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machine tools on foundations,
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MODELLING AND OPTIMIZATION OF MACHINE TOOLS ON FOUNDATIONS

This paper aims to expand existing complex mathematical models of machines in a manner that would respect the influence of their installation on the foundation. For this purpose, a method of modelling and optimization of foundations was developed. It consists of four basic parts: Mathematical modelling of machines, optimization of the number and placement of fixing (levelling) elements, optimization and modelling of the reinforced concrete foundation and modelling of the subsoil with respect to engineering geological conditions. The main optimization criterion is to increase the lowest natural frequency of the machine while reducing the foundation weight (amount of reinforced concrete).The result is a virtual mathematical model of the machine tool, including the influence of its foundation and subsoil. The proposed optimization can be used for designing new machines, machine foundations and the number and distribution of machine levelling elements. This method has been applied and tested on a virtual model of a multi-purpose machining center for workpieces up to 15 tons.

1. INTRODUCTION

Installing machine tools on the foundation and their subsequent levelling plays an important role not only in terms of correct operation, service life, but also safety. In most cases the foundation is made of a thick reinforced concrete block. The aim is to provide a sufficiently solid basis for correct levelling of machines. In large machine tools the foundation additionally reinforces an insufficiently rigid machine bed. Installing a large machine on the foundation is particularly important for achieving a higher static and dynamic stiffness.

The problem of mathematical modelling and optimization of machine tools on foundations can be divided into four parts as shown in Fig. 1.

Mathematical modelling of machines themselves (coupled modelling) is nowadays relatively well mastered. It makes it possible, among other things, to design new machines and to simulate their properties. The methods and compositions used are well described in

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the literature. This topic is presented e.g. in the publications [17] and [7], where the usage of the coupled models of machines for the design and optimization of machine tools was introduced (Fig. 2).

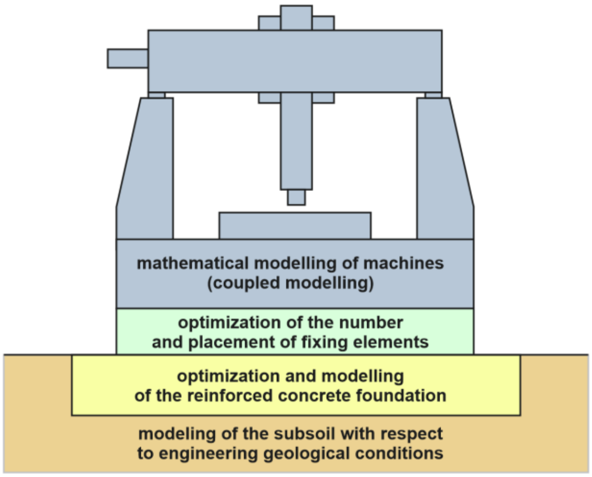

Fig. 1. Machine tool on the foundation – structure of the model and tasks

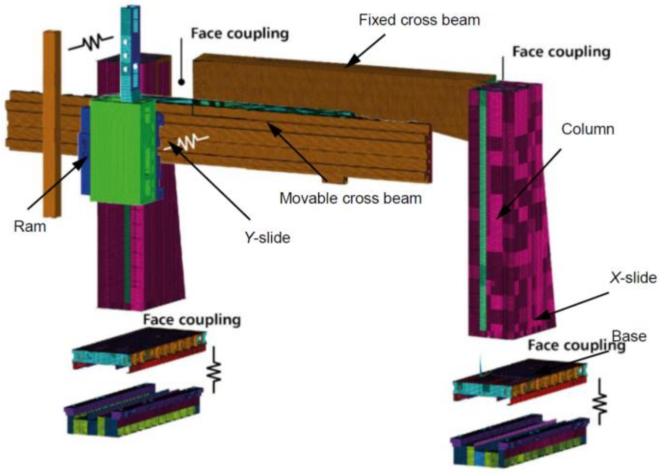

Fig. 2. Multibody system of the machine tool structure [17]

The second task represents an optimization of the number and placement of fixing elements for the machine tools installation. The methods of machine tool installation and levelling on foundation can be divided according to [15]. There is always some kind of „pads" or elements in all the mentioned cases of installation (incl. the precision grouting). The most common practice is to use height adjustable levelling wedges. This method can be considered a very efficient and methodologically correct. The authors of this paper assume the most common situation where the foundation consists of a massive reinforced concrete block and the machine is then fixed and levelled using the levelling wedges. These elements constitute the connection between the machine and the foundation. Their number and spacing thus play an important role in the overall behaviour of the machine. If fixing elements are properly designed, a slight change in their behaviour should not significantly affect the dynamical behaviour of the machine. Therefore it is good to be systematic when designing their size, number and distribution. No literature focused on the optimization of number and placement of fixing elements was found within the research.

