Recognition of Bearing Type by Spectrum Analysis

Roman Volis

Department of Electrical Power Engineering and Mechatronics
Tallinn University of Technology, 12480 Tallinn, Estonia

roman.volis@wartsila.com

ABSTRACT

The methods of bearing condition analysis advanced much since the processor technologies had enormously raised the computational power. Both smaller and larger platforms have gained in computational speed. The manufacturers of portable vibration measurement devices have got the opportunity to apply such efficient but heavy tools as digital filters, convolution, fast Fourier transforms with better resolution, wavelet transforms, pattern recognition or even neural networks with 2D- and 3D-representation of data. But even then obtaining of good results is limited with multiple conditions as shown in [1]. Having solved the problem with CPU power it may seem that there are no limitations to use the hard methods. But, the electronic component's lifetime still has the limits: read/write operations and etc. Although these limits are high, it is always good to prolong the lifetime of entire device or reduce its power consumption, or increase the diagnostic speed by using a less demanding algorithm at least at some parts of diagnostic procedure. The laboratories of bearing analysis which are commonly the part of bearing production enterprises have the best opportunities to test the bearings. The type is known, the dimensions are known. The test SW is tuned to the bearing type and the detailed diagnosis gives the best outcome. It is unlike in field service where the bearing type is unknown. Knowing it in the field would help to tune the vibrometer (as in laboratory) and then to switch on the heavy diagnostic methods. The purpose of this work was to create a prototype of software and the bearing model. The model would have the features enough to be determined by the frequency analysis of signal mix and recognized as a certain bearing type.

Keywords: Bearing Recognition; Spectrum Analysis, Fourier Transform, Vibrometer.

1. INTRODUCTION

This work is built around examining the ball bearings. The classification of bearing types is wide. In machine applications two classes of bearings are commonly used: plain bearings and rolling bearings of multiple types. Each type has its own characteristics and requires a separate research. For that reason the definite bearing type – *deep groove ball bearing* [4] – was chosen for modeling. Another reason is that the specific bearing data were published by manufacturer [4] that were enough to build a frequency-based model [2][3]. Further updated references on the issue are referred to on [6], [7], [8], [9], [10], and [11].

Detection program is closely related with the bearing model. The model will output the frequencies that are specific to the guessed type of bearing. The theoretical vibration sensor will detect the bearing model's vibration as longitudinal ultrasonic sound propagation waves through the cast iron bearing case in the radial direction towards the

edge of machine hull. A Doppler effect is applied to the model as the bearing rotating elements' position relating to the measurement point varies harmonically. The deviation of rolling elements, inner- and outer raceway ball pass frequencies [4] will result in appearing of additional frequencies. These frequencies will change equally with the change of the shaft speed.

The signal mix for testing of model was made by combining the audio record of the rotating equipment (pre-lubricating oil pump driven by electric motor) with the built bearing pattern. The electret condenser microphone used for audio record has a limited response in the low frequency range, however, the spectral contents in the region of main bearing frequencies is enough to hide a signal of bearing pattern. The test pattern was chosen such that 3 of 4 main frequencies would lie in the operating range of microphone.

Testing and bearing detection is done by finding the combinations of peaks in spectrogram of mixture. The specific frequency windows for main frequencies and frequencies originated by Doppler's effect are used to detect all the peaks inside. Then the combinations of all peaks are checked for coincidence with the exiting bearing database. If more than one coincidence is found for the group of frequencies, then operator has to decide which to select. This decision can be done considering the shaft diameter or bearing class. The main message is that no heavy methods are used so far. Now when there are a small number of winning candidates for the guessed bearing (in real environment "guessed" would mean the unknown bearing being identified) the hard methods can be used either for further identification or for the condition analysis. Thus, the purpose of this program is seen as an adjustment of vibrometer for the exact bearing.

