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DIAGNOSTICS AND MONITORING OF COMPLEX PRODUCTION PROCESSES USING MEASUREMENT OF VIBRATION-ACOUSTIC SIGNALS

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A vibration-acoustic method for diagnostics and monitoring of production processes such as cutting metals makes it possible compared with other methods to reduce the requirement for measuring equipment and it provides a computer representation of the results observed. The set of equipment suggested has low cost and it exhibits considerable flexibility compared with existing equipment.
Key words: *diagnostics, cutting, monitoring, vibration, vibration-acoustic signal.*

Setting up a production process in contemporary multifunctional lathes leading to machining of an article in five- and six-coordinate space is a complex and very critical task. Its complexity is intensified even more by the fact that contemporary lathes with programmed numerical control (PNC) have a cabinet system making it difficult for the operator to follow machining by means of sight and sound. Errors that arise in setting up the control program may be evident and concealed. With concealed errors that arise in cutting, nonuniform forces created by vibrations remaining from the previous passes that are not taken into account by the machining regime may lead to scatter in the depth of surface hardening or the degree of work hardening, and in some cases this affects the operating life of a finished article. In addition, increased vibrations or shock pulses that arise during machining may point, for example, to incorrect cutting regimes selected in this situation, low billet stiffness or imperfection of the attachment used.

Use of vibration-acoustic (VA) diagnostic methods makes it possible to remove observation from the cutting zone to a monitor screen. Here the possibilities for analyzing a situation be expanded considerably compared with normal operator observation. Shown in Table 1 are examples of the effect of disturbing factors on the production process for cutting, reasons and consequences of the effect, and also examples of VA-signal characteristics reflecting these factors.

For adequate observation of the path of test processes, it is necessary to consider a whole series of features reflecting cutting and friction parameters within the characteristics of the generated VA signals. Among these features, the main one involves the fact that VA-signal power may be assumed to be proportional to the number of acts of individual irregularity interaction taking part in the contact process during cutting and friction only within a narrow range of change in contact area [1].

Shown in Fig. 1 is an example of the change in the level of the mean square value (MSV) of vibration acceleration due to the amount of approach of the surfaces in contact with different friction rates. It can be seen that with approach at 1 μm and a rate of 0.8 m/sec the increase in VA signal is about 10 dB. With an increase in friction rate and micro-roughness size, this increase will be even greater. It is noted that with approach at several micrometers no traces of the friction pair remain.

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TABLE 1. Connection of Disturbing Factors of a Production Process with Vibration-Acoustic Signal Characteristics

Example No.	Production process disturbing factor	Reason for defects	Effect on article output characteristics	VA-signal characteristics reflecting disturbing factors
1	Increased level of relative vibrations of cutting tool (CT) and billet	Variable cutting forces, low dynamic stiffness of billet or CT	Surface waviness and roughness, dispersion of hardening depth and level of work hardening	Increase in VA-signal amplitude, change in spectral composition of signal and density of amplitude probability distribution
2	Unacceptable nonuniformity of billet surface hardness	Billet scrap	Reduction in fatigue resistance	Increase in amplitude in areas with increased hardness
3	Pits	Billet scrap	Unacceptable surface condition, lack of required strength	Increase in amplitude at pit edges, drop in amplitude within pit
4	Increased probability of CT breakage	Incorrectly selected cutting regime, incomplete PC	Article scrap connected with CT breakage	Marked increase in amplitude, appearance of unsteady bursts in amplitude, change in spectral composition and density of amplitude probability distribution
5	Nonuniformity of pass removal	Incomplete removal of PC for previous machining	Increased dispersion of strengthened depth and degree of work hardening	Increased dispersion of amplitude, change in density of amplitude probability distribution
6	Deviations in CT geometric shape, different dimension of cutter teeth	Errors in CT sharpening and fastening, wear	Reduction in surface quality and stability of surface layer properties, possible scrap	Difference in VA-signal amplitude during cutting by different teeth, VA-signal modulation with rotary and tooth frequency
7	PC malfunctioning	Errors in programming, failure in PNC system	Article scrap, creation of dangerous situation	Sharp increase in amplitude or conversely disappearance of VA signal in a broad frequency range
8	Effect of kinematic equipment errors	Low preparation quality, wear	Reduction in surface accuracy and quality, lack of surface layer stability	Appearance of mutual correlation of VA-signal envelope during cutting with vibration accompanying lathe assembly operation

