Study of Dynamic Impacts at Combined Operations of the Thin Turning and Boring

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Abstract. This research is devoted to the study of the bending vibrations of the developed threaded head design that provides simultaneously both internal and external revolution surfaces' blade processing with the finishing-boring machine tool. The experimental series are carried out on a stand equipped with a vibration spectrum analyzer and a piezo transducer. The amplitudes of bending oscillations are compared during the turning and boring tools separate operation, as well as during their simultaneous operation. A closed computational dynamic model is proposed with motion equations describing vibrations of subsystems "piece – cutting head", as well as the cutting processes during turning and boring. To reduce the vibrations level during separate and concurrent operation of boring and turning cutters, the additional axial vibrations effect in the feed direction produced on bending vibrations normal to the machined surfaces has been studied on a special processing stand. The possibility to decrease (at axial vibrations certain parameters) by 3–4 times the cutting tool oscillations during separate and concurrent operation has been established. Further experiments and theoretical calculations to increase the threaded head efficiency when pieces machining are discussed.

Keywords: Tool head · Turning · Boring · Closed dynamical system · Rigidity · Vibration amplitude · Vibration cutting

1 Introduction

Constantly increasing requirements for machines' performance impose increasingly stringent technical conditions on their manufacturers. Strict requirements for product quality indicators in the face of fierce competition are often contradictory, and the traditional approaches to the search for technological solutions are often unpromising. These engineering technology dynamics' problem statement and solution are presented in a new direction, that we identified as the 'technological dynamics". The technological dynamics is an integral part of the mechanical engineering technology and determines the vibrations' influence on the machining accuracy.

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2 Literature Review

The modern stage of engineering technology development reflecting new advances in the design, manufacture, and assembly of technological systems requires solving several problems based on the study of dynamic interactions when profile shaping with a blade tool [1–4].

It is advisable to highlight some problems specifically related to the technological dynamics field [5]:

– adjustment of recommended cutting conditions with a view to minimize vibrations amplitudes;
– the effect of technological operations concentration and combination on the change in vibrations level and the machining precision characteristics;
– the effect of vibrations in the technological system on machining quality and accuracy;
– vibrations damping [6, 7];
– the development of criteria for calculating vibrations levels, taking into account the machining precision;
– calculations of static and dynamic processing errors.

Several other equally relevant technological dynamics problems can be formulated, however, to underline the decisive influence of vibrations' processes in finishing precision machining, especially at non-standard conditions, for example, when long shafts (holes) fine turning (boring), at intermittent cutting, impact cutting (milling), etc. In these conditions it is very important to study the technological systems' vibration resistance [8, 9, 10].

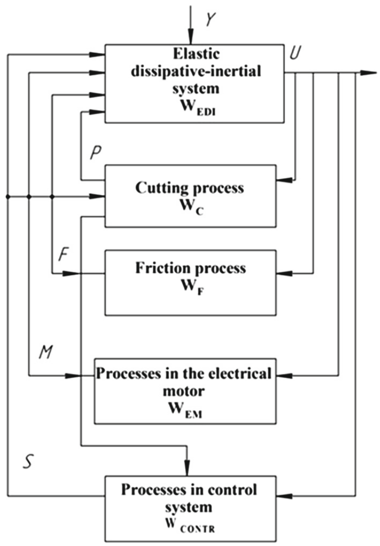

Fig. 1. Closed dynamic system [8].

The main engineering provision at technological dynamics is the dynamic system closedness, taking into account the interaction between the machine-tool equivalent elastic system and working processes. Studying the machine as a multi-circuit automatic control system, we can consider the criteria for its vibration resistance, speed, idle run vibrations level, etc.

Thus, the vibrations arising in the elastic-dissipative-inertial system (EDIS) are predetermined by the presence of feedbacks created while working processes (WP), i.e. cutting and friction processes, processes occurring in electric motors, in hydraulic actuators, in control systems (Fig. 1).

In accordance with the general vibrations theory, studying the dynamic processes, it is necessary to distinguish the vibrations' physical nature, their temporal and spatial forms. In the general case, dynamic processes during cutting are determined by the superposition of self-vibrations, free, forced, and parametric vibrations; thus, depending on the specific machining conditions, each type vibrations may be dominant.

3 Research Methodology

In this paper, using the experience in solving dynamics problems, series of design and technological solutions are considered aiming at improving the performance while ensuring the machines surface required accuracy characteristics with the use of experimental and computational methods.

