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On vibration transmissibility in a machine tool-support-foundation-subsoil system

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Abstract

The optimal combination of machine tool support and foundation type is vital for high precision manufacturing. However, there is limited knowledge and few models available for predicting the behavior of a machine tool, including its operational environment. The study presents the estimation of the machine tool-support-foundation-subsoil system parameters change onto transmissibility change. The analysis was carried out using a finite element model of a vertical lathe with a steel-polymer concrete main frame placed on a block type foundation. The purpose of this work is to identify the model parameters that have the significant impact on the vibration's transmissibility. Based on the analysis conducted it was found that the machine tool as well as foundation properties have the greatest impact on the transmissibility.

Keywords: machine tool; foundations; transmissibility; vibration isolation

1. Introduction

Within the construction of the machine tool, many different mechanical interfaces can be distinguished. They determine the static and dynamic properties of the machine, thus affecting the machining efficiency [1]. One such interface is between the machine tool and the surroundings it operates in, it consists of the following components: (i) machine tool, (ii) support, (iii) foundation, and (iv) subsoil [2]. The proper modelling and design of mentioned elements is crucial from the point of view of vibration isolation and thus the machining performance [3].

Kono *et al.* [4] pointed out that the support stiffness greatly influences the machine tool rocking vibrations, that deteriorate the surface finish of workpieces. In general, greater stiffness of machine tool supports can reduce rocking vibrations caused by drives of the machine. Conversely, vibrations caused by ground disturbances increase. Therefore, the stiffness of machine tool supports should be meticulously designed for both levels of disturbance. Consequently, the study developed models of machine tool supports and contact stiffness proposed by Shimizu *et al.* [5]. In addition, to obtain the necessary parameters values, the unit contact stiffness with several materials was measured in the normal and tangential directions to the interface. This issue has been developed in more detail in [6].

The later study by Kono *et al.* [7] provides the methodology for tuning the stiffness of machine tool supports. Using the previously described contact stiffness approach the mathematical relationship between the load of the support and its stiffness was established. On this basis, a method of arranging supports was proposed to increase their rigidity without the use of anchor bolts. The proposed method was applied to increase the lowest natural frequency of a horizontal milling machine. In the result it was increased by 15–55 % compared to popular placements schemes of three supports. The method was then further developed in [8]. The similar problem was also analyzed by Lin and Li [9] and Havlik *et al.* [10].

Mori *et al.* [11] addressed the issue of minimizing rocking vibrations using the viscoelastic damper support developed in [12]. Authors developed a model that enables quantitatively to estimate the behavior of the damper in the machine tool. Based on the model, the damper support system was applied to reduce the rocking vibration of three axis vertical machining center. As a result, it was found that the damper can attenuate residual vibrations approximately 0.5 s shorter than the original condition to the steady-state condition. Further studies by Mori *et al.* [13], [14] concerns a model-based level adjustment method, thus supplementing previous work.

Next to the support, a crucial element of the machine tool-foundation interface is the foundation itself. It plays a key role in damping vibrations transmitted from other machines, it also provides the stiffness needed for machines with low structural stiffness and is the main element in leveling and aligning the machine [15].

Tian *et al.* [16] analyzed the influence of different types of concrete foundations and subsoil properties on the dynamic characteristic of a heavy-duty machine tools. The analysis was performed using a scaled model based on multibody transfer matrix method. The established model consisted of elastic elements (i.a. bed, transverse beam, foundation) and rigid elements (i.a. spindle, slides) interconnected by experimentally identified joint interface elements. Based on the model, an analysis of the impact of the size of the foundation and the stiffness of concrete and subsoil on the vibration of the tool tip was carried out. It was found that increase of foundation size significantly increases decaying tool tip vibrations, the concrete stiffness has rather insignificant influence, and in the case of subsoil, as it becomes stiffer, the maximum displacement of the dynamic response at the tool tip decreases, but the number of oscillations increases. The work was developed in [20].