2. BUILDING THE MODEL

The bearing model suitable for this task contains the minimum required information on frequencies. Need to mention that the purpose of this model is to help to recognize the bearing type. It defined the way to build the model. That's why the development of models for calculating or simulating the bearing operation under load, or models containing the gaps is not seen as a target at this step. The main reason to use the bearing frequencies is the invariance of the bearing geometry. Sure, that under the heavy load or excessive axial misalignment, imbalance there will be forces that de-shape the bearing raceway and change the rolling elements rotation pattern. This can be observed in the frequency spectra or time waveform. However, the main frequencies originated from the bearing geometry will remain. Taking this into account the following measurement conditions would theoretically be enough to use this model:

- constant rotation speed;
- preferably no-load condition;

axial vertical position of the rotating shaft when there is no effect of earth gravity on the rotating masses [2]..

2.1 Choosing the operating equipment

The reason for selecting this type of machinery was its availability. It was mentioned before that there are certain difficulties to find an extended data for bearing geometry from different bearing producers. Only the data for NTN bearing types were by fortune available in the public network. Another issue was to find the equipment using the bearings from this database. Finally it was decided to apply a virtual bearing to the pre-lubricating pump of 20-cylinder V-type diesel/gas generator engine (Figure 2.1) using a signal mix. As no vibration sensors were available for use in this project an audio record

of operating pump was used. The electret condenser microphone had the lower frequency operating range 40 Hz. The FTF frequency lies below 40 Hz, all others − far above. The signal density in FTF-area (8-11 Hz) of the record was enough to cause the disturbances for bearing detection (Figure 2.3).

Figure 2.1   Pre-lubricating gear pump Kracht

Figure 2.2   pump gears have 10 teeth
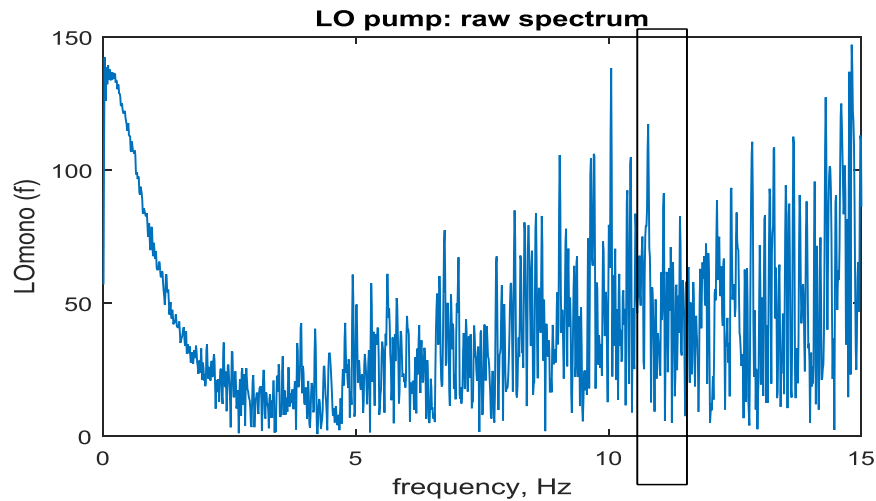
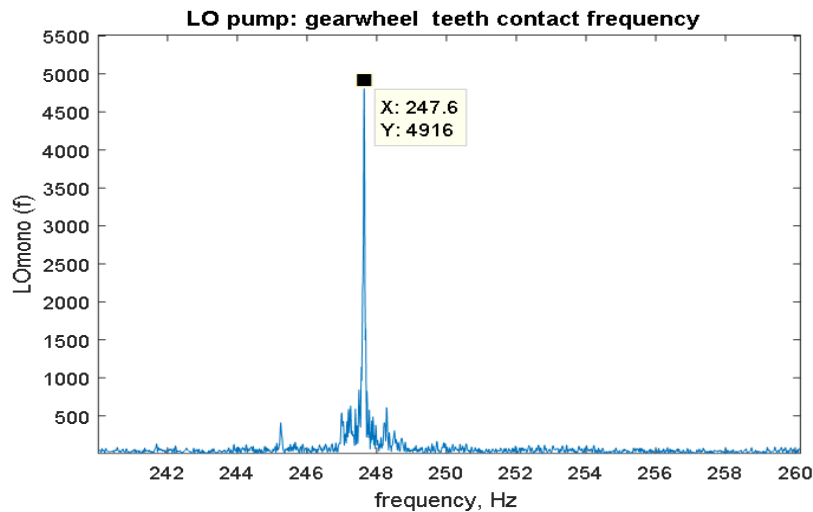Figure 2.3   FTF-area of the recorded pump sound