This indicates that contact processes in the initial phases of approach occur within the limits of elastic deformation and this is reflected well in the VA signal. It can be seen in Fig. 1 that with an approach up to 3 μm the increase in MSV of the VA-signal amplitude is close to linear, but with further approach the increase slows down, changing into a "saturated" state. This state has been given the term "acoustic equilibrium" [1]. The same effect will also be observed with an increase in contact area with retention of constant pressure.

The saturation state arises as a result of the fact that with an increase of the amount of interacting roughness (due to an increase in pressure or contact area) above a certain value some of it will be in collision and some will form adhesion bridges, increasing the stiffness of contact at the instant of impact which also compensates for the increase in number of collisions due to an increase in plastic deformation and the amount of heat [1]. The equilibrium state forms over quite a broad range of variation in contact pressure and area with retention of constancy for other characteristics of interaction in a friction pair. Primarily, among other characteristics it is necessary to refer to the hardness of surfaces in contact (this relates to the less hard element of a pair), friction or cutting rate, surface roughness and the scale of relative surface vibrations. For example, a change in amplitude MSV for vibration acceleration in the octave band with a mean geometric frequency (MGF) of

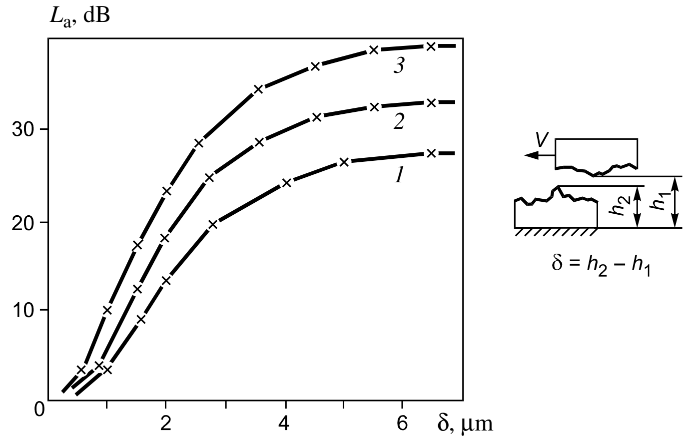


Fig. 1. Dependence of VA-signal level on approach of surfaces in contact with friction at a rate V: octave band with MGF of 16 kHz, alloy T15K6–steel 45; *1*) $V = 0.2$ m/sec; *2*) $V = 0.4$ m/sec; *3*) $V = 0.8$ m/sec.

31.5 kHz in cutting steel 45 in areas with a different hardness showed an almost linear connection of VA-signal amplitude in different frequency ranges with hardness of a billet being machined.

Experiments with friction for different pairs of materials, including fluoroplastic, confirmed that with an increase in friction rate the VA-signal amplitude MSV in different frequency ranges also increases by a rule close to linear. An increase in surface roughness for almost all of the frequency ranges leads to an increase in VA-signal amplitude. Relative vibrations over the normal to the friction surface in a contacting pair have a more complex effect upon it. For example, with low relative vibration amplitudes, not causing a sharp change in contact area or friction rate, the effect of relative vibrations may hardly be marked. An increase in the amplitude of relative vibrations leads first to modulation of the VA-signal (its amplitude changes in accordance with the phases of relative vibrations), and with resonance of individual elements of an elastic system (ES) of the lathe to modulation is added a sharp increase in VA-signal power. In this situation, there is a break in adhesion bridges over the whole contact area that disrupts acoustic equilibrium in the system causing a discharge of accumulated elastic energy, part of which is transferred into the acoustic pulse. In fact, this explains the sharp burst in VA-signal amplitude during cutting tool (CT) breakage when this is accompanied by a break in contact in the cutting zone. Shown in Fig. 2 is an example of a change in VA signal as a result of breakage of a thin drill during machining a cast iron billet at a finishing center.

