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TESTING OF THE REPEATED ACCURACY OF POSITIONING OF THE PLASMA CUTTING HEAD

SKÚŠANIE OPAKOVANEJ PRESNOSTI POLOHOVANIA PLAZMOVEJ REZACEJ HLAVY

Abstract

Paper briefly describes design of experiments aimed at verification of selected technological parameters of the plasma cutting machine. Design solution of the plasma cutting machine represents a complex kinematic structure with 9 DOF. Reaching the prescribed repeated accuracy of the positioning is one of the main parameters that is required from the machine. Full experiment design covers more than thousands experiments. Therefore reduced experiment design was prepared that requires only 32 experiments. We consider only one execution of each experiment. When the data variability should be observed, five repeating of each experiment is required, resulting in respective increase of the number of experiments.

Abstrakt

Článok stručne opisuje návrh experimentov zameraných na overenie vybraných technologických parametrov plazmového rezacieho stroja. Konštrukčné riešenie tohto stroja predstavuje komplexnú kinematickú štruktúru s deviatimi stupňami voľnosti. Jedným z najdôležitejších parametrov, ktoré sa od stroja požadujú, je dosiahnutie predpísanej opakovanej presnosti polohovania. Úplný návrh experimentov si vyžaduje viac ako tisíc experimentov. Preto sa pripravil redukovaný návrh experimentov, ktorý si vyžaduje vykonanie iba 32 experimentov. Predpokladáme pritom iba jedno opakovanie každého experimentu. Ak sa má sledovať aj rozptyl nameraných údajov, vyžaduje sa najmenej päť opakovaní každého experimentu, čo vedie k značnému nárastu ich počtu.

1 INTRODUCTION

The growing demand for increased productivity in machinery requires introduction of the brand new technological systems. One example is a three-torch plasma cutter (see Figure 1). The principle of the plasma cutting is employed for many years. The brand new design, developed at the Department of Production Engineering (DPE), FME STU in Bratislava, bounds together three cutting operations into a single technological unit – a three-torch plasma cutting head. This approach offers an increased productivity with new possibilities for complex cuts not available before [2], [10].

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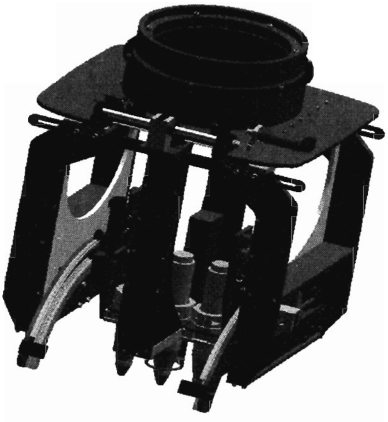

Fig. 1 Design of the three-torch plasma cutting head (courtesy of DPE, FME STU in Bratislava)

The new technology requires testing of assumed technological parameters. Repeated accuracy of positioning belongs to the most important parameters as directly affects quality of the provided cut. Therefore the big attention is paid to modeling the expected accuracy, design of experiments for testing the repeated accuracy, design the measuring tools and performance of practical design. Due to a brand new mechanical and kinematic concept of the cutting head, a number of problems occur in each of the mentioned phase of the testing process.

The complicated theoretical task is connected with design of appropriate experiments. Full experiments design covers 65 536 experiments. Therefore reduced experiment design was prepared that requires only 32 experiments.

The paper describes the three phases of the theoretical work, performed for determination of selected technological parameters of a new three-torch plasma cutting head:

1. determination of a theoretical accuracy of a positioning,
2. determination of a single-axis positional deviation,
3. determination of a positional deviation for random sequence of movements of a cutting head.

2 THEORETICAL ACCURACY OF POSITIONING

The device itself consists of several individually operated axes, either transversal or rotational. We analysed all individual axis from uncertainties point of view. Let us introduce an example of such process, demonstrated by movement of both side-torches H1 and H2.

Figure 2 introduces a kinematic scheme for movement of any of side torches, H1 and H2. The desired position *y* of a torch *8* is obtained by several rotations of a motor *2*. Motor movement is transformed over a whole kinematic chain that includes the planet gear box *3*, the two pullers *4* and *5* and a ball-screw transmission.

The whole mechanism is designated as an open loop system. The desired position is derived only from a digital encoder *1* that records angular rotation of a motor *2*. No information is provided on actual position of a torch. Neither a position sensor nor an angular sensor of a screw-bal transmission is employed. Therefore if any deviation from the ideal behavior of a whole kinematic chain occurs, the torch reaches position different from the pre-programmed one.