Figure 2.4   Gearwheel contact frequency

2.2 Fundamental Frequency

E The passport speed of the driving electrical motor is 1463 rpm which is 24,383 Hz. After the spectral analysis of the pump signal it was detected the real speed which was 24,7 Hz or 1482 rpm (Figure 2.4). The pumping gearwheels have 10 teeth each (Figure 2.2) and the resulting frequency is multiplied by 10. This correction was applied to the model.

2.3   Assumptions

The less assumptions and simplifications are used the better. However, these exist and are the following:

•   the effect of bearing case is simplified to the longitudinal sound propagation in cast iron, the obstruction for wave propagation such as shaft body or other bearing elements are not considered;

•   only the frequencies of main rotating parts are considered [2][3][4];

•   resonant properties of the bearing casing and its input to the spectrum is not considered as data are unavailable and no possibility to measure it, *bump test* [2] is not usually applicable;

- the current bearing model is assumed to be ideal: no gaps between the balls and inner/outer races;
- no load-based effects.

2.4 Model components

The main frequencies of the bearing are: *BSF, FTF, BPFO* and *BPFI* [2][3][4].
BSF. *The Ball Spin Frequency* coefficient *BSF* is calculated by the following formulae:

$$BSF = \frac{d_m}{2D_w}\left[1 - \left(\frac{D_w}{d_m}cos \propto\right)^2\right],$$

$$(2.1)$$

where: D_w – rolling element diameter;
d_m – rolling element pitch diameter;
$\propto$ – contact angle.

FTF. *Fundamental Train Frequency* coefficient *FTF* calculated as follows:

$$FTF = \frac{1}{2}\left(1 - \frac{D_w}{d_m}cos \propto\right),$$

$$(2.2)$$

BPFO. *Ball Pass Frequency of Outer ring* is determined by the race of rolling elements along its raceway and calculated as follows:

$$BPFO = \frac{z}{2}\left(1 - \frac{D_w}{d_m}cos \propto\right),$$

$$(2.3)$$

where: z – number of rolling elements in each row.
There are bearings with two rows of rolling elements. The calculation is same for each row.

BPFI. *Ball Pass Frequency of Inner race*, BPFI is calculated as follows:

$$BPFI = \frac{z}{2}\left(1 + \frac{D_w}{d_m}cos \propto\right).$$
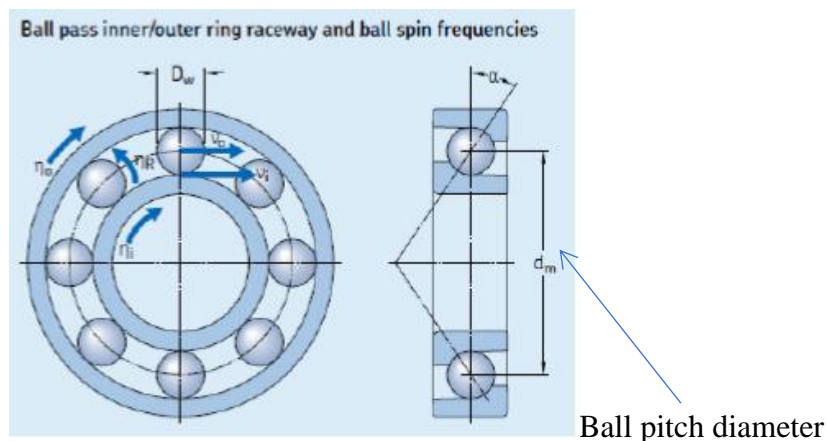
$$(2.4)$$

