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Vector analysis of the accuracy of the layout of automatically replaceable systems for delivering laser radiation to the processing zone

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Vector analysis of the accuracy of the layout of automatically replaceable systems for delivering laser radiation to the processing zone

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Abstract. The paper discusses the methodology for calculating the errors in the layout of systems for delivering laser radiation to the processing zone on the example of laser modules of CNC machines. A vector analysis of the accuracy of individual blocks in the composition of such laser modules is performed. A technique is proposed for calculating the error in positioning a laser beam depending on the number and use cases of blocks and their noncollinear axes in the laser module. Errors associated with the laser module used for private technical design, a set of blocks and their kinematic relationships, are considered. The factors affecting the error in the arrangement of transmission devices in the laser radiation processing zone are established. The proposed methodology allows us to solve both the direct and inverse problems of calculating the errors arising during the arrangement of transmission devices in the laser radiation processing zone.

1. Introduction

At present, when developing new or improving old designs of systems for delivering laser radiation to the treatment zone, the issue of lossless energy transfer is acute. In the case of using low-power radiation sources and solving engraving problems, or cutting small thicknesses, this does not greatly affect the processing process. When solving problems of laser welding, surfacing, cutting of large thicknesses and the use of high-power radiation sources and complex multicomponent systems for delivering radiation to the treatment zone, a lack of energy in the treatment zone can have a significant effect on the processes that are taking place. Therefore, the search and development in the field of reducing losses in the transfer of laser energy are relevant.

To date, the market for laser technological heads for fiber optic lasers is represented by devices for the tasks of engraving, welding, cutting, surfacing, hardening, etc. A common structural feature of these is the axial layout of the nodes of such devices. This requires a high accuracy of beam positioning inside the device. The disadvantages of the devices under consideration include a large number of connections and elements of assembly units, the need to maintain a certain accuracy of assembly of the device, especially in the axial directions, an insufficient level of interchangeability of elements of assembly units of laser heads, high requirements for the accuracy of positioning of the device in the working area, laser or machine with CNC.

This work is aimed at solving the problem of ensuring the required accuracy of the arrangement of laser heads in order to ensure the required accuracy of beam positioning directly in the processing zone.

A number of works [1–9] describe possible solutions to this problem and device layout using new assembly principles. In particular, it is proposed to consider the device of the laser head (hereinafter referred to as the module) as the result of a block-modular arrangement of interchangeable structural elements (blocks). At the same time, the structural design of the module is structurally ensured depending on the technological requirements of laser processing, which will provide flexibility and high economic efficiency of using such modules in production.

In this regard, it is necessary to develop a methodology for calculating errors in the layout of module blocks to solve issues of their interchangeability and to ensure structural accuracy when reconfiguring with respect to a given parameter of the error in positioning the laser beam at the head exit.

2. Research methodology

Let us consider the accuracy of the location of the axis of each module block from the point of view of vector analysis: it will be determined by the projection value of the vector passing through the axis of the module on the axis of the device. A laser beam is a vector emanating from a radiation source. In this regard, a constructive analysis of accuracy will also be carried out in vector form.

The error of the laser beam εR will be the sum of the mismatch between the projection values of each radius of the vector and the scalar of each radius of the vector.

Let us consider the options [10] for the layout of automatically replaceable laser modules (hereinafter U module) based on four main blocks. These are the unit of the mounting element $U_1(N_m)$, the unit of the optical system $U_2(N_m)$, the unit of the laser beam delivery system $U_3(N_m)$, the unit of the laser power supply $U_4(N_m)$. Let the execution of the module $U1_i$ be given (figure 1). Its structural formula W_U has the form according to (1):

$$W_U = U_1(N_m) \cdot P5 + U_2(N_m) \cdot P4 + U_3(N_m) \cdot P3 + U_4(N_m) \cdot P2 + U_5(N_m) \cdot P1 + Q + F \quad (1)$$

where N, m, n parameters allow choosing a set of primary and secondary $U_5(N_m)$ module blocks. $P5, P4, P3, P2, P1$ – the number of kinematic pairs of the corresponding class (5, 4, 3, 2 and 1), forming a kinematic chain module. Q , F - the number of additional degrees of mobility of the module.