Cai *et al.* [17] analyzed the efficacy of different types of isolation trenches used in machine tool foundations. The conducted analysis was based on a finite element model of a heavy-duty machine tool and its foundation-subsoil interaction. Based on fractal theory the equations for calculating the stiffness and damping of these interactions were determined. Next, using a cloud computing the effectiveness of the varied materials used to fill the isolation trench to different depths, widths, lengths, and locations were examined. It was found that the open trench and concrete-filled trench exhibited the best isolation compared to the other materials, moreover the increasing depth of the trench showed promising effects in comparison to changing the width and length of the trench.

Although the previously cited works on modeling foundations consider both subsoil properties and foundation-subsoil interactions, the subsoil seems to be only briefly analyzed.

Summing up the review of the literature, it can be stated that, despite the considerable achievements in the field, there is currently no coherent modeling method that considers the interactions occurring at the machine tool-support-foundation-subsoil system. Hence, the purpose of this work can be formulated as follows: identification of the model parameters that have the most significant impact on the transmissibility of vibrations. The identification of these parameters should contribute to the development of an effective methodology for modeling machine tool-support-foundation-subsoil systems and, as a result, its further optimization.

The paper is structured as follows. Section 2 presents the fundamentals of transmissibility analysis and finite element model of a machine tool used in the study. In Section 3, contains the results of the analysis of the machine tool-support-foundation-subsoil system parameters change onto transmissibility change. In Section 4, discussion of the results obtained was carried out. Section 5 contains the final conclusions that summarize the most important observations presented in the paper.

2. Methodology

2.1. Fundamentals of vibration transmissibility

The fundamental understanding of vibration transmissibility, begins with the relationships between responses and forces in terms of receptance: if one has a vector $\boldsymbol{f}_A$ of magnitudes of the applied forces at coordinates A, a vector $\boldsymbol{x}_U$ of unknown response amplitudes at coordinates U and a vector $\boldsymbol{x}_K$ of known response amplitudes at coordinates K [18]. The relation between a set of responses $\boldsymbol{x}$ and the applied forces $\boldsymbol{f}$ is given by the frequency response matrix $\boldsymbol{H}$, which can be written as:

$$\boldsymbol{x} = \boldsymbol{H}\boldsymbol{f} \tag{2}$$

Next, if the only non-zero generalized forces are $\boldsymbol{f}_A$ one can write:

$$\boldsymbol{x}_U = \boldsymbol{H}_{UA}\boldsymbol{f}_A \tag{3}$$

$$\boldsymbol{x}_K = \boldsymbol{H}_{KA}\boldsymbol{f}_A \tag{4}$$

where $\boldsymbol{H}_{UA}$ and $\boldsymbol{H}_{KA}$ are the receptance frequency response matrices relating coordinates U and A, and K and A, respectively. Eliminating $\boldsymbol{f}_A$ between Eq. (3) and Eq. (4), it follows that:

$$\boldsymbol{x}_U = \boldsymbol{H}_{UA}\boldsymbol{H}_{KA}^{+}\boldsymbol{x}_K \tag{5}$$

where $\boldsymbol{H}_{KA}^{+}$ is the pseudo-inverse of $\boldsymbol{H}_{KA}$. Hence, the transmissibility matrix is defined as:

$$\boldsymbol{T}_{UK}^{(A)} = \boldsymbol{H}_{UA}\boldsymbol{H}_{KA}^{+} \tag{6}$$

The set of coordinates where the forces are applied need not coincide with the set of known responses. The only restriction is that – for the pseudo-inverse to exist – the number of K co-ordinates must be greater or equal than the number of A co-ordinates.

2.2. Finite element model of machine tool

The analyzed machine tool is a lightweight vertical lathe with steel-polymer concrete frame. The frame of the lathe is a welded structure composed of steel hollow profiles which are filled with polymer concrete, this increases the structure dynamic stiffness.