Ball pitch diameter
Figure 2.5 [3] Bearing specific geometrical data

Deviation of frequency. Doppler's shift for sound propagation in cast iron:

$$K_{c.ir.} = \frac{(V_{c.ir.}+V_{BSF})}{V_{c.ir.}}, \quad \text{[case BSF]} \tag{2.5}$$

where: $V_{c.ir.}$ – sound propagation speed in cast iron (longitudinal) is taken as 7000 ms^{-1};

    V_{BSF} – maximum tangent speed of the bearing element.

$$V_{BSF} = \omega r = 2\pi f_{BSF}r, \text{[m/s]}, \tag{2.6}$$

where: ω – angular speed of the balls, [rad/s], r – ball radius, [m].

Ball radius $r = Db/2,$ (2.7)

where Db – ball pitch diameter; manufacturer's specific data.

For cast iron $K_{c.ir.} = 1.018$.

The deviation of frequency was imitated by frequency modulation *fmmod( )* [5] and *cumsum( )* [5].

Need to mention that FTF frequency was left untouched due to its small deviation: around 0,01 Hz. In [5] the proposed alternative for frequency modulation was phase modulation through the *pmmod( )* function. In case of using multiple balls in the model this option will be useful to describe each ball's input.

2.5 Signal mixing

Bering pattern was created using the same parameters as record. Both are time series with the sampling frequency 48 kHz and length 30 seconds.

2.6 Algorithm description

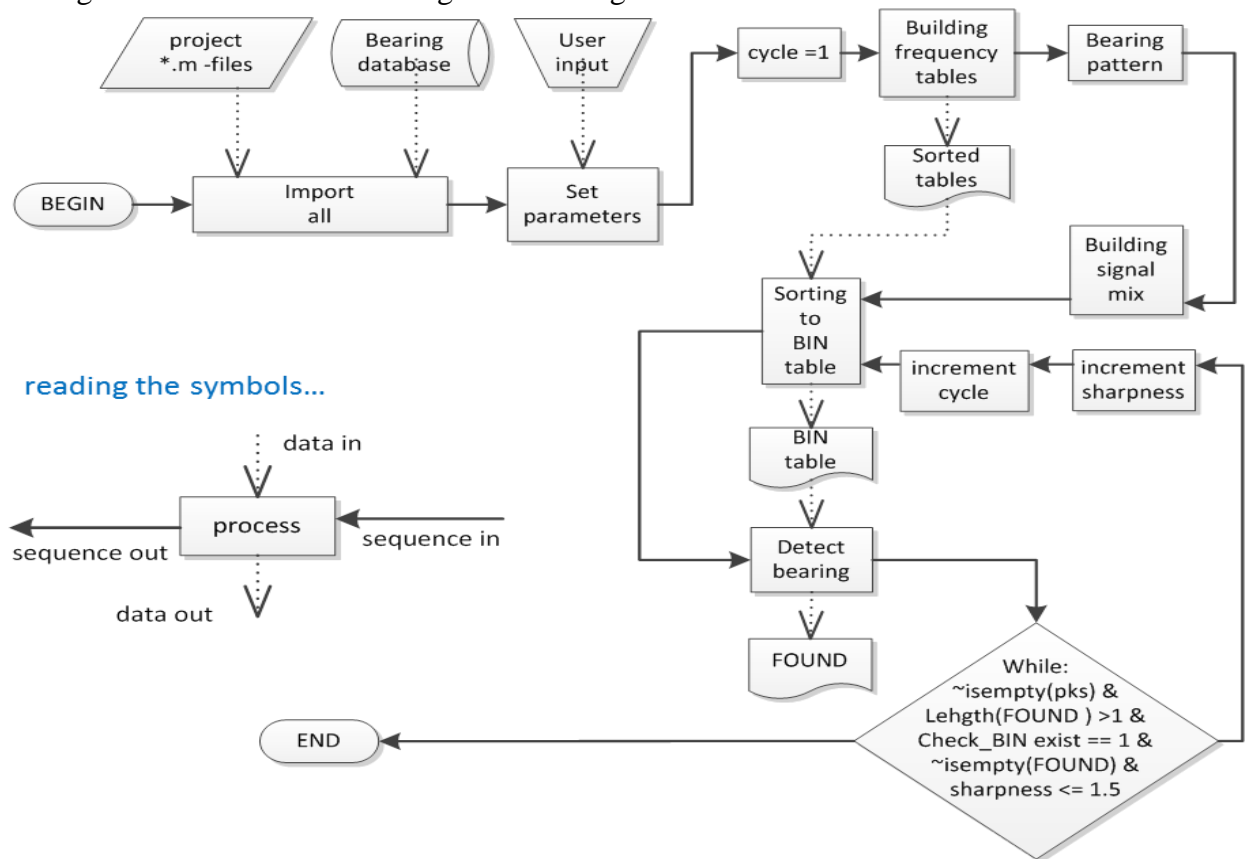On Figure 2.5 is shown the bearing detection algorithm.

