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Diagnostics of Drilling in Numerically Controlled Machine Tools

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Abstract—Cutting-tool vibration is considered on the basis of existing physical notions regarding forced, free, and self-exciting vibration in a cutting system that consists of interacting tool and workpiece subsystems. A vibrodiagnostic system is studied experimentally in the drilling of a small-diameter by means of an NI CompactDAQ measuring complex.

Keywords: vibrational stability of tools, vibration in cutting, vibrodiagnostics, vibration spectra, vibrational converters

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To ensure reliable operation of numerically controlled high-speed machine tools, the control system must ensure not only precision programmed motion of the cutting tool relative to the workpiece but also diagnostics of the machining system. The weakest link is the tool, whose strength must be sufficient for reliable operation of the automated system over the required period.

Vibration in cutting systems has long been known, beginning with Taylor's research. Russian researchers such as Kashirin, Dikushin, and Kudinov focused on the physical causes of vibration in cutting, since insight into the origins of vibration permits its prevention.

Today's high-performance structural materials (corrosion-resistant and high-temperature steels and alloys, titanium and its alloys) are difficult to machine. Consequently, tool life tends to be short (thanks to the unpredictable influence of forces and temperature on the cutting process). On the other hand, high-speed machining is used for parts that are easy to machine (made from aluminum and its alloys, for example).

For materials that are hard or easy to machine, vibration in cutting is a major concern in manufacturing, since it reduces tool life and results in premature failure of the machine tool's spindle. We should note the exception of controlled vibration, which improves tool operation (for example, in vibrational drilling).

Compact vibrational sensors (AP2019 sensors, say) are very promising for use in numerically controlled machine tools and may be adjusted with respect to different coordinates of the machine tool. However, we still lack reliable methods of vibrational tool diagnostics based on such sensors and the available resources of the numerical control system.

In the present work, we develop an automated vibrodiagnostic system for tools on the basis of a modular USB system of NI CompactDAQ type, with subsequent development of the corresponding diagnostic software (without additional hardware costs) in a numerical control system that has free computational resources [1].

Existing diagnostic methods employ different means of assessing the state of the tool in the control process. They differ in the selected physical parameters (sources of information regarding the state of the tool): for example, the cutting forces; the torque; the cutting power and temperature; the vibration in cutting (displacement, speed, and acceleration), the acoustic emission (including ultrasound); and the parameters of the machined part [1].

In physical dynamics, two basic types of vibration are distinguished: forced vibration; and self-excited vibrations. Forced vibration arises under the action of a periodic force—for example, on account of the imbalance of the rotating spindle or periodic cutter operation (for instance, in a drill or mill). In that case, the source of vibration (the spindle or cutter) forces connected system components to vibrate. As a result, the frequency spectrum of the vibration includes the vibrational frequency of the spindle (and other attached components) or the frequency of cutter introduction in the workpiece.

To understand self-excitation, we need to consider free vibration in cutting [2]. Such vibration may appear, for example, in the sudden removal of cutting force when a cutter leaves the contact zone—in other words, with the sharp elimination of cutting forces on the elastic system of the machine tool. The eigenfrequency of free vibration is determined by the rigidity and reduced mass of the elastic system [2].

When the cutting tooth enters the workpiece, the tool subsystem (spindle + tool holder + tool) is deformed under the action of the cutting force. When the cutting force is eliminated (when the tooth leaves the cutting zone), this subsystem vibrates at its eigenfrequency. We assume here that the rigidity of the workpiece subsystem (table + attachment + workpiece) is higher than that of the tool subsystem and may be ignored.

If the second action of the tool tooth does not correspond to the eigenfrequency, the chip thickness is increased, along with the cutting force. That, in turn, results in more perceptible deformation of the system, and the vibrational amplitude increases. The worst case is 180° phase shift of the vibration from the cutters with respect to the surface undulation obtained previously.

