# A LABVIEW mini-expert to identify bearing defects automatically

## The rolling-element expert virtual instrument.

**This is an example how advanced data processing of shocks produced by surface defects leads to a robust mini-expert telling if a bearing surface defect is present on one or some of the components like inner races, outer races of rollers (balls) even at very slow rotational speeds. This limits the rate of false alarms characterizing simpler methods like SPM, HF, etc.. The diagnosis is displayed by a mini-expert vi in a straightforward fashion, thus bypassing the need of a vibration expert to analyze the bearing signatures, like the CSI approach below which explains how to diagnose bearing failures.**

**Virtual instruments (abbreviated as vi's) consist of a PC with a data acquisition card. They are developed under Labview. Their front panels include controls, displays, etc. on the PC screen. Manipulating the controls (switches, rotary knobs, sliders, etc.) occurs with the pointing device (mouse) instead of your fingers. The same PC can accommodate lots of different instruments. The bearing expert is one of them. Some other dedicated instruments follow in the next web pages. They concern monitoring rotor vibrations, gear failures, flexible coupling reactions among other applications.**

**Virtual instrumentation opens the door to inexpensive transportable dedicated.**

## Problems with anti-friction bearings (from CSI seminars)

## Background information on roller-element (anti-friction) bearings

**Bearing life-cycle depends on two basic sets of variables: Application variables such as load, speed, lubrication, mounting, temperature, and shaft quality, and configuration variables such as design, materials of construction, method of construction, and quality control.**

**Approximately 90% of all bearing failures are caused by improper applications, and about 10% are caused by tone of the configuration variables. Our experience has shown that one out of every 10 bearings taken off the shelf and installed will have a defect when installed. This means that 10% of the time we have introduced a new problem into the machine at overhaul.**

**Anti-friction bearings are constructed using several distinct parts--the inner race, outer race, cages or retainers, and the balls or rollers. Three distinct parts aid us in detecting bearing defects. Each component of an anti-friction bearing develops a unique characteristic vibration signature. Typical defects detected in a vibration signature include those found in the outer race, inner race, retainer or cage, and the balls or rollers. By calculating the discrete frequencies associated with the four components, we can identify which bearing component is defective. Other data contained in the vibration signature includes information on internal clearances, looseness, adequacy of lubrication, and the effect of thrust and radial loads. Most of the above bearing problems have characteristics that are readily discernible from the fundamental running speed of the shaft (1xRPM). By analysing the signature, we are able to determine whether bearing failures are caused by an application variable or a configuration variable.**

## Anti-friction bearing frequencies.

**The predominant frequencies generated by anti-friction bearings are classified and computed as follows, based on a few characteristics of the bearing**

## Bearing parameters to compute bearing frequencies:

**Formulas have been developed to calculate critical anti-friction bearing frequencies. Five parameters must be known to accomplish these calculations:**

| | |
|---|---|
| **Bd** | **ball or roller diameter** |
| **Pd** | **pitch diameter** |
| **Nb** | **number of balls or rollers** |
| **$\alpha$** | **contact angle** |
| **f** | **RPM/60** |

| | | |
|---|---|---|
| **BPFO** | **Bearing Outer Race Frequency** | **$BPFO = f \cdot (Nb/2) \cdot [1-(Bd/Pd).\cos\alpha]$** |
| **BPFI** | **Bearing Inner Race Frequency** | **$BPFI = f \cdot (Nb/2) \cdot [1+(Bd/Pd).\cos\alpha$** |
| **BSF** | **Ball Spin Frequency** | **$BSF- =f /2. (Pd/Bd) \cdot [1 - (Bd/Pd).\cos\alpha)^2]$** |
| **FTF** | **Fundamental Train Frequency** | **$FTF = f/2 \cdot [1-(Bd/Pd).\cos\alpha]$** |

## Analysing bearing signatures

**When analysing bearings for surface defects, use the following guidelines:**
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1. **Bearing components normally fail in the following order: race defects, ball or roller defects, cage defects (unless the bearing was defective when installed).**

2. **Inner race defects and failures occur at much lower amplitudes than outer race defects.**

3. **BSF is usually generated when a ball or roller is defective. When multiple bars are defective, multiples of BSF appear, i.e., if BSF is at 800 RPM and four balls have defects, you should also see a peak at 3200 RPM or 4xBSF.**

**In all cases, a surface defect on an inner race, an outer race or on a roller (ball) generate shocks at the bearing characteristic frequencies. In a frequency spectrum, these correspond to train of frequency pulses extending from the 0-1000 Hz range normally devoted to vibration analyses to higher frequency ranges in the domain of vibro-acoustics. Such families of peaks merge with the peaks due to other causes. A real specialist must then deal with the bearing analysis to sort out other causes present in the frequency spectrum.**

**In the vibration frequency range (typically 10-1000 Hz), the patterns of frequency spectra may indeed be complex, due to problems of rotor dynamics; pumps & ventilators (blade passing frequencies, vanes, etc). Add to this problem contributions to the frequency spectra that are specific to rolling-element bearings that have nothing to do with the signatures associated to surface defects in the vibro-acoustic range (>1000 Hz):**

- **Internal looseness in a bearing has a component at l XRPM and several multiples of shaft RPM. A bearing running on the shaft or in the housing shows 3xRPM and possibly higher multiple's of RPM.**
- **Bearing misalignment can result in vibration at the number of balls or rollers times shaft RPM.**

**Trending may be another way to monitor bearing and other failures**
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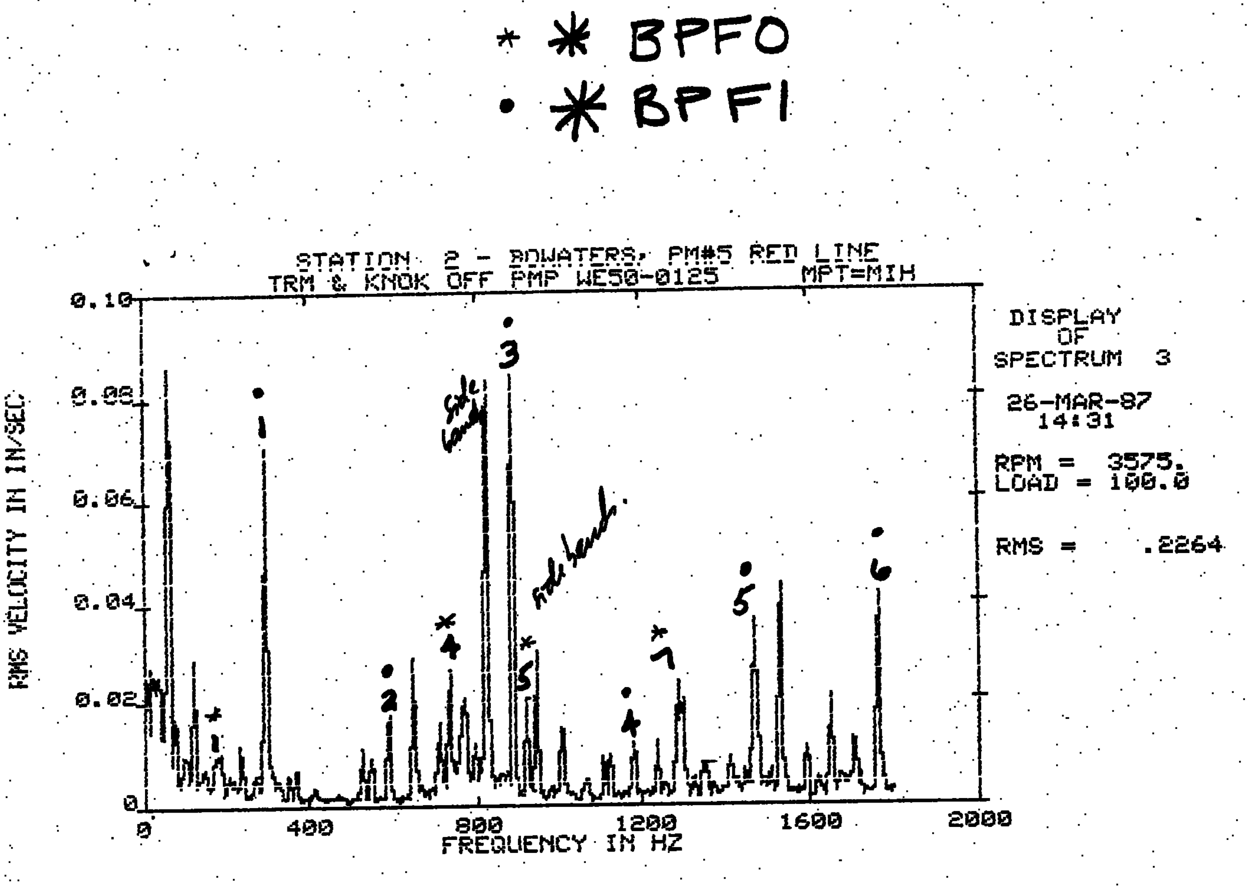
- **Vibration amplitude increases as bearing degrades and may disappear prior to failure.**
- **Baseline energy may increase across the entire spectrum and the band width broaden as the bearing degrades.**