Figure 2.6   Prototype of bearing detection algorithm.

Import all – imports all the required program modules to the workspace. Also it initializes the required variables. The bearing database containing the bearing frequency coefficients is being imported.

Set parameters – user guesses the bearing to be mixed with machine signal. Else the fundamental frequency (shaft rotation frequency), spectral resolution, minimal peak height, pattern signal amplitude before mixing and frequency window width (sharpness) are defined at this step.

Building frequency tables – the bearing database coefficients are multiplied by fundamental frequency and stored separately in *Sorted tables*.

Bearing pattern – e.g. bearing model is built.

Building signal mix – bearing pattern matrice is added to the signal matrice. The variable parameter here is pattern signal amplitude. The fast fourier transform is applied to the mixture to get a frequency domain picture. The variable parameter here are pattern signal amplitude and multiplication factor for NFFT (as per Matlab terminology) or spectral resolution.

Sorting to BIN table – it is the most important part of program. First it searches for peaks through all the mix spectra. Then it searches for these peaks coincidence with the frequencies calculated and stored in *Sorted tables*. It uses frequency windows within which the frequencies are expected to appear or oscillate. Results are recorded to the so-called *BIN-table* which contains "ones" or "zeros". Thus, "hits" will be recorded as "ones" and "misses" – as "zeros".

Detect bearing – final step where the bearing is identified. The BIN-table which rows match the rows of bearing database is checked for containing "ones" for all four frequency component. The result is recorded to *FOUND* variable with the resolved bearing name string. In case of semi-automatic test program version *while* condition is used. Then, changing the desired parameters (here: sharpness) a series of test iterations are performed to detect a winning bearing type. The winner will have the most "hits". As was mentioned before, in case of multiple winners operator has to define the appropriate bearing.

3 TESTING

3.1 Selection method

The main selection method in program is detection of coincidences of main frequencies and FM peaks. On the uppermost Figure 3.1 are shown the windows at start (horizontal) and at stop (vertical) of semi-automated testing on a BSF example. In the middle there is a center BSF frequency which is of very low intensity (pink). Two lateral peaks (brown and green) were originated by the frequency modulation. These peaks are maximum BSF frequency deviation in upper- and lower directions.

