ISSN 1068-798X, Russian Engineering Research, 2015, Vol. 35, No. 6, pp. 458–461. © Allerton Press, Inc., 2015.
Original Russian Text © F.S. Sabirov, L.G. Vainer, A.V. Rivkin, 2014, published in STIN, 2014, No. 12, pp. 18–21.

Vibroacoustic Diagnostics of Bidirectional End Milling

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Abstract—The hypothesis that high-frequency vibration of a dynamic disk system is excited by a rotating roller is verified. The information content of the vibrational signal is determined. The characteristics of the vibrational signal are compared with the rotation characteristics and the machining precision.

Keywords: grinding, vibration, machining precision
DOI: 10.3103/S1068798X15060179

Vibroacoustic diagnostics of cutting processes has been widely adopted around the world [1–4].

Rotation characteristics of machined parts were established in [5, 6]. The rotation characteristic is the dependence of the roller speed f_r on its coordinate in the grinding zone. In addition, the optimal form of the rotation characteristic was identified, such that the configurational error of the ends of the part is a minimum. In practice, the configurational error—that is, the degree to which the end surface is not perpendicular to the axis of the part—is measured in terms of the end wobble.

In bidirectional end grinding, the machining precision depends significantly on the rotation of the machined parts as they pass through the grinding zone [5, 7, 8]. When the parts are placed in an attachment permitting free rotation relative to their axis, their rotation determines the interaction of the parts with the grinding wheels and depends on parameters such as the margin removed, the supply velocity, the wheels' positional angles in the horizontal and vertical planes, and the wheel characteristics. Such basing is used, in particular, in the machining of cylindrical rollers mounted in the bushes (sockets) of a loading disk.

In bench tests of bidirectional end grinding, the rotation of the parts may be recorded by means of inductive and fiber-optic sensors. In production conditions, such sensors are inapplicable, for a number of reasons: they require special machining of the loading disk and the bush so as to insert the sensor; the control rollers must be ground in a specially prepared socket; diagnostics of roller machining in the other bushes is not possible; and the process must be stopped after the grinding of the control roller, with reversal of the loading disk.

In developing a new method of recording the rotation characteristics, we assume that vibration of the disk's dynamic system is excited at one of its eigenfrequencies when the roller turns, because it is imperfectly balanced. This hypothesis is suggested by the characteristic high-frequency sound that periodically accompanies the grinding of the rollers.

In developing a method for indirect recording of the rotation characteristic, we need to verify the hypothesis regarding the excitation of high-frequency vibration of the disk's dynamic system; to determine the information content of the vibrational signal; and to compare the characteristics of the vibrational signal with the rotation characteristic and the machining precision.

We use the basic experimental equipment in [5]. In addition, we employ the vibration-measurement system in Fig. 1a: (*1*) KD-13 RFT vibration sensor; (*2*) SM-111 RFT amplifier; (*3*) OF-111 RFT octave filter. To permit direct observation, the useful graphical information from the vibration sensor is shown on the screen of S8-13 electron-beam oscillograph *4*, with built-in memory. The vibrational signal may also be recorded at optical oscillograph *5*, for comparison with the characteristics recorded in parallel: the roller rotations *6*, the normal force *7*, and the power *8*.

Sensor *1* is mounted on lever *10*, a fixed point to which the vibration of the disk is transmitted with relatively little damping. That eliminates the need to stop the rotating disk *9* after the control roller *11* passes through the grinding zone and to reposition sensor *1* connected by cable to the amplifier or to return the disk to its initial position.

When a pulse is applied to the disk by radial impact, a characteristic high-frequency harmonic is seen in the vibration spectrum recorded by the sensor: at ~7 kHz for the 3342AD machine tool and at ~6 kHz for the 3343AD machine tool (Fig. 1b).

The same frequency harmonic is seen in the disk's vibration spectrum on grinding. The amplitude of the vibrations at that frequency is 5–8 times higher when the roller turns (Fig. 1c, curve *1*) than when it is static (curve *2*).

This effect may be used in diagnostics of roller rotation in machining. To isolate the useful frequency, an octave filter is introduced in the measuring system; it is tuned to transmit frequencies of 4–10 kHz. In Fig. 1d, we show the disk vibration in grinding when the roller turns (curve *1*) and when it is static (curve *2*), in the presence of the octave filter. The difference in the signals is even greater in this case. (The amplitude ratio is 10–15.)

