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Finite element analysis of the structural dynamics of a vertical milling machine

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Abstract

The structural stiffness of a machine tool is one of the main criteria that establishes its ability to produce accurate precision components. High stiffness is required both statically and dynamically each affecting different aspects of the machining process.

The need for high static stiffness arises from the requirement to produce parts to a desired size and shape [1] and although finish machining often takes place with small depths of cut and correspondingly light cutting forces, the resulting deflections can still be excessively large if the machine has inadequate static stiffness. The resulting deflection can thus produce out of tolerance work-pieces.

The need for high dynamic stiffness results from two separate aspects of the machining process. In the first case inadequate dynamic stiffness will result in poor quality surface finish of the machined parts due to relatively low levels of vibration occurring during finish machining operations. In the second case low dynamic stiffness can have more serious consequences when under heavy machining conditions the resulting vibration might be sufficiently high to cause the process to be terminated in-order prevent possible damage to the machine.

Traditionally machine tool structures were designed from experience with limited aid from manually carried out calculations using classical theory for such as beam bending, twist and shear. With the advent of powerful desktop computers and the associated Finite Element Software, at costs that are within the grasp of the typical machine tool manufacturer, it is now possible to determine the structural stiffness values for machine tools to a high order of accuracy and in a relatively short time scale. This paper outlines the static and dynamic structural analyses of a vertical milling machine that were to be subsequently validated against measured results [2, 3].

1 Introduction

For a thorough understanding of the behaviour of a machine structure it is necessary to analyse both it's static and dynamic characteristics. This is best achieved by the use of Finite Element techniques which involve the sub-division of the main structural members into sufficient numbers of small individual elements whose interactions with each other are determined by the construction of a stiffness matrix [4].

1.1 Elements

The types of elements that can be used for the analysis can be shell, beam or solid and choice of appropriate element type depends upon the nature of the main structural member.

In this case the elements were generated automatically using a feature of the FEA software.

1.2 Model considerations

Appropriate material characteristics were allocated to each structural member to specify such as it's Young's modulus, density and poisson's ratio.

A damping value was set for the structure as a percentage of critical damping for the materials concerned based on values measured experimentally. Individual damping factors could not be set for the various components thus a single overall value was used for the entire structure.

Full translational and rotational constraints were set at the underside of the six machine foundation connectors on the assumption that they were sat on a concrete foundation that was significantly stiffer than the machine structure.

1.3 Types of analyses

Three types of analyses were used, static, modal and frequency response.

The static analyses was carried out with loads applied and deflections calculated in the machine 'X', 'Y' and 'Z' axis directions respectively.

The modal analyses determined the first three modes, calculating the natural frequencies and the corresponding modal shapes.

Frequency response curves were calculated for the structure up to 200 Hz for loads applied in the X', 'Y' and 'Z' axis directions respectively.

The frequency response curves calculate the deflections that result at specified positions on the structure due to the applied loads throughout a specified frequency range. The measured position in this particular analysis was at the centre of the face of the machine spindle nose.

For the static and frequency response analyses the loads were applied at the face of the machine spindle in the 'X', 'Y' and 'Z' directions respectively.

The modal analyses did not require loadings to be specified, since modal shapes and frequencies are dependant only upon the machine structural characteristics and the applied constraint conditions.

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2 Machine configuration

2.1 Overall structural layout

The construction of the main machine basic structural members was as shown in Figure 1, with each individual component being made from either cast iron or a welded steel fabrication.

For the purposes of this analysis the structural members are assumed to be rigidly connected to each other at each joint interface. In practice this was only the case for the static members, whereas the moving members were supported on linear ball guide-ways. Effectively the stiffness of these units has been assumed to be infinite in these analyses.

The six foundation connectors attached to the base as shown, supported the machine on a concrete foundation.