Option A) (figure 1(a)) of the module layout U with optional longitudinal feed unit $Q = 1$ - its structural formula has the form (2):

$$W_{UA} = U_1(N_m) \cdot P5 + U_2(N_m) \cdot P4 + U_3(N_m) \cdot P3 + U_4(N_m) \cdot P2 + U_5(N_m) \cdot P1 + 1 \quad (2)$$

For option B) the layout of the module (figure 1 (b)) with an additional rotation unit, the structural formula has the form (3):

$$W_{UB} = U_1(N_m) \cdot P5 + U_2(N_m) \cdot P4 + U_3(N_m) \cdot P3 + U_4(N_m) \cdot P2 + U_5(N_m) \cdot P1 + 1 + 1. \quad (3)$$

Structural formula (3) takes into account that the number of additional kinematic connections of the module $Q = 1$, and the number of excess (additional) degrees of mobility as a result of installing an additional rotation unit for the optical system $F = 1$.

For option C) the layout of the module U (figure 1 (c)), the structural formula has the form (4):

$$W_{UC} = U_1(N_m) \cdot P5 + U_2(N_m) \cdot P4 + U_3(N_m) \cdot P3 + U_4(N_m) \cdot P2 + U_5(N_m) \cdot P1 + 1 + 2. \quad (4)$$

The structural formula (4) takes into account that the number of additional kinematic connections of the module $Q = 1$, and the number of excess (additional) degrees of mobility as a result of installing an additional axial displacement block for the optical system $F = 2$.

Expressions (2-4) show that when re-arranging the module according to options A, B, C, the number of additional connections of the module is constantly calculated to expand its functionality.

3. Practical significance

Let us present the layout diagram of each of the considered modules (figure 1) in vector form (figure 2). In the space N_i for each vector r_i we assign the value of its scalar - equal to the length l_i of the cylindrical section tied to the circle O_n.

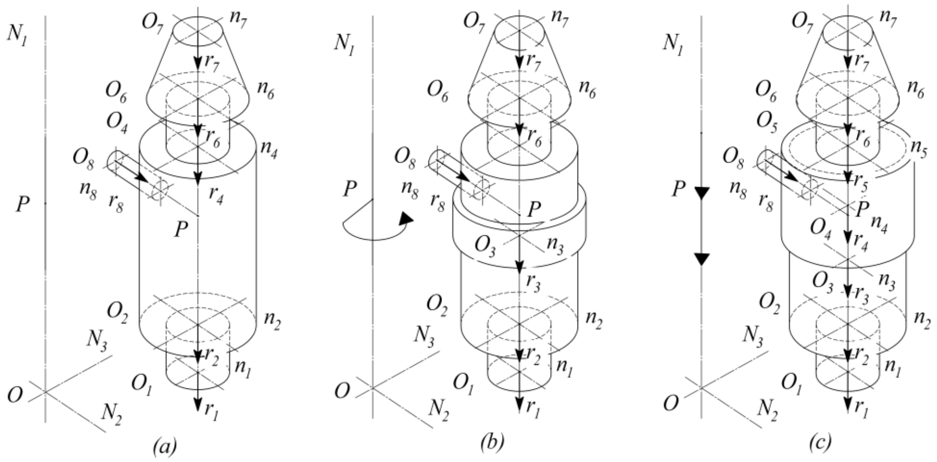

Figure 1. Block diagrams of the layout of the laser module.

Each module block $U_1(N_m)$, $U_2(N_m)$, $U_3(N_m)$, $U_5(N_m)$ is defined by the parameters r_i and l_i of one (or two for the conical block $U_1(N_m)$) of the circle n_i. Pole P is the junction point of the collimator and fiber optic wire. Let the axis N_1 be collinear to the axis of the output laser beam of the module, and the axis N_2 to be collinear to the axis of the input laser beam. To solve the accuracy problem of the module, it is necessary to ensure the orthogonality of the axes:

$$N_1 \perp N_2 \tag{5}$$

To fulfill condition (5) for vectors r_i of each axis N_i collinearity condition must be met:

$$(\overrightarrow{r_1} \parallel \overrightarrow{r_2} \parallel \overrightarrow{r_3} \parallel \cdots \parallel \overrightarrow{r_n}) \parallel N_1 \text{ и } (\overrightarrow{r_1} \parallel \overrightarrow{r_2} \parallel \overrightarrow{r_3} \parallel \cdots \parallel \overrightarrow{r_m}) \parallel N_2 \tag{6}$$