The third task is the optimization and modelling of a reinforced concrete foundation. The problems of foundations of machinery in general are covered by the book [6]. There is an overview of the types and requirements for foundations etc. Separate chapters are devoted to ways of foundations loading, analysing and design. There are also few examples of realizations, such as the foundation for a steam turbine with an output power of 1000 MW, including FEM analysis. According to the authors of [6] - the term "foundation" represents the structure under the machine having the function of support or reinforcement. It ensures the functionality and / or protects the machine and its surroundings from a certain type of disturbance. The authors of [6] also set out the requirements on foundations. It follows that the primary function of the foundation, inter alia, is increasing the static but also dynamic stiffness of the machine. In most cases the foundation is made of a thick reinforced concrete block. It provides a sufficiently rigid base for the proper levelling of the machine. In the case of big machines it provides an additional stiffness for the machine bed. This topic is studied e.g. in the literature [4],[5],[10],[11],[12],[13]. Foundation itself is also important from the perspective of the dynamical stiffness of the machine. Its monolithic concrete construction can weigh several hundred tons and its eigen-frequencies are then very low, of the order of units or tenths Hz.

The last task is the modelling of subsoil with respect to engineering geological conditions. In general, this topic is studied in a civil engineering literature. A 2D model with an approximate respect of third dimension [2] is very often chosen because of the demands on computing capabilities and computer memory. Dynamic interaction between soil and foundation is dealt with e.g.in [9], the influence of the environment on machine foundation vibrations is described in [8] and the dynamic stiffness of the subsoil is described in [14]. Application of this topic to the mechanical engineering domain is not very common. No literature was found in the machine tools application area.

However, machine tools largely depend on their foundations. It seems appropriate to extend existing coupled machine tools models with methods of optimization of the number and placement of fixing (levelling) elements, optimization and modelling of the reinforced concrete foundation and related modelling of the subsoil with respect to engineering geological conditions. This extension of mathematical models of machines by the methods described below provides new design and simulation tools and expands possibilities and reliability of the mathematical machine tools models. The objective is to improve the dynamical properties in the tool center point. The presented methods do not follow the characteristics of the machine with regard to its geometry and accuracy.

From the perspective of a machine tool manufacturer, the design of the foundation, machine fixing and levelling is an integral part of the design of a new machine. The presented new methods enable us to design the machine foundation so as to achieve the best possible dynamical properties. It is also possible to verify the robustness of the foundation design for the desired spectrum of geological subsoil conditions. It is also important to take into account e.g. complexity / segmentation of the foundation and the amount of reinforced concrete used. These can be the limiting criteria for optimization for reason of cost.

It can also be useful to deploy the calculation of the machine and foundation properties when the manufacturer or the customer need to verify whether the machine will have the expected characteristics under problematic geological conditions as well. The need may arise to design the machine foundation “made-to-measure.” Sometimes the manufacturer is faced with the customer’s requirement to place a small machine to the second floor of the building. In such an “extreme” situation it is difficult to predict the influence on the machine behaviour and to provide guarantees.

The most common machine tool installation has been to use levelling wedges (height adjustable fixing elements). The weight of the machine should be uniformly distributed on the foundation. The methods presented in this paper allow us to select an appropriate number of fixing elements while these elements are optimally distributed so as to achieve the highest possible dynamical properties.

Presented methods were applied on the case study of the multi-purpose machining center for workpieces up to 15 tons, which is an integral part of chapters 2, 3 and 4. The second case study was the application on the Gantry-type modular machining center for heavy weight workpieces – chapter 5.

2. OPTIMIZATION OF NUMBER AND PLACEMENT OF FIXING ELEMENTS

As already mentioned above, the authors of this paper assume the most common situation where the foundation consists of a massive reinforced concrete block and the machine is then fixed and levelled using the levelling wedges.

The design task of the fixing elements optimization can be simplified to maximize the minimums of the first *n* eigen-frequencies fr_i, normalized to the eigen-frequencies of the initial state Fr_i, which corresponds to the eigen-frequencies of the stand-alone machine (Fig. 3).

$$\max \min_{i \in <1,5>} \frac{fr_i}{Fr_i} \tag{1}$$

The maximum number of the fixing elements can be selected as a limitation. The optimization is based on the 0D topological optimization [1] with virtual densities applied to fixing elements. To increase the speed of calculation, it is possible to reduce the model size of the machine structure, by using e.g. the reduction method through Krylov subspaces [17].

As an example, the optimization of the number and placement of the fixing elements has been performed on the multi-purpose machining center for workpieces up to 15 tons. The machine structure model has been reduced by using the above mentioned Krylov subspaces method. The 0D topological optimization, which assumes virtual densities of the optimized fixing elements, has been used. The fixing elements were modelled using the matrix element MATRIX27. All fixing elements were defined with 2 possible states of the virtual density $\rho \in \{0,1\}$, where $\rho=0$ means that the element is not implemented in the model and $\rho=1$ means that the element is implemented. The model of the machine was assembled in ANSYS. The MATRIX27 element was then created in each node of the bottom surface of the machine. This complete model was then exported into MATLAB environment and reduced by using the Krylov subspaces method to increase the speed of further optimization (it is possible to use different kind of model reduction). The optimization task was then performed in MATLAB where the virtual density of the fixing elements was controlled (looking for the absolute extreme of the selected target function).