The displacement (positional change) *y* of a torch can be derived according to the employed kinematic scheme as:

$$y = k \cdot k_{\mathrm{skr,r}} \cdot k_{\mathrm{r,pr}} \cdot k_{\mathrm{pr}} \cdot \varphi_{\mathrm{sni}} \qquad (1)$$

where:

$\varphi_{\mathrm{sni}} = 360\,°$ – is the one turn of the digital encoder (digital encoder mounted on the motor shaft),

k – the ball-screw lead, $k = 10$ mm / 360 ° = 0,02777 mm/°,

$k_{\mathrm{skr,r}}$ – the pulley 1/ball screw ratio, $k_{\mathrm{skr,r}} = 1$,

$k_{\mathrm{r,pr}}$ – the pulley 1/gearbox ratio, $k_{\mathrm{r,pr}} = 1$,

k_{pr} – the gearbox transmission ratio, $k_{pr} = 1/14 = 0{,}071429$,

$\varphi_{sni} = 360°$ – a one complete turn of a digital encoder (i.e. one complete turn of a motor shaft).

When substituting to the equation (1) we get the displacement of both side-torches H1 and H2 that corresponds to a one turn of a motor shaft

Now we want to calculate the uncertainty of such theoretical displacement. We employ the law of uncertainty propagation. As we do not perform any repeated measurement, we calculate just the uncertainty evaluated by the type B method.

Following relationship for calculation of an uncertainty of a theoretical displacement y applies:

$$u_y^2 = \left(\frac{\partial y}{\partial_k}\right)^2 u_k^2 + \left(\frac{\partial y}{\partial_{k_{skyy}}}\right)^2 u_{k_{skyy}}^2 + \left(\frac{\partial y}{\partial_{k_{r,pr}}}\right)^2 u_{k_{r,pr}}^2 + \left(\frac{\partial y}{\partial_{k_{pr}}}\right)^2 u_{k_{pr}}^2 + \left(\frac{\partial y}{\partial_{\varphi_{sni}}}\right)^2 u_{\varphi_{sni}}^2 \tag{2}$$

After the substitution to the equation (2) we can calculate the uncertainty of the outer torch (H1, H2) displacement: $u_y = 0.01283$ mm

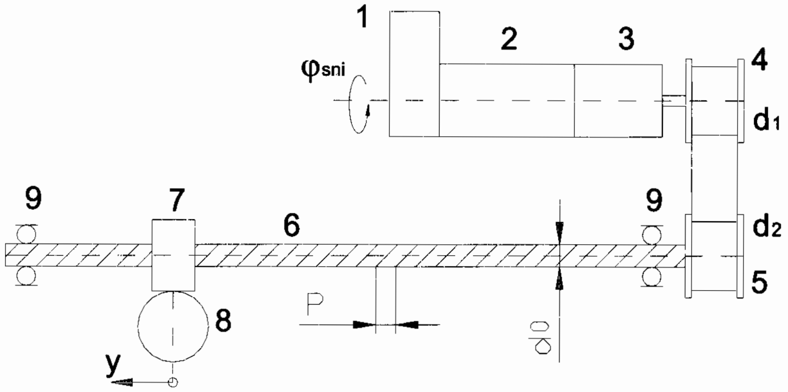

Fig. 2 Block scheme employed for movement of any of both side torches H1 or H2
1 – the angular encoder, 2 - motor, 3 – planet gear box, 4 – puller, 5 – puller, 6 – ball-screw transmission, 7 – ball sleeve, 8 – torch, 9 – screw-ball housing

3 DETERMINATION OF A POSITIONAL DEVIATION

No standard specially focused on plasma cutting heads accuracy exists. Therefore we use the standard [1] as a guide for determination of a positional deviation. We proceed as written in a standard, i.e. testing the positional accuracy in a single axis, while the others are in a standstill. This is a rather theoretical approach as the plasma cutting head performs a more complex motion in practice, when several axes work either at the same time or subsequently.

When analyzing the above mentioned terms, we see that a so called unidirectional or a bidirectional approach is used. We can restrict our analysis to a unidirectional movement. The reason is that the bidirectional positional deviation has no practical meaning for corrections of a machine performance.

The standard assumes only the variation in measured data when the positional deviation in any points is measured repeatedly (see Fig. 3). The standard assumes that this variation is caused only by imperfectly working machine. Unfortunately, the practice is slightly different. None has invented a perfect measuring instrument yet. Therefore also the observed variation of data is caused not only by the machine itself but also by the measurement process [8].

