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EVALUATION OF MACHINE TOOL FRAMES IN THE PROCESS OF OPTIMIZATION

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ABSTRACT
The article presents elaboration of problems pertaining to the evaluation of design variants of machine tool frames. The presented method has been implemented in the optimization process of geometrical parameters of frames, such as: dimensions, thickness and layout of walls. The solution obtained as the result of optimization process has been compared to the ideal variant, which in this case was a machine tool with frames suggested by the designer.
Keywords: frame, optimization, machine tool, evolutionary algorithm

1. INTRODUCTION
Optimization of machine tool frames which is conducted by the use of evolutionary algorithms requires formulation of the fitness function, which constitutes quantitative evaluation of the suggested solution to a given task. Thus, it is necessary to formulate evaluation criteria that allow the determination of the variant's value.
Machine tool frames, being a part of its load-carrying system, have a significant impact on static, dynamic and thermal properties of the overall machine tool. Proper shaping of the frames and the whole constructional system of the machine tool frequently requires meeting a number of contradictory conditions. The most important include: invariability of shapes and dimensions of the frames, as well as their links throughout the entire performance of the machine, high stiffness together with static and dynamic stability, insignificant impact of thermal phenomena on the accuracy of the machining process, ability to suppress vibrations effectively, small weight and size of dimensions. It is extremely difficult to balance the requirements facing machine tools properly, especially because only few of them can be expressed quantitatively [1, 2, 3, 4].
Due to the fact that the suggested method of frames optimization involves reducing a multi-criteria task to the scalar form, using weighted sum of partial criteria, it was necessary to develop a suitable evaluation method. Consequently, already existing evaluation methods commonly applied in the design and manufacturing process, have been used for the purpose.

2. EVALUATION IN THE PROCESS OF FRAMES OPTIMIZATION
The result of the evaluation process is the determination of *the value* of the structural solution in the respect of agreed objectives, or *the worthiness* of the variant through its comparison to the abstract, ideal solution. The most commonly used method in the evaluation process of structural solutions, is

cost analysis method, whose best known variations are: utility value method (Zwicky F.) and technical-economic evaluation method (Kesselring) [5]. Both methods have been formulated in such a general way so as to enable their application within technical systems of various domains at a randomly selected stage of the design and manufacturing process. They served as the starting point for elaborating the stage evaluation in the optimization process of machine tool frames.

1. Identification of evaluation goals and criteria vital for optimization process through establishing the system of objectives based on main discriminants together with requirement and expectation list.
2. Determination of the importance of evaluation criteria by establishing weight coefficients.
3. Attribution of parameters to the evaluation criteria in relation to particular features of the piece.
4. Determination of technical value (worthiness)W_t by the use of weighted sum of partial criteria, most frequently in relation to the assumed ideal solution. It is also recommended to determine economic worthiness W_e as well.
5. Determination of the total value W by the use of hyperbola method provided technical W_t and economic W_e values have been determined.

Optimization process of frames is a part of preparatory activities in the design and manufacturing process of a machine tool. Thus, formulating of the evaluation criteria, identifying their key role and the value functions for the purposes of frames optimization, cannot be done without taking into consideration the information collected during the initial-stages of the design and manufacturing process.

2.1. Identification of evaluation goals and criteria

The evaluation of technical properties, which takes place during the preparatory stage of the structural design, is conducted on the grounds of their technical worthiness W_t, whereas economic properties are assessed according to the calculated economic worthiness W_e. Assessment of structural solution in the respect of economic worthiness requires the determination of production costs (material costs and overall production costs). The evaluation process of constructional solutions begins with general identification of goals, which in turn allows establishing of partial criteria of the assessment. The aforementioned evaluation goals and criteria are established on the basis of requirement and expectation list prepared uniquely for a particular piece to be machined. The completeness of evaluation criteria is monitored through main discriminants [5]. The list of criteria depends mainly on the subject of the evaluation and the advancement stage of the design and manufacturing process (the level of instantiation of the variant). While formulating evaluation criteria for optimization process of the frames one should bear in mind that properties of a given solution may be expressed quantitatively only.

2.2. Attribution of parameters and weight coefficients to evaluation criteria

Apart from goal formulation, and consequently its criteria, the value assessment of a structural solution requires the determination of the criteria importance (weight). Weight coefficients are expressed with positive value in the range of [0;1] and used in consecutive evaluation steps. It is crucial, however for the weighted sum of evaluation criteria to equal one. Since the weighting of goals and criteria is a fairly subjective assessment of their importance, it is highly recommended that the final listing of the criteria and their weighs results from mutual cooperation of the designer team and the partners contracting the work. Once the evaluation criteria are formulated, the parameters, referring to particular properties of the machined object, should be attributed to them respectively. For example, the stiffness of a machine tool is described by a numerical parameter, i.e. stiffness coefficient.

2.3. Determination of the value (worthiness) of a structural variant

The optimization methods of frames suggested by the author [6, 7, 8, 9] involve the reduction of multi-criteria tasks to the scalar form due to weighted sum of partial criteria. Yet, it is necessary to conduct normalization process of the criteria prior to their summing up. Such necessity happens when the criteria are expressed in various units of measurement, or their value scales differ significantly. Once the parameter values describing the criteria are established, their standardization process commences with the use of a value function. Provided a precise relation between the value and the parameter is not known, the application of a linear function either increasing or decreasing is recommended. Once the standardization process is complete, the value of the alternative is determined by the use of a weighted sum of the criteria. Provided the considered variant is referred to the ideal solution, the quantity determined is regarded as technical or economic worthiness of the variant $W_{t(e)}$. Total worthiness of the variant W can be established by the use of hyperbola method, where the total worthiness constitutes a product of both worthiness types, scaling the values between 0 and 1.

