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Monitoring and Diagnostic Tools for Service Life Testing of Large Scale Roller Bearings

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BIOGRAPHICAL NOTES

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He built the laboratories there are equiped with HighTech technologies and equipment for Virtual Prototyping, Rapid Prototyping, Rapid Tooling,Vacuum Casting, and specialised software like Catia, ProEngineer, ADAMS, etc...)

KEY WORDS

Rating life, basic dynamic carrying-capacity, vibration monitoring, high frequency detection

ABSTRACT

This article details the design of an apparatus used in service life testing of large-scale rolling bearings on Faculty of Mechanical Engineering at University of Žilina. It describes individual steps in the design process, used parts and methods employed throughout the design process. One chapter is devoted to measurement techniques used in service life testing and deals in more detail with measurement methods and evaluation of vibrations.

DESIGN OF TESTING APPARATUS

The proposed testing apparatus was designed to carry out service life testing of large-scale bearings with a maximum outer diameter of 1300 mm. The goal was to design a testing apparatus which would evaluate rating life Lhv and basic dynamic carrying-capacity Cr in a relatively short time frame (approx. 3 months). The proposed testing apparatus must comply with certain criteria (basic dynamic carrying-capacity Cr, rating life Li 106 revolutions, revolutions in the range of 20 – 40 per minute, axial loading of the said bearings and a maximum test time of 3 - 4 months) in order to correctly evaluate the mentioned parameters.

CONSTRUCTION OF TESTING APPARATUS

The testing apparatus was designed to test large-scale rolling bearings, allowing simultaneous testing of two, single-row bearings or one, double-row bearing with outer ring diameter of 600 to 1300 mm. The maximum axial loading force is 4000 kN. Shaft rotation frequency is between 20 - 40 min-1. Under these conditions it is possible to run service-life tests of the said bearing in 3000 hours.

The basic idea behind the design of the testing apparatus was to place the tested bearing (bearings) between two plates pressed against each other by means of four hydraulic cylinders. This arrangement is advantageous due to the fact that it is a closed system and no reactive force is transferred outside this system. The bearing is placed between these two plates and attached onto the clutch of an electromotor with gear which provides the bearing movement.

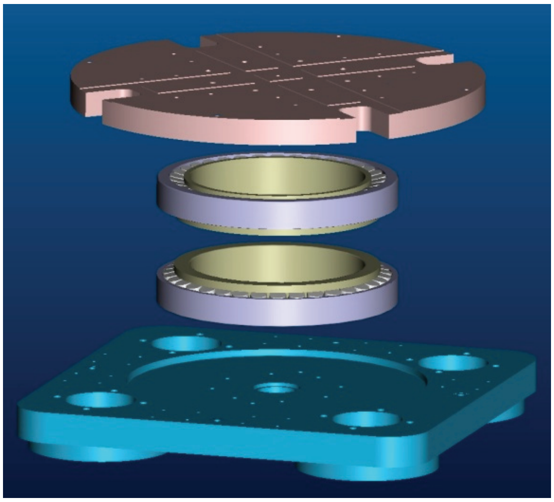

Fig. 1 *Basic idea behind the design of the testing apparatus*

The lower plate has a square profile with a width of 140 mm. The bottom part contains the electromotor with gear, the four hydraulic cylinders are placed in the corners and the upper part contains the fastening accessories for the tested bearing.

Strength analysis in CAE system Ansys/Workbench showed that the base plate ends would bend under the force exerted by the hydraulic cylinders. To overcome this problem, ring-shaped stiffeners were placed near the hydraulic cylinders, which were then welded to the bottom part of the plate, lowering the total deformation to an acceptable level.

The diameters of the cylinders were optimized thanks to the interconnection between Pro/ENGINEER and Ansys/Workbench, defining optimization with the main goal of finding acceptable strain levels by means of variation of the diameter of the additive rings.