Then, according to (5), we obtain the collinearity condition for the blocks of the laser module:

$$(\overrightarrow{r_1} \parallel \overrightarrow{r_2} \parallel \overrightarrow{r_3} \parallel \cdots \parallel \overrightarrow{r_n}) \parallel N_1 \perp N_2 \parallel (\overrightarrow{r_1} \parallel \overrightarrow{r_2} \parallel \overrightarrow{r_3} \parallel \cdots \parallel \overrightarrow{r_m}) \tag{7}$$

For three module layout cases получим:

$$(\overrightarrow{r_1} \parallel \overrightarrow{r_2} \parallel \overrightarrow{r_4} \parallel \overrightarrow{r_6} \parallel \overrightarrow{r_7}) \parallel N_1 \perp N_2 \parallel (\overrightarrow{r_8}) \tag{8}$$

$$(\overrightarrow{r_1} \parallel \overrightarrow{r_2} \parallel \overrightarrow{r_3} \parallel \overrightarrow{r_6} \parallel \overrightarrow{r_7}) \parallel N_1 \perp N_2 \parallel (\overrightarrow{r_8}) \tag{9}$$

$$(\overrightarrow{r_1} \parallel \overrightarrow{r_2} \parallel \overrightarrow{r_3} \parallel \overrightarrow{r_4} \parallel \overrightarrow{r_5} \parallel \overrightarrow{r_6} \parallel \overrightarrow{r_7}) \parallel N_1 \perp N_2 \parallel (\overrightarrow{r_8}) \tag{10}$$

Let us consider γ_{rn} location error factors $\Delta M'_{N1,2}$ of the blocks $U_1(N_m)$, $U_2(N_m)$, $U_3(N_m)$, $U_5(N_m)$ when building a module for each layout option [10]. According to option A) (figure 2 (a)) we have.

$$\varepsilon R = \Delta M'_{N_\mathrm{A}} = \begin{cases} \gamma_{N1} = \sqrt{(\gamma_{r1}^2 + \gamma_{r2}^2 + \gamma_{r4}^2 + \gamma_{r6}^2 + \gamma_{r7}^2)} \\ \gamma_{N2} = \sqrt{(\gamma_{r8}^2)} \\ 0 \end{cases} \tag{11}$$

For option B) (figure 2(b)):

$$\varepsilon R = \Delta M'_{N_\mathrm{B}} = \begin{cases} \gamma_{N1} = \sqrt{(\gamma_{r1}^2 + \gamma_{r2}^2 + \gamma_{r3}^2 + \gamma_{r6}^2 + \gamma_{r7}^2)} \\ \gamma_{N2} = \sqrt{(\gamma_{r8}^2)} \\ 0 \end{cases} \tag{12}$$

For option C) (figure 2(c)):

$$\varepsilon R = \Delta M'_{N_\mathrm{C}} = \begin{cases} \gamma_{N1} = \sqrt{(\gamma_{r1}^2 + \gamma_{r2}^2 + \gamma_{r3}^2 + \gamma_{r4}^2 + \gamma_{r5}^2 + \gamma_{r6}^2 + \gamma_{r7}^2)} \\ \gamma_{N2} = \sqrt{(\gamma_{r8}^2)} \\ 0 \end{cases} \tag{13}$$

Further, by accepting the orthogonality condition:

$$\gamma_{ri} = l_{ri} \tag{14}$$

where l_{ri} the length of each hole n_1, n_2, n_3, n_4, n_5, n_6, n_7, n_8 is given constructively in the form of parameters l_1, l_2, l_3, l_4, l_5, l_6, l_7, l_8.

Let us bring expressions (12 - 14) to the form:

$$\varepsilon R = \Delta M'_{N_\mathrm{A}} = \begin{cases} \gamma_{N1} = \sqrt{\left(l_1^2 + l_2^2 + l_4^2 + l_6^2 + l_7^2\right)} \\ \gamma_{N2} = \sqrt{\left(l_8^2\right)} \\ 0 \end{cases} \tag{15}$$

For option B) (figure 4b):

$$\varepsilon R = \Delta M'_{N_\mathrm{B}} = \begin{cases} \gamma_{N1} = \sqrt{\left(l_1^2 + l_2^2 + l_3^2 + l_6^2 + l_7^2\right)} \\ \gamma_{N2} = \sqrt{\left(l_8^2\right)} \\ 0 \end{cases} \tag{16}$$

