APPLICATION OF THE HYBRID FINITE ELEMENT METHOD IN MODELING OF STATIC PROPERTIES OF MACHINE TOOLS LOAD-CARRYING SUBSYSTEMS

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Summary

Paper presents an application of the hybrid finite elements method for the static calculations of a load-carrying system of a medium size machine tool. Five different models of the machine tool structure are analyzed. Models include components of the workpiece branch of machine tool, i.e. column, knee and guideway connection between these structural elements. The modeled machine tool, model variants and static stiffness analysis of the investigated machine tool are described in the paper. The results obtained for the different model variants are compared and evaluated. Effectiveness of the analysis for different model variants is assessed.

Keywords: load-carrying system, machine tool, guideways, simulation investigation, modeling, analysis of static properties

Zastosowanie hybrydowej metody elementów skończonych w modelowaniu właściwości statycznych podukładu nośnego frezarki

Streszczenie

W artykule przedstawiono przykład zastosowania hybrydowej metody elementów skończonych do projektowych badań symulacyjnych właściwości statycznych podukładu nośnego frezarki wspornikowej średnich rozmiarów. Wykonano modelowanie tego obiektu i opracowano pięć wariantów jego struktury bryłowej. Modelowanie obejmowało fragment gałęzi przedmiotowej tego układu. Opracowano modele korpusu stojaka i wspornika oraz połączenia prowadnicowego, łączącego te elementy. Przedstawiono obiekt modelowania, warianty modelu oraz wykonano analizę obliczeniową do wyznaczenia statycznych właściwości tego obiektu. Zestawiono i porównano wyniki uzyskane dla poszczególnych wariantów modelu. Dokonano oceny efektywności obliczeń dla poszczególnych wariantów modelu.

Słowa kluczowe: układ nośny, obrabiarka, prowadnice, badania symulacyjne, modelowanie, analiza właściwości statycznych

1. Introduction

Hybrid finite element method allows to generate various model variants of the investigated machine tool [1, 2, 3]. The models' variety applies to the

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machine tool structural elements. Structural elements may be modeled using rigid finite element method (RFE) or deformable finite element method (DFE). One may also use a hybrid approach which combines both of the aforementioned methods [2, 4, 5, 6]. During the construction of the load-carrying system model (discretization) some components of the system may be regarded as rigid bodies or deformable. Also a particular body can be partially rigid and partially deformable within certain areas. Information on the influence of the discretization technique on the results must be considered when choosing a modeling approach. Such information may be obtained through the comparative analysis presented in the paper. The analysis is focused on the comparison of static deflections obtained for a few model variants of the machine tool. Results of static analyses carried out by using various hybrid models and traditional rigid and deformable finite element methods. The procedure may be viewed as a validation of the hybrid model structure. Thus the validation includes the comparison of results obtained through the analysis of five model variants different with respect to the discretization of the structure whereas contact joints are modeled identically [2, 7]. DFE and RFE models are used as references for comparison because of their discretization levels.

2. Analyzed object

A medium size (width of table is 320 mm) typical vertical milling machine has been selected for the analysis of the knee-column subsystem. The model consists of the column, knee and the guideway enclosing support. The complete load-carrying system of the milling machine with marked analyzed components is shown in Fig. 1.

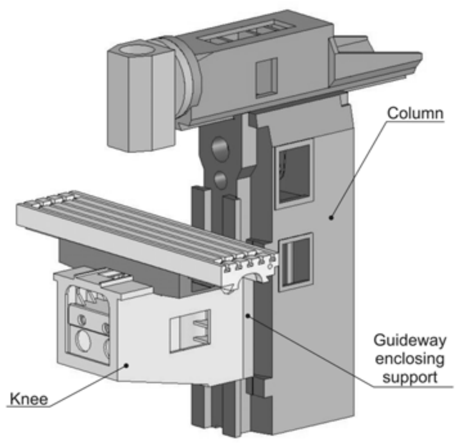

Fig. 1. Load-carrying system of the vertical milling machine: analyzed components are marked in the figure

Frame elements of the investigated milling machine are geometrically to complex to be modeled very accurately that may result in model of a very large size. Therefore, the geometry of the analyzed components has been simplified during the discretization process. The purpose of the geometry simplification is a reduction of the model which does not impact significantly the results of the analysis. As a consequence minor round corners, small holes, chamfers, small ribs and gating system elements are neglected. The effects of these simplifications are shown in Fig. 2.

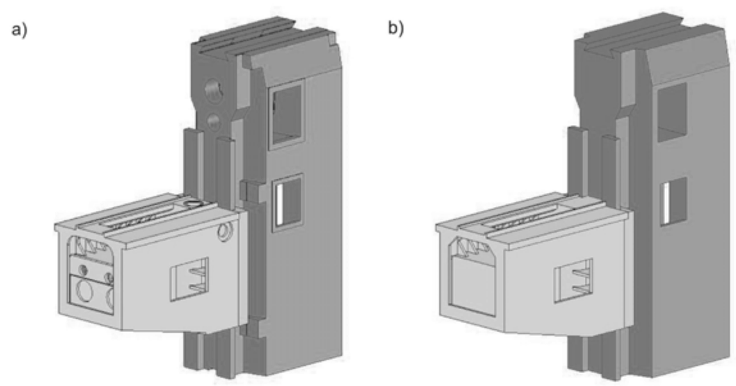

Fig. 2. Effects of the frame elements geometry simplifications:
a) non-simplified elements, b) simplified elements

Also, it is noted that strongly preloaded joints have no significant influence on the analysis results while they contribute to the model complexity. Therefore the contact joint at the interface of the knee and the enclosing support has been neglected. The elements of the enclosing support and the knee are considered in the model as one solid element (homogeneous material). This simplification is shown in Fig. 3.