BSF range	
LoPeak, Hz	HiPeak, Hz
133,7406	138,7338

Table 3.1   BSF deviation peaks

The start value for the sharpness window is *DevBSF/2/0.2*, which is *6,248 Hz*. The end value for the window *DevBSF/2/1.3 = 0.9612* Hz.
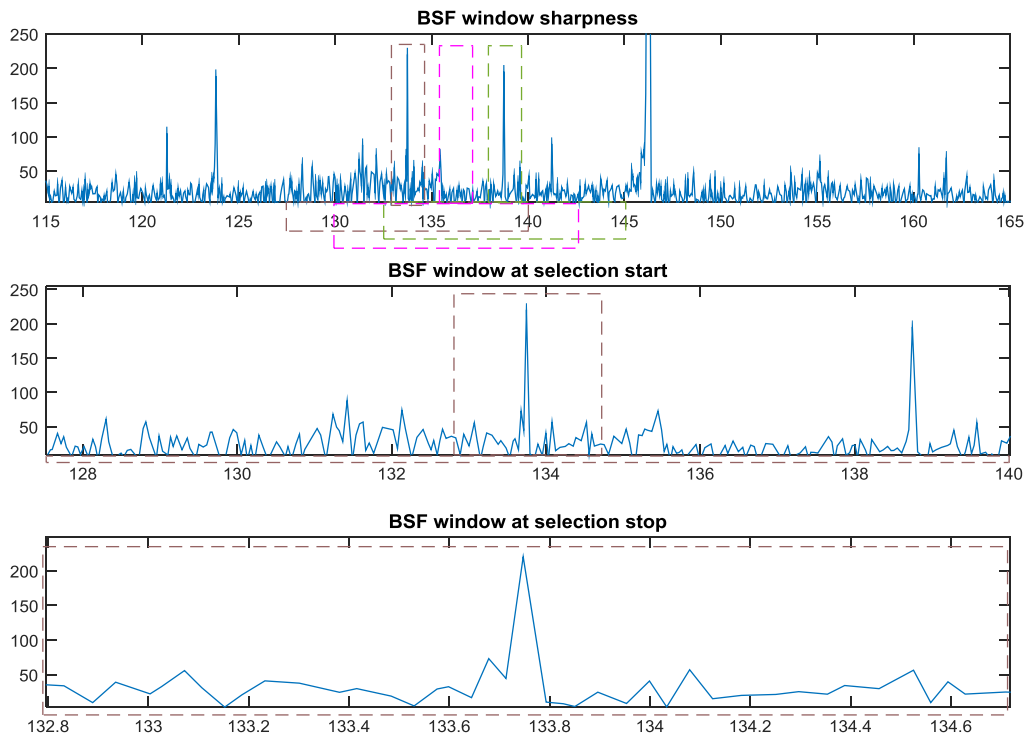
Figure 3.1   Testing using changeable frequency window ("sharpness")

It is seen that the possibility to narrow the search range gives a good result. The center peak is still the dominant. If some higher peak is also present in the same window this will result in erratic "hit" in BIN-table. Though there is a chance that there will be no coincidence in another peak area and in the main frequency window.

3.2   Test results

The series of tests were carried out with variation of the following parameters: amplitude of the pattern signal, spectral resolution and sharpness. Totally 85 (14+14+12+12+15+18) test iterations were performed to obtain these results:

Parameter	Tests					
selected	34	34	34	34	34	34
Amp of pattern	1	x10	1	x10	1	x10
NFFT resolution	1	1	2	2	2	2
MinPeakHeight	0,001	0,001	0,001	0,001	0,001	0,001
Sharpness	0,2-0,46	0,2-0,46	0,46-0,79	0,46-0,79	0,46-1,0	0,46-1,3
1						
2	14	14	0	0	0	0
3	14	14	12	12	15	18
4	0	0	0	0	0	0
31	14	14	0	0	0	0
32	14	14	0	0	0	0
33	14	14	0	0	0	0
34	14	14	12	12	15	18
35	14	14	0	0	0	0
36	14	14	0	0	0	0

Table 3.2   Guessed pattern 34 (bearing NTN16048) and its competitor, No: 3 (NTN16003)

The Table 3.2 illustrates that the wrong bearings are detected during the test parameter change. The experiments with frequency windows were more successful that with minimum peak height. Use of *MinPeakHeight* parameter in *findpeaks()* function