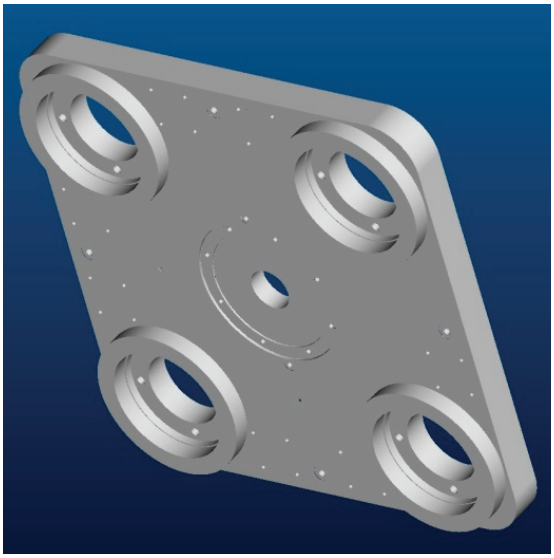

Fig. 2 *Lower plate with additive rings*

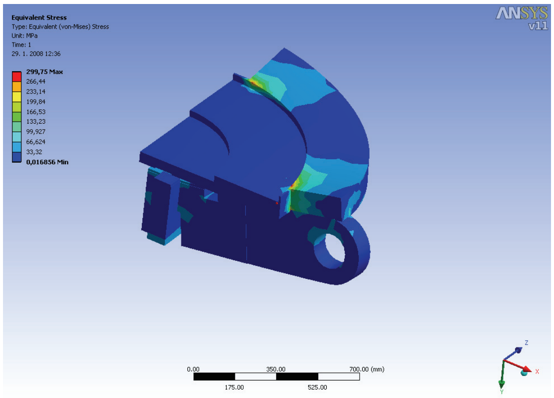

Fig. 3 *Strength analysis of the lower plate*

The upper plate was originally designed as massive weldment of the plate and four cross-placed ribs, containing openings to place pivots through the eyes of hydraulic cylinders. However, from a technological point of view, this concept was disadvantageous because of the complexity when welding the upper plate and the resulting finishing of the functional areas would be uneconomical in view of the budget allocated for the testing apparatus.

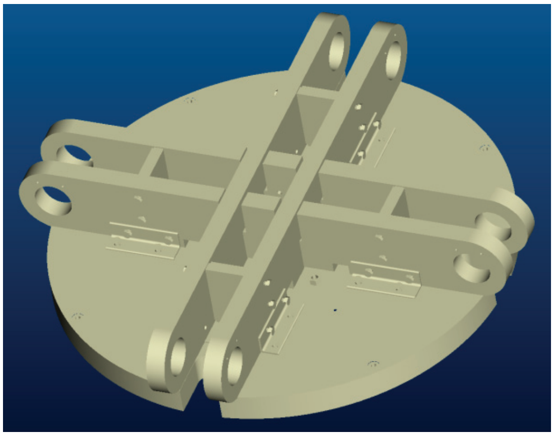

Fig. 4 *Upper plate as the assembly mounted*

To this end, the construction of the upper place was modified and an assembly system was used. This change required modification of the plate, which was also optimized in Ansys/Workbench using the finite elements method with criterion of allowable strain.

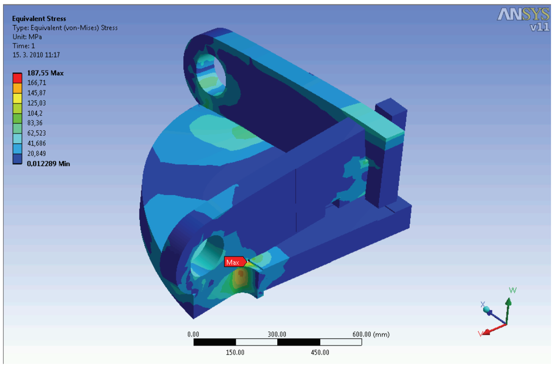

Fig. 5 *Strength analysis of the upper plate*

Because of time restrictions and the loading method used, the testing apparatus was designed in such a way so as to allow the concurrent testing of two single-row bearings of the same type oriented against each other, or one double-row bearing. A fastening apparatus was designed to place the bearings into the testing apparatus. The inner rings of bearing were fitted to the central shaft, which was connected to the output axle of the gear via a clutch with involute splining. This arrangement allowed for the shifting of the axle with inner rings in the axial direction. This shift is caused by the pressing of tested bearings in the axial direction. The outer rings of the bearings are placed in two rings which contain temperature and vibration sensors and the output sensor data were used in the evaluation of the bearing life-time.