**This again requires quite a lot of expertise to interpret frequency spectra, as shown below with some results from actual failures.**

## Frequency analyses of actual bearing failures in the frequency spectra (from CSI seminar).

**Suppose you want to pinpoint whether a bearing has some surface defects on either of its components: inner race, outer race or roller. You perform a frequency analysis from an accelerometer placed as near to the bearing as possible. Here is what one can get (from CSI seminar).**




**Between 0 and 2000 Hz, one gets plenty of peaks. Are these peaks caused by bearing defects? One then displays a list of all peaks vs. frequency (modern versions should probably use a cursor). In this list one tries to spot contributions from bearing surface defects after computing them from the rotational speed and the bearing characteristics or, else, from such programs as ATLAS from SKF (see Appendix).**

Machine: TRM & KNOK OFF PMP WE50-0125
Meas. Point: E50-0125 -MIH --> TRM & KNOK OFF PMP W MTR IB HORZ
Date/Time: 26-MAR-87 14:31:57 Peak Value Units: IN/SEC RMS

| PEAK NUMBER | FREQUENCY (Hz) | PEAK VALUE | ORDER VALUE | PEAK NUMBER | FREQUENCY (Hz) | PEAK VALUE | ORDER VALUE |
|---|---|---|---|---|---|---|---|
| 1 | 38.06 | .0296 | .64 | 15 | 821.88 | .0925 | 13.78 |
| 2 | 59.63 | .0902 | 1.00 | 16 | 881.77 | .0848 | 14.79 |
| 3 | 74.02 | .0191 | 1.24 | 17 | 916.09 | .0243 | 15.36 |
| 4 | 119.76 | .0318 | 2.01 | 18 | 941.41 | .0305 | 15.79 |
| 5 | 177.61 | .0117 | 2.98 | 19 | 1001.20 | .0172 | 16.79 |
| 6 | 182.77 | .0117 | 3.06 | 20 | 1175.57 | .0122 | 19.71 |
| 7 | 235.07 | .0125 | 3.94 | 21 | 1235.11 | .0138 | 20.71 |
| 8 | 293.94 | .0746 | 4.93 | 22 | 1283.70 | .0248 | 21.53 |
| 9 | 587.84 | .0191 | 9.86 | 23 | 1294.32 | .0228 | 21.70 |
| 10 | 647.29 | .0297 | 10.85 | 24 | 1469.25 | .0406 | 24.64 |
| 11 | 707.97 | .0169 | 11.87 | 25 | 1528.91 | .0465 | 25.64 |
| 12 | 732.70 | .0271 | 12.29 | 26 | 1649.24 | .0235 | 27.66 |
| 13 | 763.50 | .0225 | 12.80 | 27 | 1703.23 | .0140 | 28.56 |
| 14 | 791.55 | .0119 | 13.27 | 28 | 1763.21 | .0436 | 29.57 |

| TOTAL MAG | SUBSYNCHRONOUS | SYNCHRONOUS | NONSYNCHRONOUS |
|---|---|---|---|
| .2264 | .0553 / 6% | .1555 / 47% | .1551 / 47% |

**Figure 11-11. Bearing Frequencies.**

**One spots in the list frequency rays with a dot for a defect on the outer race, while stars are for a defect on the inner race. <u>That is undoubtedly the job of a specialist and is no automatic diagnosis to put in every hand.</u>**

## The idea behind the bearing expert.

**The above procedure some specialist to do the job. One should try to find an easier way and streamline the diagnosis so that one only needs to connect the accelerometer to an instrument, enter the bearing characteristics and let it run to obtain an automatic diagnosis. That is what basically was done hereafter using a test rig with calibrated bearing defects to validate the results.**

**Before describing the method in detail, let us outline what the method consists of.**

1. **One performs the analysis in the vibro-acoustic domain between 1(2) and 12 KHz. This eliminates vibration contributions.**
2. **Shocks due to surface defects occur at the characteristic bearing frequencies. They do not generate single frequencies. Instead one gets families of equally spaced frequency rays. That is why this can cause the frequency spectra to be loaded with peaks. A better way to reduce the number of peaks to examine is to use cepstra. Cepstra differ from normal frequency spectra by the fact that they perform an analysis not in terms of frequencies but in term of periods of shocks. Well-used, they reduce a signal to very few peaks, paving the way to an automatic diagnosis of bearing defects.**
3. **Cesptra are somewhat insensitive to the attenuation of the sound waves produced by the defects. In this way, the accelerometers need not be located very close to the bearing to produce a reliable diagnosis.**
4. **Cepstral techniques deserve some care when implementing them. This is further discussed in this document.**

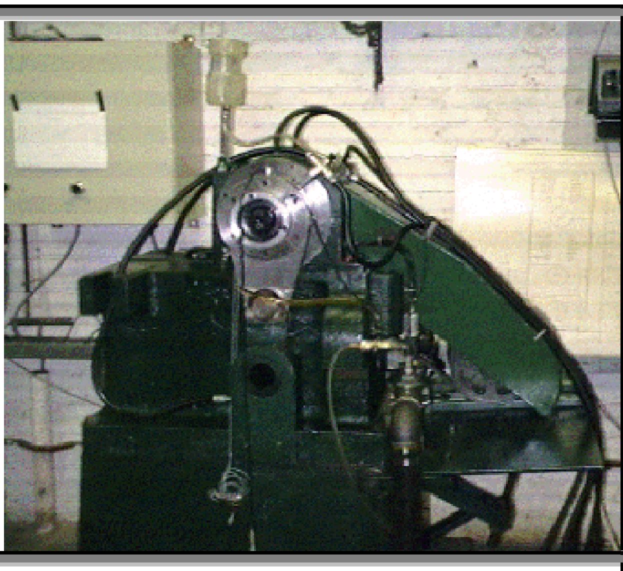
**As a result, one presents a bearing expert to diagnose surface defects in rolling-element bearings. It is extremely easy to use and does not require a vibration specialist to run.**

**The bearing expert was validated in the lab using a full-scale test rig.**

**Details of its inner workings are given below.**

## Test rig

**The rig features variable speed from 60 to 1550 rpm, radial loads from 0 to 10 Tons, completely separable roller or ball bearings on which calibrated defects are introduced on races and/or rollers (balls). These defects have increased severities with widths ranging from 0.1 to 0.4 mm. Bearing tested are SKF22NU15EC and FAG 1215TV**



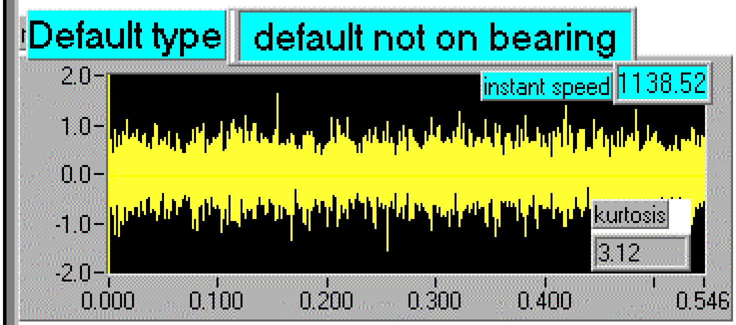
**The test rigs with hydraulic jack, the test bearings and the variable speed drive. Not shown: a hydraulic unit for lube and high-pressure jack (100bars).**

