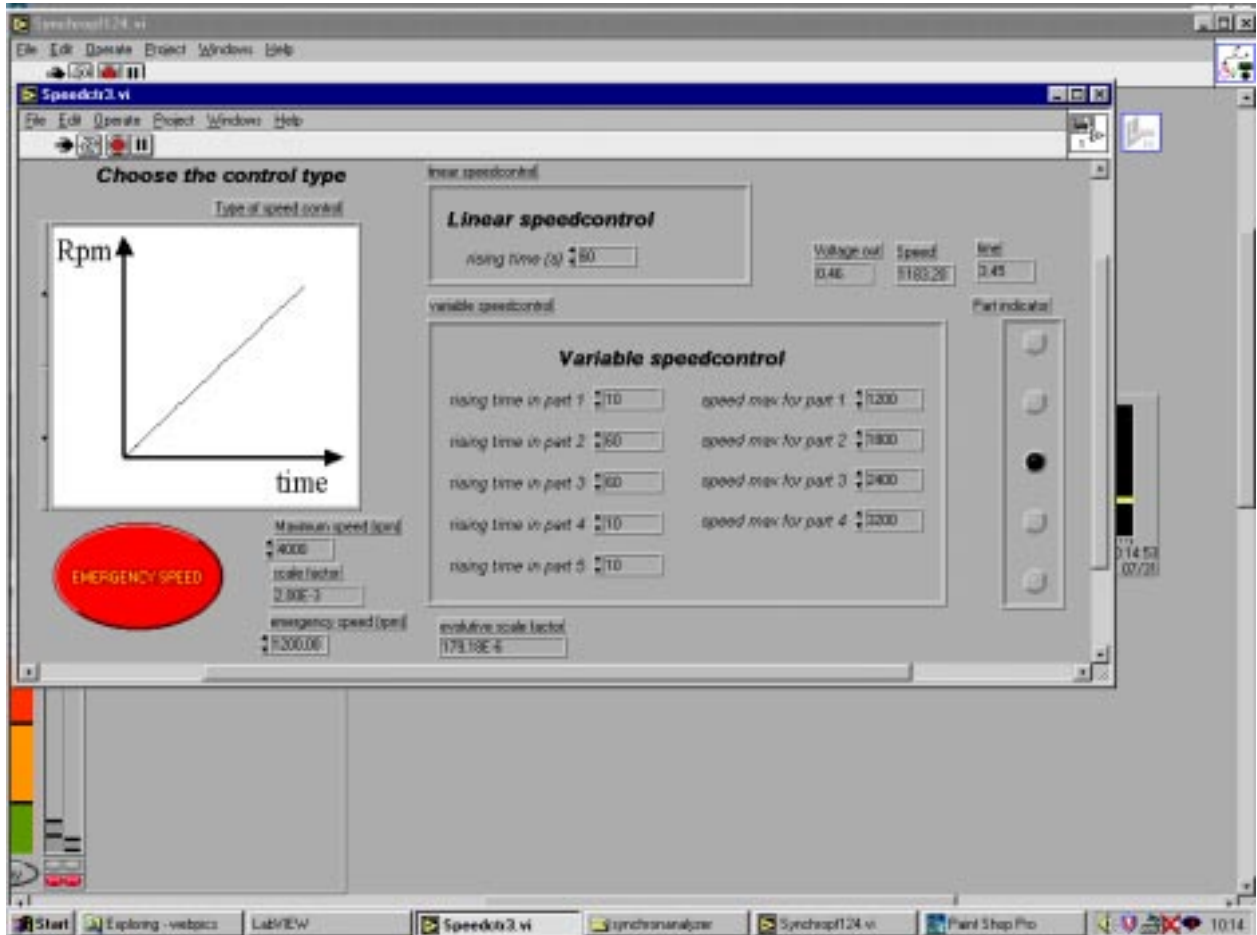
Pairs of eddy probes on which to perform full spectral analyses are acknowledged in the right-hand side list box with their relative angular position counted using the direction of shaft rotation as positive.