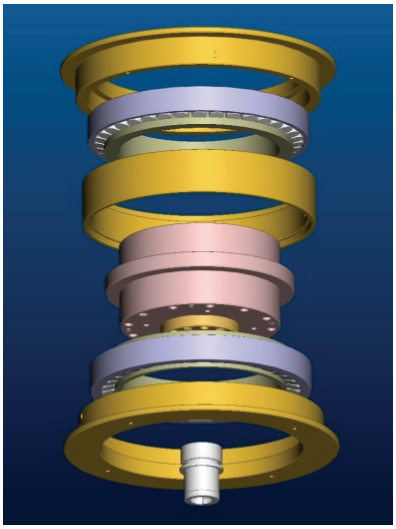

Fig. 6 *Testing bearings with the fastening apparatus*

The testing apparatus was designed in CAD system PTC Pro/ENGINEER and stress load calculations were performed in Ansys/Workbench. Management of all data was assured by a PDM system Pro/INTRALINK.

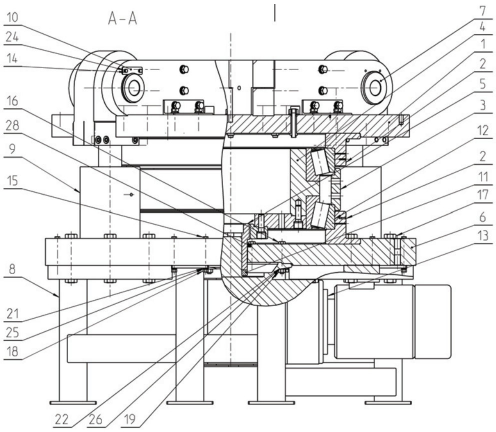

Fig. 7 *Assembly drawing of the testing apparatus*

The hydraulic aggregate, which is a part of the testing apparatus, consists of a pressure unit, regulating pressure in hydraulic valves which in turn exert axial force onto the tested bearings. A separate circuit assures bearing lubrication during the whole duration of the service life test. The cooling circuit and an external radiator are activated once the oil temperature exceeds a certain limit. All components of the hydraulic aggregate are controlled via a PLC controller.

Fig. 8 *Hydraulic aggregate*

TESTING APPARATUS CONTROL/AUTOMATION

The testing apparatus is equipped with a control unit to assure automated and autonomous functioning without the need for human intervention. In our case, a Siemens S7-CPU224XP PLC controller was used, along with digital and analogue I/O expansion modules (EM223 and EM235, respectively). Based on various input signals, the PLC controller operates action units or signaling components. The outputs are then switched according to preprogrammed sequences to assure correct function of the testing apparatus.

The PLC controller ensures a controlled switching of individual electric tractions, such as main electromotor startup via a frequency transducer (with direct torque control - DTC), which assures the rotation of evaluated bearings and associated tractions on the hydraulic aggregate (pressure-force circuit, lubricating circuits, cooling circuit). Another use of PLC controller is to control electric parts of the testing apparatus and to terminate the test process in case critical values are exceeded.

In order to allow for a service-free and continuous, 24 hour functioning of the testing apparatus, certain criteria and operational boundaries were formulated. These can be divided into two groups. The first group consists of switching unit control, control of electric tractions (including those on the hydraulic aggregate), control of communication with the datalogger, control of PC-database connection, etc. The second group consists of variables which monitor/evaluate directly the condition of tested bearings. These include monitoring of RPMs, pressure in hydraulic cylinders, temperature of lubricating oil, magnitude of vibrations, etc. (see next paragraph for more information regarding this subject). All monitored variables have alert and critical limits, of which the latter terminate the testing process.