**One of the bearings tested FAG 1215TV test bearing: completely separable to introduce calibrated defects on races and balls. Inner bores are 75 mm. Shocks were measured with resonant accelerometers at first (freqs at ca 5 KHz). Later normal off-shelf general-purpose accelerometers were used instead to use standard accelerometers from conventional monitoring system. Their responses were digitally high-passed to eliminate low-frequency contributions of vibrations and get true shock signatures.**

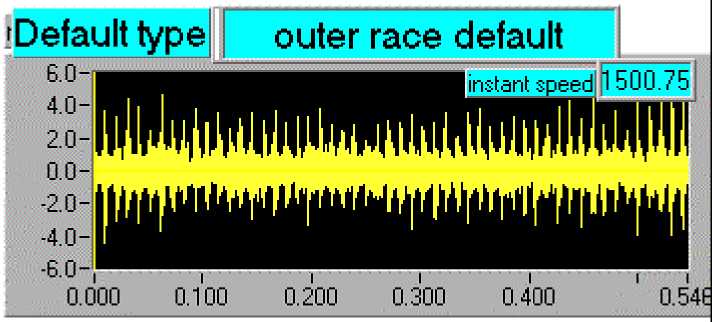
**Left-hand side: The test rigs with hydraulic jack, the test bearings and the variable speed drive. Not shown: a hydraulic unit for lube and high-pressure jack (100bars). One of the bearings tested FAG 1215TV test bearing. Inner bores are 75 mm. Shocks were measured with resonant accelerometers at first (frequency at ca 5 KHz). Later normal off-the-shelf general-purpose accelerometers were used instead to use standard accelerometers from conventional monitoring system. Their responses were digitally high-passed to eliminate low-frequency contributions of vibrations and get true shock signatures.**

## Raw defect signatures: see Table below along with miniexpert diagnoses

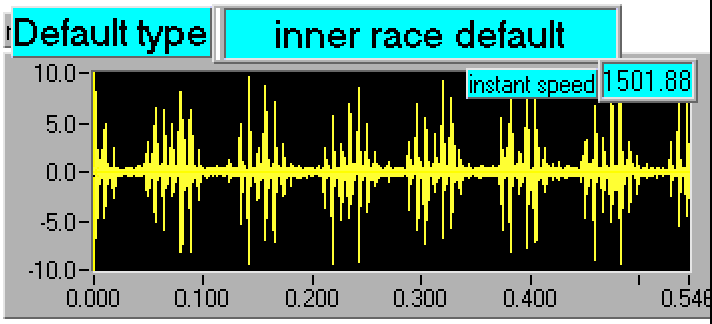
Raw signatures :Sound bearing: typically gaussian noise. Surface roughnesses in bearings exhibit very little spatial correlation. As a result, sound bearings tend to produce acoustic responses that are almost gaussian noise. Such a noise is characterized by a Kurtosis (random variable) close to 3.



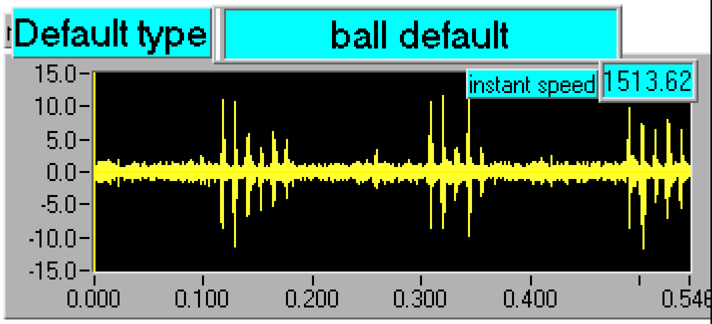

**Outer race defect:** Succession of shocks with about the same amplitude whose spacing can be derived from the B(all)P(assing)F(requency)O(uter) race characteristic frequency of the bearing, depending on the pitch diameter, the ball (roller) diameter, the number of the rollers (balls), the angle of contact (if any) and the shaft rpm. Rotational speed is 1500 rpm in this example obtained with a calibrated defect on the outer race of a SKF22NU15EC As all other responses they are digitally high-filtered from 2 KHz on.




**Inner race defect:** Succession of shocks modulated over a period corresponding to a shaft rev. Shock spacing corresponds to a B(all)P(assing)F(requency)I(inner) race that can be computed from standard formulae, knowing the pitch diameter, the ball diameter, the speed and the contact angle. Shaft rpm is again 1500 rpm like in all following signatures.

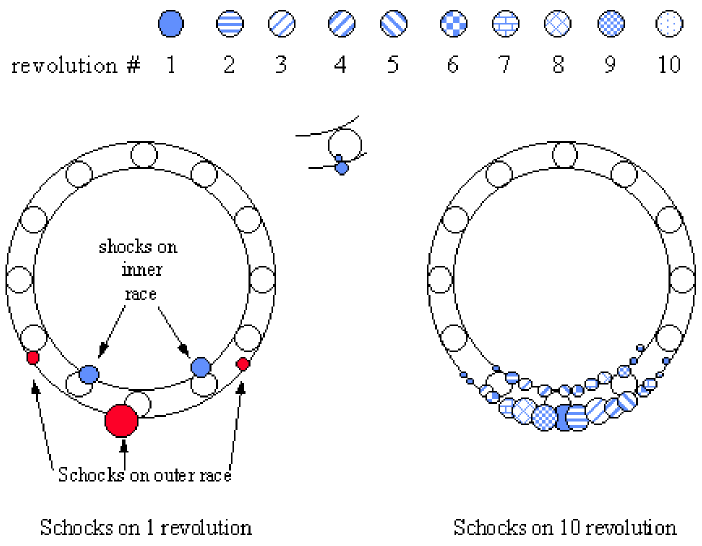



**Roller (roller)surface defect:** Same remark as before except that shock spacing corresponds to twice the characteristic B(all)S(pin)F(requency) and is modulated with a period corresponding to one cage rev.



## Expert system as a LABVIEW vi: Basic idea behind data processing

Suppose that a surface defect appears at the surface of a ball (roller) as shown below. This defect will cause successive shocks as it encounters either the inner or the outer race. If the load carried by the bearing is vertical downward, such shocks tend to increase with the pressure between roller and races. This pressure reaches a maximum when the contact between the defect and the races are aligned with the load zone. That is the case when the defect is below. As the positions of the contacts depart from the vertical, the shocks they produce decrease in amplitude.



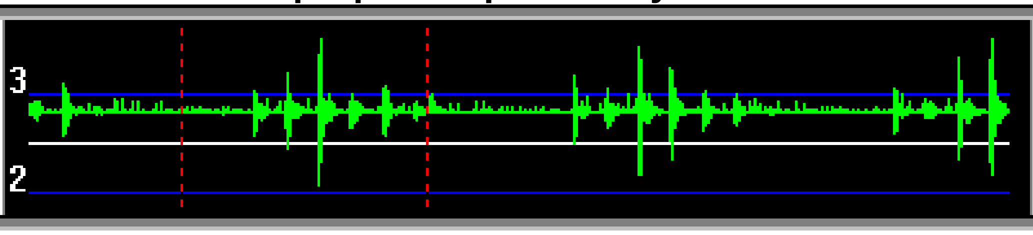

Shocks altogether disappear when the ball is located in the upper part of the outer race since there is no longer any pressure between the ball and either race. In this reasoning, the outer race is supposed fixed and the bearing is not pre-constrained (look at suffix C which is C3 in the test bearings).

That is what one conveys in the left-hand-side representation of the bearing for one cage revolution. Blue circles indicate the positions of the ball defect with the inner race, whereas red circles have the same meaning with the outer race.

Circle radii are proportional to shock intensities. They depend on some distribution of the load zone. In order to account for the attenuation of shock waves through the roller as sensed by an outboard accelerometer, one could further reduce the intensities of the blue circles, although this was not really observed with the experimental results from the test rig. The right-hand side bearing shows the position of contacts of the defects with the races over several cage revs.

