DYNAMIC BEHAVIOUR OF MACHINE TOOL MOTOR SPINDLE BY EDDY CURRENT MONITORING

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Abstract: *The objectives of this paper were to measure the displacements of an integrated spindle of a milling machine tool using Eddy current transducers and to evaluate effects by signal processing and analysis in order to identify the causes. For achieving the objectives, we analyzed a number of elements by computing and processing signal considering the waveform and frequency and identifying defects and their location. To reduce the vibrations amplitudes of a circularity diagram on one or more rotations, we developed an experimental model with the aim of intervention on the defect for extending the lifetime of the element that generates vibrations.*

Key words: *vibrations, displacements, spindle motor, eddy-current, defect correction, lifetime.*

1. INTRODUCTION

Appearance of vibration is inevitable given the dynamic of milling process which is subject to system-piece machine-tool difficulty in terms of productivity, quality and cost. Vibrations analysis has long been used for the detection and identification of the machine tool condition. Predictive maintenance is directed towards recognizing the earliest significant changes in machinery condition [1]. Thin-walled work piece is greatly influenced by the vibrations of the cutting process with the risk strains wall piece. The machining of thin walls generally generates milling chatter, that damage surface roughness and manufacturing tools [2, 7].

Besides appearing as an important factor for vibration behavior deterioration of machines had to do with displacements and deformations that appear while the bearings due to the operation machine tools, especially in dynamic conditions poor. Angular contact ball bearings have been widely used in machine tool spindles, and the bearing preload plays an important role on the performance of the spindle. With the development of high speed machining, for high speed milling, heavy cutting at low speed and light cutting at a high speed are often performed on a single machine tool spindle, thus, high stiffness at low speed and low temperature rise at high speed are required [6].

In this paper the displacements were evaluated and experimental data was processed in connection with the effect of the dynamic behavior of bearings of the vibratory main spindle by using Eddy-current transducer [3]. A dynamic analysis of measured frequencies having in view the influences of the rigidities on the quality of main spindle running (motor shaft) was done.

Vibration analysis is used to identify the causes starting from the effects given defects upon dynamic behavior of spindle motor or its components (especially bearings).

2. OBJECTIVE PRESENTATION

Today, a frequent problem in the manufacturing industry is the vibrations induced by metal cutting (turning, milling and boring operations). Vibrations in boring operations or internal turning operations, for example, are inevitable and constitute a major problem for the manufacturing industry.

Tool vibrations in metal cutting affect the result of the machining, in particular for the surface roughness. Furthermore, tool life is correlated with the degree of vibration and produced acoustic noise [5].

Vibration and noise occurring in the machine-tools operation together with those existing in the environment have negative influence on safety operations on these machines, productivity and mechanical processing accuracy and human body. Noise and vibration are factors which are becoming increasingly important to purchasers who want a certain product quality or have a requirement to minimize the health risks [4]. Vibrations of a piece of industrial equipment cannot be only a employees' discomfort, also leading to future machine problems or failure.

Implementing a customized vibration control treatment is a simple and affordable venture that can improve equipment operation while contributing to a more pleasant, safe workplace and improved employee satisfaction. Specialized machinery and equipment utilized in industrial environments often endure inadvertent abuse caused by environmental vibrations [11 and 12].

A machinery piece may produce vibrations that affect its own stability, or may be affected by vibrations transferred from other equipment.

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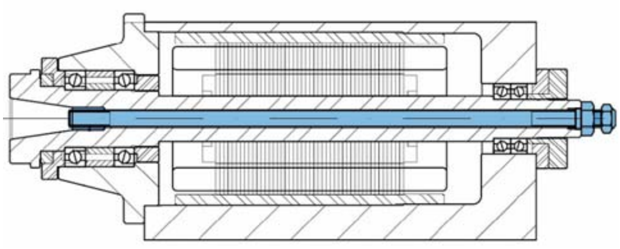

Fig. 1. Spindle motor presentation.

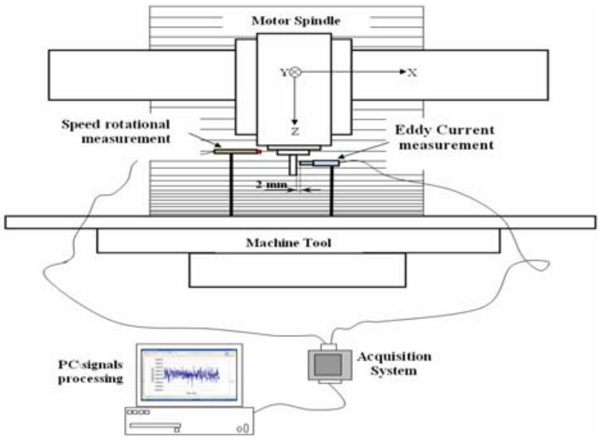

Fig. 2. Test device.