Speed control (1)



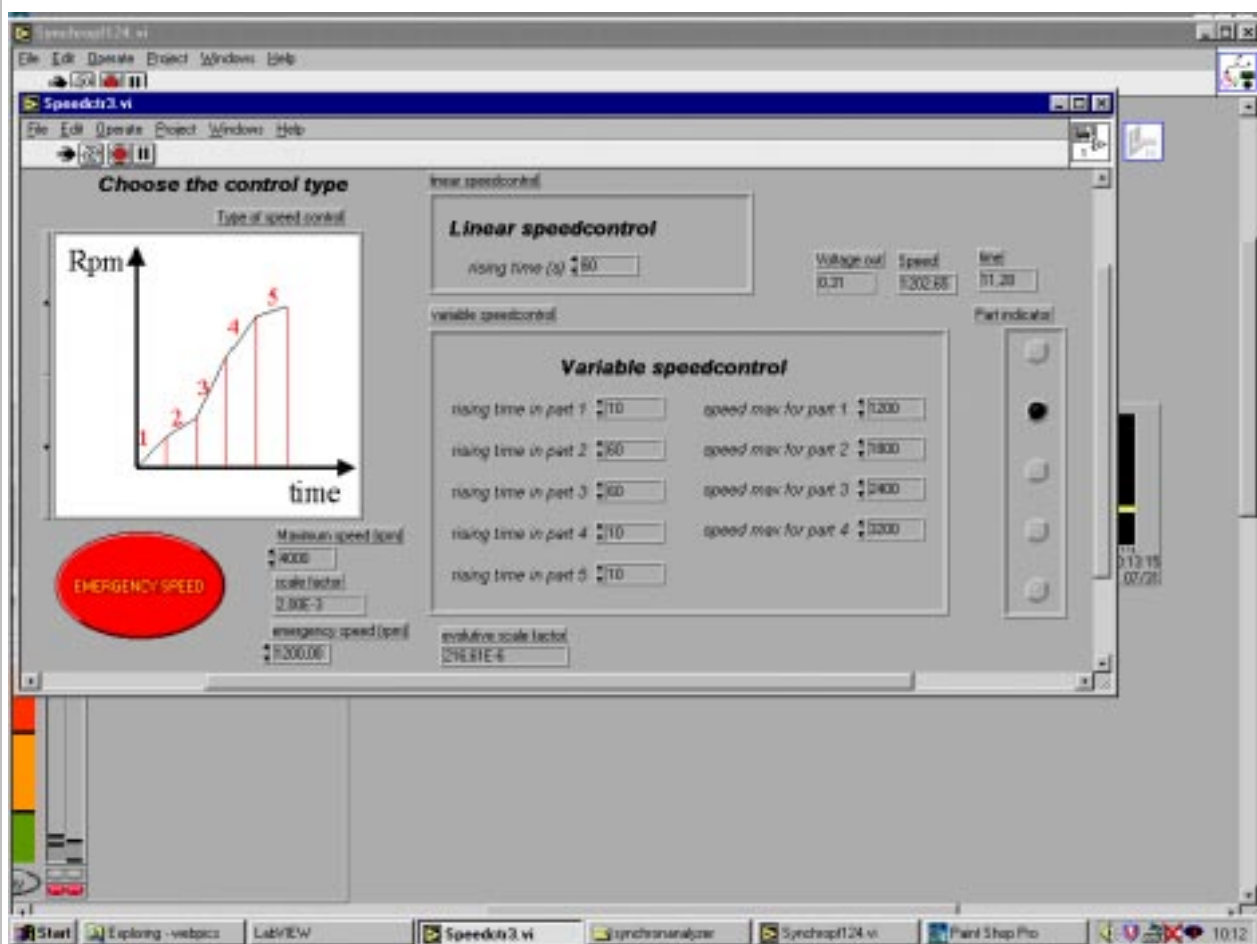
In a separate vi executing concurrently with the data acquisition, the "Type of speed control" picture ring selects how the speed varies. When selecting "Manual control", the thyristor variable frequency driver of the induction motor is controlled by the operator via a rotary knob.

Speed control (2)



In the next ring entry as shown above, the thyristor variable frequency driver of the induction motor is driven by the DAC of the MIO card. The speed rises linearly from the emergency speed (1200 rpm) to the maximum speed (4000 rpm here) within the time span entered into the "rising time" control (60 sec here). Pressing the emergency speed button returns the rig to lowest speed in case of too severe vibrations.

Speed control (3)



The last entry of the "Type of speed control" picture ring control performs a more sophisticated rig start-up sequences, where speed gradients vary in several contiguous speed intervals as selected by controls under the heading "Variable speedcontrol". An indicator monitors to which interval the current speed belongs as it starts increasing. In this way, one can select faster speed gradients as one passes through a critical speed and conversely.



The main panel shows the installation. It is an outright digital picture here but could be anything else helping the operator locate sensors. It could even be a picture ring indicator to get zoomed areas of the machine being monitored.

The Internet button allows a remote user to control the vi from Netscape Navigator when in "Yes" position. Otherwise, the vi can be only visualized without any remote control over Internet. For details, consult axheneum@ulb.ac.be.

Speed indicators show the machine average speed in rpm and Hz over the current data acquisition.