Now the main red circle can be viewed as the source of the acoustic wave generated by the defect and the subsequent blue and red circles like echoes of this main shock waves. These are not real echoes as one encounters in the propagation of acoustic shock waves. The latter would be much closer spaced. The former are pseudo echoes caused by the dynamic and kinematics of bearings and their surface defects.
Attenuated echo-like shock waves lend themselves to cepstral techniques when one wishes to separate them from the main incident shock wave and reach a high data compression ratio. To this aim, one must exert some care to obtain sound cepstra according to L.F. Pau [Failure Diagnosis and Performance Testing Series Control and Systems Theory vol. 11, Marcel Dekker]:

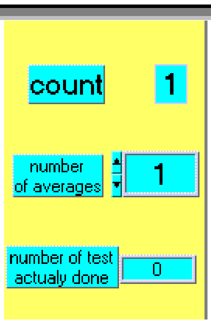
**Centering the buffer of data within a load cycle and windowing it for proper cesptral analyses.**



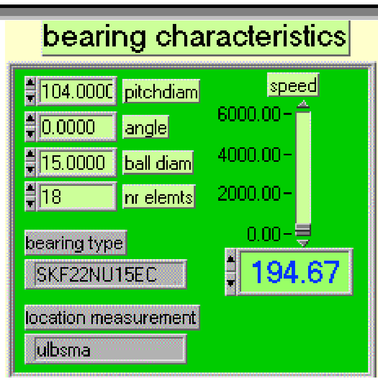

**Steps:**

1. **It is important to start the data acquisition when the defect enters its load zone and terminates it when leaving the zone. Therefore one samples the acoustic response over a time span extending over several load zones for ball defects (the longest of all corresponding to successive cage revolutions). One then narrows the time window to correspond to a maximum energy in its center and to extend over half a cage revolution. As shown in the picture below, one samples the shocks over a few cage revs and then extract a shorter part of the data acquisition window to center it over half a cage rev.**
2. **one then applies a double exponential window w(t) simulating an attenuation of shock waves when departing from the window center. Like other defects, outer race defects lacking specific load zones now generate attenuated echoes fit for cepstral analyses.**

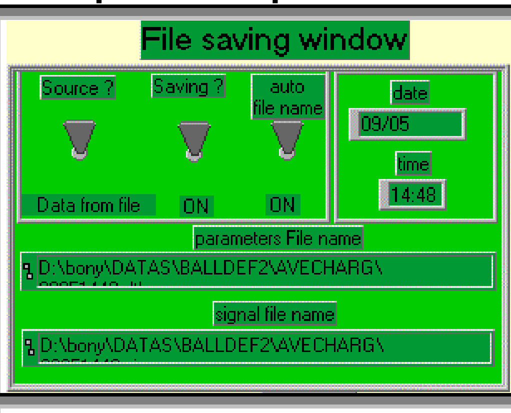
# Description of the Labview bearing mini-expert front panel



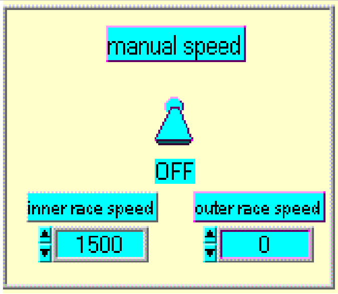

The control window to select the number of averages to be used for identification



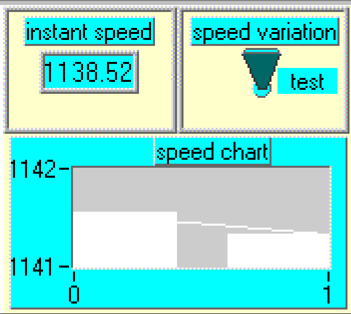

A «bearing characteristic window» to enter the geometric data of the bearing in order to compute the characteristic frequencies from the rotation speed
These data can be obtained with standard programs like SKF ATLAS for most standard bearings in the nomenclature.



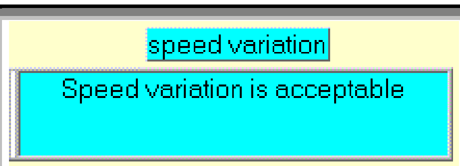

the «file saving window» to chose between on-line or delayed analysis.
Several switches are available:
Run a diagnosis from either a file or real measurements with a MIO card from National.
Save the result from real measurements or not
Auto file name generates automatic filenames with encoded dates and times. Otherwise the user must enter his choice.




In case the vi does not measure speed, one can enter the speeds of the inner race and the outer race manually. One assumes these speeds to be correct and steady.

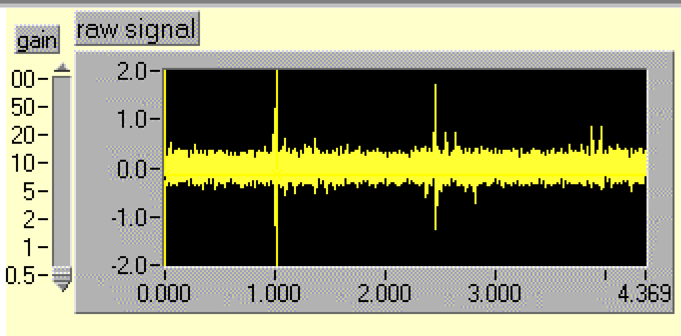



For automatic speed measurements, the instant speed is monitored. With the switch one can reject too fast speed variation for the diagnosis.

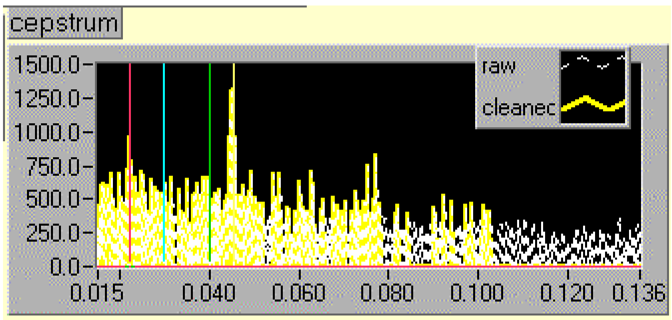



This display is more important when one runs the expert with a number of averages bigger than one. The speed can vary between successive acquisitions.

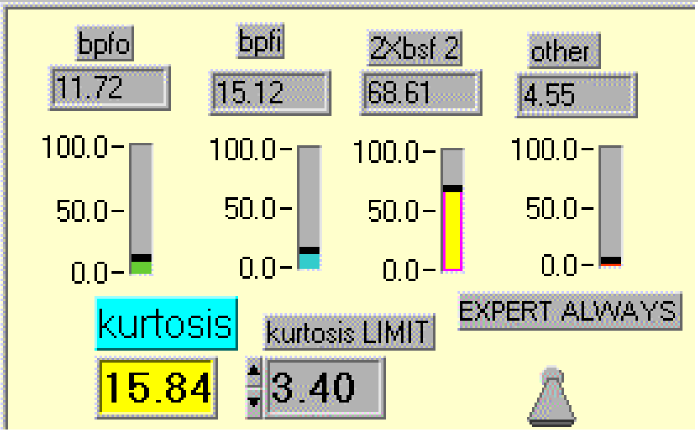
The indicator mentions whether the speed variations are OK for the diagnosis.

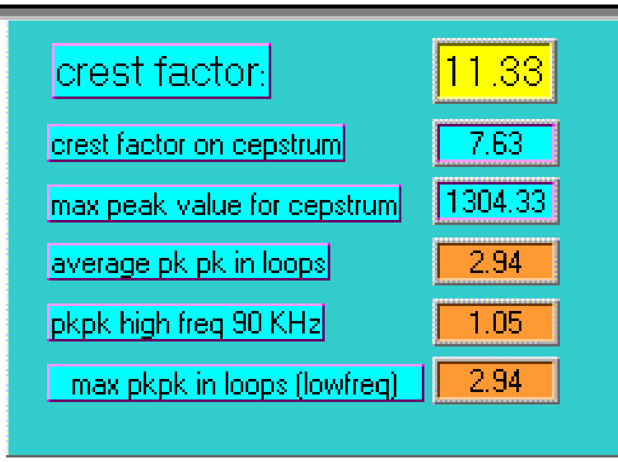



The raw signal from the accelerometer (here unscaled) in time doamin (sec)
Gain cursor for the MIO card to get the full dynalics: 0.5 fro +-10V, 1 for +-5V, etc.




Cepstrum for the range of quefrencies associated to bearing defects. Green for BPFO, cyan for BPFI, yellow for ball or roller, red highest value outside these quefrencies. An algorithm cleans the cesptrum from noise.




This panel provides a summary of the diagnosis.

Four bar graphs show values that are derived from weighed contributions to the cepstrum caused by the standard bearing defects. Basically it sums up the amplitudes of the cepstrum around the first few quefrencies for shocks caused by the typical defects BPFO BPFI and BSF (2X) according to some appropriate weighing. The last bar graph corresponds to the same weighing applied to the highest remaining peak outside those for standard defects.