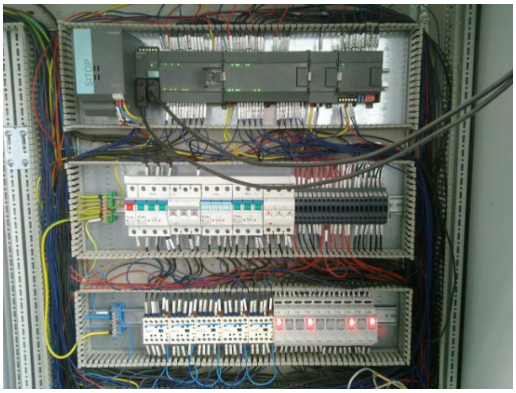

Fig. 9 *PLC controller with switching and protecting units*

DATALOGGER

A device was needed to process and store signals from the transducers monitoring various quantities in order to evaluate the condition of the evaluated bearing. A commercial datalogger equipped with a DSP controller and USB interface (for communication with a PC) was used. The device also includes analogue inputs which can be setup for a variety of input voltage or current ranges. Also present are digital inputs and outputs, which are also used for communication with the PLC automat, allowing for the termination of the test process once critical limits are reached.

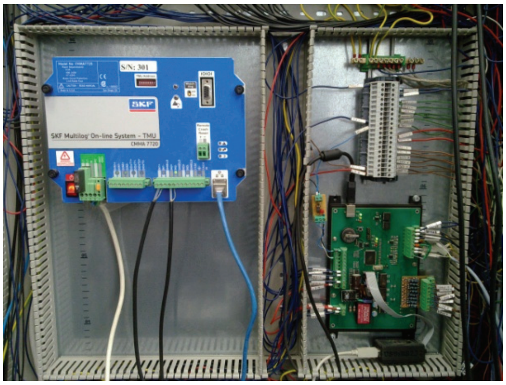

Fig. 10 *Datalogger (right) and SKF TMU monitoring unit (left)*

The datalogger processes signals from transducers, which measure RPMs of the bearing inner circle, pressure in hydraulic valves, temperature of outer area of outer bearing circle, input and output temperature of lubricating oil, environmental temperature and vibrations (for more details see end of paragraph). The datalogger was designed universally, which also allows for evaluation of signals from transducers of other quantities. All measured quantities are recorded in a MySQL database. The role of this database is not only to archive acquired data but also to calculate certain other parameters such as force due to pressure of hydraulic valves, the total number of revolutions for the duration of the life test, attained dynamic load and durability. It is also possible to specify the recording interval (between 10 seconds up to 2 minutes), which in turn poses certain hardware requirements on the storage system.

In order to facilitate access to the database, a html-based web interface was created. Upon verification of the user, it is possible to monitor saved data in either table or graph format for the whole duration of the test process or for a specified time period.

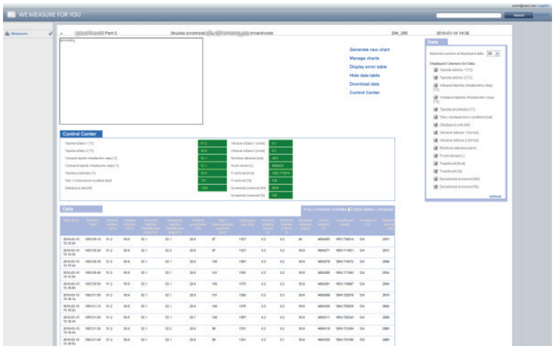

Fig. 11 *Web interface allowing data assessment*

During service life testing, but also in some real-life scenarios (such as paper machines, axle bearings on the railway carriage, etc.), it is important to monitor the bearing temperature. In case of insufficient or improper lubrication or in case of damaged bearings, excess temperature is generated due to additional stress, which will be evaluated as temperature rise on the appropriate sensor affixed to the bearing. Thus, temperature is a very important quantity to monitor and record in the databse using the datalogger. Temperature is measured on the outer area of the outer bearing circle (due to testing methodology restrictions - it is impossible to place the sensor within the bearing without mechanical damage to the bearing) using a temperature sensor. Larger bearings can exhibit thermal lag, which will cause temperature rise detection delays on the outer area of the outer bearing ring.