Thus, self-excited vibration in the cutting zone (sometimes known as self-oscillation) is produced by the unpredictable interaction of several factors—for example, when the vibration from the cutter is delayed in phase by 180° (π rad) with respect to the preceding cutting tracks, while the cutting power is sufficient to overcome the damping of the vibration. Such vibration may be called self-excited vibration or chatter. The tool subsystem then vibrates at its eigenfrequency (with no external inducing force) and the cutting forces increase significantly. That impairs the machining precision, the tool life, and the spindle life.

Hence, in a system with positive feedback, when surplus potential energy is present (thanks to the spindle's electric motor), the prevention of vibration calls for reduction in the amplification factor, phase shift away from positive feedback (180°), or both.

Prevention of self-excited vibration in cutting and chatter is possible if the frequency of action of the tool's tooth matches the eigenfrequency of the tool subsystem—in other words, when the surface undulation (which may not be visible to the eye but expresses itself as change in the physicomechanical properties of the surface layer) and the cutting vibration are in phase (0°). At that spindle speed, the chip thickness remains constant, cutting is smooth (noise-free), and the cutter may descend considerably without the appearance of defects. This is known as the sweet spot [2].

Two methods may be used to determine the spindle speed with no chatter [2].

(1) Determination of the eigenfrequency of the tool subsystem by means of an accelerometer and an impact hammer. On that basis, the transfer function of the system may be found, and analytical prediction of the vibration involves calculation of the sweet spot. That calls for a mathematical model of the vibrations in the system.

(2) Determination of the sweet spot by control cutting. This method provides more precise data but entails a large number of experiments with different combinations of the spindle speed and the cutting depth.

Having found the sweet spot, we may ensure stable and productive system operation (with a particular combination of the machine tool, the tool holder, and the tool). It makes sense to use both methods, so as to obtain more reliable information regarding the vibrations in the machine tool's elastic system.

The specifics of the self-excited vibration will depend on the particular cutting process in manufacturing. For example, turning on a lathe with a single cutter will differ from multicutter milling by a monolithic or composite tool, since the mill teeth increase the frequency of the external perturbing force. In drilling (countersinking, reaming, etc.), the vibration depends on the torsional vibration of the corresponding axial tools (especially a small-diameter bit with variation in its length).

Methods of simulating technological systems in engineering physics and dynamics are divided into two classes: methods for distributed systems and lumped systems. In distributed systems, the processes are described by partial differential equations; in lumped systems, they are described by ordinary differential equations. In dynamics, as a rule, lumped systems are considered. Various assumptions and simplifications are adopted (for example, reduced parameters and generalized parameters) so as to convert the actual distributed systems to lumped systems.

In the present work, we continue the experimental research of [3]. Specifically, we consider the drilling of small-diameter holes on a 500V/5 machining center with a Siemens SINUMERIC 840D numerical control system (rated spindle speed 1500 rpm, maximum speed 8000 rpm), with the goal of developing a method of tool vibrodiagnostics.

The experimental conditions are as follows: helical bits of diameter 2.85 and 4.7 mm (P18 steel); drilling depth 8 mm; 298 × 110 × 10 mm prismatic workpiece (14X17H2 steel). We use an HSK 63-2/20-100 mandrel with a spring clamp. In drilling, the spindle speed is $n = 250$, 500, and 600 rpm, and the axial supply is 0.06 mm/turn. This axial supply is maintained by the software, by establishing supply levels of 15, 30, and 36 mm/min in the numerical control system. To reduce the test time, no lubricant is supplied to the cutting zone. Each experiment is conducted at least three times; the number of repetitions depends on how similar the results prove to be.

The measuring unit of the automated research system consists of a modular USB system of NI CompactDAQ type, containing an analog–digital synchronizer and a multichannel NI cDAQ-9172 chassis connected to an industrial PC.