The finite element model of a lathe in question was built using the Midas NFX preprocessor [19]. The model consisted of 347,655 degrees of freedom and 92,703 finite elements. The detailed description of the model can be found in [20] and [21]. The structural loop and finite element model of the lathe in question was depicted in Figure 1.

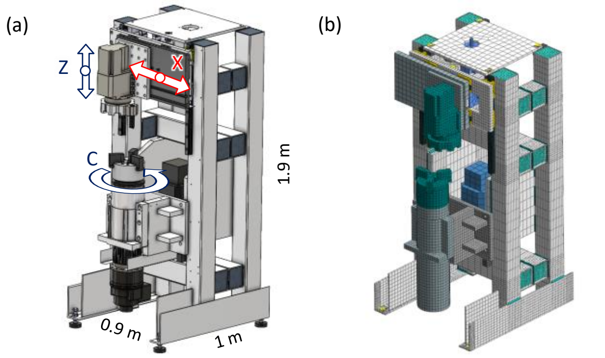

Figure 1. Vertical lathe with steel-polymer concrete frame: structural loop (a) and finite element model (b).

For the purposes of the presented analysis, the remaining elements of the machine tool-environment interface had to be considered in the machine tool model, i.e. (i) support, (ii) block type foundation, and (iii) subsoil. The model of the machine tool-support-foundation-subsoil system is depicted in Figure 2.

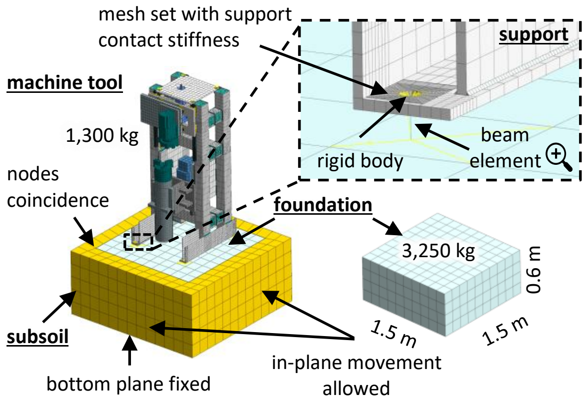

Figure 2. Simplified model of the machine tool-support-foundation-subsoil system.

To describe the damping of the subsoil model a complex stiffness damping was used, thus damping matrix $\boldsymbol{C}$ can be expressed as [22]:

$$\mathbf{C} = \mathrm{j}\eta\boldsymbol{K} \tag{7}$$

where: $\boldsymbol{K}$ – model stiffness matrix; j – imaginary unit, η – loss factor.

Next, using Nastran Solver (SOL108) direct frequency response analysis was conducted, the excitation force placement and response measurement points were depicted in Figure 3.

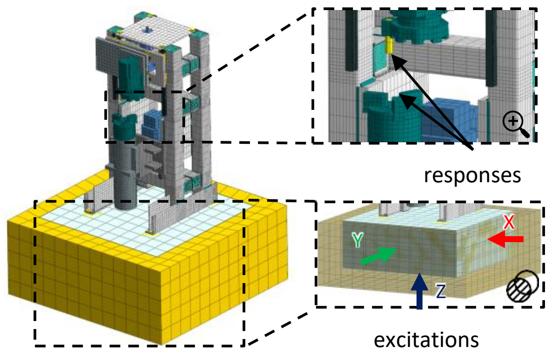

Figure 3. Direct frequency response analysis setup.

3. Results

Based on the finite element model developed, the analysis of how the change of machine tool-support-foundation-subsoil system parameter values influences the vibration transmissibility, was conducted. The mass-spring-damping properties (i.e., Young's moduli, densities, and loss factors) of each of the system components were changed (increased by a 10 %) and then the resulting transmissibilities were compared to the original system case. The analysis was carried out in three perpendicular directions (consistent with the axes adopted in Figure 1 and Figure 3). The exemplary results: (i) transmissibility from foundation to tool T_{FT} and (ii) transmissibility from foundation to workpiece T_{FW} in X direction, are depicted in Figure 4.