The model presented in the Fig. 1 is a spindle motor, which identifies parts, especially ceramic ball bearing. This paper aims to characterize the dynamics of the electric motor for determining the causes of vibration and reducing their effects.

3. EXPERIMENTAL DEVICE

The main objective was to obtain the dynamic behavior of the main spindle while running, using displacement transducers without contact ("Eddy current") positioned at 2 mm from the master tool (high accuracy balanced tool inserted in the tool holder HSK A63).

Tests are made on a milling machine, 5-axis numerically controlled, having a motor of 34 kW with a range of speed from 50 up to 13 000 min^{-1} (Fig. 2). The rotational speed and phase angle are measured with a laser tachymeter.

The signal is acquired through an acquisition card and then processed on a specialized program of vibrations and signal processing.

Tests were carried out starting from a speed of 500 min^{-1} up to 12 000 min^{-1}, the step being of 500 min^{-1}. Signal acquisition and analysis was achieved through the soft Digitline Fastview [10].

An Eddy current is a local electric current induced in a conductive material by the magnetic field produced by the active coil. This local electric current in turn induces a magnetic field in opposite direction to the one from the active coil and reduces the inductance in the coil.

By changing the distance between the target and probe, the impedance of the coil changes correspondingly. This impedance change can be detected by a carefully arranged bridge circuit. The Eddy currents are restricted to shallow depths near the conductive target surface. Their effective depth is given by Eq. (1),

$$\delta = \frac{1}{\sqrt{\pi \cdot f \cdot \mu \cdot \sigma}}, \quad (1)$$

where f is the excitation frequency of the circuit, μ – target material magnetic permeability, and σ – target material conductivity.

The target material must be at least three times thicker than the effective depth of the Eddy currents to make the transducer successful [9]. It is assumed that the Eddy currents are localized near the surface of a semi-infinite solid, and the actual Eddy current amplitude decreases quadratically with distance.

4. DYNAMIC RESULTS

Further, the vibration measurements made for speeds of 2 000 min^{-1} and 12 000 min^{-1} will be presented. Comparing the results, it can be seen that the amplitudes for 2 000 min^{-1} are about 0.023 mm (Fig. 3) while for 12 000 min^{-1} are overall amplitudes about 0.039 mm (Fig. 4). Through the wave form signal, the response in time of the displacements, we can determine the spectral response for a speed of 2 000 min^{-1} and 12 000 min^{-1}. After obtaining the FFT transformation, one could find that at 2 000 min^{-1} the main frequency corresponding to the rotation speed is 33.33 Hz (Fig. 5), where there is a peak of amplitude of 0.0012 mm. In case of 12 000 min^{-1}, the displacement amplitude is about four times bigger, having a fundamental frequency corresponding to rotation speed of 200 Hz (Fig. 6).

Thus, comparing the measured values with the required value of machine tool of 0.0015 mm for a proper functioning, we note that 0.004 mm is very high. In addition, this magnitude develops the exact frequency of order 1, which is the fundamental one. Following the analysis phase, we determine the angular position of the vibration vector and ascertain that it remains constant with variations of ±2 º.

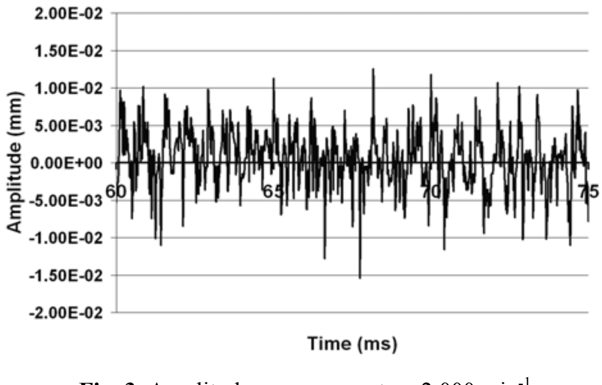

Fig. 3. Amplitude measurement on 2 000 min^{-1}

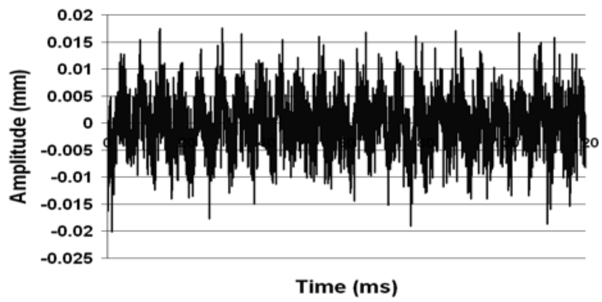

Fig. 4. Amplitude measurement on 12 000 min^{-1}.