Bottom left: a colored bar-graph shows the admissible levels of vibrations according to ISO 2672 norm and the class to which the machine belongs ("Limit 10-1000 Hz). Next are bar-graphs for individual sensors and alarm buttons (top: current status, bottom: latched memory of past alarms).

Next to these bar-graphs are constantly refreshed trends of the overall "rms10-1000 Hz" ISO2372 levels in mm/sec rms and the contribution of the component at the rotational frequency ("rmsH1"). One notices that the first trend is very "stormy". The reason is that the rig was fitted

with eddy probes and one tried (it does not make much sense) to express the vibrations in mm/sec by differentiation of the eddy probe signals. It turns out that some sharp peaks affect these signals, due to the presence of the thyristor bridge. Mini accelerometers will soon be installed on the rig bearings. The software is ready to integrate them once to get proper ISO 2372 levels.

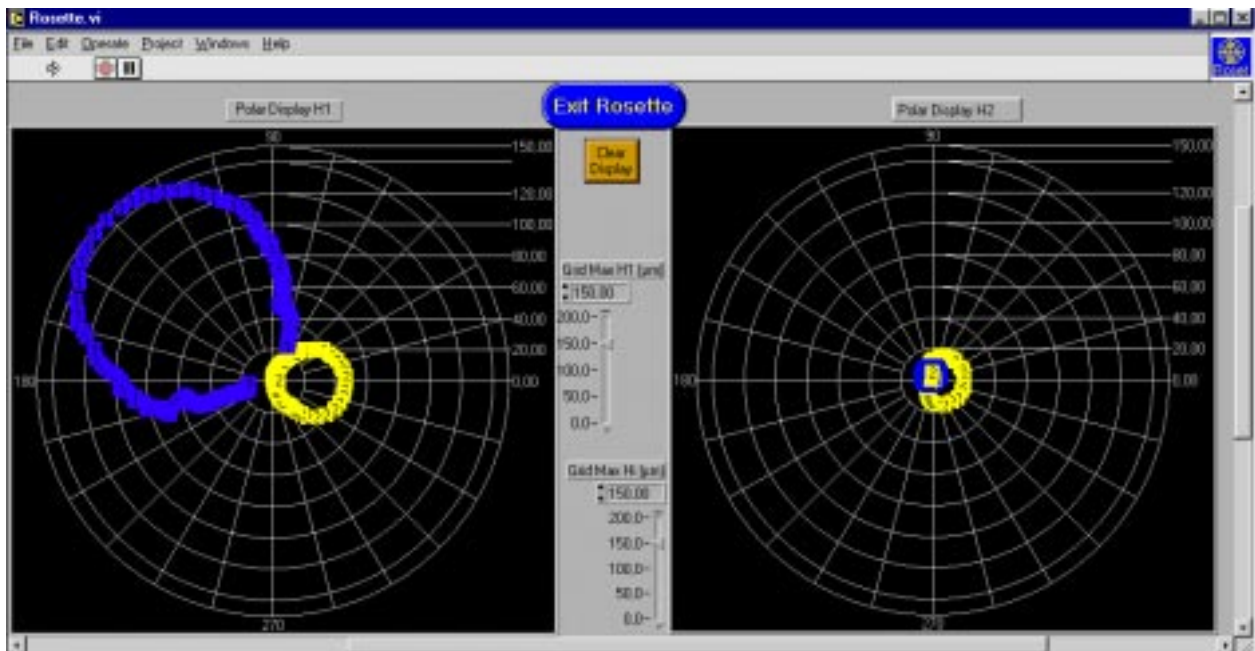
In this case one gets the short trend over one minute as controlled by the switch in "fast store" mode and the corresponding control. Switching to slow store shows longer trends over a quarter of an hour with a 5 seconds resolution. In such a way the operator can follow how the machine vibrations has recently behaved as a result of various operational changes. The red line indicates where the most recent values were refreshed and moves across the display to the right until it reaches the display end. It then falls back to the left, time scales are then refreshed and the cursor resumes its progression to the right all over again.

The same reasoning applies to the speed history.

Basically that is all an operator needs: vibration trends, how they compare to vibration norms and a quick way to locate where the sensors in alarms are on the machine.