These and a number of other VA-signal properties make them markedly different from signals that are a function of cutting force or temperature. These differences sometimes complicate identification of the situation in a lathe (additional information may be necessary), but for example, with finishing or operation with a small CT in heavy multifunctional lathes VA-signal monitoring may appear to be the only way of observing the situation in the cutting zone. Therefore, enterprises concerned with the production of critical components in lathes with PNC by means of contemporary technology requiring setting up should have mobile units for observing cutting in the stage of its verification, and also for carrying out a production audit of the equipment used [2].

In order to create a VA-observation system it is possible to use not only accelerometers but also microphones and other vibration sensors. This relates to optical sensors with a radiator and an infrared radiation receiver. This optical pair makes it possible to monitor vibration movement of a rotating tool or billet by the contactless method. With the possibility of using different primary converters, their choice is accomplished taking account of the recording frequency range and its "useful signal–noise" ratio (accelerometers emphasise high frequencies and vibration movement instruments emphasise low frequencies). For example, microphones receive noise generated not only by cutting but also by other lathe mechanisms. It is necessary to be sure that in the frequency range selected the level of useful signal exceeds the level of background interference (more than 10 dB).

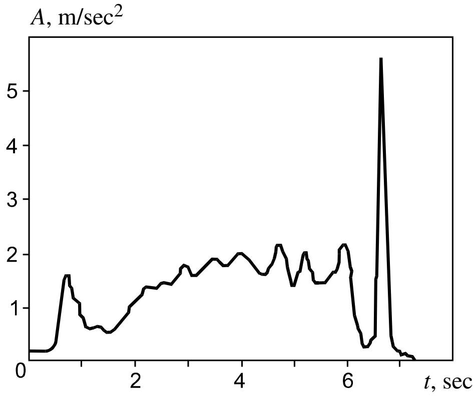


Fig. 2. Example of a change in VA signal (octave band with MGF of 31.5 kHz) with drill (∅5 mm) breakage during drilling cast iron at a finishing center.

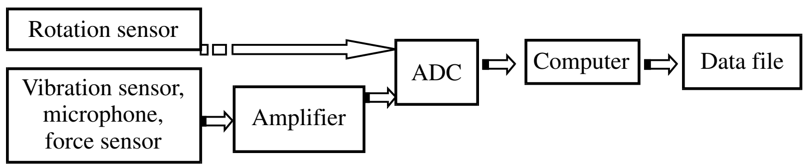


Fig. 3. Layout for connecting equipment in a mobile diagnostic unit.

In choosing the frequency range, it is necessary to consider the convenience of placing the primary converter in the lathe, the form of the production operation, cutting regime and the expected nature of the disturbance (wear, breakage, pits, change in hardness, etc.). In the absence of experience in these areas, the choice is made by experiment. Theoretical and experimental research [3] shows that the higher the frequency selected, the less is the level of disturbance created by operating assemblies of lathes. However, with an increase in VA-signal frequency the more difficult it is to overcome the distance from the cutting zone by passing through mobile and weakly tightened joints. Therefore, choice of the frequency range is accomplished on a compromise basis.

Currently, all the components that are required for any enterprise to create its own VA-unit realizing practically any version for processing information supplied from a microphone, an accelerometer or a vibration movement sensor are readily available in the market. With the presence of force or torsional moment sensors, it is possible to add a force measurement channel. Shown in Fig. 3 is an example of a scheme for connecting equipment into a single unit. Accelerometers, microphones, and amplifiers required for them are normally available at any enterprise (it is necessary to measure noise and vibration in accordance with safety requirements). There are also computers, but in order to provide mobility for the unit it is best to use small computers (Notebook type). Thus, in order to create a diagnostic unit, enterprises may additionally need rotation and force sensors (if they are required) or an analog-digital converter (ADC). These components may be acquired without particular problems or fabricated by their own efforts. An advantage of such a unit over overseas multifunctional units (such as made by Bruel and Kjaer) offered on the market involves the following:

- the price of the unit is an order of magnitude lower;
- software for the unit may be supplemented and modernized in accordance with new tasks that arise in an enterprise;
- protocols for analyzing VA signals and other information may be custom-tailored.