The results of the optimization of fixing element position for the tested machine are summarized in Table 1. The number of fixing elements was limited to 25 and 35 pieces. The second column of the table shows the eigen-frequencies of the machine – the current state without the optimization. The third column shows the maximum attainable frequency if the machine lies continuously on the fixing elements (calculation of the model on Fig. 4).

The next columns show the results of optimized variants for 25 and 35 fixing elements, including a quantification of the difference compared to unoptimized variant. Fig. 5 and Fig. 6 show the approximate optimum positions of the fixing elements for both variants.

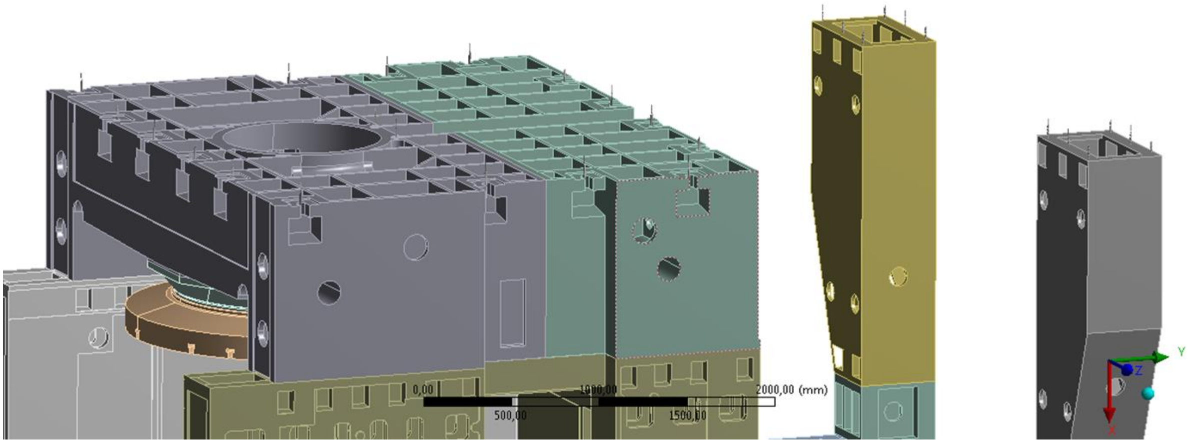

Fig. 3. A model of the machine without fixing elements – the initial state with frequencies Fr_i

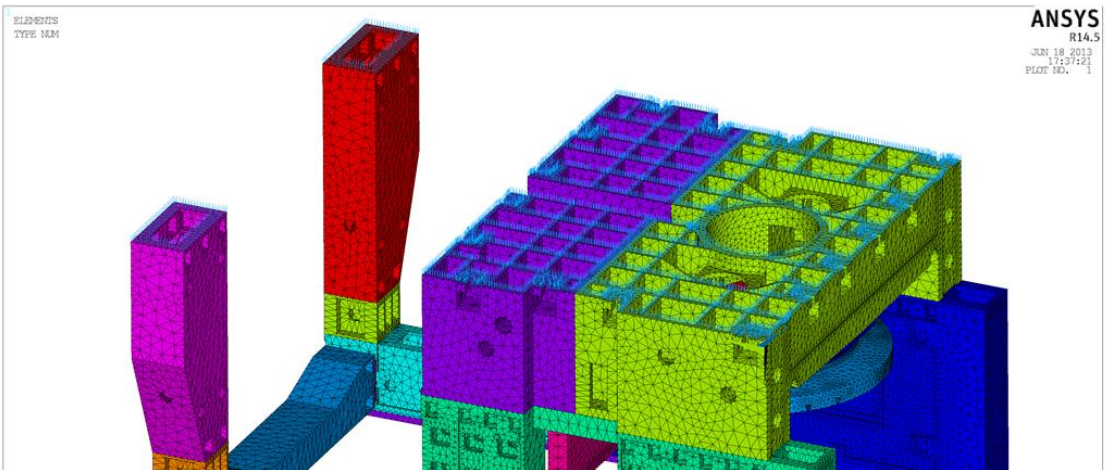

Fig. 4. Fixing elements (light blue elements) placed in each node on the bottom surface of the machine

Table 1. Results of the topological optimization for 25 and 35 fixing elements

Eigen-frequency [Hz]	Machine (current state)	Max. reachable	25 fixing elements	Difference to the unopt. variant	35 fixing elements	Difference to the unopt. variant
1.	18.9	23.8	20.2	107%	21.4	113%
2.	23.0	27.5	23.8	104%	25.8	112%
3.	35.7	46.2	38.3	107%	40.2	113%
4.	41.6	46.6	42.1	101%	44.7	107%
5.	44.2	49.0	44.5	101%	46.4	105%