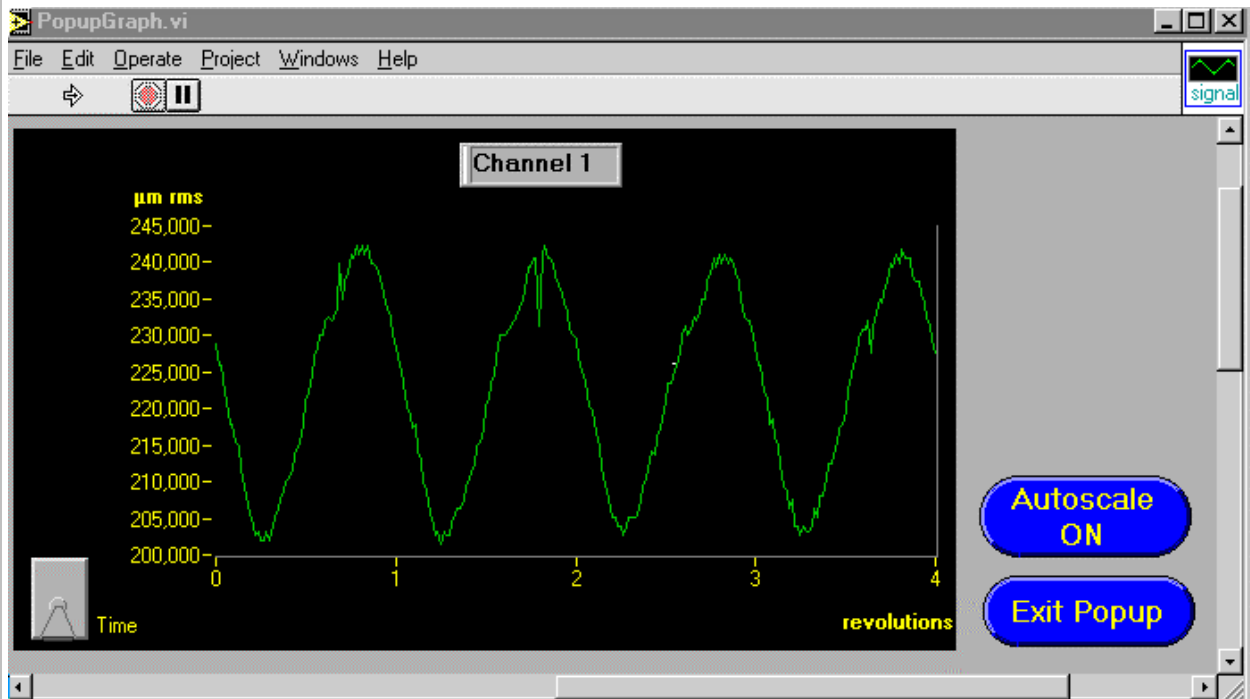
Other buttons at top right are reserved for more experienced vibration specialists. These are "General Display" for time and frequency analyses, "Rosette" for vector displays and finally "Orbit" for orbit displays. Let us press "General Display".

Vector monitoring



Using the picture control kit, one can use the screen as an oscilloscope with remanence to monitor the vibration vectors for selectable orders: H1, H2, H3. This display corresponds to the crossing of horizontally and vertically split critical speeds for sensors 1 and 2. One can clear the scope with the "Clear Display" button and adjust full scales with sliders or the associated digital controls.

