Survey on stiffness and damping of machine tool elements

Survey on Stiffness and Damping of Machine Tool Elements

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1. Introduction

In Computer Aided Design of machine tool structures it is common practice to treat the complete machine tool as consisting of one piece of elastic material. In this manner it is assumed that the connection between two elements of the machine tool model is rigid for every degree of freedom, or in the case of a linkage, is rigid for some degrees of freedom. The input for the computer program consists of the geometry of the elements and the material properties such as: modulus of elasticity, shear modulus and specific mass. Material damping can be neglected.

The co-operative work in Computer Aided Design of machine tools within the CIRP Technical Committee Ma also follows the procedure mentioned above *.

This way of modelling ignores the real conditions in the machine tool which is built up from a number of elements that are more or less connected by means of springs and dampers.

Although the model mentioned above is basically wrong, the results of the analysis are not always useless.

Until now there are roughly three reasons for omitting from the model the springs and dampers which are formed by the connecting elements:

1. there exist relatively few reliable numerical values of these springs and dampers,
2. the form in which these data are available, is largely unsuitable for direct use in CAD,
3. the introduction of damping into existing programs makes these programs more complicated and—last but not least—more expensive.

The aim of this paper is to present a survey of the available work on the stiffness and damping of the connecting parts of machine tools. The survey concerns mainly the work of the following members and their collaborators:

Professor J. G. Bollinger,
University of Wisconsin, Madison, U.S.A.,
Professor F. Koenigsberger and Dr. R. Bell,
University of Manchester, Great Britain,
Professor H. Opitz,
T. H. Aachen, West Germany,
Profesor J. Peters and Mr. P. Vanherck,
University of Louvain, Belgium,
Professor A. C. H. van der Wolf and Mr. J. A. W. Hijink,
University of Technology, Eindhoven, the Netherlands.

2. Categories of Connecting Elements

2.1. Machine Tool Joints

Until now most of the work on machine tool joints was concentrated upon the surface stiffness [1, 2]. This depends on: the materials in contact, hardness, machining process, surface roughness, relative orientation of the surface layers, size of the contact area, flatness deviation and the contact pressure. For some materials and surface conditions values are known. But there is no model considering all the factors which influence the surface stiffness. Experiments to obtain data about the surface stiffness were often carried out on test-pieces which were small and thus rather rigid.

When computing a joint by means of the finite element method [3] the surface stiffness characteristics can be incorporated in the non-rigid model of the joint. It is shown that for a number of joints the surface deflections contribute only 10% to the overall joint deflection.

For bolted joints a method [4] to compute the stiffness of the joint starts from the stiffness of the combination of flanges and bolts and the surface stiffness of the flanges. The results are satisfactory only for relatively stiff flanges and bolts placed in line with the walls.

* A. Cowley: Co-operative work in Computer Aided Design in the CIRP. Annals of the CIRP, Vol. XXI (1972).

As far as the damping of joints is concerned no satisfactory model is available, but the following facts are known [1, 5]:

— the dynamic and static stiffness which occur with dry surfaces in contact is the same, the damping is negligible,
— the introduction of a lubricant adds damping to the structure, the damping coefficient being independent of the normal load,
— the damping coefficient for joints with metallic contact depends on the pressure distribution on the surface, the surface condition and the viscosity of the lubricant,
— the mechanism of normal damping is analogous to squeeze film damping of a lubricant film.

2.2. Plain Slideways

The characteristics normal to the sliding motion of plain slideways are almost the same as for joints and the same difficulties and possibilities occur.

In the direction of sliding the dynamic characteristics are mainly determined by the damping caused by friction, the mass of the carriage and the stiffness and damping of the drive.

The damping caused by friction is non-linear and may be either possitive or negative, which means either stable sliding or self excited oscillations (stick-slip) [6, 7, 8, 9, 10].