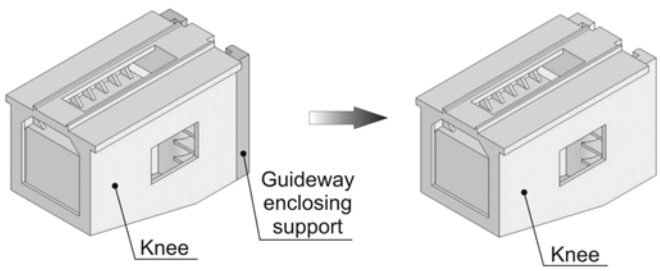

Fig. 3. Model simplification – neglecting the compliance
of the enclosing support-knee contact joint

Knee-column geometry assumed for the modeling is shown in Fig. 4.

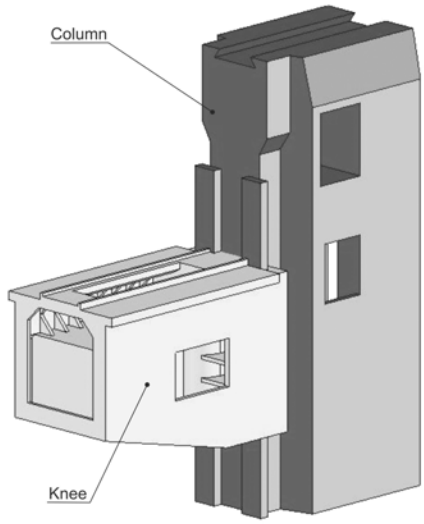

Fig. 4. Final geometry (after simplifications)
of the knee-column structure

3. Modeling

Three variants of the hybrid model are proposed to analyze the impact of the modeling approach on the obtained results. Also the reference models are constructed: RFE model and DFE model. The models can be characterized as:

- Variant RFE: all model components are rigid bodies that are modeled using rigid finite elements (RFEs);
- Variant H-1: vertical planes that cross the knee and the column divide them into the rigid (RFEs) and deformable parts (DFEs);
- Variant H-2: division of the column as in the H-1 variant whereas the knee is fully deformable;
- Variant H-3: division of the knee as in the H-1 variant whereas the column is fully deformable;
- Variant DFE: all components of the model are treated as deformable bodies and modeled using deformable finite elements (DFE).

The considered variants are illustrated in Fig. 5

Contact joints at the interface of the considered guideway connection are discretized according to the requirements of the hybrid finite element method. The analyzed rectangular guideway connection consists of six contact surfaces. The surfaces’ notation, placement and dimensions are given in Fig. 6. The assumed discretization (division into contact finite elements) remains identical for all variants (Fig. 7).