The high-frequency vibration of the disk due to the roller rotation in machining, as seen on the oscilloscope screen, may be regarded as the vibrational characteristic of roller rotation. To record the vibrational characteristic of roller rotation over the whole machining zone, we need to make the necessary adjustments to the image. The vertical scale of the vibrational characteristic of roller rotation is selected so that the maximum signal amplitude does not exceed the size of the screen; the amplifier is set accordingly. The useful signal is measured with respect to the vibration of the idling disk.

We conduct a special test to verify that the anomaly in the vibration of the disk's dynamic system at one of its eigenfrequencies is due to dynamic imbalance of the roller.

First, we prepare two groups of test rollers: (1) with artificially created imbalance (with the creation of a slot of height 2 mm on the cylindrical surface); (2) with the roller's unmodified initial imbalance.

In the tests, rollers (diameter 14 mm, length 14 mm) are ground in one pass in single control bush (supply rate 2.5 m/min, margin 0.12 mm at the two ends), with constant infusion of grinding fluid. Ten tests are conducted for the rollers in each group; for purposes of randomization, tests of rollers in each group alternate. In grinding, the rotation of all the rollers remains the same and corresponds to an optimal rotation characteristic [5]. The wobble of the machined ends is 2–4 μm.

Comparison of the vibrational characteristic of roller rotation on oscillograms with higher scan rate (Fig. 1e) shows that the artificial imbalance sharply increases the amplitude of the signal (by a factor of 8–10); harmonics with the constant frequency of ~7 kHz are the strongest. Thus, the increased disk vibration (relative to idling conditions) is due to imbalance of the roller. Note that, according to the azimuthal grinding speed (30 m/s) and the roller diameter, its rotation frequency should not exceed ~0.7 kHz.

For analysis of the information content of the vibrational characteristic, we record the vibrational characteristic of roller rotation in parallel with the roller speed, the normal cutting speed, and the power consumed in bidirectional end grinding.

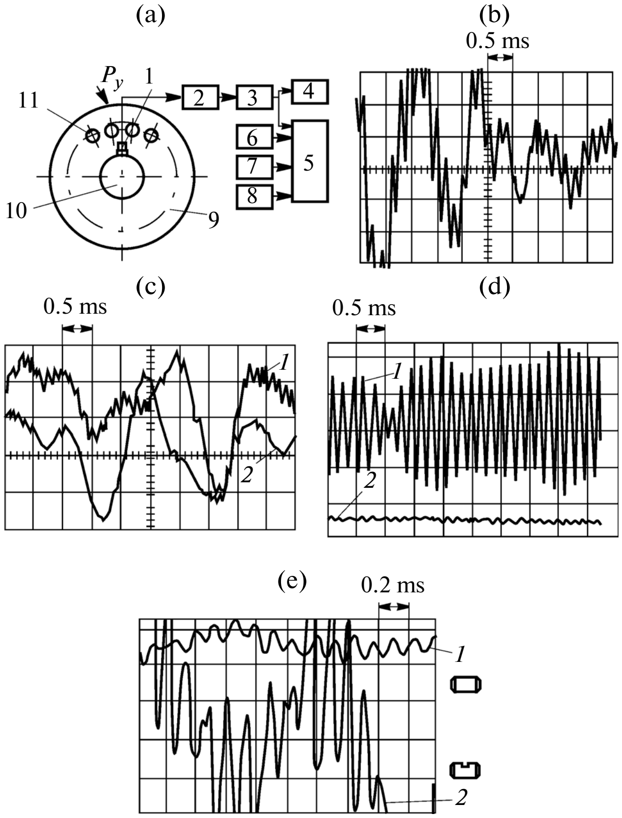

Fig. 1. Indirect recording of the rotation characteristic: (a) measuring system (notation in the text); (b) oscillogram of the disk vibrations under the action of a pulsed load; (c, d) oscillogram of the disk vibrations in the grinding of a rotating (*1*) or static (*2*) roller without (c) and with (d) an octave filter; e) excitation of disk vibrations in the grinding of a rotating roller with its initial (*1*) and artificial (*2*) radial imbalance.

Three types of vibrational characteristic of roller rotation are observed, as for regular vibrational characteristics [6]. In Fig. 2, as an example, we show rotational vibrational characteristics of the first (a) and third (b) types. (We do not show the second type, with the roller at rest and then resuming its rotation in the second half of the grinding zone.)