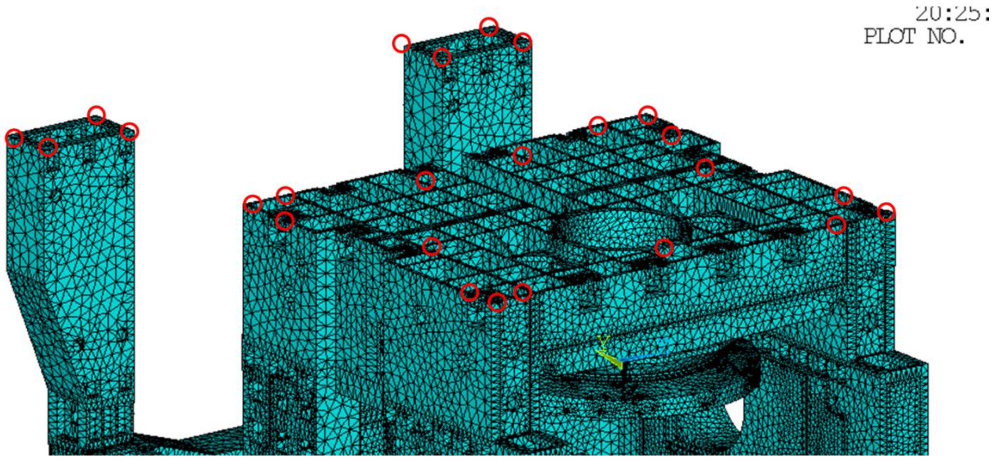

Fig. 5. Optimal distribution for the task with 25 fixing elements

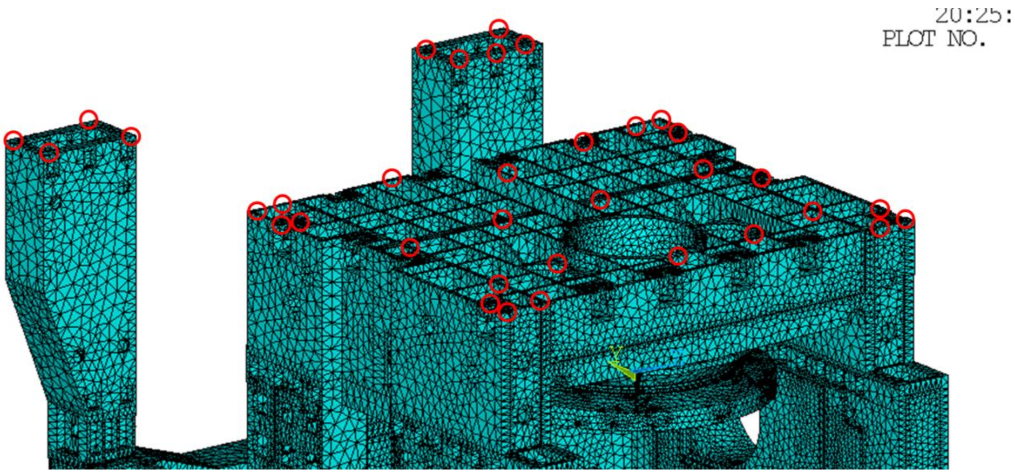

Fig. 6. Optimal distribution for the task with 35 fixing elements

3. MODELING OF SUBSOIL WITH RESPECT TO ENGINEERING GEOLOGICAL CONDITIONS

The modelling of subsoil in this paper precedes the optimization of the foundation to include the subsoil model into the optimization. When designing a simplified soil model, it can be assumed that the stress caused by gravity forces in the soil is much higher than the stress caused by the machining process and by the movement of machine parts. This assumption allows linearization of soil stiffness in a specific point after adding gravity load. This linearized stiffness can be used in further analyses. The soil is thus replaced by a spring with a linearized stiffness. Furthermore, soil behavior can be considered only in compressed state. Material models which describe the full three-dimensional soil behavior are inappropriate for this type of analysis, because there are no straightforward methods which can identify the full material model with the required type of soil.

The proposed method of soil behavior identification can be divided into the following three steps:

1. Loading the soil by its own weight;
2. Loading the soil by the weight of the concrete foundation and machine;
3. Linearization.

Known composition of soil layers (e.g. from geodetic resources) is a prerequisite for obtaining data for deformation characteristics.

Table 2. Compressibility ranges of soil [16]

Type of soil	C	Type of soil	C
Soil	20-40	Loose Sand	60-150
Soft Clay	30-70	Dense Sand	150-200
Tough Clay	70-90	Sand and Gravel	250
Hard Clay	90-120	Gravel	300

A simplified STRESS-STRAIN curve for specific soil, which is further used for estimating the equivalent stress in the soil, can be obtained by calculation from the following relationship [18]:

$$e^{C\frac{\Delta h}{h}} - 1 = \frac{\Delta\sigma_{ef}}{\sigma_{ef}} \qquad (2)$$

where C is the compressibility coefficient of subsoil [-], Δh is the change in the depth of soil from the initial value h due to application of external load $\Delta\sigma_{ef}$. The stress change $\Delta\sigma_{ef}$ due to application of external load changes from the initial value of the effective consolidation stress σ_{ef}. This relationship is only valid when the relationship between stress and strain in the semi-logarithmic scale creates a straight line (Fig. 7).