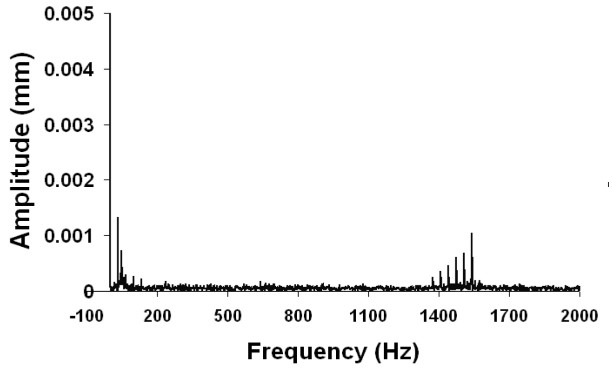

Fig. 5. Frequency spectrum for 2 000 min^{-1}.

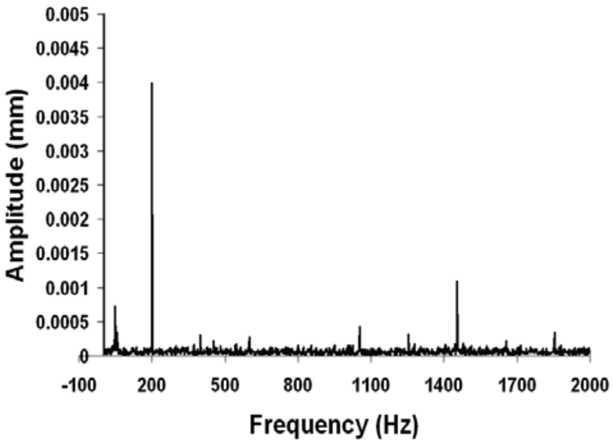

Fig. 6. Frequency spectrum for 12 000 min^{-1}.

5. EXPERIMENTAL ANALYSIS

The results obtained from measurements have revealed a number of dynamic features of the main spindle. Figures 5 and 6 shows significant vibration amplitudes increase with increasing rotational speed which requires the assumption of the bearing existence excited faults. Therefore our analysis will deal primarily with emphasizing dynamic phenomena caused by bearing defects, dynamic phenomena monitored by Eddy current type transducer. These sensors can provide information necessary to evaluate real clearance running or running and also the dynamic frequency analysis spectra. Figure 7 shows the trend of the displacements obtained as a result of the change from 2 000 to 12 000 min^{-1}. Thus, we can distinguish between the different amplitudes at maximum and minimum speed and also the top displacement at the 5 600 min^{-1}.

Our attention is directed to the peaks shown in Fig. 7, which indicate the importance of proper harmonic vibration of order 1. This observation requires two assumptions:

- taking into account an unbalance of the spindle (motor spindle)
- and the second related to a deformation off the main spindle end.

Thus, it is necessary a frequency analysis of bearing elements because they are subject of deformations. Figure 8 shows a bearing configuration for the frequency calculations and identification of critical frequencies.

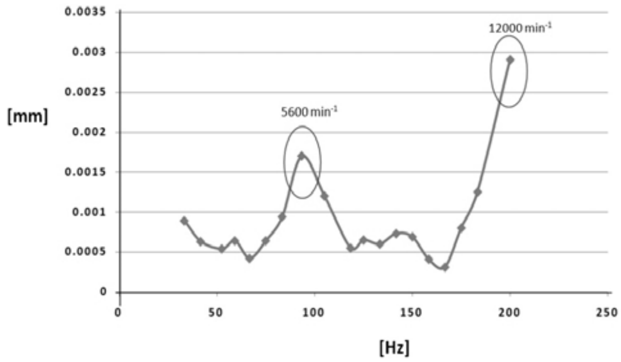

Fig. 7. Trend of dynamic measurement.