Sound bearing emit signatures with Kurtosis around 3 due to normal spatially uncorrelated surface roughness. Shocks raise Kurtosis. When it exceeds the "Kurtosis limit" entry, an automatic diagnosis follows if the switch next to it is low. Otherwise the expert declares "no shock no diagnosis"

If the switch is up an automatic diagnosis occurs. It may still consistently detect the same type of fault repeatedly, because cepstral techniques are very sensitive. Beware nevertheless that they are also sensitive to noise that could cause random diagnoses. If this occurs, discard the diagnosis.

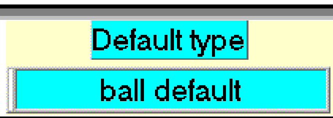
Some other parameters describing the ruggedness of various displays.

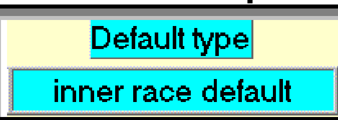
Pk-pk values of 1KHz-12KHz filtered signatures of the accelerometers provide some idea about the severity of the shocks.

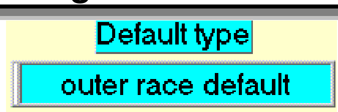
The vi does not provide an absolute severity scale, but a good identification of a defect.

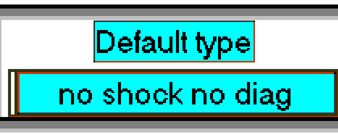
The experience shows that absolute severities are hard to achieve, despite what some vendors pretend. With brand-new healthy bearings, their scale has quite often led to diagnose ghost faults.

## Examples of diagnoses



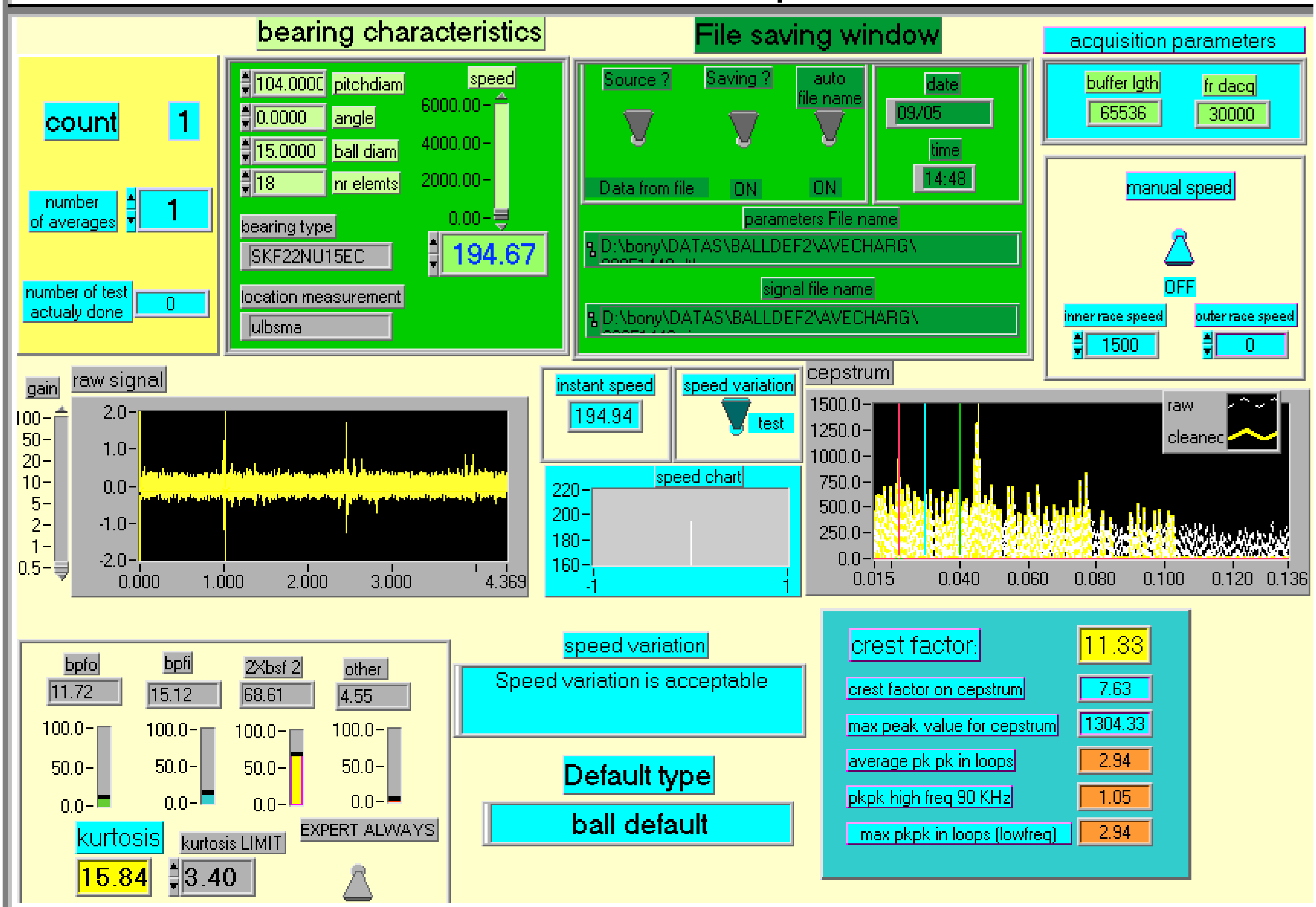




These are examples from actual rig measurements of almost fool-proof diagnoses. The last one corresponds to a sound bearing with a close to 3 Kurtosis and the "Expert always" switch down. In case shocks are caused by another component than the bearing and yet at a frequency close to those of a characteristic bearing failure, another diagnosis is **"Default not on bearing". These diagnoses are only what matters to the end user.**

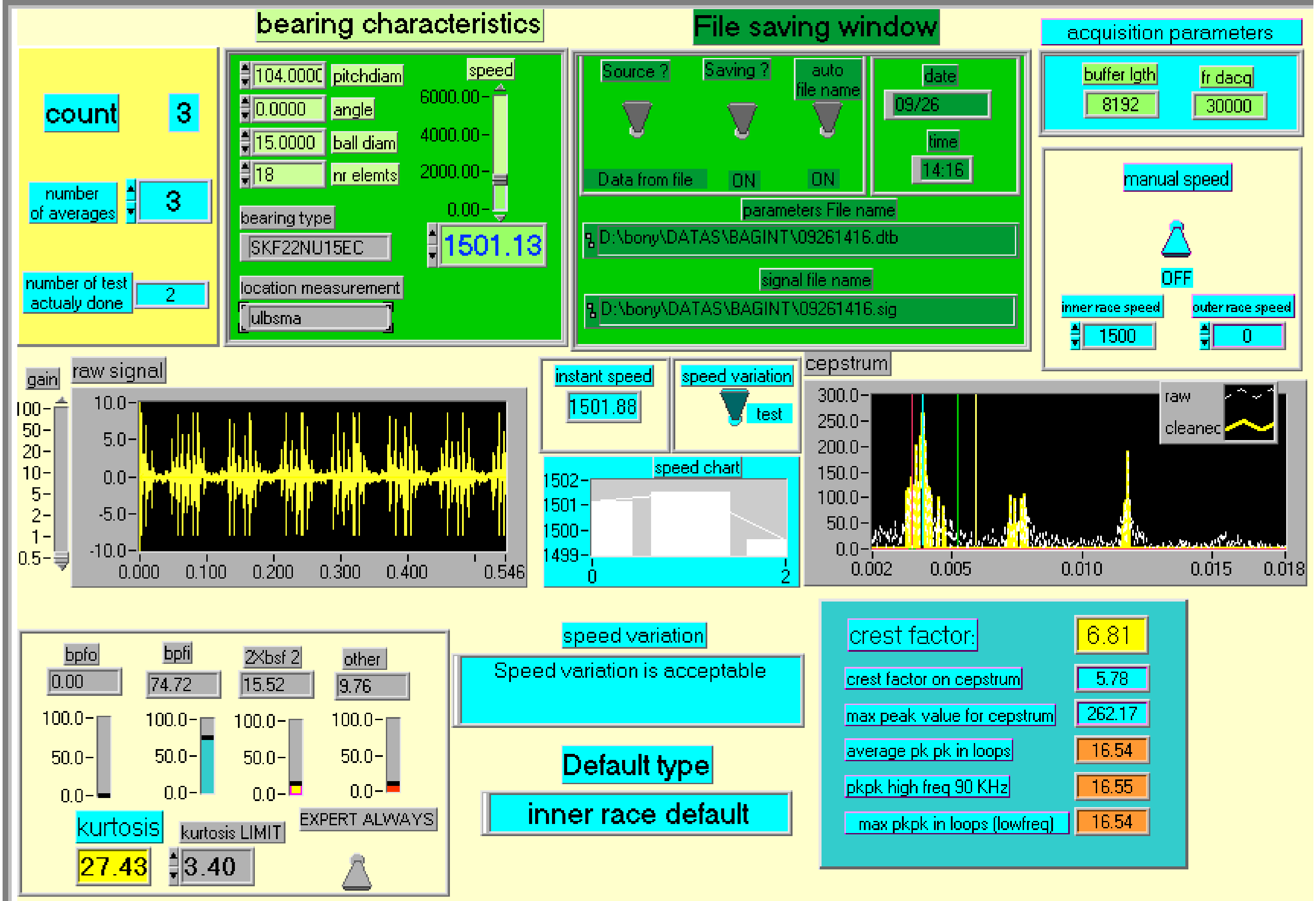
## Gallery of case studies with full Labview bearing expert panels