This research object represented the original design cutting head, embodying the idea of combining processed piece and concentrating two final finishing operations: boring and turning. The cutting head can rotate, and the piece shall perform the feed movement, or vice versa: the piece is mounted on the spindle flange, and the cutting head is attached in the device producing a feed movement. The processed pieces' samples set includes: a sleeve, a hollow shaft, a pipe, a rack element, etc., and both the cylindrical surfaces to be machined have a common axis.

The technological task herein investigated allows to get at least three positive results: a combination of operations that allows reducing the processing time, the ability to process low-stiff thin-walled pieces (provided by the cutting forces reciprocal direction that compensates their deforming effect), as well as achieving high axial alignment of the surfaces machined with a tool which rotation axis coincides with one of piece due to mounting on a common spindle.

The designed and practically implemented cutting head with two simultaneously operated cutters is shown in Fig. 2. Figure 2a shows its structure, and Fig. 2b represents a general view.

The design is based on well-known chisel heads for turning, which, without forming a single assembly, are separately used for turning the same piece's outer surface and boring the inner one.

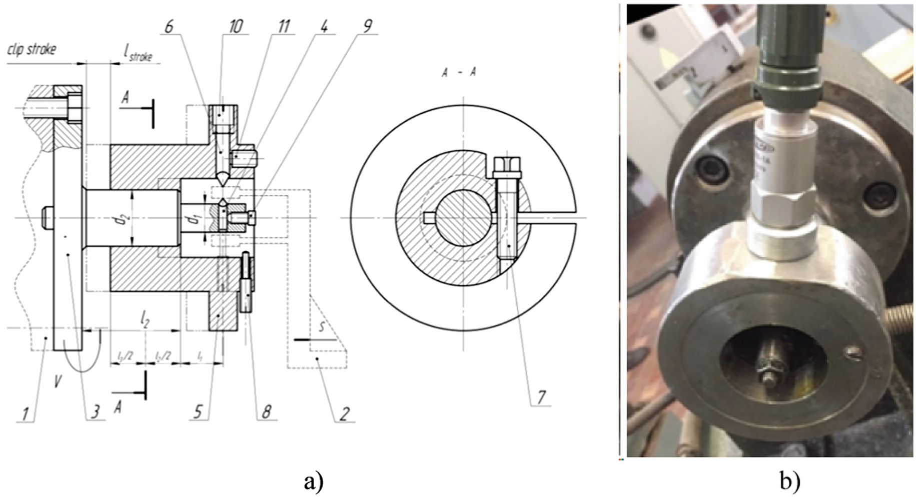

Fig. 2. Cutting head: (a) structure; (b) general view.

The cutting head is fixed on the spindle flange 1 (fixture) of the finishing boring machine-tool. The workpiece 2 is fixed in the fixture. The cutting head consists of boring bar 3 with a cutter 4 for boring, and a holder 5 with a cutter 6 for turning. The workpiece 2 is installed coaxially to the cutting head rotation axis. To set the cutters 4 and 6 position, the holder 5 is transferred (shifting to the left until it stops) into the adjusted position and fixed with a screw 7. The boring bar 3 has a cutting part of l_1 length and d_1 diameter and a fitting part of l_2 length and d_2 diameter that mates on the slip fit *H7/h6* with the holder 5. The holder 5, shifting within the stroke limits l_{stroke}, alternately takes two positions: working, i.e. the extreme right (solid lines) and adjusting i.e. the extreme left position (dash-dotted lines). Both positions of the holder 5 are fixed with a terminal connection using screw 7. Note that the holder 5 being in adjusting position, the access to cutter 3 is open and its longitudinal axis coincides with the axis of the adjusting screw 8, which sets the desired position of cutter 4 fixed by the locking screw 9. The adjusting position of holder 5 also allows us to set the desired position of cutter 6 with a screw 10 and fix it with a locking screw 11.

The task of studying the considered variant of boring head design for the vibration resistance and operability supposes the practical tests results' analysis with further comparison to the vibrations calculations data for the selected dynamic model. The cutting head design schematic sketch as shown in Fig. 3 was the basis for the studied design model development.

