Control of mobile equipment for the processing of marine shaft lines

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Abstract. The purpose of the research is to develop solutions for mobile equipment control in the processing of marine shaft lines; to solve the issues of geometric accuracy of processing; to create a corrective program to address the issues of accuracy of the geometric parameters processing; to give reasons for the application of linear electrohydraulic step drive (LEHSD) in mobile equipment control. The analysis of schemes and mathematical dependencies for calculating the trajectory of the tool movement of a mobile machine when processing shaft lines is carried out; the choice of the optimal zone for finishing the shaft line, taking into account the beats. The object of the study is a ship shaft line. The paper presents an original scheme of rotation of the shaft line section, as well as schemes for changing the position of the shaft line during processing; justifies the possibility of using a linear electrohydraulic step drive (LEHSD) with a corrective program for processing taking into account automatic measurements and a specified error.

1. Introduction

The increasing hydrodynamic forces acting on ship shaft lines and stern tube assemblies due to the increased power of main propulsion units, size and mass of propeller screws and shafts of modern naval vessels require continuous control of the quality of the shaft surface layer, the correctness of the geometric cylindrical shape of both the shaft itself and the bearing surfaces that ensure its rotation. Uneven friction wear of shafts necks, fretting corrosion, cracks, corrosion of shaft surface, scuffing and other damages are eliminated by grooving with subsequent surface plastic deformation. More detailed analysis of defects arising during operation of shaft line parts of sea and river vessels, as well as methods of their elimination are considered in paper [1].

The alignment of the shaft line axis plays a special role in ensuring optimal operation modes and grooving. The adjusted alignment ensures that the shaft line and associated mechanisms are brought to a position thus ensuring the rational distribution of loads on the shaft line components, its supports and the engine. Traditional methods of aligning shaft lines by fractures and displacements, centering methods by changing the actual loads have a measuring error of up to 10% and experimental errors caused by a human factor. The latest alignment techniques – finite element analysis ANSYS, laser-computer alignment, automated alignment on bearing loads – require calculations of process parameters both during installation and operation, and during pre-repair fault detection of the shaft line [2]. The same parameters shall be taken into account in the shaft line grooving to eliminate defects. At the same time, it is necessary to form a strictly cylindrical profile of the shaft line. The measuring system...
in this case may be operated as defining for input parameters in processing automation. The method to control the geometric accuracy of ship shaft lines proposed in [3] takes into account radial beats of cross section, deviations of shaft real profile from cylindrical shape. The study proposes the algorithm to calculate the geometric accuracy of shaft shape, scheme to measure the error of shape and position of axis of composite shafts. Design of the unit to control the geometric parameters is developed and tested, possibility of automated processing using proposed algorithms is justified. The authors’ conclusions make it possible to supplement the method of calculating the shaft line with dynamic numerical models obtained on the basis of a digital analogue of the shaft line or its elements.

Many scientists worked to optimize the cutting process and improve the processing accuracy. Works [5, 8, 9, 10] emphasize the relevance of numerical-software control in part process. The advantages of part process on CNC machines include reduced preproduction time, high technical level of processing quality, reduced labor intensity and duration of production processes, programs for automatic control of processing, minimization of random factors. The disadvantages include the complexity of implementation and the need to equip machines with numerical software control.

The object of the study is a ship shaft line, the purpose is to create a method for ship shaft line grooving and to study the possibility of processing automation taking into account the geometric accuracy of deviations of the real profile from the cylindrical shape.

The shaft line of the ship engine is considered unstiffened in the sense that:

- first, its rotation axis is not stationary, its position depends on the quality of alignment, the quality of the cylindrical shape of the shaft and rollers, the quality of the surface of the shaft and rollers;
- second, the intrinsic compliance of the shafts far exceeds that of the process system. The ratio of the length L to the diameter D of such shafts is more than 12 (L/D>12). For large-tonnage ships, in which the shaft diameter reaches 900 mm, turning operations are carried out on special unique shaft lathe machines with a base of much more than 10 m. In this case, the presence of cutting forces leads to oscillations, and the technological system becomes very sensitive to external forces accompanying the cutting process.

Therefore, processing of shaft lines is very difficult, and the most efficient may be the automated processing with program control, which can ensure the stability of the system during processing. The spatial position of the mobile machine plays an important role in ensuring the geometric accuracy of shaft rework. Each machining of a part requires a machine geometry that is parallel to the cutter tip feed line and the machined part axis.