In many cases, in order to analyze a situation in the cutting zone it is sufficient to consider a record of the change in VA-signal parameters with time. This form of presenting VA information is the most understood and accessible for analysis

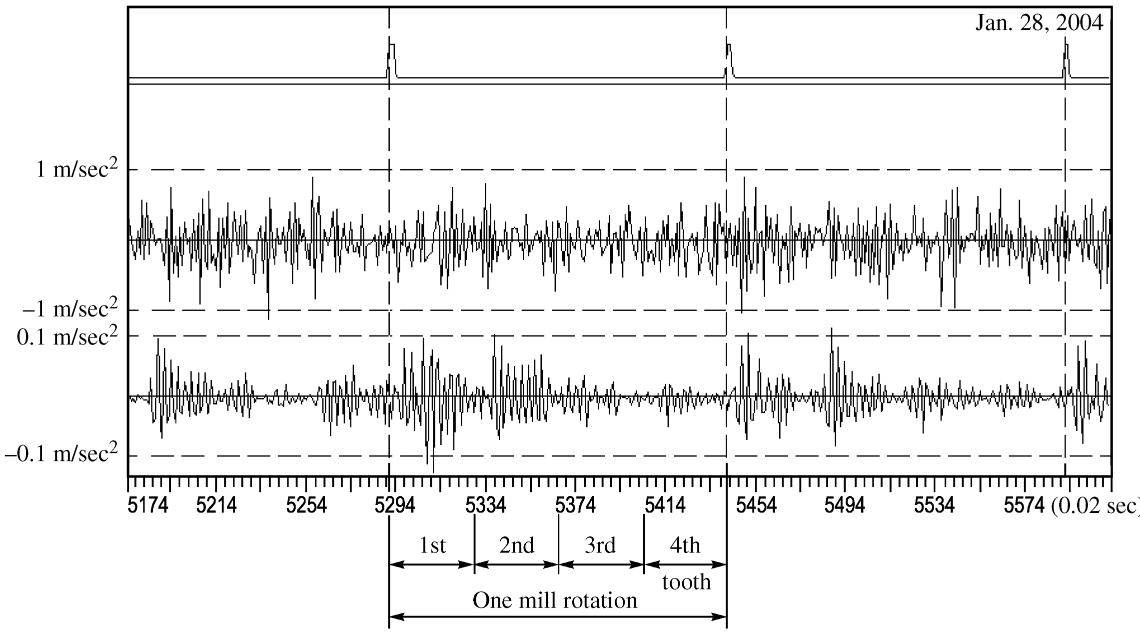
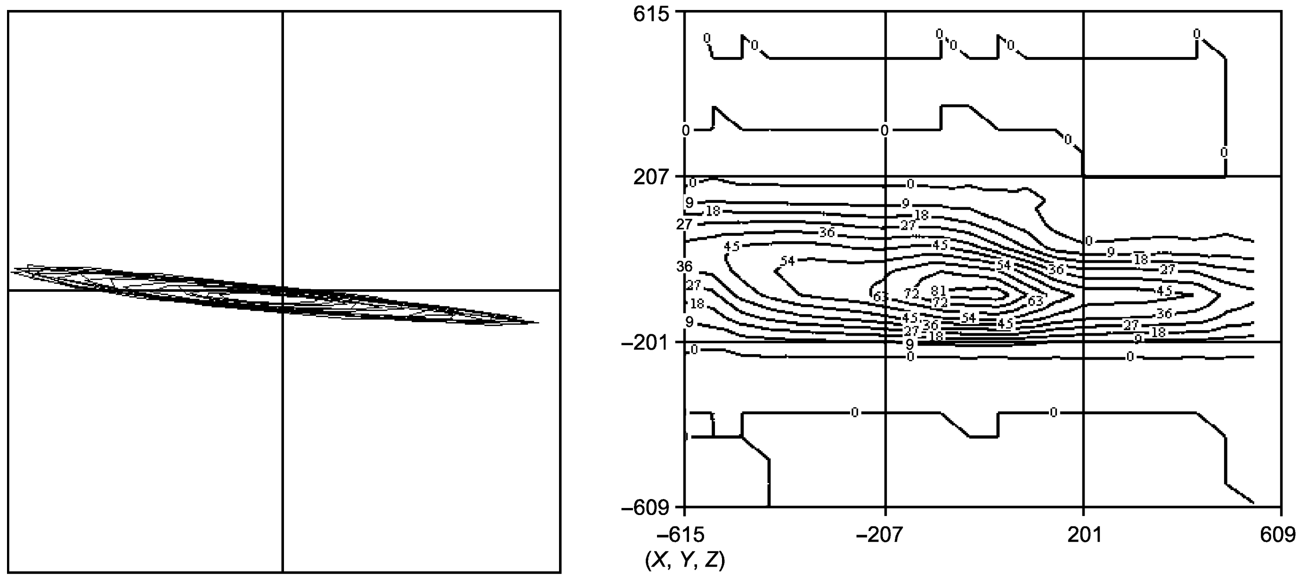