resulted in the winning of unexpected frequencies powerful peaks. So, this option was temporarily left out from the program and from this paper.
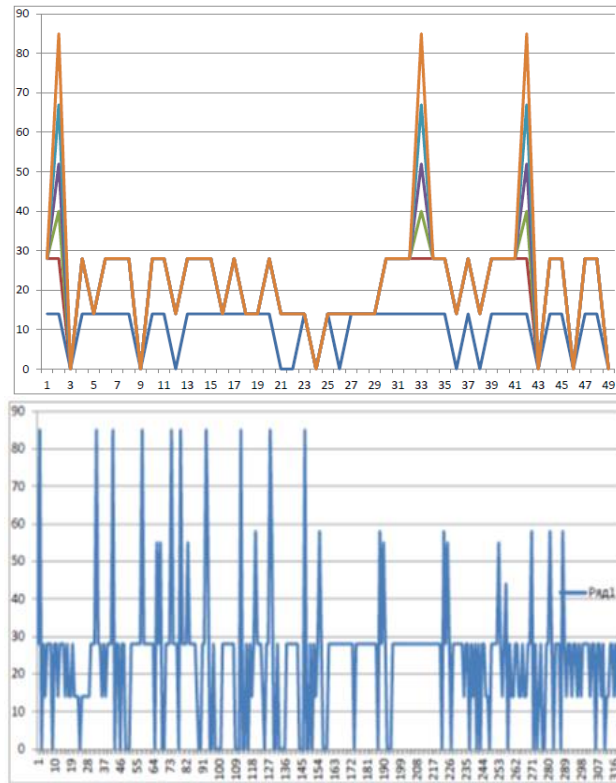

Table 3.3   Success of pattern 34 (here 33. Count starts from 2nd row) in part- and entire database

Table 3.3 represents the non-unique results that must be interpreted by a human. It can be done if additional qualifying parameter is added.

Table 3.4 shows it on an example with shaft diameter. It is seen that pattern 34 has a ball pitch diameter 300 mm while other winners have 26 mm and 23.5 mm correspondingly. So, knowing the diameter of shaft which is a bit less than the pitch diameter (Figure 2.5) operator can confirm the bearing type NTN16048, or pattern 34.

	A	B	C	D	E	F	G	H	I
	Bearingnu...	BPFO1	BPFI1	FTF1	BSF1	Nb	Bd1	Pd1	Phi
	Cell ▼	Number ▼	Number ▼	Number ▼	Number ▼	Number ▼	Number ▼	Number ▼	Number ▼
1	Bearing nu...	BPFO	BPFI	FTF	BSF	Nb	Bd	Pd	Phi
2	16001	3.0731	4.9269	0.3841	2.0419	8	4.7498	20.4978	0
3	16002	3.5903	5.4097	0.3989	2.3722	9	4.7498	23.4950	0
4	16003	3.1476	4.8524	0.3935	2.2398	8	5.5372	25.9842	0
34	16048	8.1908	9.8092	0.4550	5.5158	18	26.9748	299.9994	0
43	6002	3.5903	5.4097	0.3989	2.3722	9	4.7498	23.4950	0

Table 3.4   Selecting the right bearing from FOUND

4   DISCUSSION

There are assumptions made in the model development. The model needs to be extended in order to stipulate these and enclose to the real bearing spectra. The

development of detection program uses the frequency window as a selector. It was decided not to use detection by amplitude peaks due to erratic output. More, the amplitude detection method depends on many conditions: damping of contact of sensor probe with measurement point, location of measurement point. Frequency invariance is less dependent in this sense. To improve the detection quality a shaft diameter data should be entered to the bearing database. To make a program work faster the procedure of finding peaks can be limited by the area of interest. Each area of interest is specified by the minimal and maximal frequency value of the sorted frequency tables for each component. Another option is to restrict these areas of interest for peaks finder by the frequency windows. For example, for BSF frequency window the computations could be reduced $\frac{\frac{F_S}{2}}{2DevBSF}$ = 4801, times where $\frac{F_S}{2}$ is half of Nyquist frequency, $2DevBSF$ – approximate frequency window for BSF considering devciation. This, however, depends on model; it may require other zones of interest. So far, a limited number of steps used the heavy computational load. FFT was taken only twice (Table 3.2) for a series of iterations. Depending on NFFT resolution it consumes *res*NFFT*log(NFFT)* floating point operations (between 10^7 and 10^8 here) which would be sensitive for smaller CPU platforms. Another weighty part is peak finding. Using *MinPeakHeight* solely to ignore the near-zero peaks reduces the peaks array. Other procedures in the program only scan the arrays for coincidence of values. Next iteration contains less data than the previous one.