2. Materials and methods
The analysis of diagrams and mathematical dependencies for the calculation of motion trajectory of a mobile machine tool during processing of shaft lines providing the geometric accuracy of cylindrical resurfacing was carried out [4]. The scheme for the calculation of the error correction of the initial setup of the machine, the original scheme for the calculation of the error correction of machine setup during subsequent processing, as well as expressions for the calculation of errors and the direction of cutter feed allow considering the direction of the cutter feed during processing. Shorter shafts, such as a step shaft of an engine, are traditionally processed on stationary lathe machines firmly fixed on the rotation axis. Their generatrix is formed based on the geometry of the cutter movement according to the program or the template feedback. Rigid positioning of the part does not exclude the need to optimize the cutting modes, increase the stability and operability of the tool, increase the rigidity of the technological system and balance, as well as the accuracy of processing. These tasks are successfully solved using CNC machines. This suggests the need to equip CNC machines with an adaptive cutting tool control system to ensure the geometric accuracy of machined parts. The ship shaft line has a non-stationary rotation axis, which significantly complicates the process of creating the correct cylindrical shape during processing. Therefore, all the above tasks are saved alongside with additional accounting for beats during the shaft line rotation, the need to use measuring systems, which data would allow quickly changing the cutter feed during processing. There are known devices and techniques for automatic measurement of parameters of cylindrical parts [3].
Using these devices and guided by the cutting tool position correction schemes we propose an original method of installing a mobile machine controlled by a linear electrohydraulic step drive with a small stroke and numerical program control.

![Figure 1. Scheme of the shaft line section rotation: 1 – shaft line section, 2 – flanges, 3 – shivers, 4 – drive belts, 5 – electric motor of controlled electric drive, 6 – support bearings or lunets](image)

It is proposed to use a portable small-sized machine for the repair of shafts of large-capacity sea vessels, which allows implementing both turning and grinding, and in the presence of a milling head – the milling of the shaft line.

Since there is uncertainty of the rotation axis of the shaft line, and during the recovery treatment there is a decrease in diameter, the defects must be cut so that the rotation axis retains its previous position relative to the body and rolling bearings of the shaft line.

![Figure 2. Schemes for changing the position of the shaft line: a) at single asperity δₐ; b) after passing to the depth t](image)

Beatting on a cutter at an incorrectly selected cutting depth leads to tool breakdown and damage of the rolling surface, and even to the deterioration in its shape – with each turn the defect is “reproduced” in the same dimensions. In general, the value of beat \( \Delta_n \) depends not only on the defect value \( \delta_a \), but also on the angle \( \varphi_p \) of the tool location relative to the shaft (Figure 2, a):

\[
\Delta_n = \delta_a \left( a \cos \varphi_p + b \sin \varphi_p \right) b^{-1},
\]
where \( a = 0.5 (R - r) \) – half of the distance between the bearing axes at the angle \( \psi = 60^\circ \), \( b \) – height of the shaft line axis relative to the bearing axes.

With sufficient accuracy the beating may be defined as

\[
\Delta_n = 1.155 \delta_0 \cos \left( 60 - \varphi_p \right)
\]

For these conditions the relative beating value \( \delta_{do} = \Delta_n \delta_{dl} \) for some angles is shown in Table 1. The table shows the relative beat in the presence of only single asperity \( \delta_{do1} \), single depression \( \delta_{do2} \) and simultaneously a depression and protrusion \( \delta_{do0} \) in their worst relative position when they are simultaneously on bearings. It should be noted that \( \delta_{do0} = 0.5 \) at \( \varphi_p \approx 124.34^\circ \).

**Table 1.** Relative beating of the shaft line in the presence of protrusions and depressions on the surface

| \( \varphi_p \), deg | 0  | 30  | 60  | 90  | 120 | 150 | 180 |
|---------------------|----|-----|-----|-----|-----|-----|-----|
| \( \Delta_{do1} \)  | 0.577 | 1  | 1.154 | 1  | 0.577 | 0  | ( ) |
| \( \Delta_{do2} \)  | -0.577 | 0  | 0.577 | 1  | 1.154 | 1  | 0.577 |
| \( \Delta_{do0} \)  | 0  | 1  | 1.731 | 2  | 1.73  | 1  | 0  |

The greatest beating for \( \delta_{do0} = 2 \) is observed in the zone \( \varphi_p = 90^\circ \). It is least favorable for correcting the beat and improving shape. From this point of view, the zone \( \varphi_p = 180^\circ \) is the most acceptable. Obviously, due to the defect there should be a different initial position (Figure 2, a) of the tool (moment of touch) depending on where the cutter (processing area) will be located at the angle \( \varphi_p \). The proposed relationship for assigning the cutting depth \( t = \delta_d/2 \), where \( k \) – processing pass number, which practically sets the alignment coefficient \( K_{al} = 0.5 \), will not work effectively in all positions of the machine. So, at the alignment coefficient \( K_{al} > 0 \) in the zone \( \varphi_p = 90^\circ \) when eliminating a single defect, the “reproduction” of the error will be observed. At \( \varphi_p = 120^\circ \) it is possible to use the alignment coefficient \( K_{al} \leq 0.423 \) to eliminate the single asperity; and at \( \varphi_p = 124.34^\circ \) – \( K_{al} \approx 0.5 \).