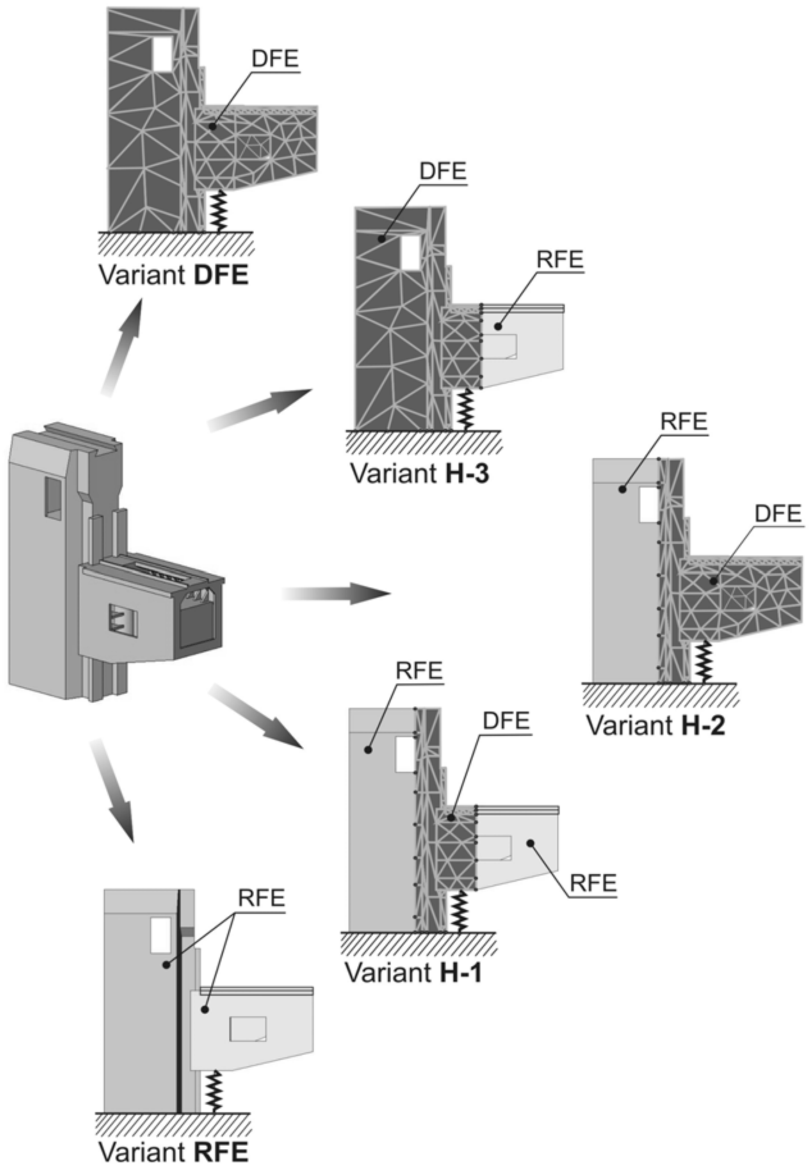

Fig. 5. Discretization variants of the knee-column system

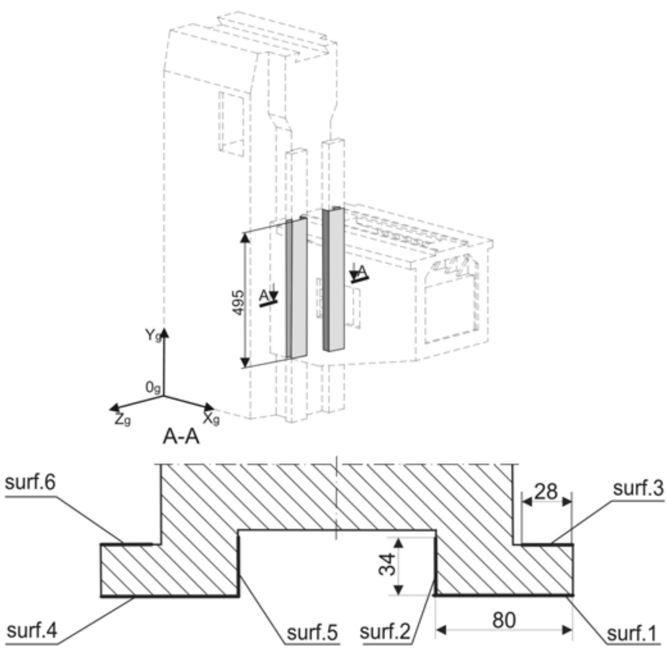

Fig. 6. Notation and dimensions of the contact surfaces
in the knee-column system of the milling machine

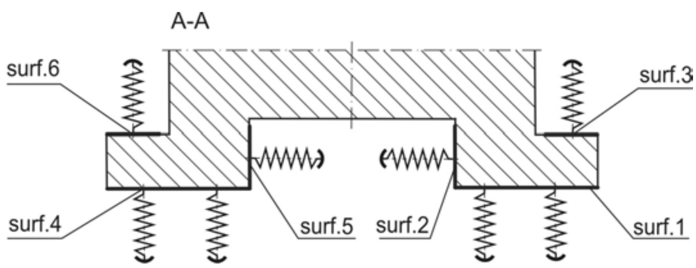

Fig. 7. Discretization of the contact surfaces in the knee-column system
of the milling machine

The contact structure incorporates also two-sided spring element that models the kinematic chain of the knee feed drive system. The modeling of this element is unified in the considered variants through the introduction of the elements that models the nut (Fig. 8).

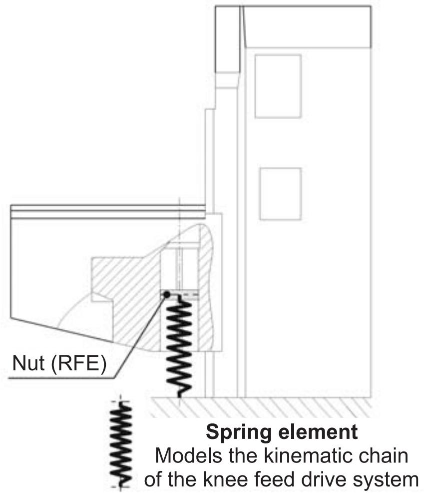

Fig. 8. Modeling elements of the knee feed drive system

Two set of calculations are carried out for two different machine tool configurations. The configurations are different with respect to the relative location of the machine tool subassemblies. In the first configuration referred to as max, table-sledge subassembly is at its most distant location relative to the sledge-knee guideways. The illustration of the variant that includes major dimensions is shown in Fig. 9.

Another set of calculations is carried out for the case when the sledge-knee subassembly is at the minimum distance of the sledge and the column (in the direction of the sledge-knee guideways). This configuration variant, referred to as min, is illustrated in Fig. 10.

Basic data that characterize quantitatively the model variants are given in Table 1.