Dynamic measurements are essential to obtain damping values. Measurements show that damping depends upon slideway materials, velocity, lubricant and mass. Because of the complex functions of a number of parameters there is little merit in the development of analytical model [8].

Resonance curves for a number of friction coefficients and sliding speeds can be obtained by analogue models [11, 12].

2.3. Roller Bearings and Guideways

Based on the Hertz theory Palmgren developed a set of equations for calculating the deflections of all common types of bearings subjected to radial or axial loading. The equations give only fair results for bearings without clearance and no preload.

For cylindrical roller bearings the influence of radial clearance, accuracy and preload on the radial stiffness has been examined and monograms are made [13].

Thrust bearings, which are an important part of the feed-drives of NC machines, have also been examined [14, 15]. High preloads ensure higher stiffness and bearings with a relatively large number of rolling elements give increased stiffness but a reduction of the load carrying capacity.

The clamping stiffness of taper roller bearings depends on the normal load and the rotating speed of the bearings [16, 17]. Due to frictional resistance the clamping stiffness of a non-rotating bearing is 20 to 30 times higher than the clamping stiffness of a rotating bearing. Between 300 and 1100 cycl/min the clamping stiffness is constant. A theoretical model for a rotating bearing has been developed.

About the damping of roller bearings no values can be found. In order to provide an effective antifriction guideway, rolling element guideways can be used. Their static stiffness is a function of the number of rolling elements and the load eccentricity [18, 19]. Below a certain frequency the dynamic stiffness of roller guideways can be less than the static stiffness. Therefore squeeze film dampers can be added [20] to get better dynamic results.

2.4. Hydrostatic Bearings and Guideways

The design of hydrostatic bearings concerns mainly the static stiffness, the maximum load and the flow rates.

Dynamic investigations of hydrostatically supported spindle bearing systems show that it is possible to optimize this kind of systems by changing the damping and stiffness of the bearings through the oil pressure and dynamic viscosity [21, 22, 23]. In this respect the hydrostatic bearing has a considerable advantage over the roller bearing.

A critical review of work done on the dynamic behaviour of thrust and journal bearings is given by Koenigsberger and Cowley [24].

Some research on the static stiffness of hydrostatic guideways with different frames [25] has been carried out.

2.5. Aerostatic Bearings and Guideways

Aerostatic bearings have an advantage if used in cases where very low friction and high accuracy is needed. To reach sufficient load carrying capacity and stiffness presents problems, especially as far as the low dynamic stiffness and pneumatic instability [26] are concerned.

2.6. Dampers

Two kinds of dampers can be distinguished: the passive dampers and the active dampers.

The passive dampers can be subdivided in to the following: damper between two machine parts, damped added mass, Lanchester damper and impact damper.

In these systems the fluid film damper [27] is often used. It can be easily implemented in a CAD program.

The analysis of the impact damper can only be handled on an analogue computer.

In an active damper [28] energy is added to the system. As in the case of the impact damper, it will be difficult to use this damper in CAD.

3. Conclusions

In table 1 a survey of the usefulness of the different categoeris is given.

From this survey the following fields of research are recommended:

— dynamic stiffness and damping of joints and plain guideways,

— dynamic stiffness and damping of rollerbearings.

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TABLE 1

Survey of the categories

Category	Stiffness	Usefulness in CAD	Damping	Usefulness in CAD
Machine tool joints	known, but only specific knowledge of static stiffness	by means of special finite element programs	something known	not useful
Plain slide ways	some specific knowledge	by means of special finite element programs	something known by means of analogue models	not yet, specific too
Roller bearings and guideways	much knowledge about static, some about dynamic stiffness	useful	unknown	—
Hydrostatic bearings and -guideways	much knowledge about static, some about dynamic stiffness	useful	some knowledge	useful
Aerostatic bearings and -guideways	much knowledge about static, some about dynamic stiffness	useful	some knowledge	useful
Dampers	—	—	known	only passive dampers