3. OPTIMIZATION OF VERTICAL MILLING MACHINE FRAMES

The evaluation method described in the second section has been also applied for the optimization of selected milling machine frames, using the evolutionary algorithm and the finite elements method for the purpose. Two types of tasks were carried out along the optimization process of the headstock body and slide. The first task focused on searching of the most favorable arrangement of the frame's walls, as well as their optimum dimensions and holes. Having completed the first task, the second one commenced including the results obtained before. The aim of the search was in this particular case to find out the optimum wall thickness of the frame.

The subject of the model research was the headstock body and slide body of a vertical milling machine depicted in the illustration 1. The benchmark accepted for the research was a machine tool model with the body recommended by the designer. In order to obtain more detailed assessment of the milling machine stiffness, the optimizing calculations were carried out at six points of the machine's operating space (illus. 1). The model used as the subject of optimization was loaded with three cutting force components applied in the direction of *x*, *y* and *z* axles.

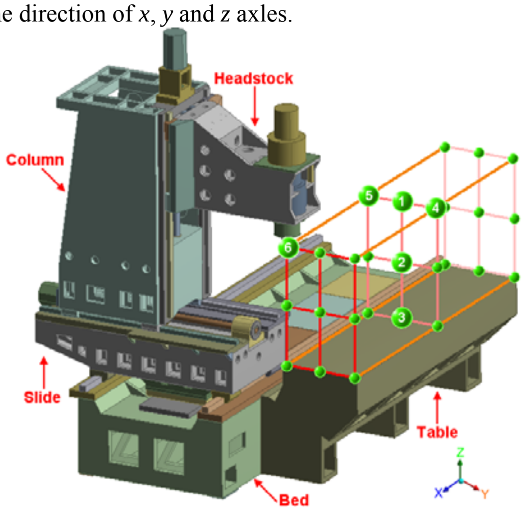

Figure 1. Geometrical model of a vertical milling machine

In order to evaluate geometrical variants of the frames, seven partial criteria were defined:

- c_1, c_3, c_5 - average stiffness towards x, y and z axle;
- c_2, c_4, c_6 - stiffness arrangement towards x, y and z axle;
- c_7 - cost of material for the frame - frame weight.

The first six are related to the static stiffness of the machine tool and are used to determine technical worthiness.The stiffness coefficients towards x, y and z axles were calculated as a quotient of force components and displacements measured at the spindle's tip towards force operation. Stiffness arrangement towards x, y and z axles was determined in relation to standard deviation.

4. OPTIMIZATION RESULTS

The application of evolutionary algorithm aims at optimum selection of geometrical parameters, which in turn entails the lowest weight of the machine frames, simultaneously preserving desirable static stiffness. The optimization process resulted in the reduction of the slide weight, as compared to the initial variant, at the level of 10,6%. Unfortunately, such a significant weight reduction has its consequences. The best variant obtained in the course of optimization displays lower average stiffness in relation to the initial model (tab. 1). Optimization of slide provided slightly better results of the static stiffness arrangement of the variant. Yet, the stiffness uniformity towards z axle in this case deteriorated by 0,7%.

Table 1. Optimization results of the milling machine headstock body and slide.

Criteria	Unit	Initial model	Slide optimization	Parameter change %	Headstock optimization	Parameter change %
Average stiffness - axle x	kN/mm	53,6	52,5	-2,1	53,8	0,4
Average stiffness - axle y	kN/mm	135,6	132,5	-2,3	135,2	-0,3
Average stiffness - axle z	kN/mm	92,3	89,6	-2,9	90,5	-1,9
Stiffness arrangement - axle x	kN/mm	11,2	10,9	-2,1	11,3	0,7
Stiffness arrangement - axle y	kN/mm	60,5	60,4	-0,2	59,8	-1,2
Stiffness arrangement - axle z	kN/mm	26,2	26,3	0,7	26,1	-0,2
Material costs – slide weight	kg	664,9	594,6	-10,6	594,6	-
Material costs – headstock weight	kg	353,9	353,9	-	350	-1,1

5. CONCLUSIONS

The example included in the article attempts to take advantage of the presented deduction method in the execution of multi-criteria optimization tasks for machine tool frames. The final result of optimization process of geometrical parameters in case of milling machine slide and headstock is a compromise between high stiffness and low weight. It can lead to a situation where machine tool stiffness decreases as compared to the initial model (tab. 1). It should be emphasized however that weight reduction is frequently much bigger than the undesirable decrease of stiffness factors, and in this case it equaled approx. 74kg. The evaluation method presented in the article allows formulation of criteria of various importance, which may be perceived as the method's strengths or shortcomings at the same time. Since the process of weighting criteria is a subjective assessment, it is advisable to conduct it within a team of experts and in mutual cooperation with clients. Evaluation process reflecting the presented method can be used in tasks related to the selection of geometrical parameters and topological optimization, as well.

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