Raw time-domain signal

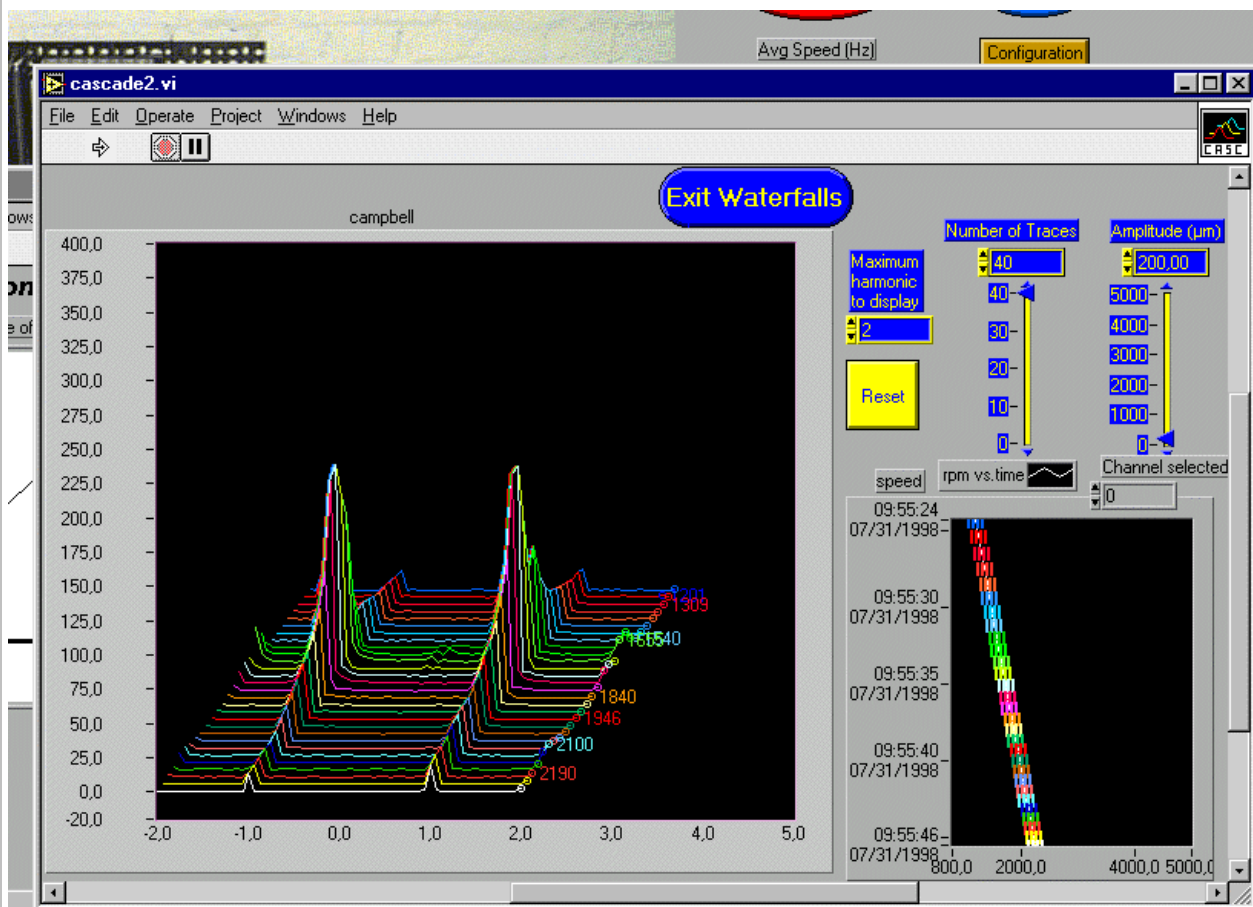


One can visualize the underlying vibration signal in time as it comes out of the sensor. The example shows the raw signal from an eddy probes with its offset. Vibrations correspond to the time-varying part of the air gap, while offsets are linked to the shaft position. This vi panel is surrounded by the general display where all other information like speed, etc is available.

The bottom left-hand side switch can be toggled to get a frequency spectrum either in linear or log coordinates. "Autoscale on" zooms upon the most sensitive scale which can vary in time depending upon the signal amplitudes.

Glitches on the time response prevent a proper differentiation of the signal to get vibration levels in velocity units. This caused jumps in the ISO2372 10-1000 Hz trends of the main panel. At any rate, vibration norms involving any kind of proximity sensors express vibrations in pk-pk values for the complete orbit (VDI2059, e.g.), thus never require differentiating sensor signals. As soon as the rig is equipped with accelerometers, a future release of the web page will give better and more realistic ISO2372 trends.

Speed gradient and frequency cascades



The above vi displays a real-time FIFO of cascaded full spectra for the pair of eddy probes 1 and 2 when the rotating speed crosses the split critical around 1700 rpm. Cascaded spectra are labeled by the speeds at which they were captured. The speed gradient can be observed on a doubly flipped time labeled speed graph with color codes matching those of the cascades for an easier analysis of both displays. The cascade vi was adapted from a vi floated on INTERNET. Chances are that using the official Labview version, it would execute faster.

One could not resort to a normal time for the speed gradients chart because of the synchronous samplings that does not perform at equal time intervals. For example, the successive data acquisitions over 16 revs extend over times spans that are inversely proportional to speed and the speed varies! In the general displays for short term and long-term trends one gathers these signatures occurring with a variable time pitch and produces outputs at a constant time rate. This allows using less time-consuming charts and later intensity charts labeled with a fixed time tick.

Cascade displays are impressive but very inefficient in terms of graphic usage. Here this was partly alleviated using FIFO where the last acquired spectrum appears as the base line of the cascade, moves all remaining spectra upward by a position and then expels the last one (the most ancient one) out of the FIFO buffer. They have other drawbacks:

- *Little memory depth, as shown when we want to visualize the crossing of the critical speeds*