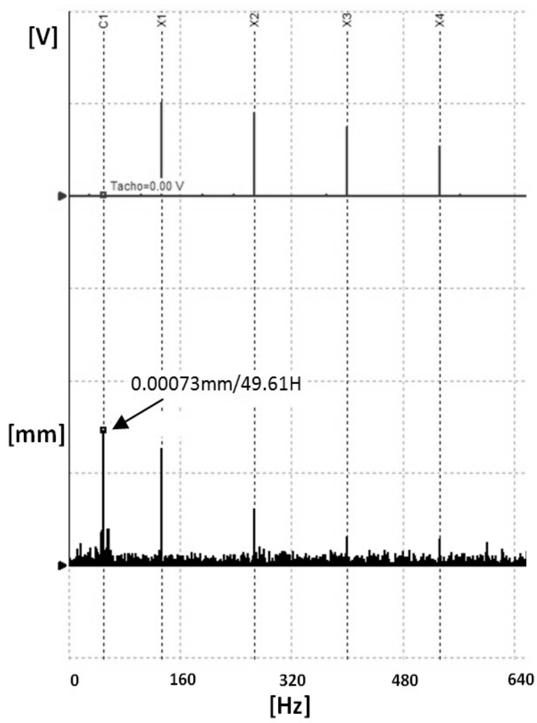

Fig. 8. Frequency identification source for an electrical motor.

Following the spectrum, the identification of the excitation frequency of an electrical motor in the same production hall was performed (Fig. 8). This frequency is identified for the speed range. Also, we can see the running frequency and the second and third order harmonics compared with the amplitude of the frequency of 49.61 Hz. This situation occurs when we are dealing with excitatory factors.

Therefore the amplitude analysis is also important. By exciting the elements at critical frequencies for corresponding speeds, we observe an important increase of amplitude.

In Fig. 9 the frequency peaks around 1 500 Hz are shown. They lie between the harmonic frequencies, leading to the hypothesis of a defect or clearance/running.

In formulae 2, 3 and 4 one presents the calculation of frequencies for the cage, outer and inner rings. In Fig. 11 the frequency values calculated are given for rolling elements – cage, inner and outer rings, and also the dynamic