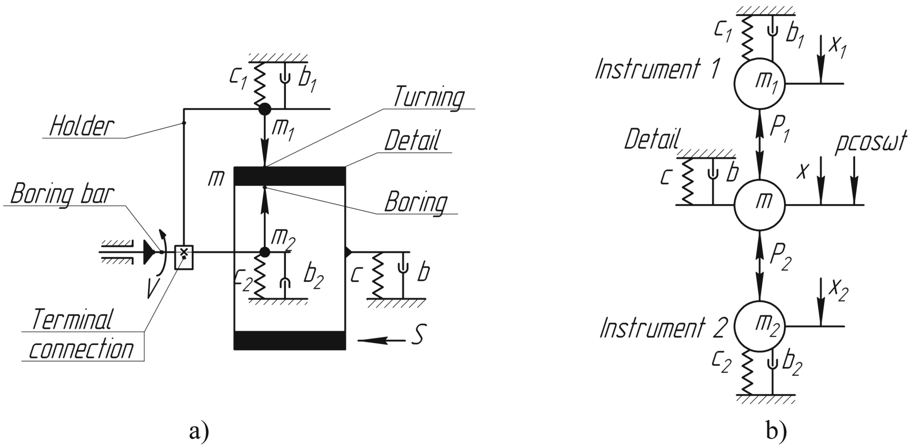

Fig. 3. Dynamic models: a – machining design scheme; (b) design model with effective forces; C_i – stiffness coefficients, b_i – dumping coefficients, m_i – equivalent mass.

To solve problems on vibrations and vibration resistance of some elastic system interacting with two cutting processes, we apply driving forces or kinematic perturbations. To render the solution more definite, we further assume the elastic system influenced by the harmonic driving force $p \cos \omega t$, applied to the piece from the side of its mounting on the machine table. Thus, we distinguish three vibrating subsystems: this one of workpiece, the subsystem of holder for turning, and the subsystem of boring bar for boring. Each of these subsystems is described by a linear link with lumped parameters: mass m_i, stiffness C_i and damping coefficient b_i. The main interactions between subsystems occur through cutting processes. The theory of cutting process dynamic characteristics description, often used in dynamic calculations, which characterizes the process inertia: the cutting force P phase lagging respectively to the change in the cut thickness u, as well as its dependence on the rate of change, can be represented as

$$T_p \frac{dP}{dt} + P = -K_p \sin \varphi_u U + K_s \cos \varphi_u \frac{dU}{dt} \quad (1)$$

where T_p is chip cutting time constant,

K_p is cutting coefficient (cutting rigidity),
φ_u is angle, projecting the vibrations' direction on the main cutting movement direction,
K_s is cutting speed coefficient.

This use of the formula in our two cases requires clarification. Studying this threaded head design of great interest are the vibrations normal to the treated surfaces and directly affecting the longitudinal- and cross-sections shape as well as processing roughness. Therefore, the computational model is constructed as one-dimensional with one coordinate axis X coinciding with axes X_1 and X_2 for boring and turning, respectively (Fig. 3(b)). The X axis is directed upward perpendicular to the rotation axis and coincides with the position of cutters' tips. The projecting angle φ_u becomes equal to 90°, thus excluding from consideration the velocity coefficient K_s. It is also worth noting that the structure formation time constants' numerical values: Tp_1 - for turning and Tp_2 - for boring, as well as the cutting coefficients K_{p1} - for turning and K_{p2} - for boring must take into account the features caused by processing the same material when same speed and same feed values. The dynamic displacements coordinates of the three generalized masses m, m_1, and m_2 are denoted by x, x_1, and x_2. The force P acquires the meaning of cutting forces components P_1 and P_2: P_{p1} when turning and P_{p2} when boring. A variant of the calculated dynamic design cutting head scheme, interacting through cutting processes with the machines piece, is shown in Fig. 3. A piece of mass m, moving in the x-axis direction, is shown conventionally resting its right end into a fixed support (Fig. 3(a)), that imitates its high rigidity in this direction. Elastic damping suspensions of masses m, m_1 and $m_2$are shown conventionally offset from x-axis that describes their movement.

The movement equations system shall be:

$$\begin{cases} m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + cx = P_1 + P_2 + p\,\cos\omega t, \\ m_1\frac{d^2x_1}{dt^2} + b_1\frac{dx_1}{dt} + c_1x_1 = P_1, \\ m_2\frac{d^2x_2}{dt^2} + b_2\frac{dx_2}{dt} + c_2x_2 = P_2, \\ T_p\frac{dP_1}{dt} + P_1 = -K_{p1}x_1, \\ T\dot{P}_2 + P_2 = -K_{p2}x_2 \end{cases} \tag{2}$$

Further transformation of the system (2), with the transition to dimensionless parameters and the vibrations amplitudes calculation results will be considered in the following studies of simultaneous finishing turning and boring processes.