Using this computer and LabVIEW 8.5 software, the filters and amplification factors of the measuring unit are adjusted for AP2019 sensors with the follow-

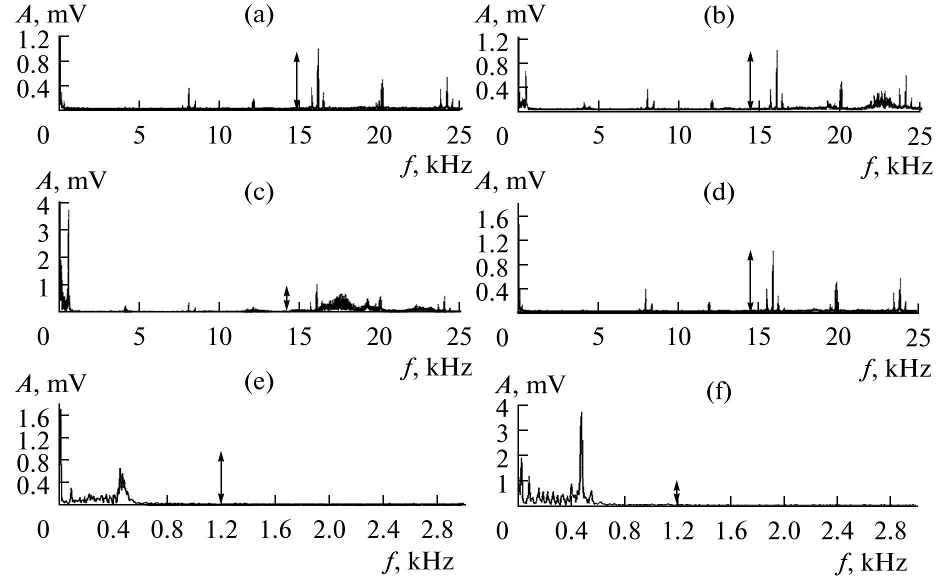

Fig. 1. Spectrograms of axial vibrations (amplitude–frequency characteristics) of the bit with respect to the machine tool's Z axis: after the spindle motor is turned on (a); at the midpoint of motor operation (b); and immediately before (c) and after (d) bit fracture; (e, f) spectrograms within the narrow frequency range 1–3 kHz corresponding to those in Figs. 1b and 1c. The vertical arrows show the scale unit.

ing characteristics: diameter 3 mm; length 3.6 mm; frequency range 0.5–30000 Hz, sensitivity 0.5 mV/g (g = 9.8 m/s^2) or 0.051 mV/(m/s^2). All the tuning operations and the operation of the measuring unit (including selection of the signal-sampling frequency) are controlled by LabVIEW 8.5 applications, which are preliminarily assembled from independent functional modules.

The measuring system may be set up for the collection, analysis, and display of signals from sensors at the immobile end of the spindle (adjusted with respect to the Z coordinate) and immobile lateral sensors (adjusted with respect to the X and Y coordinates). The preliminary measurements of the spindle rigidity are 16.3, 21.6, and 48.5 N/μm along the X, Y, and Z axes, respectively [4].

In this measuring system, analysis of the vibration spectrum within the given frequency range permits not only determination of the time shifts of the signals along the X, Y, and Z axes but also display of the amplitude–frequency characteristic of these signals, which is a better indicator of the changes in bit operation during its wear and failure. In Fig. 1, as an example, we show the spectrograms of axial bit vibrations with respect to the Z axis: after switching on the spindle motor (a); at the midpoint of bit operation (b); and before (c) and after (d) bit fracture. In Figs. 1e and 1f, we show some of the spectrograms within a narrower frequency range.

Analysis of the spectrograms indicates that, in bit operation, some spectral harmonics at particular characteristic frequencies or within the corresponding frequency band are more sensitive to bit wear: correspondingly, the amplitudes at those frequencies increase as wear progresses.

For bits of diameter 2.85 and 4.7 mm, the characteristic frequency reflecting wear of the bit is f_{wi} = 500 Hz, as well as neighboring frequencies in the range 450–550 Hz. Table 1 presents experimental values of the maximum amplitude $A_{w\max}$ and time $\tau_{w\max}$ at a vibration frequency of 500 Hz along the Z axis of the machine tool.