Imperfections of the measurement process can be evaluated by a measurement uncertainty. The uncertainty can be calculated in two ways. The type A method takes measured data into account, the type B method analyses the measuring instruments employed. The respectable and reliable measurement results comprise the estimate of a positional deviation in particular points and an appropriate value of the expanded uncertainty of that estimate (see Fig. 4).

The above mentioned law of uncertainties propagation is employed for calculation of measurement uncertainties. More details about this topic will be published in the next papers.

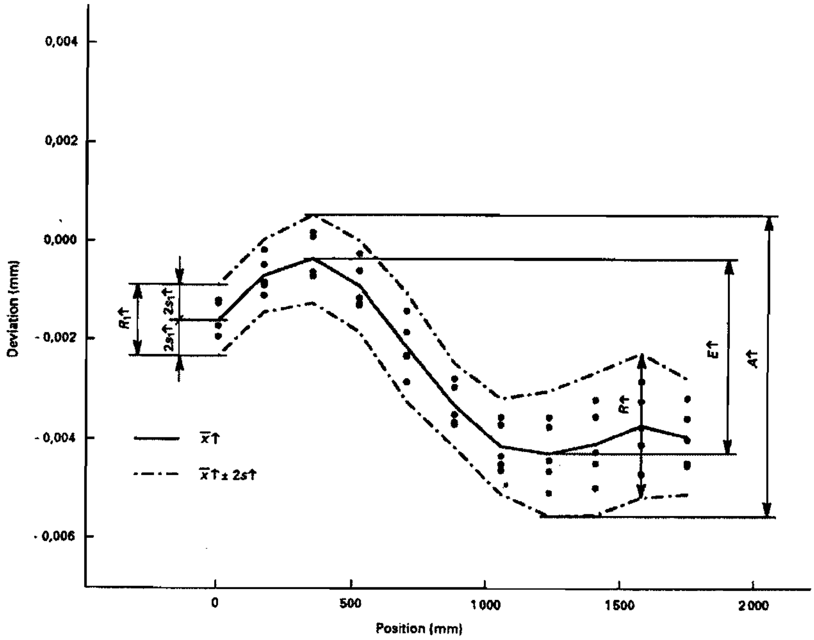

Fig. 3 Example of evaluated data processed according to the standard [1]

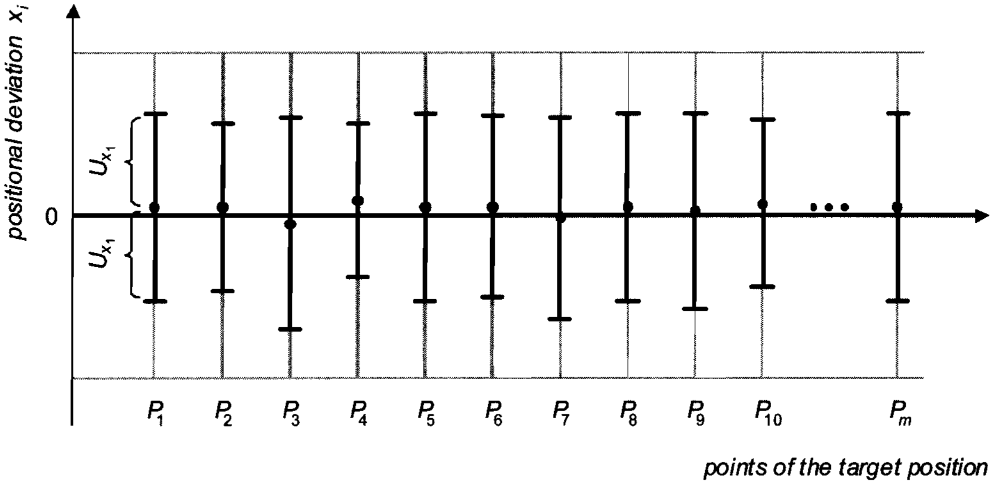

Fig. 4 Respectable measurement results – positional deviations x_i and the expanded uncertainty U_{xi}

4 DESIGN OF EXPERIMENT MODELS

Described prototype has not been tested in practice. As the cut quality is the most important requirement, proper experiments proving the assumed quality parameters must be performed [7], [9]. The positional deviation of torches in different operational modes must be verified first.

In general, experiment is defined as any intervention to the system with the aim to observe or measure effects of that intervention [5], [6], [7]. Experiment involves combination of different values (levels) of facts that are considered to affect the output from the system. As testing of all variations (tests) represents improperly big amount of tests, incomplete experiment designs are recommended. They investigate only a restricted selection from all possible combinations. Experiment design according to Taguchi represents an approach that significantly reduces amount of necessary tests and introduces also further advantages.