## Ball defect at low speed



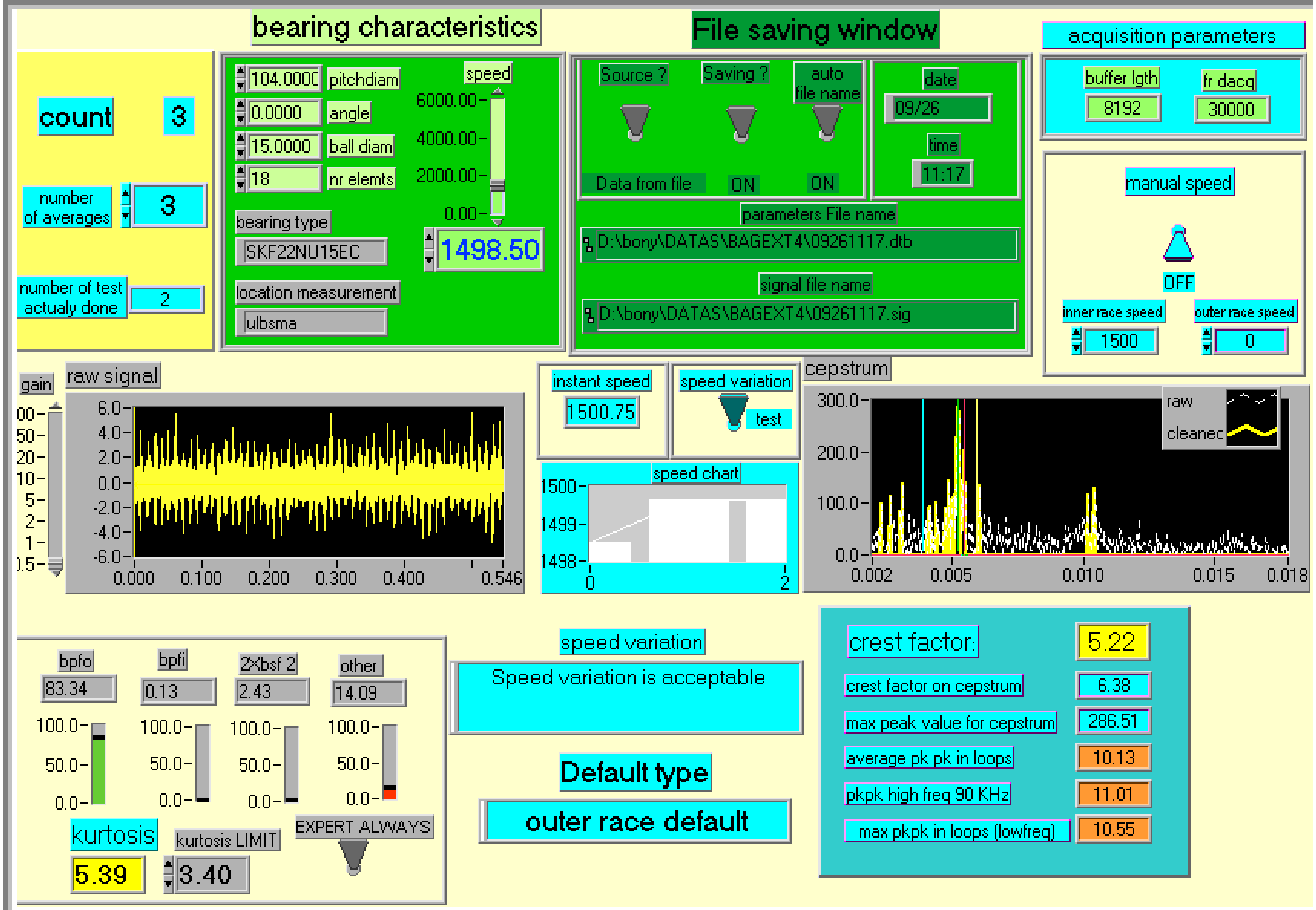

**The bearing was damaged with a 0.2mm groove on one roller. SPM says it is slightly or not damaged above 400 rpm. At lower speeds, SPM severity scale indicates the bearing is healthy.**