Table 1. Characteristics of the saddle-knee model variants

Variant	Number of elements:		Number of DOF
	RFE	DFE	
RFE	1	0	6
H-1	2	3598	3246
H-2	2	6032	5682
H-3	2	4167	3876
DFE	2	6601	6189

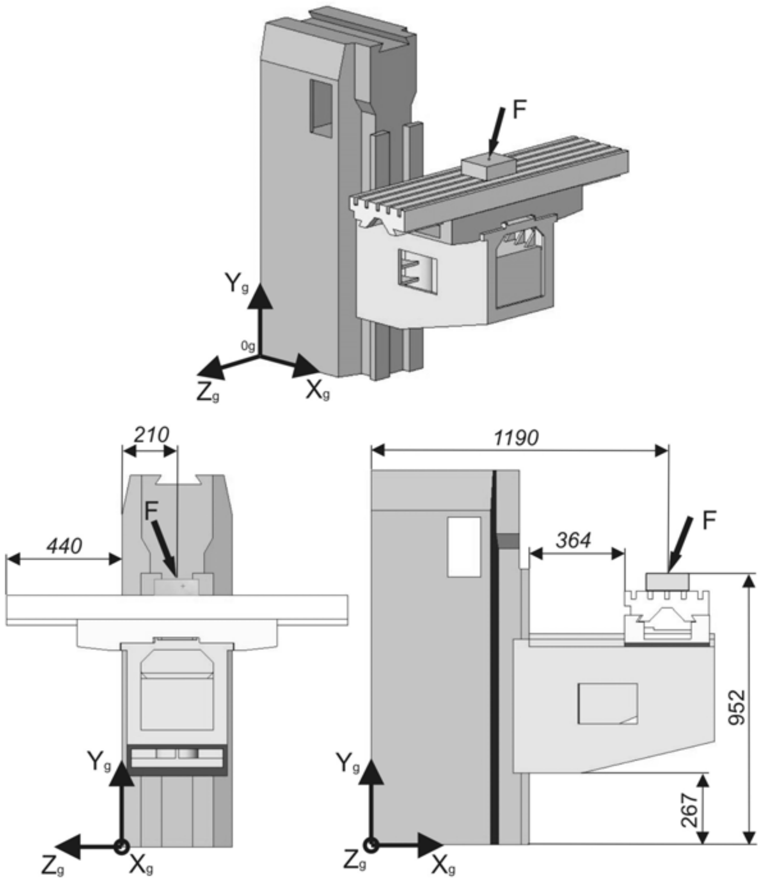

Fig. 9. Geometry description of the knee-column system in the max configuration variant

The applied loads ranged from 1 kN to 10 kN every 1kN. The load, referred to as the cutting force, simulates the force generated by the cutting process.

The comparison of the considered models is done on the basis of displacements at the cutting force exertion point. The displacements calculated by solving five analyzed model variants for min and max configurations are projected onto the cutting force direction. The comparison of the results is shown in Fig. 11 and 12.

Figures 13-18 present static characteristics at the point of force exertion projected onto the axes of the global coordinate system.

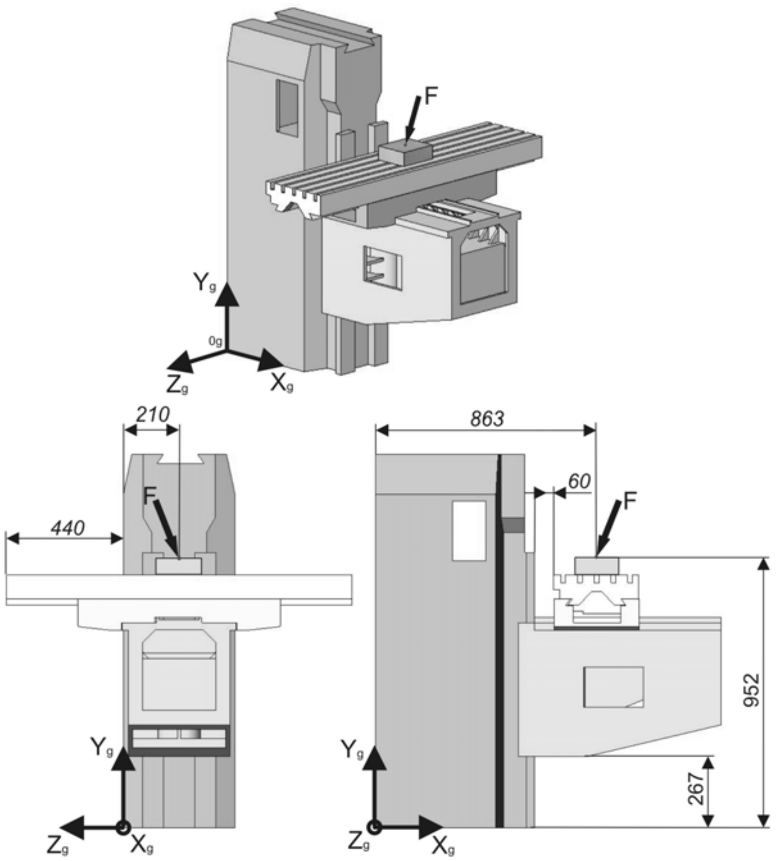

Fig. 10. Geometry description of the knee-column system model in the min configuration variant

Figure 19 shows a comparison of the surface pressure distribution at the contacting surfaces (Fig. 6) of the guideway at the maximum force of 10 kN for five discretization variants calculated for min configurations. Since the presented surface pressure distribution is representative for the considered analysis, such the comparison is not made for other contacting surfaces of the guideway. Since the presented surface pressure distribution is representative for the considered analysis, such the comparison is not made for other contacting surfaces of the guideway.