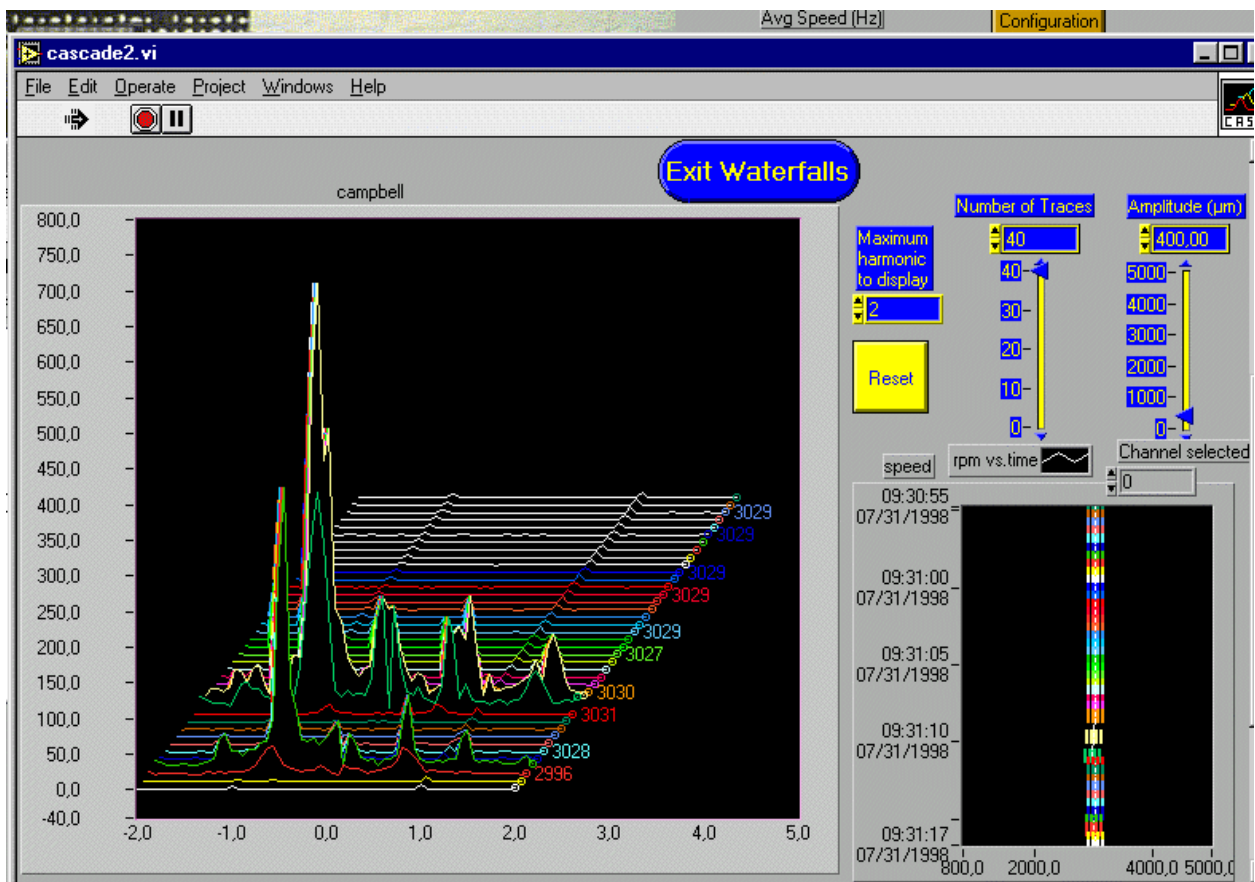
and other problems arising during the test rig startup.

- An inaccurate positioning of the spectrum orders due to successive slanted base lines.

This shows in the cascades for Mathieu rubs next.

Actually, one may wonder whether cascades, though flashy and impressive they may seem, are not a thing of the past when powerful color graphics cards and the matching displays were not yet available and monochromatic displays were the rule.