Proper lubrication and cooling of bearings is necessary for proper functioning. For this reason a separate lubricating circuit is utilized. Input and output lubricating oil temperatures are monitored and recorded in the database. By monitoring the output oil temperature it is possible to detect elevated temperature within the tested bearing (due to additional friction, seizing of rolling element, cage damage, etc.) before this temperature is detected on the outer diameter of the bearing circle surface.

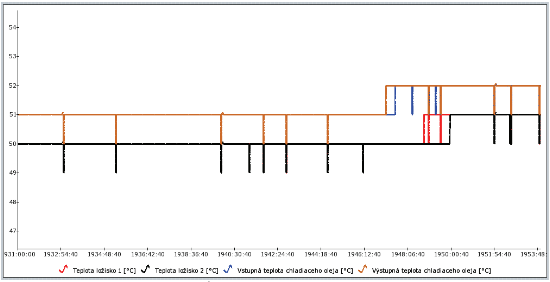

Fig. 12 *Trend plot of bearing temperatures, input and output oil temperatures (°C)*

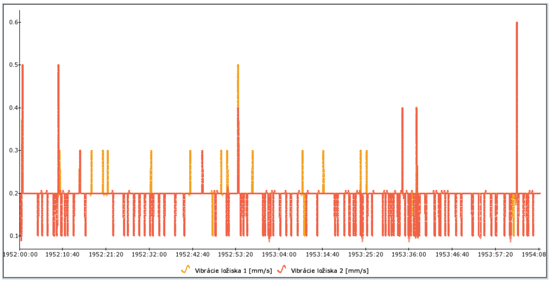

Fig. 13 *Trend plot of overall vibrations (mm/s)*

Vibrations are also detected and recorded (see chapter 5 for more details). Total vibrations are used for monitoring and evaluating the overall dynamic state of the testing apparatus. Vibrations are detected using accelerometers, which are based on deformation of piezoelectric crystals located within the sensor itself. Deformation of the crystal generates an electric signal directly proportional to the measured acceleration. The obtained signal is then fed to on-line monitoring converter (SKF CMSS 530), is filtered, integrated and output as analogue quantity of speed [mm/s] in RMS or peak values. RMS speed is recorded in the database using a datalogger, with values set for alert and termination of the testing procedure.

SKF MONITORING

It is possible to evaluate the overall dynamic state of the device by monitoring the total vibrations. However it is not possible to determine which anomaly causes a specific state. For this reason, an independent device (manufactured by SKF TMU CMMA 7720) was used to monitor the bearing (and device) state. This device is capable of evaluating various vibration types based on data acquired from accelerometers. These are then recorded in an independent database and evaluated via SKF Optitude Analyst. The mentioned software suite allows review of recorded data, monitor bearing state trend, evaluate vibrations at various time points, spectral analysis using FFT, set alarms for individual vibration sensors, etc.

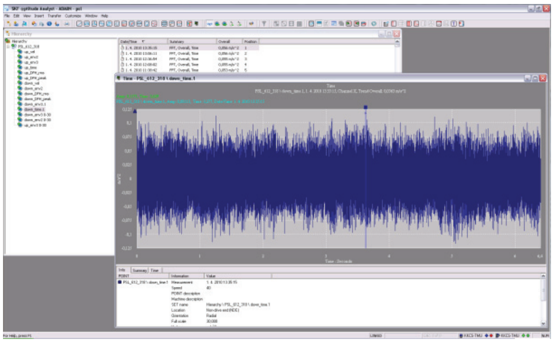

Fig. 14 *SKF Optitude Analyst - user interface*

The following bearing vibration measurement types were defined using the SKF TMU measurement unit:

Total vibration monitoring

Total vibrations represent the total vibration energy within a certain frequency range. We can obtain information about the current state by measuring total vibrations of the whole machine or individual parts (for example rotor with respect to the machine or machine construction) and comparing them to normal values. Abnormal operation can be detected if normal values are exceed.