For option C) (figure 4c):

$$\varepsilon R = \Delta M'_{N_\mathrm{C}} = \begin{cases} \gamma_{N1} = \sqrt{\left(l_1^2 + l_2^2 + l_3^2 + l_4^2 + l_5^2 + l_6^2 + l_7^2\right)} \\ \gamma_{N2} = \sqrt{\left(l_8^2\right)} \\ 0 \end{cases} \tag{17}$$

To fulfill condition (4.5), it is necessary and sufficient to fulfill condition (16), when all the blocks of the module are aligned:

$$L_{rN1} \in (l_1, l_2, l_3, l_4, l_5, l_6, l_7) \in N_1 \perp N_2 \in L_{rN1} \in (l_8) \tag{18}$$

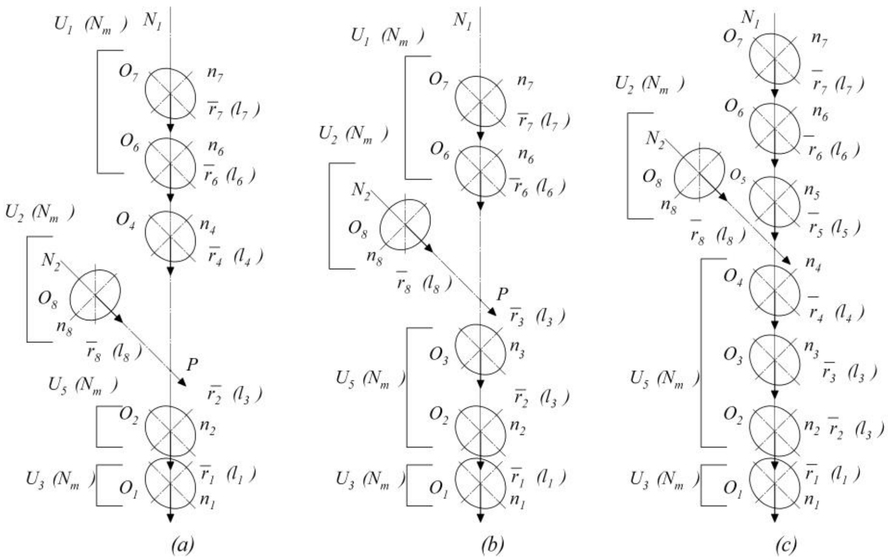

Figure 2. Block diagrams of the layout of the laser module.

In practice, to ensure alignment of the location of the holes $n_1, n_2, n_3, n_4, n_5, n_6, n_7, n_8$ relative to the axes N_1, N_2 is a laborious task. In this case, condition (18) is not satisfied, since each circle rotates relative to the pole полюса $O_n \in N_1, N_2$. According to (10), this leads to the need to take into account in the calculations the installation error of each module block. The procedure for calculating the manufacturing error of each block can also be carried out according to the procedure [10]. In this case, in the expressions (15,16,17) it is necessary to take into account already the projections of the vectors $\overrightarrow{\mathrm{r_m}}$ on the corresponding axis $\mathrm{N_m}$.

Taking the error of the block $\mathrm{U_1(N_m)}$ to be constant, it can be excluded from the calculations. Then it is possible to estimate the error of interblock rearrangement, and choose the module assembly option that provides the smallest error of the coaxial arrangement of blocks and the error of beam positioning from the condition $\varepsilon\mathrm{R} \to min$.

4. Conclusions

The accuracy of beam positioning is complexly influenced by the assembly error of the blocks. The approach considered in this work on the basis of vector modeling of accuracy parameters is effective for application in production processes based on the hybrid cycle of additive processing, since it is in this case that a separate group of part surfaces is sequentially grown in a given direction, with respect to which further machining is also carried out. By ensuring the formation of the surface of the part along the additive cycle in the direction of its main axial vector вектора $\{r_i\}$, the principles of unity and conservation of bases are ensured. Knowing the accuracy parameters of the hybrid additive treatment cycle for the equipment in question, the procedure for calculating the accuracy of the machining of the openings of the body parts is greatly simplified, due to the minimization of εR values.

The approach to modeling the error in the block layout of laser modules proposed in the work is also effective in solving the inverse problem - when the module alignment errors at the assembly stage are determined by the specified accuracy parameters of each block.

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