Thus, we measure A_{wi} at f_{wi} = 500 Hz (Table 1). In addition, we determine the machining time $\tau_{w\max}$ corresponding to maximum amplitude: $A_{wi}(500, \tau_{w\max}) = A_{w\max}$. Table 1 also presents mean values of these parameters $A^{\text{ave}}_{w\max}$ and $\tau^{\text{ave}}_{w\max}$, obtained from the results of three experiments for each of the three spindle speeds 250, 500, and 600 rpm.

It is evident from Table 1 that, with increase in spindle speed n from 250 to 500 rpm, $\tau^{\text{ave}}_{w\max}$ rises slightly (from 187 to 229 s). With further increase in n to 600 rpm, $\tau^{\text{ave}}_{w\max}$ falls slightly (to 222 s).

At the same time, with increase in n from 250 to 600 rpm, the mean (over three experiments) maximum amplitude of the vibrational acceleration $A^{\text{ave}}_{w\max}$ increases uniformly from 39 to 63.2 m/s^2.

Besides the characteristic frequencies in the spectrograms of the vibrations with respect to the X, Y, and Z coordinates (the spectrograms for the X and Y coordinates are not shown in Fig. 1), harmonics due to spindle rotation are also present. For spindle speeds of

Table 1

n, rpm	Experiment	$\tau_{w\max}$, s	$\tau^{\mathrm{ave}}_{w\max}$, s	$A_{w\max}$, mV	$A^{\mathrm{ave}}_{w\max}$, mV/(m/s^2)
250	1	183.8	187.1	2.25	1.95/39.0
	2	124.8		1.50	
	3	252.6		2.10	
500	1	204.0	229.3	3.60	2.03/40.6
	2	206.6		–1.30	
	3	277.4		1.20	
600	1	246.8	221.8	3.90	3.16/63.2
	2	274.2		3.10	
	3	144.4		2.50	

Table 2

Fundamental spindle speed, rpm		
250	500	600
Additional frequencies due to spindle speed, Hz		
10, 50, 120	20, 100, 250	20, 120, 290

The additional frequencies are seen on the spectrogram of the Z vibrations by changing the scale on the frequency axis (by means of LabVIEW 8.5 software).

250, 500, and 600 rpm, regardless of the coordinate (X, Y, or Z) and the bit diameter (2.85 or 4.7 mm), all of the spectrograms include frequencies corresponding to the fundamental rotational frequency of the spindle and other structural components of the spindle assemblies: 8, 16, and 24 Hz. At the Z axis, there are three other low frequencies, whose numerical values depend on the fundamental rotational frequency (Table 2).

CONCLUSIONS

(1) We have developed a diagnostic system to study the vibration in cutting processes on a numerically controlled machine tool. It includes the hardware and software for automated research systems based on the NI CompactDAQ measuring system (produced by National Instruments).

(2) The vibrational converters employed are AP2019 sensors, which are compact (diameter 3 mm, length 3.6 mm) and may readily be introduced and adjusted in a 500V/5 machining center.

(3) So as to improve the sensitivity of the vibrosensor signal to change in the tool's cutting properties (as wear progresses), the operational algorithm of the diagnostic system includes a module for converting the time characteristic of the signal to its amplitude–frequency characteristic.

(4) When holes of small diameter (2.85 and 4.7 mm) are drilled in a stainless-steel workpiece, the characteristic frequency reflecting wear of the bit is $f_{wi} = 500$ Hz, as well as neighboring harmonics in the range 450–550 Hz.

(5) Wear of a small-diameter bit is accompanied by the appearance and significant increase of a vibrational-acceleration signal. With increase in spindle speed from 250 to 600 rpm, its amplitude increases from 39.0 to 63.2 m/s^2. After this signal reaches a maximum (at the characteristic frequency), the bit fractures. This information proves useful in bit diagnostics.

(6) The bit life to complete wear and fracture is not very dependent on the bit speed: in the range 250–600 rpm, it is 187.1–229.3 s.

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