Total vibrations can be used to evaluate low-frequency dynamic states, such as unbalance, abaxiality, mechanical clearance gap, construction resonance, insufficient base stability, shaft deformations, excess wear or broken rotor plates. Evaluation of total vibrations was designed in a certain frequency range so as to allow evaluation of higher harmonic frequencies. The SKF TMU unit calculates RMS speed [mm/s] by integrating the signal obtained from accelerometers. The overall value allows for dynamic monitoring of the whole device. The SKF Optitude Analyst software suite allows spectral analysis using previously recorded values of velocity, diving the signal into various amplitudes representing individual frequency components. FFT spectra contain information which can help localize malfunctions, identify their cause and using trends predict time until critical state is reached. RMS speed is used for overall vibration evaluation due to the fact that for identical generated dynamic motion the speed is constant, independent of frequency.

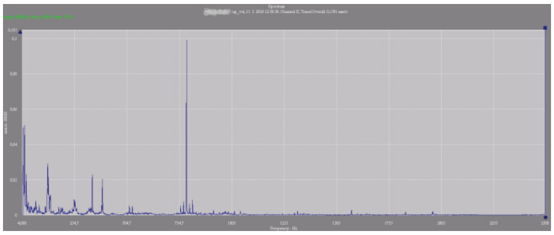

Fig. 15 *Spectrum plot of overall vibrations (mm/s)*

High frequency detection (HFD)

High Frequency Detection method is capable of early detection of bearing defects. This method outputs the total value of vibrations generated in the high frequency range (5 kHz - 60 kHz) due to small defects.

Accelerometers are used in high frequency measurements and values are recorded in g. HFD measurements can be done in either peak or RMS modes. It is common practice to measure both RMS and peak values which are then compared (Peak/RMS ratio) and trends bearing state development.

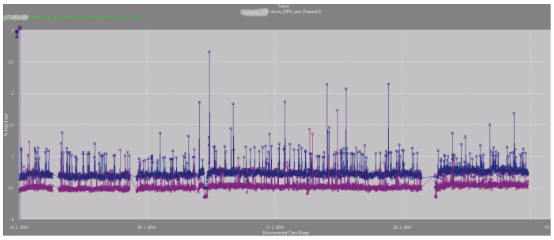

Fig. 16 *Trend plot - High Frequency Detection (Peak/RMS ratio)*

Envelope method

This method is used to filter low-frequency vibration signals associated with motor rotations and amplify signals produced due to bearing faults, which can be observed in specific signal ranges. Enveloping is used most commonly in rolling bearings and in analysis of cog wheel engagement, where low amplitudes of repeated vibration signals can be overlapped by vibration noise coming from motor rotations and construction.

Movement of rolling elements over the defect area generates a small, periodic signal with a frequency equivalent to the bearing defect type. However, the mentioned vibration signal energy is very low and is lost when overall vibrations are measured. In order to focus on these specific, periodic signals in frequency ranges typical for bearing defects, enveloping is used to filter out low frequency signals and amplify periodic pulsed signals. Real-life applications have shown that this method is a viable indicator of general machine faults.

For the purpose of evaluating the service life of bearings, two envelopes were used. This was necessary because the rotation frequency is too low and the detected defect frequencies could be erroneously filtered using this method. Filter type 3 was used for slow processes (500Hz - 10kHz), while filter type 2 was used for frequencies 50Hz - 1kHz.

Figures 17. and 18. show the spectral analysis of vibrations after applying envelope type 2 and 3 filters.

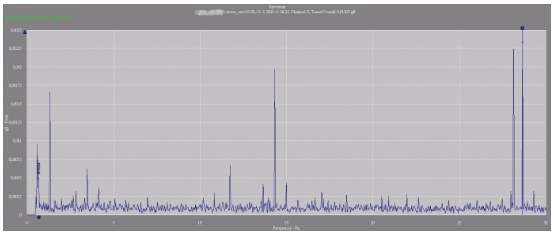

Fig. 17 *Spectrum plot of envelope with applied filter type 3*

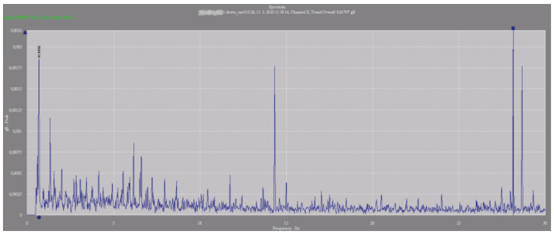

Fig. 18 *Spectrum plot of envelope with applied filter type 2*

Notable differences in amplitudes are visible in the frequency range of 0 – 10 Hz.