Optimization for less powerful hardware platforms is another topic that is planned as soon as the program gives the best results.

5   CONCLUSION

As a result of this work the pilot model of bearing and a recognition program were developed. The bearing model was mixed with the recorded sound of operating gear pump. The bearing could be identified. However, it was not unique. Among the detected types there were the bearings that were filtered out by additional parameter – approximate shaft diameter. The idea of primary detection of bearing type works. It requires the human decision. To automatically detect the exact bearing type the detection methods must be developed further. It can be achieved by using a bearing test bench or a suitable bearing simulation model. Additionally an access to the specific geometrical data of other bearing brands would make the program more universal.

ACKNOWLEDGMENT

CONFLICT OF INTERESTS

The author would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

REFERENCES

[1] Jian Chen, Robert Randall, Ningsheng Feng, Bart Peeters, Herman Van der Auweraer. *Automated diagnostics if internal combustion engines using vibration*

analysis. School of Mechanical and Manufacturing engineering, University of New South Wales, Sydney 2052 Australia. LMS International, Interleuvenlaan 68, B-3001, Belgium {jian.chen1@unsw.edu.au}.

[2] Victor Wowk. *Machine Vibration. Measurement and Analysis.* Copyright: © 1991 by McGraw-Hill, Inc. ISBN: 0-07-071936-5

[3] SKF Group. *Railway Technical Handbook*. *Volume 2*. Copyright © SKF Group 2012. PUB 42/P7 13085 EN – September 2012. ISBN 978-91-978966-6-5. http://www.skf.com/binary/tcm:12-96059/13085EN.pdf

[4] www.ntnamericas.com. *Formulas to Calculate Bearing Frequencies.* Copyright © NTN Bearing Corporation 2018. http://www.ntnamericas.com/en/website/documents/brochures-and-literature/tech-sheets-and-supplements/frequencies.pdf

[5] А. Б. Сергиенко. *Communications toolbox – обработка сигналов и изображений.* Mathworks: Documentation (Release 14) \ Communications Toolbox. Copyright © 2001-2014 Softline Co.

[6] Vu Trieu Minh, Riva Khanna, "Application of Artificial Intelligence in Smart Kitchen", *International Journal of Innovative Technology and Interdisciplinary Sciences*, Vol. 1, no. 1, pp. 1-8, Nov. 2018.

[7] Vu Trieu Minh, Reza Moezzi, Minh, Mart Tamre, "Fuzzy Logic Control for a Ball and Beam System", *International Journal of Innovative Technology and Interdisciplinary Sciences*, Vol. 1, no. 1, pp. 39-48, Nov. 2018.

[8] Ivan Ovchinnikov, Pavel Kovalenko, "Predictive Control Model to Simulate Humanoid Gait", *International Journal of Innovative Technology and Interdisciplinary Science*s, Vol. 1, no. 1, pp. 9-17, Nov. 2018.

[9] Mart Tamre, Robert Hudjakov, Dmitry Shvarts, Ahti Polder, Maido Hiiemaa, Mart Juurma, "Implementation of Integrated Wireless Network and MATLAB System to Control Autonomous Mobile Robot", *International Journal of Innovative Technology and Interdisciplinary Sciences*, Vol. 1, no. 1, pp. 18-25, Nov. 2018.

[10] Moustafa Aboulkheir, "Development of Dual Clutch Transmission model for Hybrid Vehicle", *International Journal of Innovative Technology and Interdisciplinary Sciences*, vol. 1, no. 1, pp. 26-33, Nov. 2018.

[11] Nitin Afzulpurkar, "Automatic Control of Clutch Engagement and Slip for Hybrid Vehicle", *International Journal of Innovative Technology and Interdisciplinary Sciences*, vol. 1, no. 1, pp. 49-61, Nov. 2018.