Fig. 4. Example of a VA-signal record in machining an article of complex shape with a four-tooth end milling cutter: the upper record is marks from the sensor for mill rotations; the central record is the VA signal in a broad frequency range at the spindle head; the lower record is the VA signal in the octave band with a MGF of 8 kHz at a billet being machined.

even to a non-specialist in the field of vibration acoustics. Shown in Fig. 4 is an example of such a record. Information was recorded during finishing an article of complex shape with a four-tooth end milling cutter in a six-coordinate lathe. The upper record reflects information with a marker for mill rotations (the fragment of the record contains two complete mill rotations). The lower record was obtained with an accelerometer installed on the component and recording the VA signal in the octave band with a MGF of 8 kHz, and the central record was obtained with an accelerometer installed on the spindle head and recording of the VA signal over a wide frequency range. From the records it can be seen that for one mill rotation with a total load only two teeth operate (lower part of the record in Fig. 4). Only a weak disturbance is observed from the other two teeth that points either to incorrect installation of the mill, or incorrect tooth sharpening. It can also be seen that between the input and output of teeth there is an interval with a small value of VA signal, and this means the mill teeth operate without overlapping that leads to interruption of cutting and unloading of the lathe PC. In this situation, the entry of each tooth with be accompanied by an impact leading to worsening of machined surface quality. Comparison of the lower and central records in Fig. 4 indicates that kinematic disturbances at the spindle head have little effect on cutting when the disturbing action from mill operation dominates.

Cutting is always accompanied by CT and component vibrations. Not only vibration amplitude and frequency are important, but also the spatial trajectory of vibratory movement of the tool during cutting. For example, predominance in observed trajectories of tool vibratory movement over the normal to the surface being machined (radial vibrations) points to the danger of intense self-vibrations occurring in this direction. The low-frequency form of these vibrations (normally it is called loss of stability) excludes the possibility of further cutting, the high-frequency form is accompanied by strong noise, machined surface quality worsens, and there is a reduction in CT durability.

It is possible to obtain information about the geometry of oscillatory movement in any plane by means of two accelerometers installed in this plane in mutually perpendicular directions. The trajectories of vibratory movement in different frequency ranges may also be determined visually in the simplest cases. However in practice, especially with a random nature for vibrations, this qualitative analysis may appear to be ineffective. In this case, it is useful to construct two-dimen-