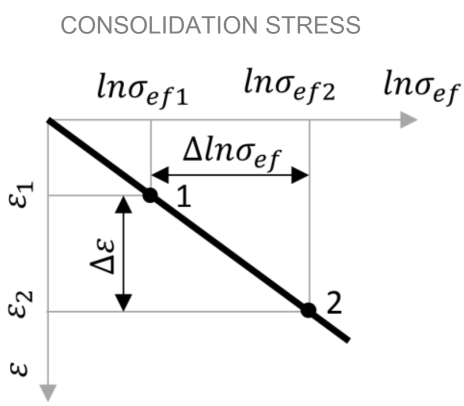

Fig. 7. Prerequisite characteristic of consolidation stress [18]

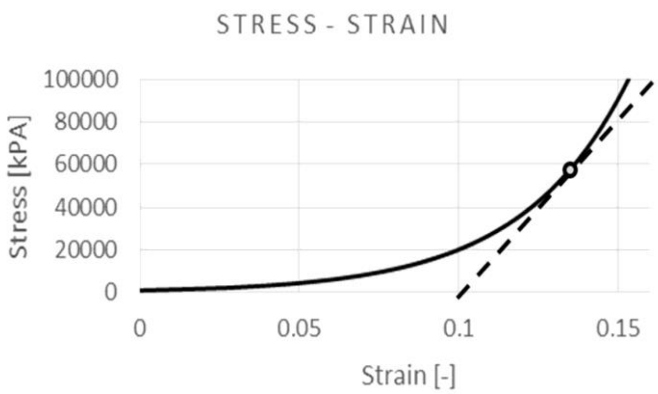

Fig. 8. Final linearization of stress-strain curve in specific point [18]

Otherwise it is called overconsolidated soil (soil was loaded with higher stress in the past than now) and the compressibility factor C must be determined by oedometer modulus E_{oed}, which can only be obtained by oedometric tests.

With data from geodetic resources it is possible to determine the approximate value of the coefficient of compressibility C. Subsequently, it is possible to draw the deformation curve of soil in an incremental way. It is necessary to note in which range the oedometer modulus E_{oed} was set. Thus, it is possible to determine the substitute stiffness of the springs using linearization at specified operating points (Fig. 8). For the machine dynamics simulations it is possible to use the determined constant stiffness as a soil substitute (Fig. 9).

After stress-strain curve linearization, it is possible to determine stress value directly, which is useful for checking the load capacity of the foundation base. By comparing it with the recommended value for a given soil from geodetic resources, it can be checked whether there is no stability state issue. Limit states of stability are divided into specific categories. It is not allowed to exceed the tabular calculation capacity in any of them.

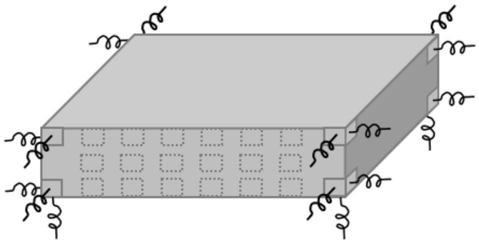

Fig. 9. Spring mounted foundation

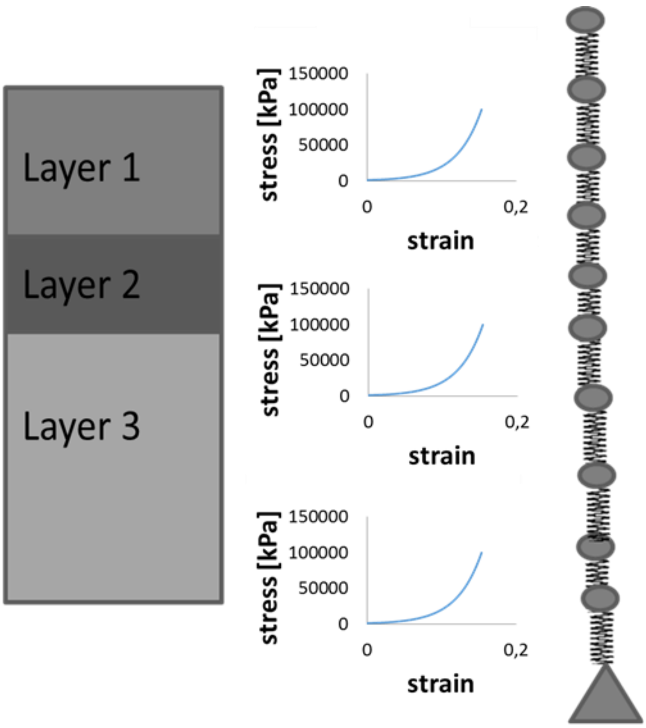

Fig. 10. Example of calculation of substitute stiffness for multilayer foundation as series of springs

There are usually more than one layer of different soil types in the foundation. In this case the calculation of substitute stiffness of linear springs may be performed using series of nonlinear springs. Where each layer has several springs and lumped masses of the soil in layer (Fig. 10). The spring has nonlinear stiffness of the layer. The series of springs is then load by its own weight. Then it is loaded by concrete and machine tool. The last step is to linearize the stiffness at this point.

