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Influence of material stiffness and damping on dynamic behaviour of production machines

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The development of new production machines is driven with aim to improve their productivity and precision. Focusing on the mechanical properties of the machine structural parts assembly, the key properties are static and dynamic stiffness. For example in machine tools, machining limits depend strongly on the dynamic stiffness of machine tool – workpiece assembly, see Altintas [1]. Another aspect is to reduce inertia masses of motion axis components, as this is beneficial to the motion axis speed and acceleration. A possible improvement is in replacement of structural parts from steel, cast iron to composite or hybrid materials as they might improve the behavior due to their lower density, adequate stiffness and larger damping. A comprehensive study of composite and hybrid materials application into the machine tool was published by Mohring [2] stating that hybrid materials might be a future in machines design. However, a key question is whether a component with higher damping can improve a dynamic stiffness of the machine assembly as the most of the assembly damping happens in connection interfaces. This might lead to a situation, where a replacement of a single structural component by a new one with higher damping might not significantly influence the global assembly damping and the assembly stiffness.

A simulation model was assembled with aim to evaluate the effect of structural parts stiffness and damping on the dynamic behavior of the machine assembly. The model used description of the basic motion equation in modal coordinates y

$$[I]\{\ddot{y}\} + [\Phi]^T\,[C]\,[\Phi]\{\dot{y}\} + [\Lambda^2]\{y\} = [\Phi]^T\{F\}\,. \tag{1}$$

Aim of the model was to assembly the damping matrix C of the structural parts assembly. The basic equation for the damping matrix C in modal coordinates is given as

$$[\Phi]^T\,[C]\,[\Phi] = [\Phi]^T \sum_{j=1}^{m} \left(\frac{2\zeta_j}{\Omega}\right)[K_j]\,[\Phi] + \alpha + \beta[\Lambda^2] + [\Phi]^T \sum_{j=1}^{m} \beta_j [K_j]\,[\Phi] + \cdots. \tag{2}$$

In the Eq. (2), there are members corresponding to the Raleigh damping (α, β) of the whole assembly and members corresponding to the damping of each component (index j denotes the component and its part in the global stiffness matrix) using either constants β from the Rayleigh damping or modal damping ζ of component.

Generally, it is difficult to estimate Rayleigh parameters α, β for a model of production machine, as the assembly is full of connection interfaces, etc. For the evaluation of the single component material change effect on the global assembly behaviour, only the first member in Eq. (2) was taken into the account. This member is using a modal damping ζ of each component of the model. The idea was to use the modal damping values, which are taken from the experimental modal analysis of the structural parts from various materials. And to make artificial modal damping ratios for the simplified models of connection interfaces, which would be estimated so that the average damping of the structural parts assembly corresponds to the damping of the real machines, which might be for example 2.0 - 4.5 % for the first structural mode shapes. Several values of modal damping ratios ζ of structural components from steel, cast-iron, composites and other materials were published by Novotny [3]. A brief overview is given in Table 1. Those values, together with the material stiffness were used in the simulation model.

The model was demonstrated on a case study using a 5-axis mill turn center, which is composed of a spindle, cross-slides, transverse beam and bed as the main structural components. A prediction of dynamic behavior when changing the structural material of each component from cast – iron to composite material with average damping ratio ζ = 1.0 % is given in Fig. 1. In the case study, damping ratio of connection interfaces (housings of linear guide-ways) was approximately 30 % to match the expected dynamic behaviour of assembly.

Table 1. Basic modal damping ratios for structural components

Material	ζ [%]
Steel	0.01-0.1
Cast iron	0.1-0.2
Polymer concrete	0.4
Fibre composites	0.1-0.6
Hybrid fibre composites	0.2-1.4
Hybrid particle composites	0.5-2.0

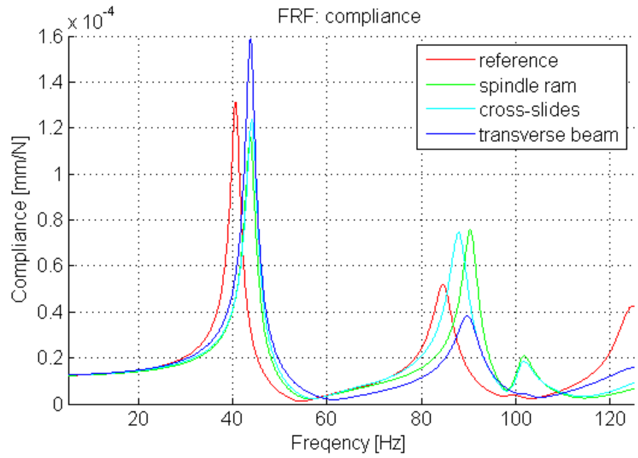

Fig. 1. Comparison of dynamic behavior of the machine tool assembly

The case study results in Fig. 1 showed that the application of composite materials to the transverse beam increased the dynamic compliance of assembly by 21 % with a slight frequency increase. Therefore, the design change would reduce the machine productivity. On the other hand, the application of composites to the spindle ram reduced the dynamic compliance by 13 % with a slight frequency shift. This would help the machining productivity, the question is if the higher material costs of composites can be justified by this improvement of the dynamic behaviour. The simulation model demonstrated a capability for predicting the dynamic behavior of the structural parts assembly using the modal damping of structural materials and modified damping in connection interfaces. Experimental verification will be the part of future works.

Acknowledgements

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References

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