# Inner race defect



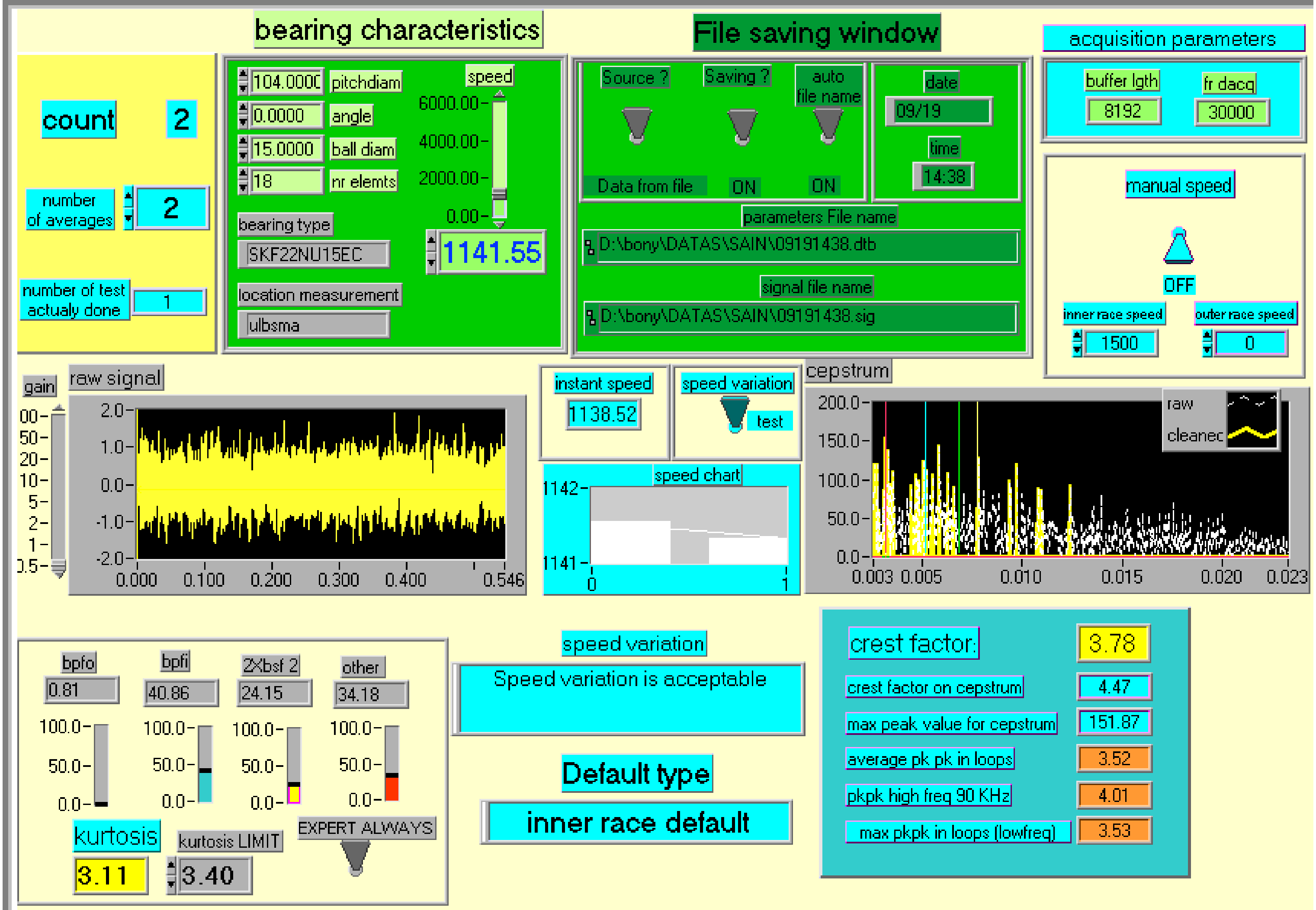

**The bearing was damaged with is a calibrated 0.2 mm groove on the inner race. At 1500 rpm SPM would specify that the bearing is slightly damaged**.

## Outer race Defect

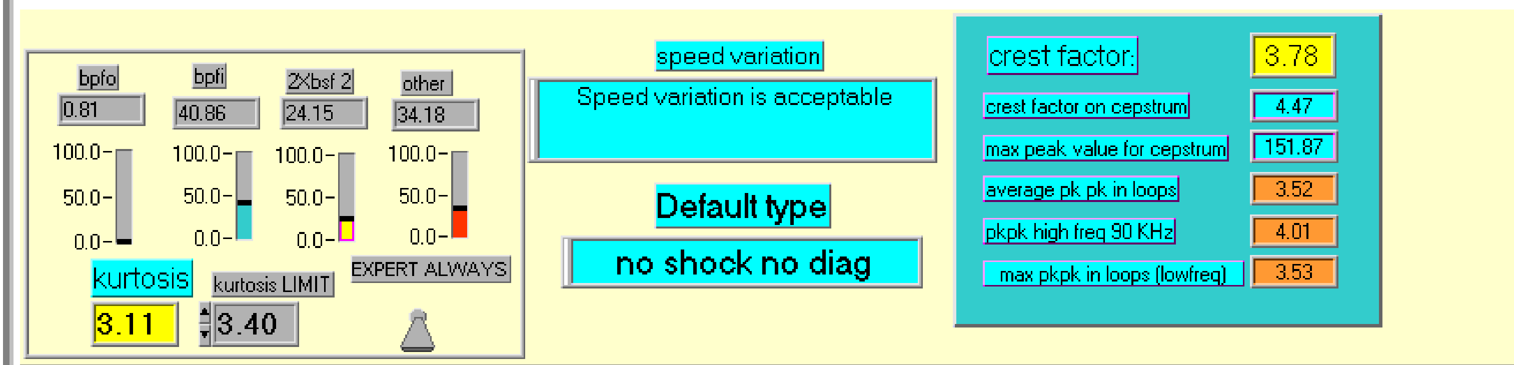



**With 0.4 mm groove at the surface of the outer race.**

# Sound bearing




**The "Expert Always" is up. This overrides a too low Kurtosis and carries out the diagnosis al the same. It tells that one detects an inner race defect. This may correspond to a very minute defect and should be believed with some caution. Next comes the diagnosis for the same response and the "no shock no diag(nosis)" message**



## Conclusions

### Identification of defects is superior and top easy and validated on a full-scale test rig.

**One need not be a vibration and/or acoustics specialist to run the expert. The expert focuses on surface defects and nothing else. That is what makes it efficient and easy to use.**

**Using signatures obtained with the test rig with bearings fitted with various types of surface defects and increasing defect severities, the mini-expert consistently identified the defects correctly.**

**Bearings were either of the roller type (SKF22NU15EC) or of the ball type (double row spherical FAG1215TV). These bearings share the interesting property that one can easily implement calibrated defects on the surface of all elements (races and rollers or balls) because one can separate their components easily "lego"-style without breaking any of their components.**

### Identification runs down to very low speed and is reasonably insensitive to sensor location.

**Remember that Kurtosis and cepstra (through the log transform) are a-dimensional criteria. They perform extremely well to identify bearing defects despite somewhat "poor" acoustic paths between the source of the shocks and the outboard accelerometer and/or despite very low rotational speeds (down to 60 rpm and tiny 0.2mm wide defects, it never failed). Of course, do not locate the accelerometer very far from the bearing to investigate.**

### Severity scales

**Kurtosis and cepstra become somewhat useless to assess fault severities. The latter must rely on the amplitudes of the shock waves as measured by the outboard sensor, eventually with notions like carpet, peak levels as in SPM or other methods.**

**One could not establish reliable severity charts based on shock amplitudes. Some well-established scales like from SPM also failed with sound bearings that were mistakenly declared faulty, even at high speeds lie 1500 rpm.**

**Absolute severity scales require a careful placement of the accelerometers and these must exhibit precise characteristics. Accelerometers used for vibration monitoring may exhibit varying frequency responses in the vibro-acoustic domain and thus may prohibit the use of severity charts.**

### Questioning the feasibility of fool-proof absolute severity charts

**Severity charts like from SPM systems with SPM accelerometers (resonance at 32 KHz) performed well to follow defects with increasing widths from 0.2 to 0.4 mm. That is fine for trending. However, some sound bearings were declared as faulty by SPM right from the start, thus causing a false. With SPM, faulty bearings systematically went unnoticed when rotating below 400 rpm.**

**It would be nice to merge reliable severity charts, if any exist, in the above LABVIEW vi to reach an unsurpassed bearing expert that, for sure, tells that the bearing is faulty (done**

**without false alarms with the present vi) and by how much (not done).**

## Using ATLAS to enter the bearing characteristics

**The Appendix shows how to get bearing characteristics required by the bearing expert.**

**In order to eliminate a small inconvenience, one could link the above bearing mini-expert to data banks like SKF ATLAS to save the user the transcript of the bearing dimensions.**

**If ATLAS does not hold the specific bearing type you read on the outer ring but rather a generic type, you should verify if it comes up with the same number of rolling elements as you actually have.  They may be variations on the same theme, depending on the cage execution.**

**Never blindly enter the engraved reference you read on the outer race of a bearing into ATLAS. For example, the SKF bearing of the tests read 22NU15EC. In ATLAS you must enter NU2215E. More o this I the Appendix.**

## Measuring speed

**The mini-expert expects to know the rotational speed rather precisely. This was done from one-top/rev TTL pulses fed to the 24-bit counters of National Instruments MIO cards. If one cannot afford measuring the speed directly, one can enter its value read from other devices in a plant, thus by-passing the module measuring speed.**

## Using standard accelerometers

**Accelerometers were standard products as are available in common vibration monitoring systems. That bypasses the need to install special types of accelerometers resonating at higher frequencies like in other commercial solutions.**

**Accelerometers must be mounted properly to respond to frequencies up to ca 10 KHz. One should not use highly resonant accelerometers to run the expert. Standard accelerometers are just fine.**

## Hardware required

**A PC with a National MIO-10 card or upward. Note that using cards like PCI-MIO-1 opens the door to all other virtual instruments developed  in this research project: gear defect analysis, rotor vibration monitoring with full spectra and some others like fast digital data recorders.**

Any question? Would you like to run the expert with a library of cases from the test rig? This could be done upon request.