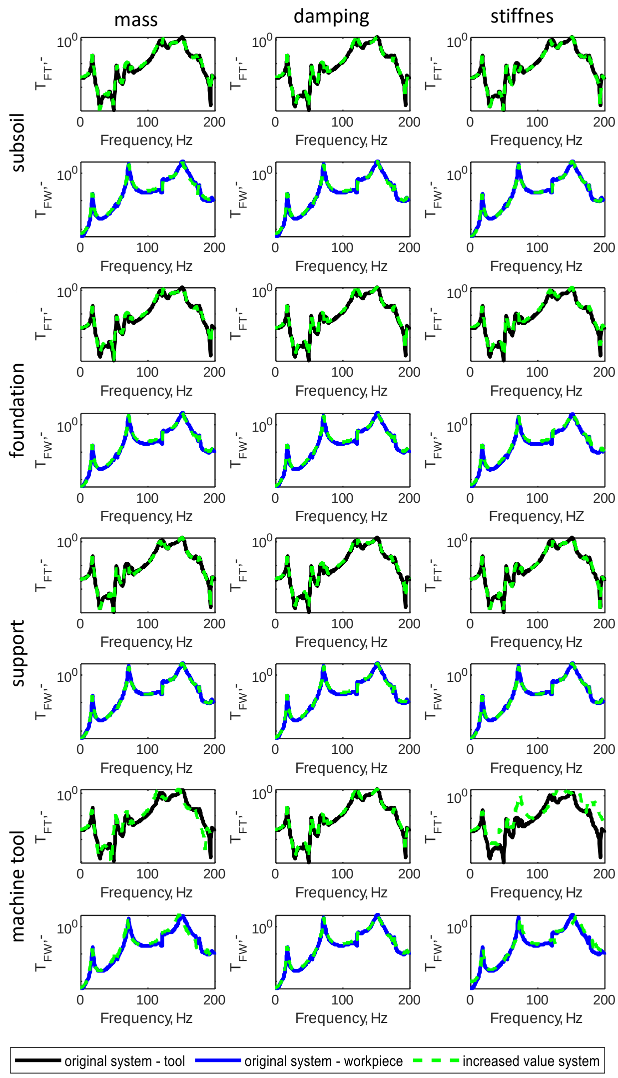

Figure 4. Comparison of transmissibilities in X axis – logarithmic scale.

Analyzing the obtained results, the differences are barely visible (slightly better on a linear scale, but still). This is due to the sensitivity analysis method adopted, where a 10 % change in the parameter was assumed. This allowed to avoid distorting the actual relationship between the parameters describing individual elements of the machine tool-support-foundation-subsoil system, although the obtained differences are not vivid (this does not mean that the system parameters have negligible impact). To present the impact of individual parameters more clearly on the change in transmissibility, it was decided to introduce the indicator Δ that describes the difference between compared transmissibilities:

$$\Delta_{FT,FW} = \sum_{\omega_{start}}^{\omega_{end}} \left| \boldsymbol{T}_{FT,FW}^{orig}(\omega_i) - \boldsymbol{T}_{FT,FW}^{inc}(\omega_i) \right| \cdot 100\ \% \qquad (8)$$

where: $\boldsymbol{T}_{FT,FW}^{orig}(\omega_i)$ – vector of original system transmissibility between foundation and tool (FT) or foundation and workpiece (FW); $\boldsymbol{T}_{FT,FW}^{inc}(\omega_i)$ – analogously determined vector for a system with increased parameter values.

The Δ indicators for tool Δ_{FT} and workpiece Δ_{FW}, were calculated for each parameter and then normalized within subsequent directions to maximum value. The results were depicted on a bar plot in Figure 5.