If we compare the length $L_{VH\Sigma}$ of sections where disk vibration is excited with the length of sections where the roller turns and the cutting force appears (in other words, where the margin is removed), we find that they agree. Therefore, the parameter $L_{VH\Sigma}$ of the rotational vibrational characteristic corresponds to the parameter L_{rr} of roller rotation in the zone of margin removal (Fig. 2c).

Another important parameter of the rotational vibrational characteristic is the level H of the useful signal on the oscillogram (relative to idling conditions), which is variable, as the tests show. Since the

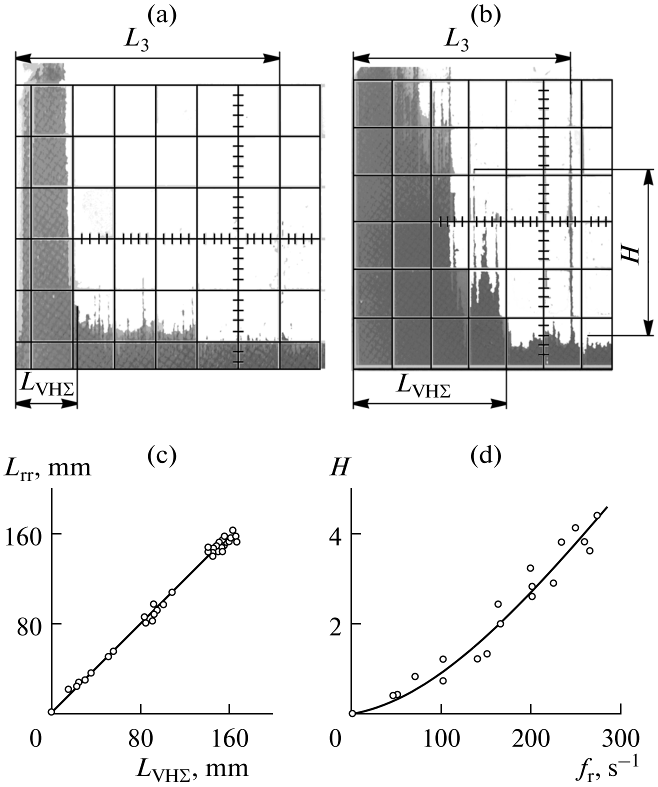

Fig. 2. Sample rotational vibrational characteristics for rollers of the first (a) and third (b) types; comparison of the parameter $L_{VH\Sigma}$ of the rotational vibrational characteristic and the parameter L_{rr} of roller rotation (c); and the relation between the level H of the useful signal and the roller speed f_r (d).

excitation of disk vibrations is due to roller imbalance, and the corresponding perturbing force is proportional to the square of the angular velocity, we may assume a quadratic relationship between H (measured in the scale divisions on the oscillograph screen) and the roller speed f_r (s^{-1}).

Our analysis shows that the relation between these parameters (Fig. 2d) may be written in the form $H = a_1 f_r + a_2 f_r^2$, where a_1 and a_2 are regression coefficients found by the least-squares method. For the specified conditions $a_1 = 0.58 \times 10^{-3}$, $a_2 = 0.368 \times 10^{-4}$.

This formula permits the use of H to characterize the speed of roller rotation.

CONCLUSIONS

(1) In bidirectional end grinding, the increased disk vibration (relative to idling conditions) is due to imbalance of the roller.

(2) The extent of the vibrational characteristic of roller rotation permits identification of the sections where it rotates with margin removal. The form of the rotational vibrational characteristic reflects the variation in roller speed.

(3) The use of the vibroacoustic signal for diagnostics of the workpiece speed permits determination of the rotational parameters determining the machining precision [6, 9–11]. This method does not require interruption of the technological process [12–15]. (There is no need to stop and reverse the loading disk, for example.) This approach may be recommended for the adjustment of systems used in bidirectional end grinding.

(4) The proposed method permits diagnostics of machining in any regular basing bush of the loading disk; identification of the influence of geometrical errors in the bush's basing surfaces (initially and after wear) on the behavior of the workpiece and the machining precision; and corresponding certification of each bush with fixed technological conditions and position of the grinding wheel.

ACKNOWLEDGMENTS

Financial support was provided by the Russian Ministry of Education and Science (state program 9.1429.2014/K).

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Translated by Bernard Gilbert