4. OPTIMIZATION AND MODELING OF REINFORCED CONCRETE FOUNDATION

As already mentioned, in most cases the foundation is made of a thick reinforced concrete block. This reinforced concrete foundation may affect the machine tool properties both positively and negatively. The structural optimization algorithms may be employed in order to control the effect the foundation has on machine tool properties.

The following study presents results of employment of structural optimization algorithms in optimization of machine tool foundation. The employment of optimization algorithm are advantageous because contradictory demands maybe fulfilled. The most common demands are requirements on dynamical properties. The dynamical properties as eigen-frequencies and FRFs are directly connected with quality and efficiency of machining process. The other requirements may include the weight of foundation as it is connected to cost of foundation. There may be various constraint on dimensions of foundation also.

These requirements form a criteria and constrains in optimization. The suitable optimization algorithm should be chosen based on the nature of the criteria and constraints.

The following study presents optimization of foundation of machine tool presented in chapter 2 (Fig. 3). The chosen criteria are second eigen-frequency and weight of foundation. Based on this criteria the most suitable optimization algorithm is NSGAII [3]. The optimization task was defined as follows

$$\begin{array}{c} \max Fr_2 \\ \min M \end{array} \tag{3}$$

where Fr_2 is second eigen-frequency and M is weight. The maximization of second eigen-frequency was chosen as criteria because second eigen-frequency is dominant in machining. The minimization of weight was chosen to get cost efficient solution.

The optimization parameters has been specified as various dimension of foundation (see Fig. 11 and Fig. 12). The resulting pareto front for our case is shown on Fig. 13. The x-axis is a weight normalized by weight of original variant of foundations. The y-axis is the eigen-frequency normalized by eigen-frequency of machine tool without foundation.

The resulting pareto front is a curve of trade-off between normalized weight and normalized eigen-frequency. With rising weight we get higher eigen-frequency which goes in limit to eigen-frequeny of machine tool without foundation (normalized eigen-frequency = 1). The Fig. 13 shows original variant of foundation which has been designed using usual procedure (without finite element computations). The chosen variant has about 33% more weight but has superior eigen-frequency. The shape of original variant (in yellow) and chosen variant are shown on Fig. 14.