Effectiveness of the particular model variants, which is quantified by the computing time, is compared in Fig. 20 and 21 in the form of the bar plots for configurations max and min respectively.

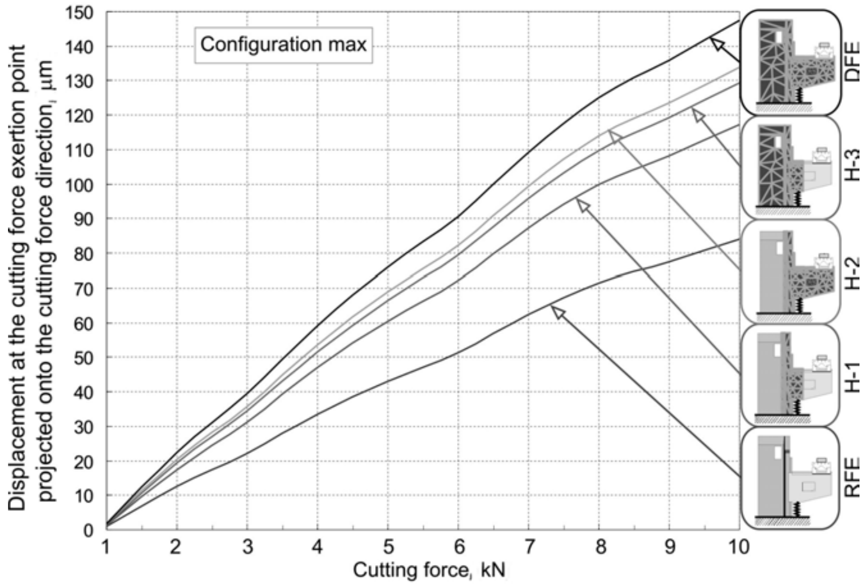

Fig. 11. Comparison of static characteristics at the cutting force exertion point projected onto the cutting force direction for the analyzed model variants and configuration max

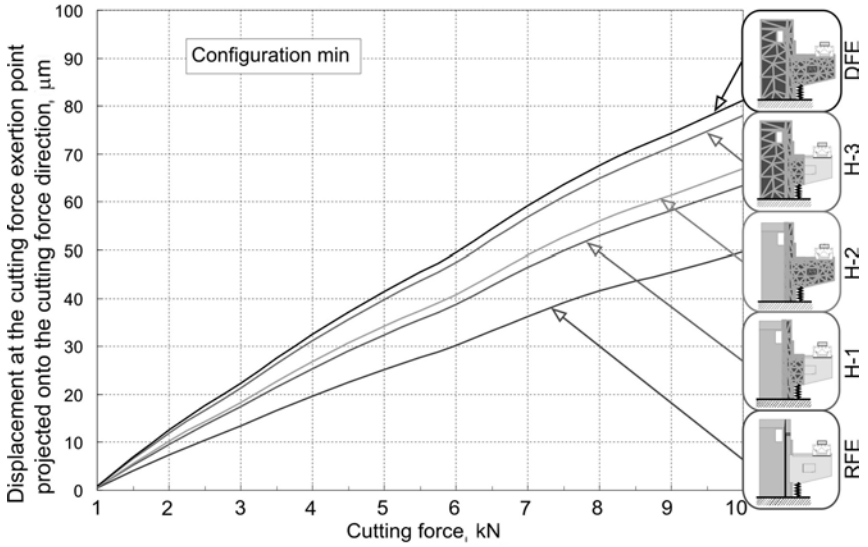

Fig. 12. Comparison of static characteristics at the cutting force exertion point projected onto the cutting force direction for the analyzed model variants and configuration min

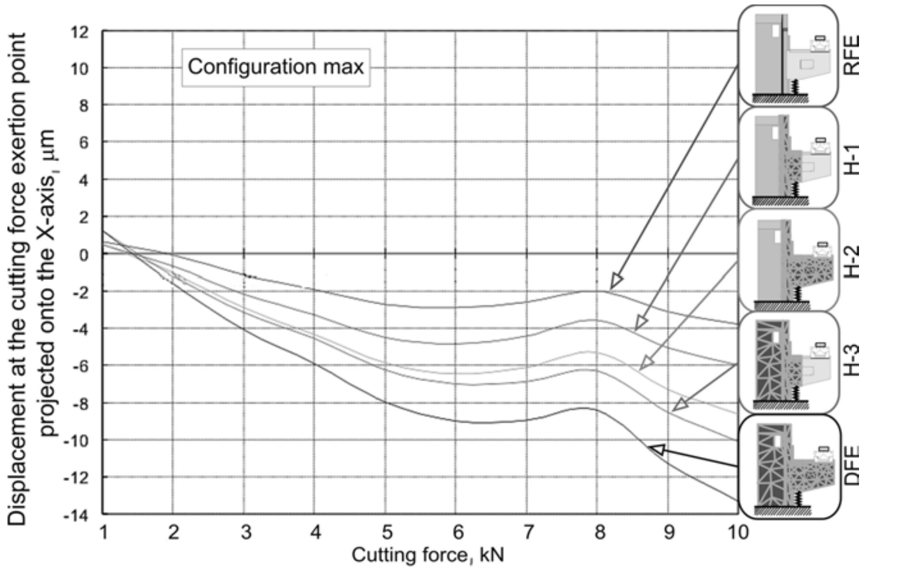

Fig. 13. Comparison of static characteristics at the cutting force exertion point projected onto the X-axis of the global coordinate system for the analyzed model variants and configuration max