The installation base of the shaft line is formed as a connection with bearing supports. Due to the final stiffness of this connection it is possible to deflect the shaft line with the treated surface so that the rotation axis remains parallel to the axis of the shaft during deflection. At the beginning of processing, the process base is the machined rolling surface. As its width decreases during processing (to the value \( a \), Figure 3, 2), the moment comes when the remaining surface under the influence of pressure is plastically deformed and decreases (Figure 3, 3) in diameter to \( D1 = 2(R-h) \).

**Figure 3.** Instability of the linear generatrix of the shaft line: zone 1: 1 – plastic deformation (PD) is absent, 2 – beginning of the PD; 3 – result of processing; zone 2: 4 – beginning of PD; 5 – result of processing (here \( a – PD \))
At the same time, the surface with a diameter D1 becomes the technological base until the end of the passage. As a result, the diameter of the surface after treatment from the moment of deformation to the end of the passage (Figure 2, b) will have a diameter equal to D2 = D1 − 2 h (ϕр). Besides, in the zone ϕ < 90° the surface will “leave” from a cutter and under the influence of high pressures will be rolled out (Figure 3.4 and 3.5) to the diameter close to D2. This section on the periphery of the shaft line is the source of cracks and delamination of the surface edges. At the end of the passage, the cutter will deepen into the rolling surface forming a shape close to the oval one in the zone ϕ > 90°.

It is known that at the end of the passage the best conditions for obtaining high accuracy in the absence of beating are observed in the zone ϕ > 90°. Thus, this zone may be recommended for finishing when the beating is eliminated. The zone ϕ > 90° is characterized by an increase in error at the end of the passage. The greatest error is observed in the zone ϕр = 180°.

Thus, to ensure high accuracy of a part that does not have a stationary rotation axis it is necessary to:

• control the cutting depth during machining on the basis of the results of the initial and processed surface inspection, which is most expedient using CNC technology and modern technical measurement tools;
• mobile equipment shall have a reliable lateral feed tracking support ensuring, according to the results of active control, a cylindrical (or predetermined) shape of the treated surface that meets the requirements for the parts of the furnace support units with sufficiently productive cutting modes;
• automatic controlled cutting technology, which will achieve the highest accuracy of processing parts with minimum labor costs and expenses, which should be provided by a new method of obtaining a given accuracy of the shape of the treated surface based on active control, is the best assembling technology for the repair of the shaft line.

The developed devices for automatic measurement of cylindrical shape parameters [2, 3], as well as procedure for determining the geometric parameters of rolling surface shape of large-sized cylindrical parts with nonstationary rotation axis set the task of choosing the control device for cutting in the mode of error accounting and simultaneous correction of cutting tool installation and adjustment of cutting forces [4]. Processing requires the use of a fast-acting support with a small stroke controlled automatically.

As the actuator of the drive we propose to use a hydraulic cylinder as part of a linear electric step drive (LEHSD), which may provide high speed, which is especially important when processing a distorted profile of the shaft line. The choice of LEHSD is made on the basis of the study of dynamics, which determines the operability of the drive, processing accuracy and speed. The LEHSD use makes it possible to implement digital control quite easily and meets the requirements of compactness and convenience of layout on the transverse support. The diagram of the power transmission system (Figure 4) in the drive with feedback on the movement of the transverse support is protected by patent No. 91746 of the Russian Federation, MPK F15B21/08 “Automatic step linear electrohydraulic drive” [11].
3. Results and discussion
The results of experimental processing confirm the results of studies on the drive dynamics and the preservation of the stability of the position of the transverse support, which indicates the operability of
the mobile machine and the possibility of its use for processing shaft line. A correction program may be implemented using CNC based on LEHSD, which will provide a cylindrical surface (or other specified profile) based on the results of measuring the first passage when installing the machine with an error relative to the axis of the part.

The original rotation scheme of the shaft line section is presented, as well as the diagrams for changing the position of the shaft line during processing. The possibility of using a linear electrohydraulic step drive (LEHSD) with a corrective program for processing taking into account automatic measurements and a given error is justified.

It is possible to implement a corrective program using CNC on the basis of LEHSD that allows obtaining a cylindrical surface (or another given profile) based on the results of measuring the first passage when installing the machine with an error relative to the axis of the part.

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