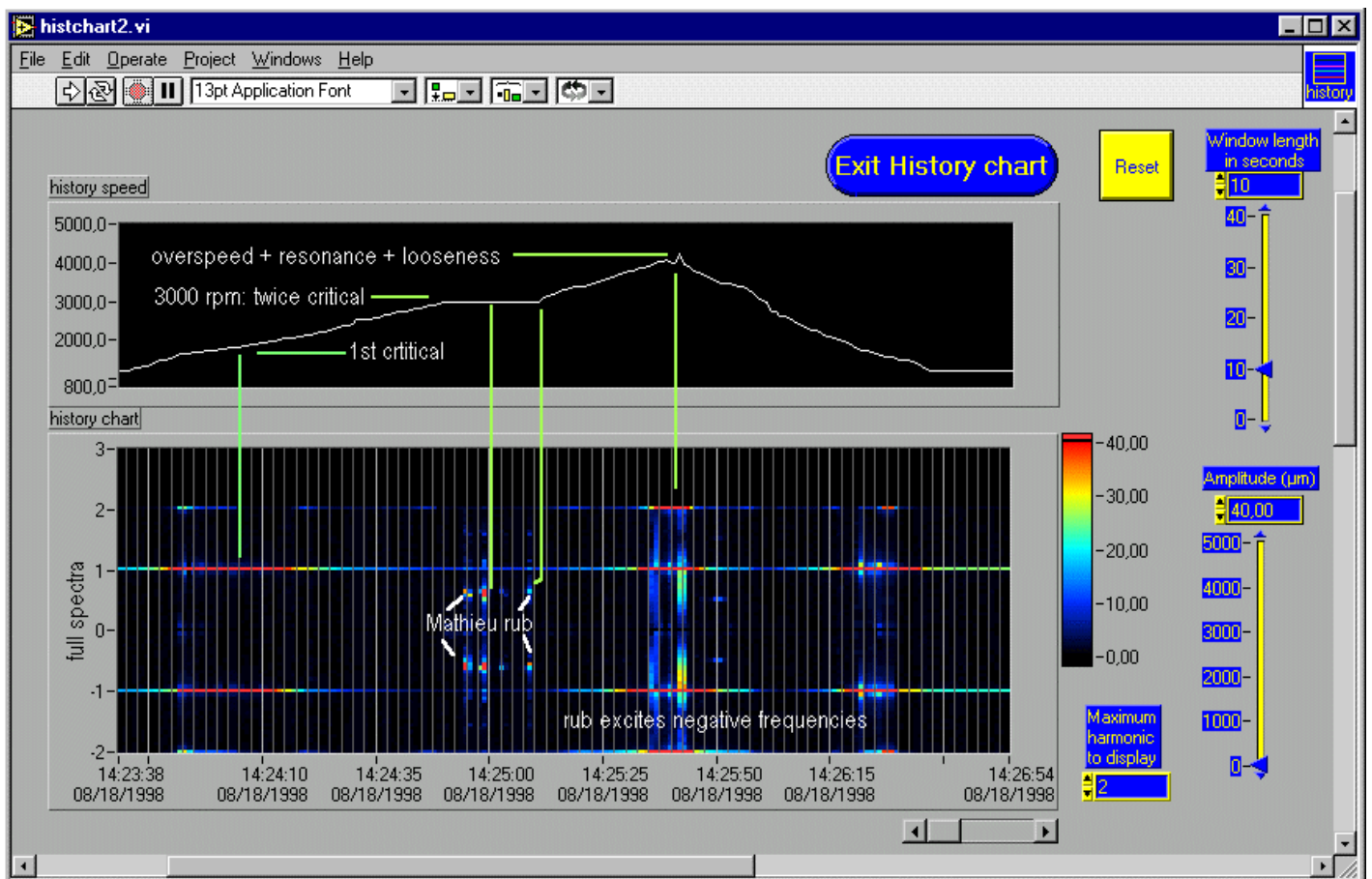
Cascades for Mathieu rub



The machine is now rotating at a constant ca 3000 rpm speed, i.e. approximately at twice the shaft split critical speed. One then approaches an unsleeved bearing to gently touch the shaft. This triggers the so-called Mathieu rub translating into very strong $1/2$ subharmonics with a dominant minus $1/2$ component. This shows in the cascaded full spectra, but is difficult to say for sure that one indeed deals with $1/2$ subharmonics because of the skewed display.

And what about visualizing the previous cascade of spectra when crossing critical speeds and this one?

Labview intensity charts as an alternative to cascades



With Labview intensity one exploits modern color displays more efficiently than with cascades. In this case, one can get the full trend of full frequency spectra both when crossing the first split critical speeds, when triggering Mathieu rub, when reaching the second critical speed, then when slowing down the machine to cross the 1st critical this time downward. The trends of the speed and other operational parameter can be examined at a glance and visually correlated with frequency spectra!

A colored scale indicates the amplitude in the intensity chart and is easily modified.

There is no longer some inaccuracy in spotting the subharmonics $-1/2$ and $1/2$. One notices a red spot for $H_{-1/2}$ at the third occurrence of Mathieu rub at 3000 rpm. The rub pushed the shaft counter the shaft rotation at $1/2$ the rotational frequency. That is Mathieu rub.

One also notices that crossing the 1st critical speed cause the running-speed harmonic H_{+1} to last longer than H_{-1} . This is a well-known behavior when crossing a split critical speed. At first the positive H_{+1} is excited, then H_{-1} dominates between the split speeds and then again the forward whirl H_{+1} is higher than H_{-1} when leaving the critical zone.

When reaching the second critical speed above 4000 rpm, the rig starts vibrating heavily. There is probably rubbing. One notices that stronger amplitudes spill near H_{-1} than around H_{+1} . This further indicates rubbing

sending the shaft to vibrate counter the rotation.