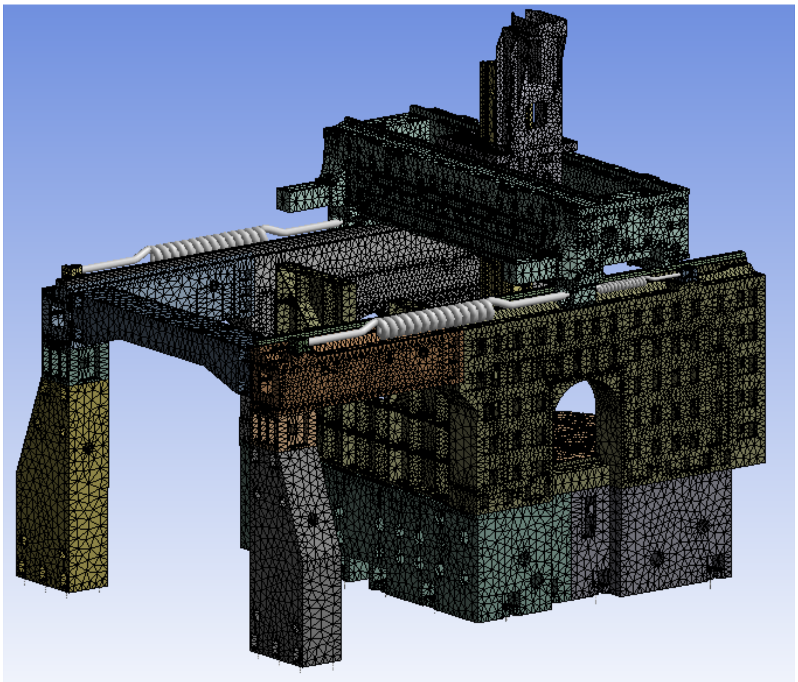

Fig. 11. The machine tool model used for the first case study

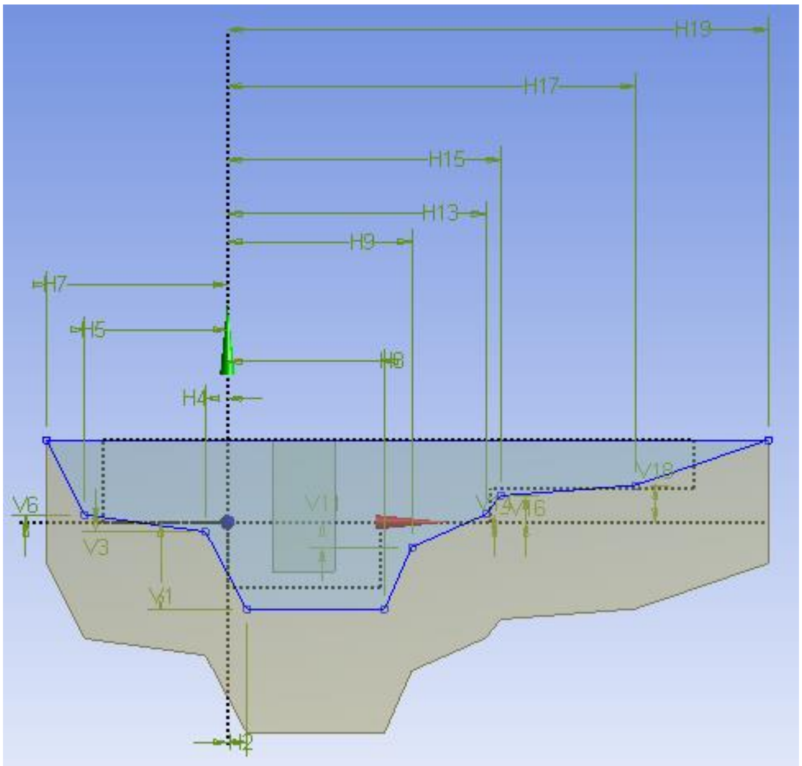

Fig. 12. The optimization parameters of foundation

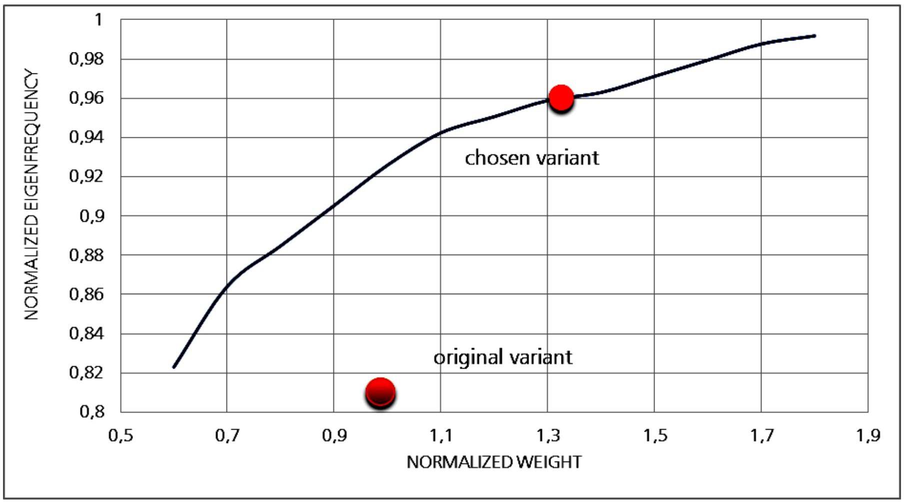

Fig. 13. Pareto front

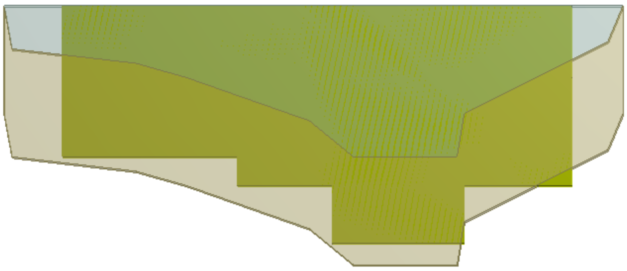

Fig. 14. The chosen and original (in yellow) foundation

The chosen variant has shape that has been determined as optimal during optimization. The chosen shape has not been constrained in any way and therefore may not be doable. This study aimed to explore feasibility of employment of structural optimization in machine tool foundation design and to simplify this task no manufacturability conditions has been specified. But in case of optimization of real foundation it would be prudent to include constraints which would ensure that designed foundation is possible to build. This study presents a procedure to control the influence of foundation on machine tool properties. The study presents usage of multicriterial optimization algorithm to compute the trade-off curve. The trade-off curve may be used to pick the ideal variant of foundation based on various preferences (dynamic properties, cost, etc.)

5. APPLICATION CASE STUDIES

Presented methods were applied on two case studies. The first one was done on the multi-purpose machining center for workpieces up to 15 tons. This application example has been already presented in chapters 2, 3 and 4.