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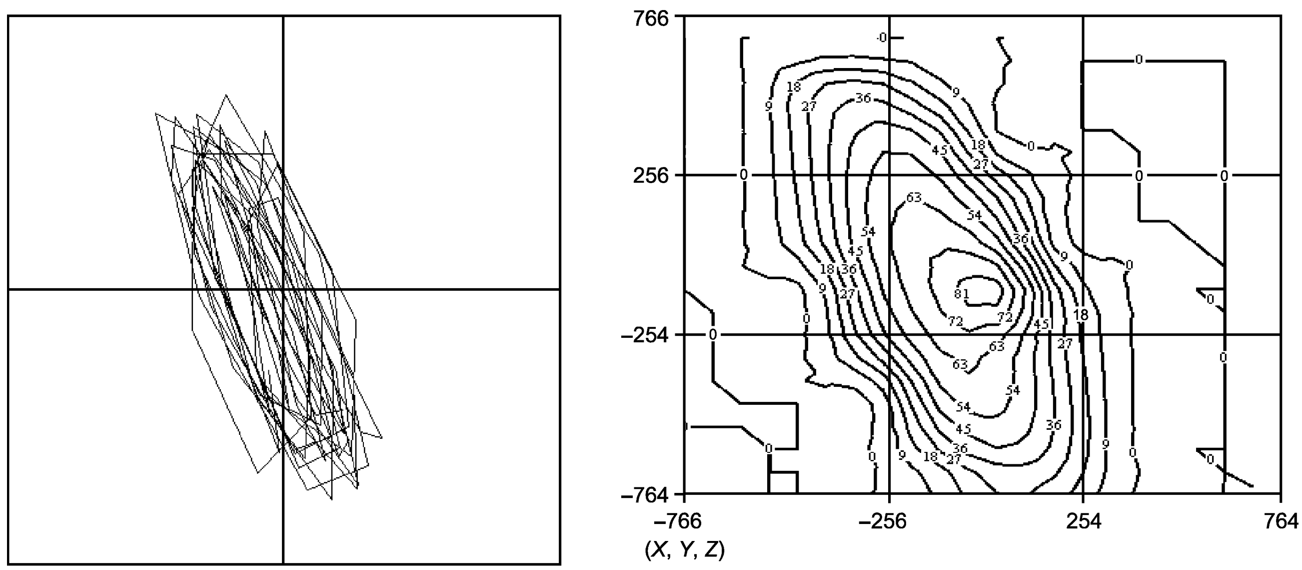

b

Fig. 5. Example of tool vibration trajectories and their histogram during finishing of cast iron (*a*) and aluminum alloy (*b*).

sional histograms (combined distribution density of oscillatory processes with two accelerometers) in the form of a surface whose height expresses the probability density for passage of a trajectory through the corresponding section of the test plane. Shown in Fig. 5 is an example of constructing the trajectory for vibratory movement in the octave band with a MGF of 2 kHz with fine finishing for cast iron (Fig. 5*a*) and finishing aluminum alloy (Fig. 5*b*), and the corresponding two-dimensional histograms (they are expressed by lines of equal level). It can be seen that in finishing cast iron with a loose turning there are radial trajectories of CT oscillatory movement. In finishing aluminum alloy, the turning before separation retains its elastic properties that appear to be sufficient in order to prevent intense radial vibrations. Here the vibration trajectories approach a tangential direction. It is often difficult without VA-diagnostic methods to determine the tendency of a cutting towards excitation of CT (or billet) vibrations having trajectories drawn out in the radial direction. For example, this tendency only appears with an increase in tool wear, a change in machined material characteristics (within tolerances), and within frames of the control program where there is machining of areas of an article with reduced dynamic stiffness. Analysis of vibratory movement trajectories in some phases of machining may reveal individual trajectories with radial directionality that points to the fact that with some variations of machining conditions this phenomenon may acquire a stable character leading either to the impossibility of further machining, or worsening of machining, a reduction in tool durability and an increase in tonal noise. It is possible to adopt measures previously as a result of an increase in CT and billet stiffness and in a direction normal to the machined surface (for example by means of an attachment), to change the tool sharpening angle, to correct the cutting regime, etc.

The mobile unit suggested for performing VA studies may be used for not only setting up a control program and the production process itself, but also for developing algorithms of continuous monitoring for machining in lathes operating without an operator, and also for regular evaluation of the condition of production equipment, and for finding reasons of negative action on the production quality of the kinematic pairs of lathe assemblies. Here we are talking about diagnosing generating defects in lathe assemblies, the search for defects of kinematic pairs developing a disturbing effect during cutting, determination of the form of PC lathe element vibrations affecting the CT and billet relative vibrations [4].

Experience of creating and using diagnostic units accumulated at ÉNIMS OAO and MGTU STANKIN points to their high information potential that is still not exhausted.

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