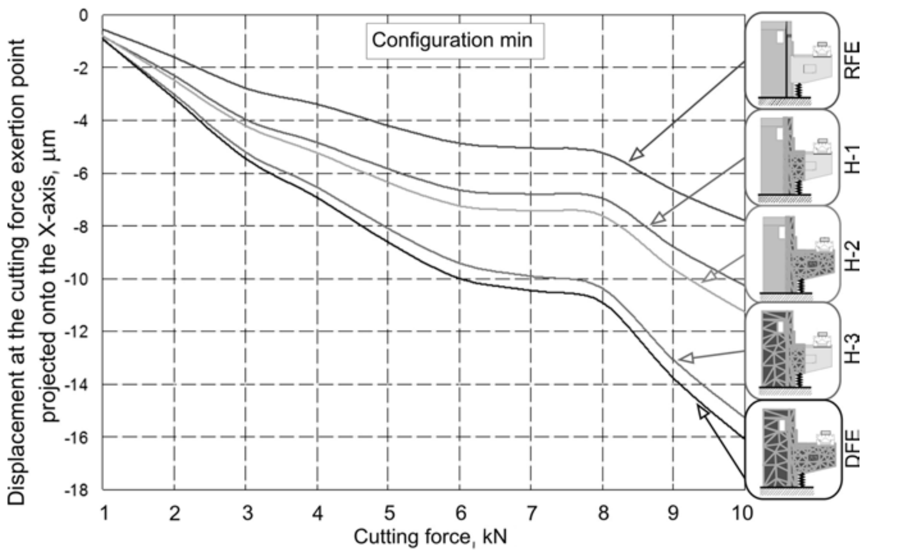

Fig. 14. Comparison of static characteristics at the cutting force exertion point projected onto the X-axis of the global coordinate system for the analyzed model variants and configuration min

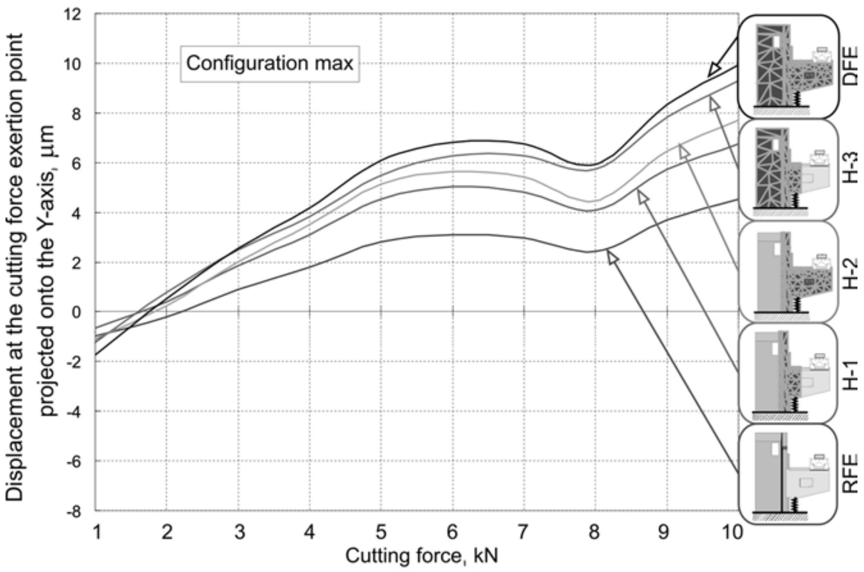

Fig. 15. Comparison of static characteristics at the cutting force exertion point projected onto the Y-axis of the global coordinate system for the analyzed model variants and configuration max

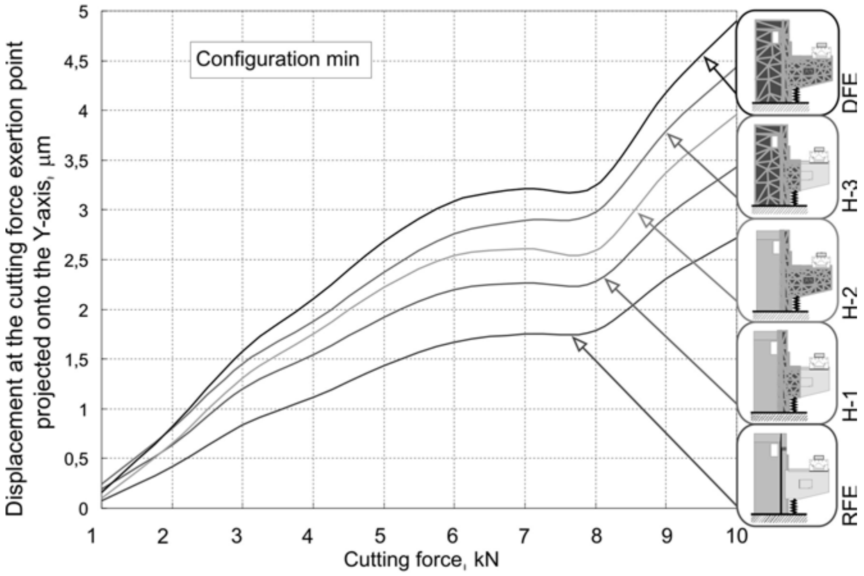

Fig. 16. Comparison of static characteristics at the cutting force exertion point projected onto the Y-axis of the global coordinate system for the analyzed model variants and configuration min