The second case study was the application on the Gantry-type modular machining center for heavy weight workpieces. The method of the modeling subsoil and foundations for this machine tool was chosen with regard to the possibility of changing model parameters. The model is created by interconnecting dynamic models of subcomponents in Matlab / Simulink, which were FEM analyzed using ProEngineer / ProMechanica program Fig. 15. By connecting state space models of individual components in Simulink a good agreement of frequency characteristics was achieved in comparison with FEM analysis. This partial verification confirmed the functionality of the method of connecting state-space models even when already reduced FEM models are used. To achieve a reasonable quality of the complex model, it was necessary to use FEM model description with 200 states for each component. If positions and speeds were exported, the number of modal states rosed to 2x200. The connected complex models in Simulink are given by the sum of physical properties of individual FEM models. This complex mathematical model consists of the discrete model of ballscrew and servodrive, state-space model of machine superstructure, simplified model of gear rack-pinion gantry drive, 2D pattern of spring flaps between superstructure and concrete foundation, state space model of concrete foundation, model of soil, 2D pattern of spring flaps between foundation and machining tables and three machining tables (the clamping plate is made of 3 modules of the same table).

Input values of the machine model are forces from servo drives, cutting forces and reactions from fixing elements connected with the foundation. The output of the model are speeds and positions of points to which the force reactions was transferred. Deformation given by the difference of positions of nodes and stiffness creates a force reaction at the base and with the opposite sign to the machine. Machine tables and the foundation are analogously connected. 3 identical state-space table models are used (to create 1 large clamping plate), but the input force to relevant nodes is different depending on the table placement on the foundation. Linking the base model with an absolutely rigid reference is realized by flaps which are defined by the equivalent soil stiffness determined with the help of information from geodetic resources.

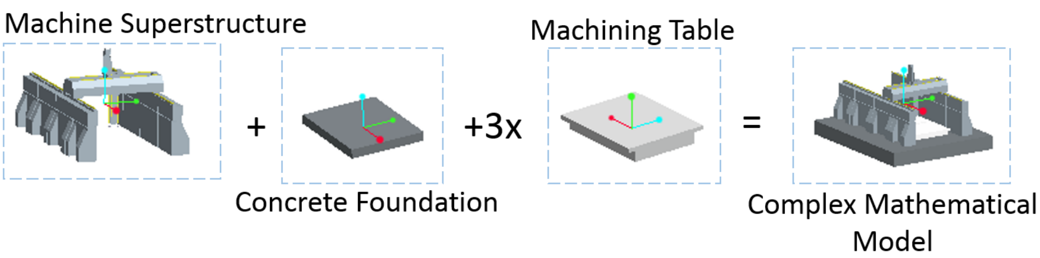

Fig. 15. Partial FEM models of machine components; The clamping plate is made of 3 table modules

Visualization via wireframe model was implemented to the mathematical model of the machine Fig. 16. This visualization is based on the monitored deflection of nodes on a machine model. In the first stage of visualization it is necessary to perform at least 2-second time-simulation, while a harmonic signal of definable frequency is fed to the servo-drive (X-axis or Y-axis).

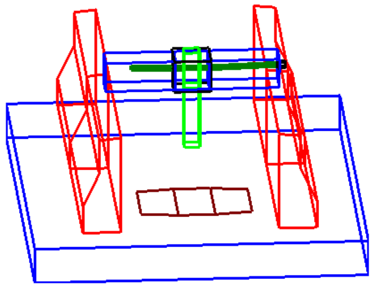

Fig. 16 Vizualization of complex model

Thus it is possible to achieve excitation of the machine in problematic frequencies and visually check the movement of the entire complex model.

One possibility of wire visualization GUI is to store log data at a specific excitation frequency. The complex model is quite large (includes over 2000 states) and for this reason time simulations are quite time-consuming. These stored waveforms displacements for different frequencies can be retrieved in the future, without the need of lengthy simulation.

6. CONCLUSION

The main objective of this work was to expand existing complex mathematical models of machines in a manner that would respect the influence of their installation on the foundation. This objective has been achieved.

A method of modelling and optimization of foundations was developed. It consists of four basic parts: Mathematical modelling of machines, optimization of the number and placement of fixing (levelling) elements, optimization and modelling of the reinforced concrete foundation and modelling of the subsoil with respect to engineering geological conditions. The main optimization criterion is to increase the lowest natural frequency of the machine while reducing the foundation weight (amount of reinforced concrete).

The result is a virtual mathematical model of the machine tool, including the influence of its foundation and subsoil.

- The proposed methods and optimization can be used for designing new machines - their foundations and the number and distribution of machine levelling elements.
- A secondary benefit is the more reliable complex model of the machine which enables us to study the influence of the machine foundation on cutting process stability and its influence on precision (through the Frequency Response Function).
- It is also possible to use these models to study the influence on machine drives. However, this was not the aim of the presented work.
- There is a further possibility to use the results of this study to determine the effect of foundation on machining stability.

Presented methods were applied on the case study of the multi-purpose machining center for workpieces up to 15 tons, which was an integral part of chapters 2, 3 and 4. The second case study was the application on the gantry-type modular machining center for heavy weight workpieces – chapter 5.

ACKNOWLEDGMENTS

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