Literature describes two-level multi-factors experiment designs most often. We recommend at least four levels for selected factors in this application (see Table 1). To be able to execute measurements for each level for all nine factors, total number of tests reaches $N = 4^7 \times 2^2 = 4\ 096 \times 4 = 65\ 536$. If each measurement is repeated for five times, overall number of tests reaches $N = 5 \times 65536 = 327\ 680$. That is quite a lot.

Positioning accuracy of the plasma cutting machine can be measured in different modes:

1. each axis (mechanism) is measured separately. Resulting overall positioning accuracy is calculated,
2. positioning accuracy is measured for combination of movements in several axis. Resulting overall positioning accuracy is calculated again,
3. positioning accuracy is measured for combination of movements in all axes.

Proposed experiments design follows the third measurement mode [6], [7].

5 DESIGN OF MULTI-LEVELS MULTI-FACTORS EXPERIMENTS

Method employing Taguchi's approach to quality control is most suitable for experiments design in cutting machine testing. We recommend to apply the modified version of orthogonal configuration $L32(2^1 \times 4^9)$ [12]. It is a composite model for 32 tests. Original version considers one two-level factor and nine four-level factors. This model is modified for two two-level factors and seven four-level factors, so $L32\ (2^2 \times 4^8)$. Last column is not full.

For described model L32 is valid: production of any pair of column vectors is not vector integrated in configuration and is not orthogonal to any other vector from configuration at the same time. Only influence of main factors is usually assumed in such configuration. Influence of possible interactions is neglected.

Strategy for experiments execution is as follows:

1. experiment based on orthogonal configuration is executed and main effect of each factor is estimated,
2. estimates of main effects are used to select the best combination of levels of individual factors. Prognosis of output for selected combination is estimated,
3. if obtained result does not confirm the prognosis, one can assume that interactions deflect the estimates of main effects. Then actions must be taken to eliminate interactions and new experiment must be executed.

Total number of $N = 5 \times 32 = 160$ experiments is obtained for five repetitions of each measurement. That means reduction to 0.05 % of the original complete experiments design.

6 CONCLUSIONS

The presented paper introduces three stages of theoretical work, aimed at verification of the expected performance characteristics of a newly designed three-torch plasma cutting head. First, we tried to determine the theoretical positioning accuracy of individual head axes. The example for calculation of side torches displacement and its respective uncertainty is presented. Next we discussed the guidelines for measurement of the positional deviation in a case of the single-axis movement. At last the presented possibilities for the reduced experiments design, prepared by a Taguchi approach, for real technological application. Reduced design significantly decreases number of required measurements but still provides enough information for further analysis and following technical modifications of tested device.

This paper represents only a theoretical basis for experiments design, their evaluation and processing of obtained data. Further modifications are expected after obtaining the real measurement data.

REFERENCES

[1] ISO 230-2:1997 *Test code for machine tools – Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes.*

[2] GROS, P., BENIAK, J. Torch rotating unit for universal plasma cutter. In *Proceedings of the 7th International conference Mechanical Engineering* 2003, p. 92 (in Slovak).

[3] SMUTNÝ, L. & FARANA, R. Smart fibre optic sensors for small displacement measurement. In *Proceedings of SPIE,* 2004, Vol. 5445, pp. 332-335, ISSN 0277-786X. ISBN 0-8194-5368-4.

[4] KUREKOVÁ, E, HALAJ, M. BOHUNICKÝ, A. Design of experiment for verification of the repeated accuracy of positioning of the plasma cutting machine. In *Proceedings of International Conference Aplimat 2005,* Bratislava, 6 pp. on CD (in Slovak).

[5] TEREK, M., HRNČIAROVÁ, Ľ. *Statistical quality control.* Published by IURA EDITION, Bratislava 2004, ISBN 80-89047-97-1 (in Slovak).

[6] TAGUCHI, G. *Taguchi on Robust Technology Development.* ASME Press, New York (NY), 1993.

[7] VDOLEČEK, F. Automation and diagnostics. In *Proceedings of the international conference Strojné inžinierstvo '04,* Bratislava, pp. S1-197 to S1-204, 2004, ISBN 80-227-2105-0 (in Czech).

[8] WIMMER, G., PALENČÁR, R., WITKOVSKÝ, V. *Stochastic models of measurement.* Published by Grafické štúdio Ing. Peter Juriga, Bratislava, 2002, ISBN 80-968449-2-X (in Slovak).

[9] Catalogues of MicroStep company.

[10] EN ISO 9013:1995: *Welding and related processes* (in Slovak).

[11] www.L32OrthogonalArray.com.

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