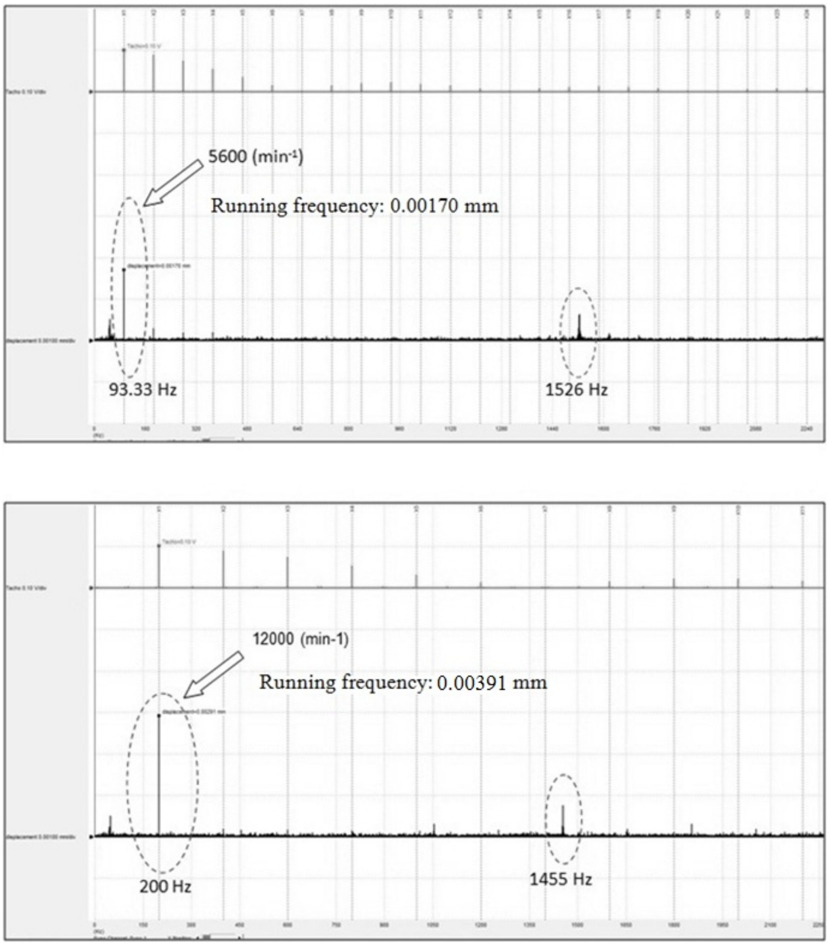

Fig. 9. Frequency spectrum for 5 600 min^{-1} and 12 000 min^{-1}

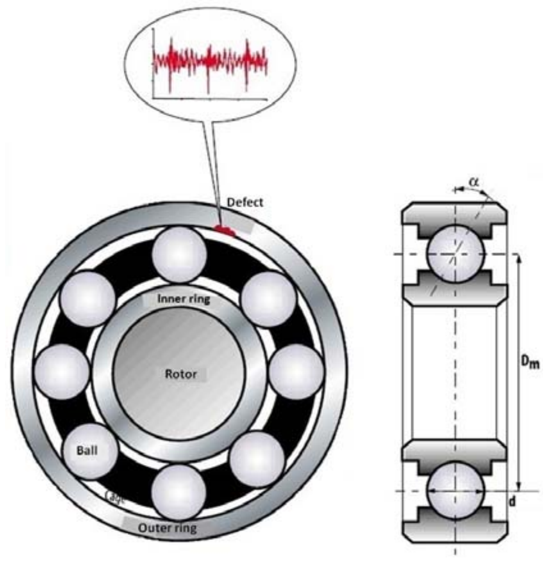

Fig. 10. Bearing configuration, default frequency.

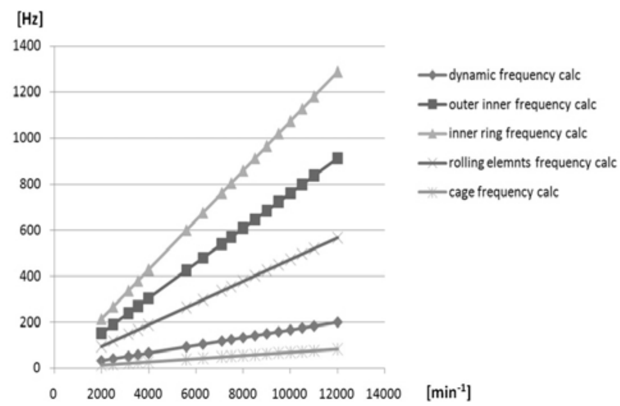

Fig. 11. Frequency calculation.

frequencies (Fig. 10) [8]. In Eqs. 2, 3 and 4 F_c is the cage rotational frequency, F_e – frequency of outer inner and F_i – frequency of intern inner, with F_a – spindle rotational frequency, d – ball diameter, D_m – medium bearing diameter, α – contact angle, and n – number of balls.

$$F_c = \frac{1}{2} \cdot F_a \cdot \left(1 - \frac{d}{D_m} \cdot \cos(\alpha)\right), \quad (2)$$

$$F_e = n \cdot F_c, \quad (3)$$

$$F_i = n \cdot (F_a - F_c). \quad (4)$$

From the achieved measurements one could find that the entire range of speeds of rotation the frequency of 1 500 Hz (± 30 Hz) was found on all frequency spectrums, with the remark that the amplitude is corresponding to the third harmonic amplitude of order 1. Following these frequencies on the graph in Fig. 11, we can validate the frequencies of the bearing element, especially common inner ring.