Experiments on the study of dynamic interactions when turning and boring with a cutting head have been carried out on a special stand assembled on the basis of a finishing boring machine. The experiment tools included a set of incisors, which geometry is recommended for fine cutting, cutting modes also varied while experimental series; samples used were made of steel 45. Vibrations were measured with a piezometric transducer and visualized on a PC using the ConSpect program.

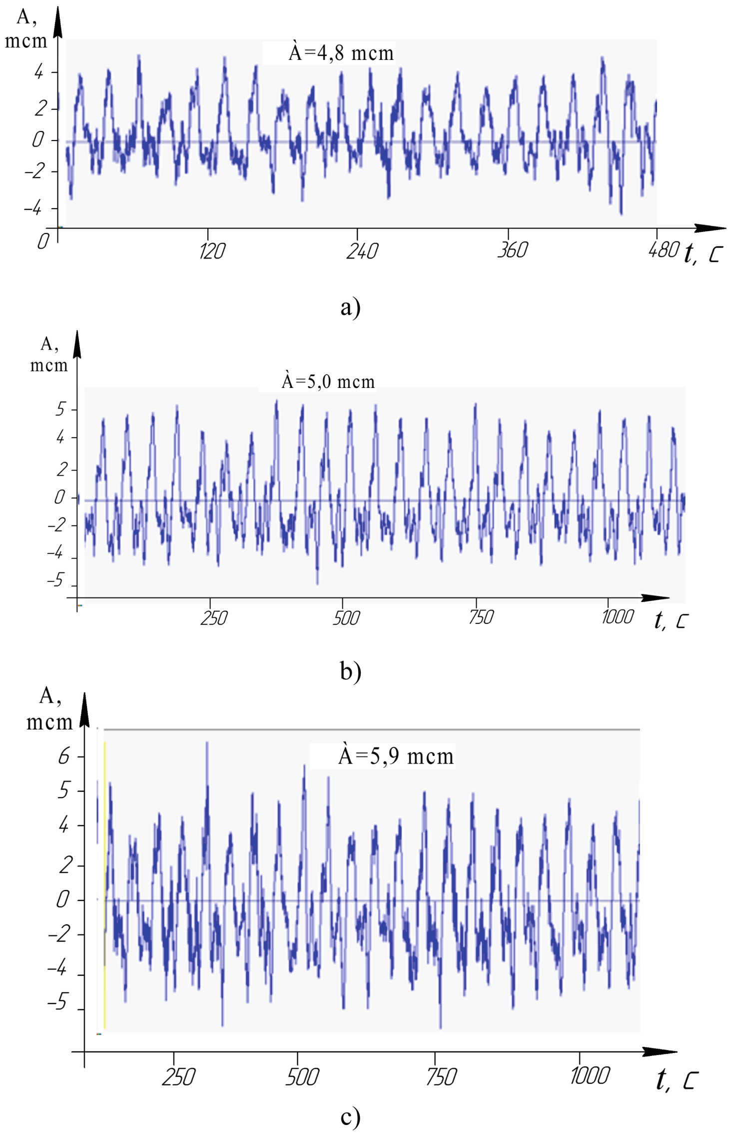

Fig. 4. Oscillograms of vibrations at t = 0.05 mm, $f_{вр}$ = 16 Hz, s = 0.8 mm/s; (a) boring; (b) turning; (c) concurrent boring and turning (part measurements).

4 Results

Experimental measurements of the stiffness of the closed system of the process are: the rigidity of the cutting head 10 N/mm, the boring bar 16 N/mm and items fixed in the spindle head, of 11.5 N/mm. Figure 4 shows the results of forced vibrations amplitudes measurements taken separately at boring, turning, as well as when two cutters simultaneous operation.

The results analysis allows estimating vibrations amplitudes values under different machining conditions, denoting that with simultaneous operation of boring and turning cutters, the total vibration amplitudes slightly differ from the amplitudes registered when cutters separately operated under the same cutting conditions. It should be noted that in some experiments, an increase in the total amplitudes (~ 1.5 times) compared with the amplitudes during separate operation was registered.

To assess the possibility of reducing the forced vibrations amplitudes, experiments were performed engaging additional vibration effects that affect the cutting head bending vibrations. Several researches on vibration cutting describe the positive effects of flexural vibrations damping with the help of axial vibrations.