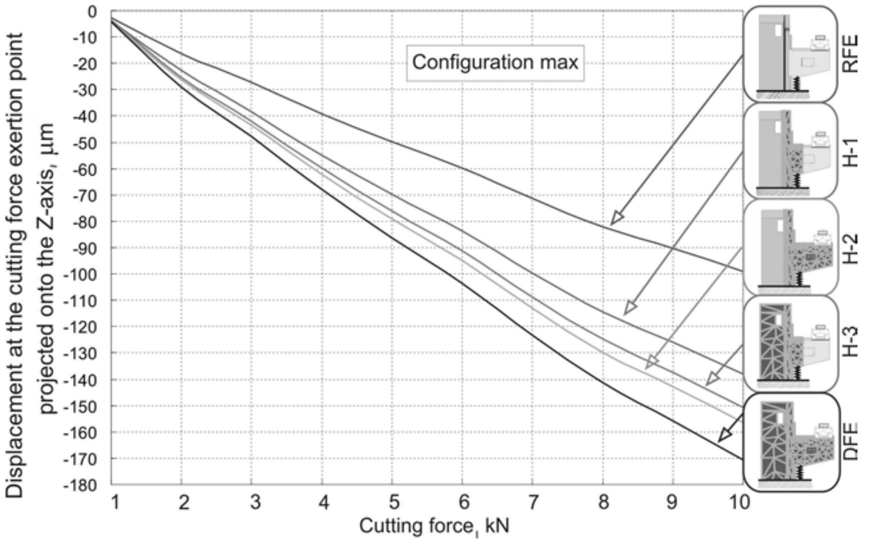

Fig. 17. Comparison of static characteristics at the cutting force exertion point projected onto the Z-axis of the global coordinate system for the analyzed model variants and configuration max

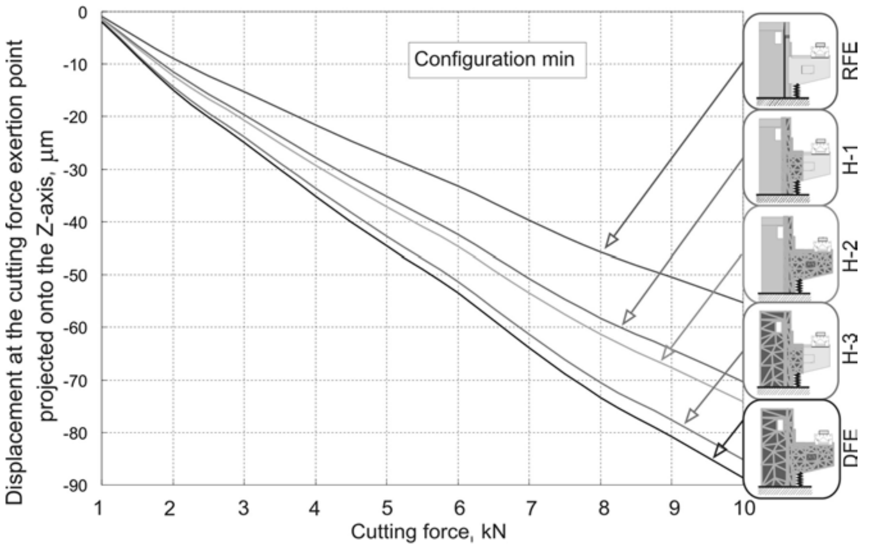

Fig. 18. Comparison of static characteristics at the cutting force exertion point projected onto the Z-axis of the global coordinate system for the analyzed model variants and configuration min

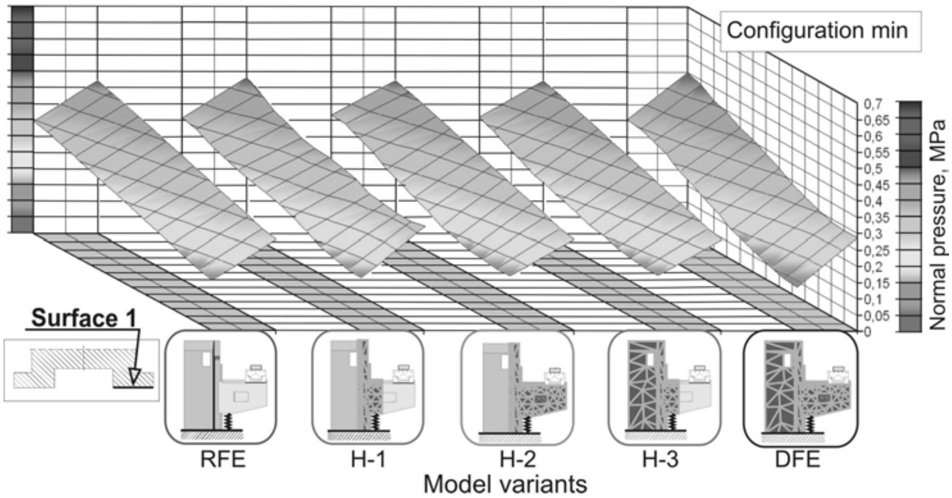

Fig. 19. Comparison of the surface pressure distribution at the contacting surfaces of the guideway at the maximum force of 10 kN for five discretization variants calculated for min configurations