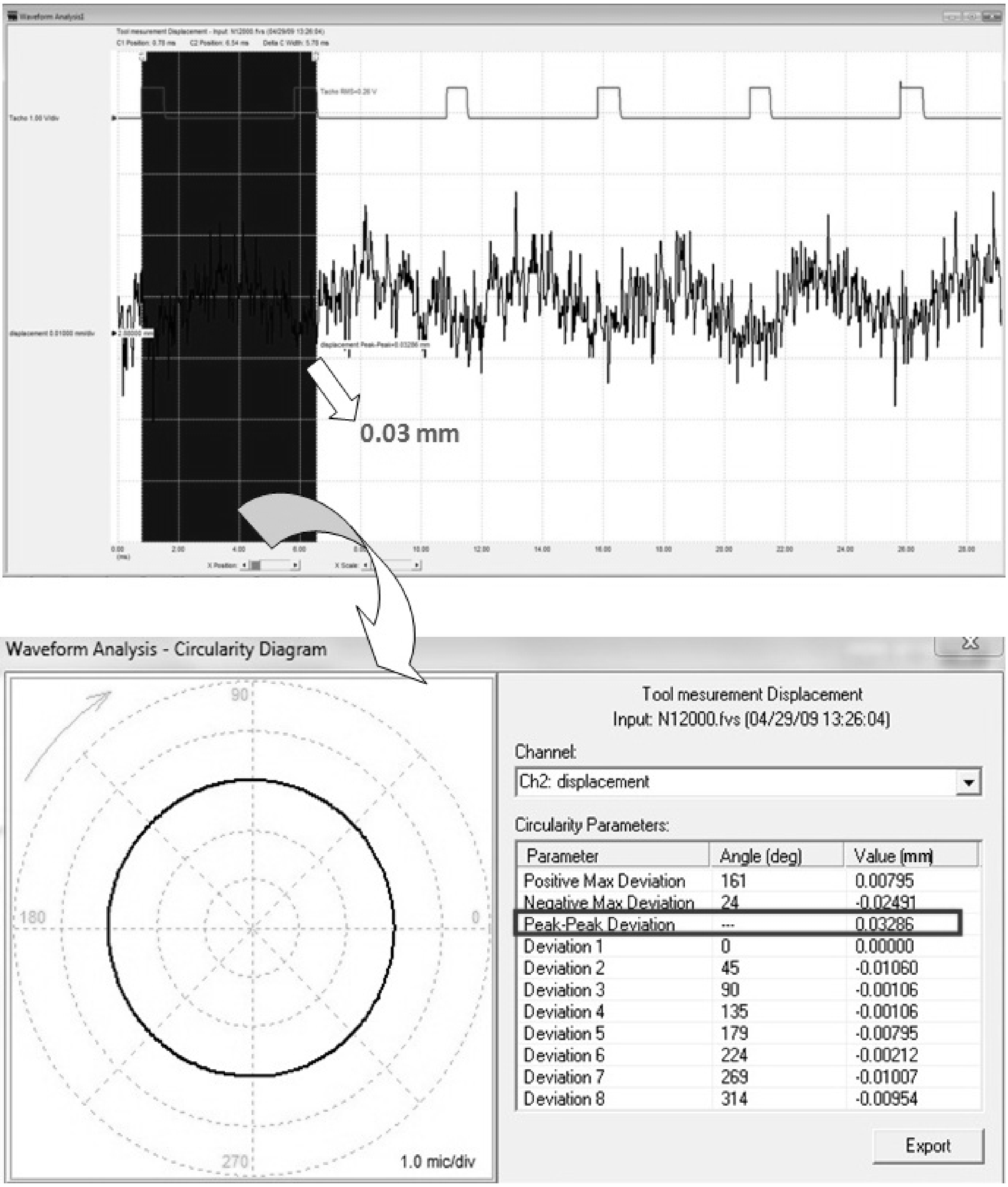

Fig.12. Circularity diagram of waveform analysis

The magnitude of this frequency is much smaller than the magnitude of the fundamental frequency amplitude. Thus, we focus on the dynamic analysis of the existing vibration fundamental frequency.

Based on measurements acquired using Eddy-current transducers and the signal processing, the circularity diagram was obtained for a complete rotation. During a rotation, the corresponding displacements are around 0.03 mm.

Analysis allowed the determination of the rotation angle where the maximum circularity errors are encountered (45º and 270º in regard with the zero position of tachometer). By this analysis, the defect on the motor spindle is determined followed by an adjustment of the bearing clearances.

In the first phase, this adjustment in bearings (tightening) could improve the behavior of the machine tool spindle by reducing the amplitudes up to half of the global displacements.

5. CONCLUSIONS

This paper presents the dynamic behavior of the spindle using experimental study for a CNC milling machine with 5 axes. Eddy current transducers were used to measure the unloaded tool real displacements. This information is very important for determining the vibrations source. The measurements show a remarkable correlation between stable and unstable aspects of the behavior of motor spindle at vibration of the tool during cutting.

The frequency comparison made at 2 000 min^{-1} and 12 000 min^{-1} allowed the unbalance existence validation - vibrating effect caused by the main shaft bearing wear, especially the front bearings that are in the tool direction.

In perspective, an analytical study will be conducted to determine the influence of displacement measured at 12 000 min^{-1} during cutting processes. Finally, by solving the problem, we succeed to increase the lifetime of the main shaft bearings before changing.

This method allows verifying the machines-tools performances from dynamic point of view and can be used to determine the condition of different parts of the machine tool (such as main spindle bearings) in working conditions.

The application of this method is essential for both production and maintenance. The development of this method represents a further step in our research [10], focusing on a three dimensional model for the full experimental characterization of machine-tools.

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