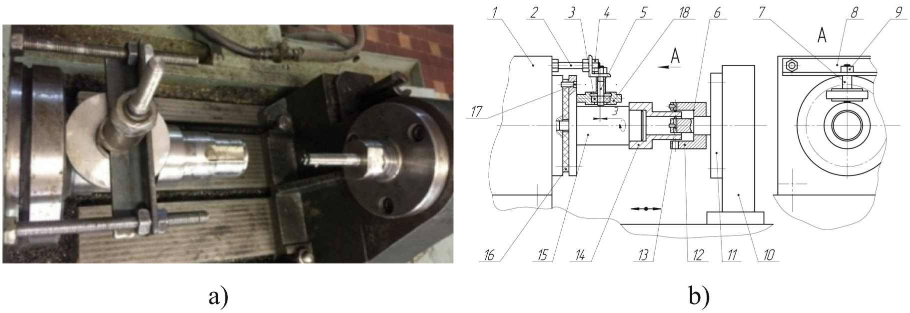

Fig. 5. Experimental stand for oscillations study with axial vibrations: (a) photo of the stand; (b) vibration drive design.

Experiments included stand studies (Fig. 5) of the vibrations effect along the feed direction on the cutting head bending vibrations normal to the machined surface.

The machined workpiece 4 was attached to the mounting mandrel 15, which flange was pressed to the spindle head flange 1 through an elastic gasket 16 using screws 17. The elastic gasket 16 (8 mm thick) had axial rigidity equal to 2 N/µm. Eccentric roller 18 mounted on axis 5 (e = 0,2 mm) with the bearing 3 was pressed against the adjusting mandrel rotating flange; at that the friction forces ensured the roller rotation and axial vibrations transmission amplitude of 0,2 mm and the roller rotational speed of 18 Hz at spindle rotation frequency of 16 Hz. Force clamping the roller to the rotating piece flange was regulated by means of a stud 2, a nut 4 and a corner. The cutting head with a turning cutter 6 and a boring cutter 13, with a boring bar 11 and a sleeve 12 was fastened in the fixture 10. When assembling the stand, the alignment between the mounting mandrel, the processed piece, and the cutting head was ensured.

Refer to view A for positioning of the spindles relative to the spindle head housing, the bracket 8 and axis 5 mounting details.

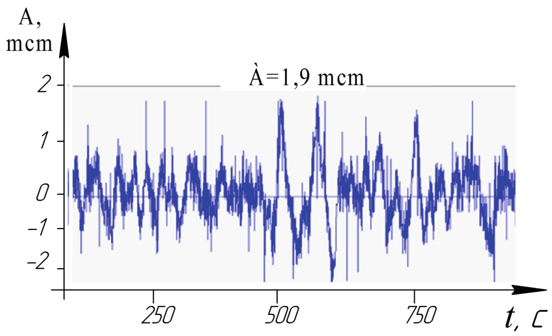

Fig. 6. Oscillograms of vibrations when axial vibrations imposition at t = 0,05 mm, $f_{вр}$ = 16 Hz, s = 0,8 mm/s; boring and turning at the same time.

The roller's rotation during the eccentricity provides a harmonic force perturbation along the feed direction due to periodic elastic deformations of the elastic gasket. In the experiments, the vibration machining modes providing a significant decrease in the bending vibrations amplitudes are identified when periodic axial perturbations (Fig. 6), at that the vibration amplitudes decrease by 2–3 times.

The beneficial effect of axial forced vibrations has been established to be accompanied by the variability of cutting coefficients Kp, which generates additional friction forces. It is worth noting that active vibration damping was achieved in our experimental series with sufficiently large amplitudes of axial vibrations, involving a change in the state of the layer being cut.

5 Conclusion

In the study, in accordance with the technological provision for operations concentration and combination, the design of a cutting head for the simultaneous finishing turning and boring of rotation surfaces was investigated. The tool forced bending vibrations amplitudes for simultaneous and separate operation of the cutters are identified:

- it was experimentally established that the simultaneous interaction of two cutting processes that occur during boring and turning can either increase or decrease the vibrations of the workpiece;
- a decrease in the amplitudes of oscillations is determined by a combination of dynamic parameters of the subsystem of the boring and turning tool;
- dynamic computational models have been developed to determine the vibrations amplitudes;

– experimentally established the useful effect of axial forced vibrations on bending the vibrations damping.

A program for PC-aided calculations at further research is developed to determine combinations of cutting modes, cutting head static and dynamic parameters during turning and boring to determine the minimum amplitudes while turning and boring.

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