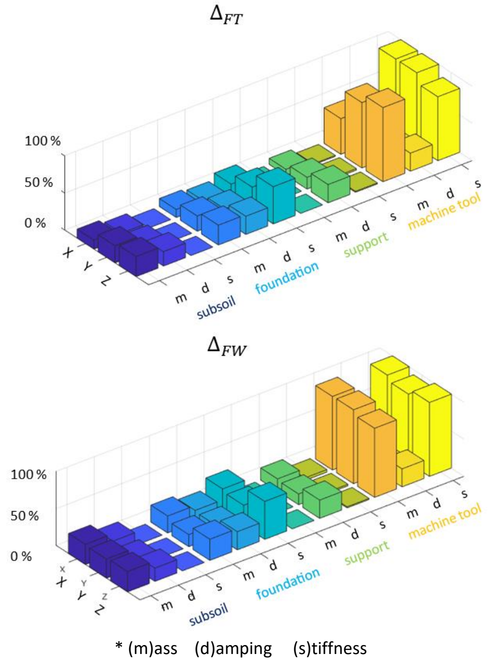

Figure 5. Sensitivity analysis results, the Δ indicators values.

4. Discussion

Analyzing the obtained results, the properties of the machine tool itself have the greatest impact on the vibration transmissibility. And here, of course, the variability of the properties characterizing the structural loop of the machine may be significant, although the user often does not have the opportunity to shape them. However, the user may influence the properties of a subsoil-foundation-support system on which the machine will rest. Analyzing these, it can be noticed that the most significant are properties of foundation as well as mass and damping of a subsoil.

The subsoil seems to be particularly interesting due to the significant possibility of shaping or selecting its properties – the selection of various materials often significantly differing in the values of individual properties [23]. However, in order to fully exploit this potential, the selection of subsoil should be preceded by a model analysis of the solution. Thus, particular care must be taken in case of subsoil modeling. However, the literature states that it is extremely difficult to map the subsoil properties [24].

Moreover, the relationships between subsoil properties and machine tool dynamics may be not so obvious in real life application (it should be stressed that the presented research only covers sensitivity analysis of independent parameters of mass-spring-damping properties of the system in question), since with increased subsoil stiffness comes the increased subsoil mass (increased compaction of subsoil), with increased mass of foundation comes the increased subsoil compaction, *etc.*

When it comes to analyzing the support, it can be seen that in all three directions its stiffness seem to have only a limited impact, which in fact coincides with the studies presented by Kono *et al.* [7], [8] and Mori *et al.* [13], [14]. This does not mean, however, that support properties do not determine the nature of rocking modes that characterize the machine tool. This is still a significant part of the system, although of less importance compared to the others analyzed components. However, when it comes to support damping, it is clear that it has a significant impact on vibration transmissibility. Hence, the search for methods to increase support damping seems particularly justified and appropriate [11], [12].

The presented research should be treated as a preliminary study. Its main limitation is the lack of incorporating the damping at the foundation-subsoil interface in the model. Moreover, the analysis of only one machine tool and one type of foundation makes it difficult to generalize the observations at this stage.

5. Conclusions

Despite significant progress in modeling the static and dynamic properties of machine tools, there is still a lack of a consistent methodology that considers subsoil, foundations and supports.

The paper presents an analysis of machine tool-support-foundation-subsoil system parameters change onto vibration transmissibility change. Based on a finite element model established it was found that foundation properties as well as the properties of a machine tool itself have the greatest impact on vibration transmissibilities. The other factors that have a significant impact on the vibration transmissibility are damping of the subsoil and the support. Therefore, in case of modelling a particular care must be taken in modeling them. Additionally, an important aspect to consider is the incorporation of foundation-subsoil interaction into the analysis, as this aspect can contribute to additional system damping [25], [26] .

Further work should include the analysis of diverse types of foundations as well as the different structural loops and sizes of machine tools.

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