Intensity charts can be stacked together to obtain a trend of frequency spectra for several sensors or pairs of sensors when using full spectra without clogging the whole display. Furthermore, Labview (intensity or standard) charts are not merely graphics objects. They also manage circular buffers. One can easily change their length and the part of it that is displayed. The display gets refreshed as new spectra come in. One thus gets a continuous real-time trend of (full) frequency spectra in several ways: wrapped around (time-consuming), cursor moving with the most recent spectrum, etc. Better to see in action and not on this static page.

One can load the underlying circular buffer in a intensity graph or chart elsewhere for further analysis with two-dimensional cursors to navigate through the spectral history and get the amplitude anywhere on a digital indicator. Such cursors can be active in any number.

With a horizontal cursor, one can select any frequency component H_x to be displayed vs. time ($H_x(t), t$) or vs. speed ($H_x(\text{rpm}, \text{rpm})$) or any other slow parameters acquired in the chart above that can accommodate any number of curves like temperatures, pressures, thermal expansions, etc. Dragging the cursor at x recovers the spectral ray at x from the buffer corresponding to the intensity chart, where x can be any negative or positive number in step $1/N$ starting from zero where N is the number of revs over which the successive spectra are computed. For example if you wish to see what happens with harmonic $-1/2$, place the cursor the horizontal cursor at $-1/2$. From the cursor position, the vi infers which rows of the underlying buffer is concerned and extracts it for a Bode diagram to be plotted vs. rpm. If spectra are stored up to say the n th harmonic off the running speed and n is big enough, one can follow the blade frequency in a ventilator vs.time or vs. speed, if the intensity chart say it is worth looking at.

A vertical cursor selects spectra to display. Two cursors may define a number of spectra to show on a cascade, where you are sure that something has happened.

In other words the underlying buffer of an intensity chart (and intensity graph) acts like a platform from where to perform further analyses operating cuts anywhere to get refined views like Bode plots on any order of the vibration while keeping an excellent overview of the whole spectral history over a much longer periods than what cascades permit. Nowadays plenty of RAM memory is available at low cost and the amount such intensity charts absorb becomes a side issue.

Orbits



The shapes or vibration orbits may help diagnose bad alignments in shaft lines with thick-film sleeve bearings. When the load applied to the hydrodynamic oil film becomes excessive, an unbalance does not cause an elliptical orbit any more but rather a banana-shaped orbit. That is best viewed in x-y cartesian coordinates like here. Applying a complex-valued Fourier transform to the complex-valued time orbit is the first step to get full spectra which are none other than the amplitude of the resulting two-sided Fourier transform where the negative frequencies (here orders due to synchronous sampling) are not complex conjugates of their positive counterparts. Negative frequencies are linked to backward whirl while positive ones concern forward whirl.

The vibration generally traverses the orbit in the shaft rotation sense. Sometimes in both directions like in eight-shaped Lissajous. Then better rely upon full spectra to decide in which senses the Lissajous are traveled for individual pairs of frequencies.

Conclusions

Full spectra are powerful tools to diagnose shaft vibrations.

The above vi collection demonstrates that Labview is very helpful implementing order tracking of vibration in rotating machinery. They are more hidden treasures that have not been shown here like Using the digital filter tools to doubly integrate accelerometer signals and eliminate the lower frequencies without phase shift or, else, the computation of instantaneous speed gradient based on successive TTL pulses of the phase pickup and the 20 MHz internal clock of the MIO E cards from National.

The PCI MIO E 1 card and its Labview drivers turned out to be extremely reliable. Not only did it manage to acquire vibration signatures and successive periods of shaft revolutions simultaneously, but its versatile counters and drivers also generate the clock for programmable switched-capacitance anti-aliasing filters without loading the PC processor, while the DAC control the test rig speed.

The collection of vi's allows to monitor 16 eddy probe vibrations in real-time with a 200MMX-based PC under W95 way above 6000 rpm. When connecting accelerometers, one must insert anti-aliasing filters to hold this processing speed. This is due to the implementation of synchronous sampling through oversampling and then variable-pitch speed-driven decimation.

This was an exacting task for the PCI-MIO E 1 card that got equal to expectations. Do not forget that one uses the same card for all other applications like JTFA in gear vibro-acoustic monitoring of profile damages, the bearing mini-expert (also vibro-acoustics) and the study of the reactions of flexible couplings, not to mention impact testing and the determination of transfer functions with white and other types of noises as sources of excitation. Thus one lands with a PC serving multiple applications with a single card. The PC is an [ACME lunch-box](#).

Finally a test rig allows the simulation of important and complex problems in rotor dynamics. It is fully automated under Labview and provides the last stage to validate vi's before moving to real-life bigger machinery.