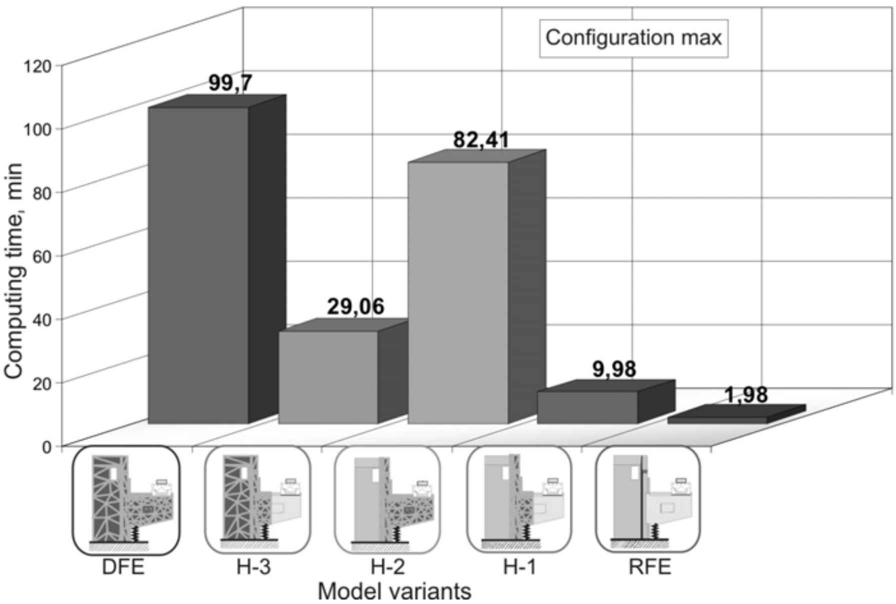

Fig. 20. Comparison of the computing time for five model variants for configuration max

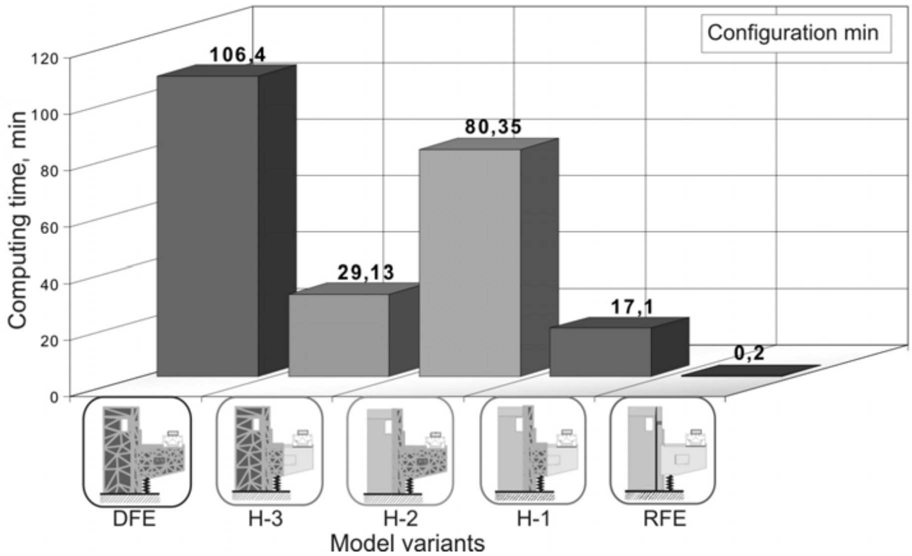

Fig. 21. Comparison of the computing time for five model variants for configuration min

4. Conclusions

Static analyses of the milling machine load-carrying subsystem model variants show a qualitative similarity of the displacement characteristics at the cutting force application point and surface pressure distribution at the contacting surfaces. This agreement supports the claim that load-carrying system can be modeled using hybrid models.

Nevertheless particular model variants bring quantitatively different results. This is evident when displacements of the cutting force application point are compared: two extreme variants, i.e. DFE and RFE are different by 57-60% at the maximum force. Results delivered by the hybrid models are within limits set by the reference models (DFE and RFE) over the whole range of the cutting force variation.

Normal pressure at the contacting surface of the guideway are usually larger for variants that demonstrate larger deformability of the system components. This phenomenon is amplified when regions located in the contact joint vicinity are deformable. This observation, according to the author, confirms existence of a strong coupling between contact phenomena and elements deformability.

Significant differences between computing times of particular model variants suggest a need for a trade-off between the analysis accuracy and the time of the modeling and computing. Time required for model construction and solving becomes an important factor when the analysis covers many points of the working space and multiple loading scenarios.

Presented results imply that H-3 variant is an optimum model. The results delivered by this model are similar to DFE model whereas computing time is reduced by 27-29%.

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