Bearing defect frequencies can be calculated based on individual bearing geometries and can indicate whether the defect is present on the outer or inner track, rolling elements or due to cage damage. Based on these frequencies it is possible to identify the defect on the bearing via spectral analysis of measured vibrations.

Successful identification of the defect type, location and magnitude thereof depends strongly on the number of vibration types that are measured, recorded and evaluated. To this end, multi-parametric vibration monitoring was implemented in the proposed large-scale bearing testing apparatus.

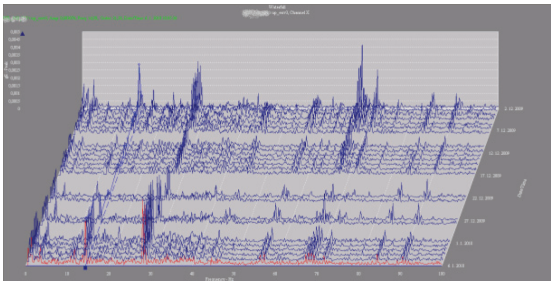

Fig. 19 *Spectrum waterfall plot of envelope*

SPM MONITORING

The shock pulse method is a patented technique used for evaluation of signals originating from rotating rolling bearings and is crucial to effective monitoring of machine conditions.

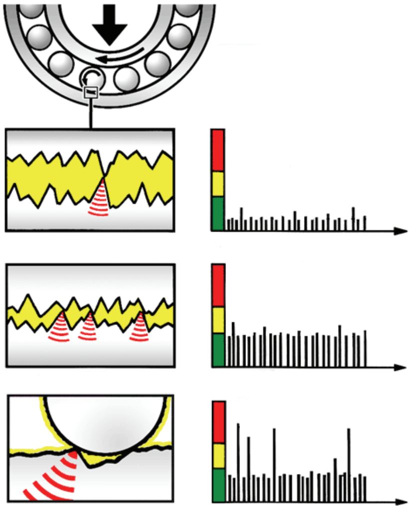

Fig. 20 *SPM - Bearing monitoring (principle)*

SPM is based on a shock transducer operating at 32 kHz, which produces large oscillation amplitudes via weak pulses originating from bearing defects. Machine vibrations of substantially lower frequencies are filtered. Pulse signals are expressed in the decibel scale using a microprocessor which processes input signals from sensors. This measurement method monitors not only bearing defects but also problems associated with lubrication.

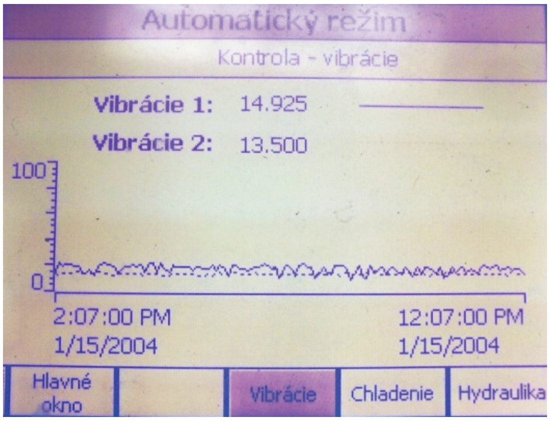

Fig. 21 *Shock Pulse Method (SPM) monitoring*

By using the mentioned measurement method it was possible to enhance the overall safety of the continuous testing process, as one of the monitored stop parameters is based on SPM sensor outputs.

CONCLUSION

An apparatus for service life testing of large-scale rolling bearings was designed and constructed at the University of Zilina. Bearings are evaluated based on numerous monitored quantities. The

Fig. 22 *Testing apparatus*

whole bearing testing process takes advantage of various modern technologies, such as those manufactured by SKF and SMP Instrument.

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