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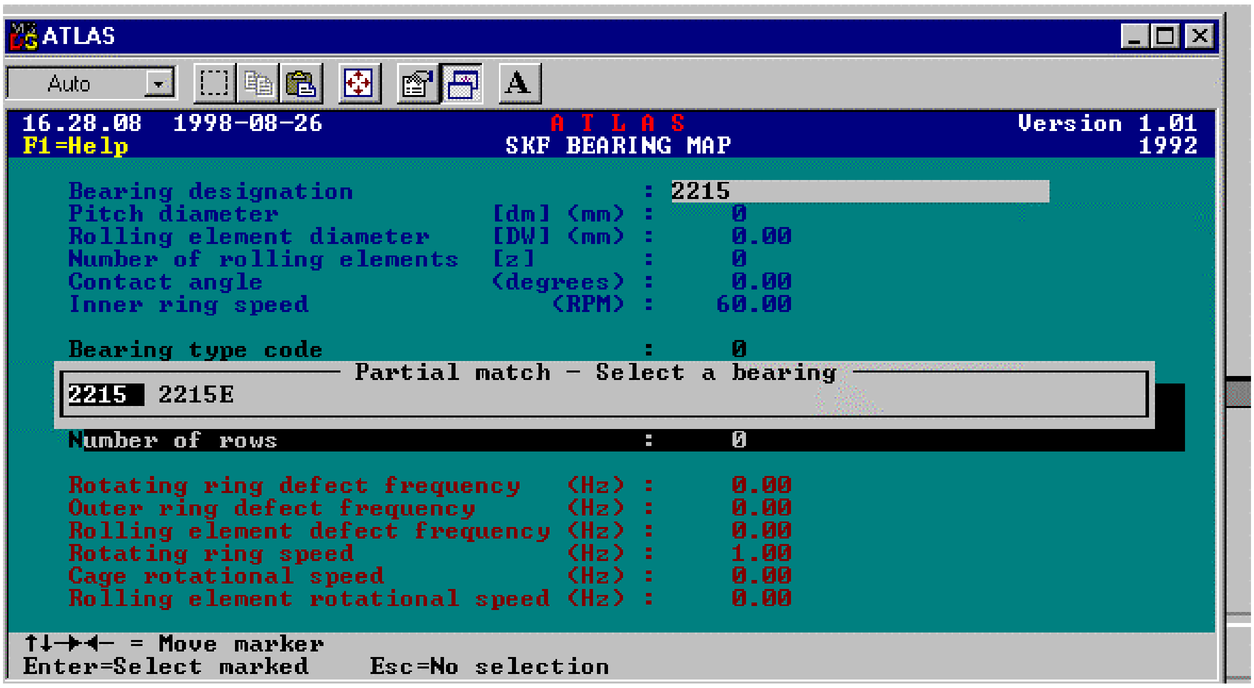
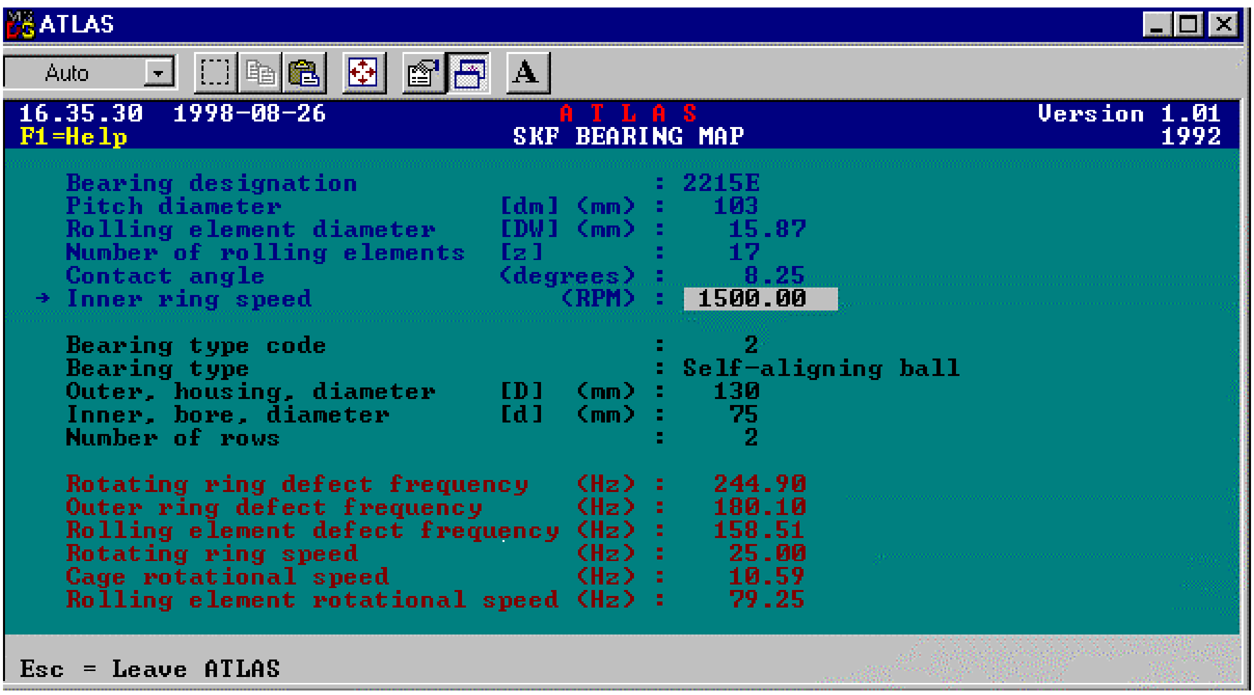
# Appendix: How to use ATLAS.exe from SKF to retrieve bearing dimensions for SKF 22NU15EC

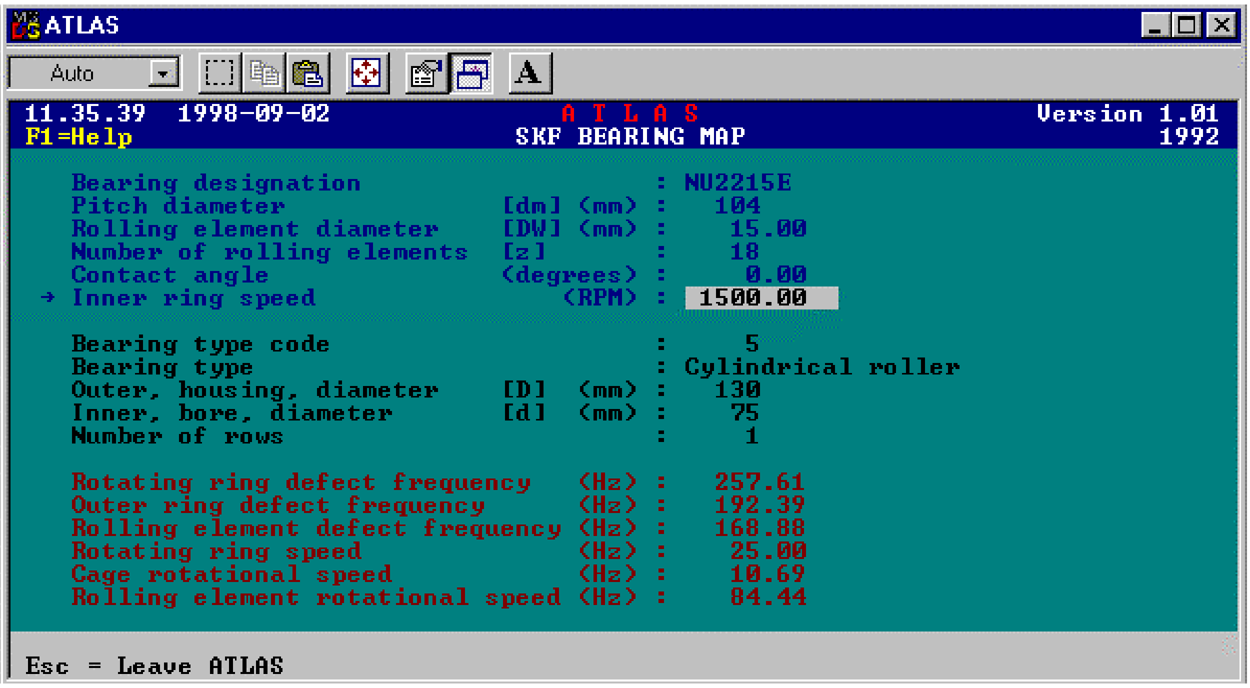






**The number of rolling elements in the SKF22NU15EC of the test rig is 18 instead of 17 in ATLAS and 22NU15EC is not a ball but a roller bearing. So be careful when entering the type of bearing you want to investigate ad do not rely on what is written on the outer race.**

## Correct entry in ATLAS




**Typing the prefix NU first despite what is engraved on the outer race (22NU15EC) yields the correct number of rollers.**

**Another point: the diameters of the rollers and the pitch were approximated in the expert. Despite this, its diagnosis was correct all the time. The expert is robust.**