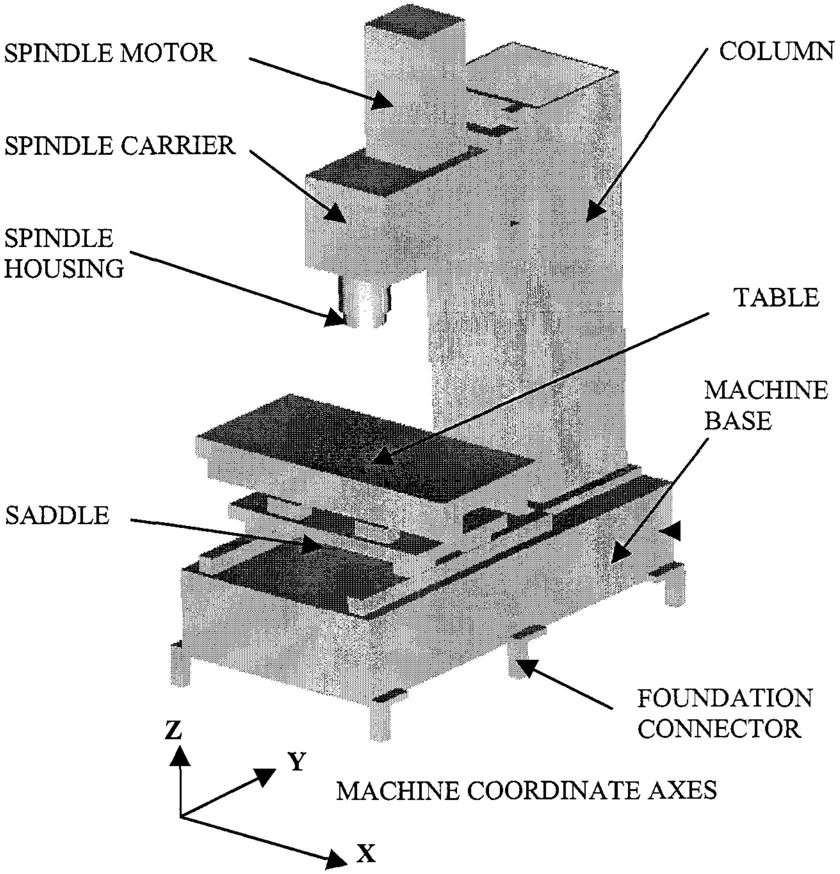

Figure 1: Three axis machining centre structural configuration

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2.1 Individual structural components

Each of the six main structural components was modelled in a 3D solid modelling software package using dimensional information obtained from the corresponding, original manufacturing drawings.

All significant features were modelled in detail as shown in figure 2 and figure 3 below in order to maintain overall accuracy of results. Cosmetic features with no obvious contribution to stiffness were omitted.

For the steel fabrications the welds were modelled as if continuous and with full width penetration of each plate.

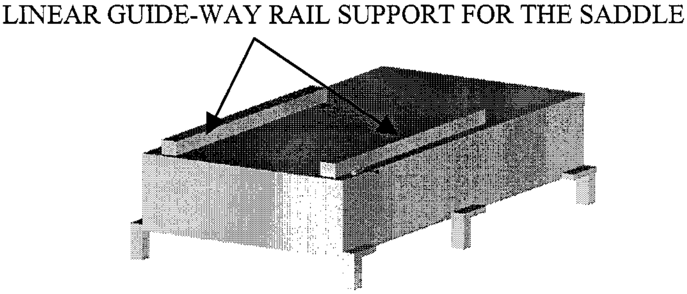

Figure 2: Machine base fabrication

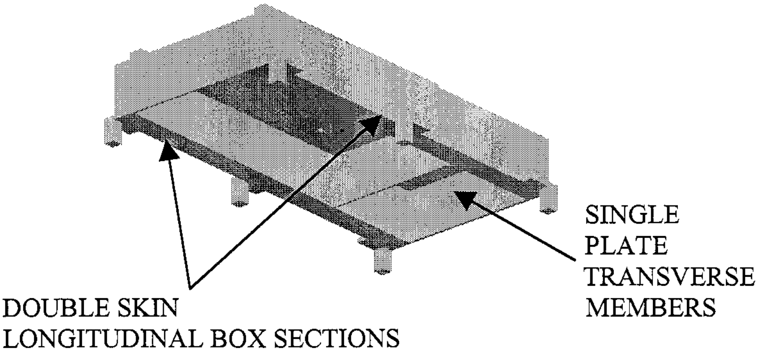

Figure 3: Machine base fabrication (underside view)

2.2 Model assembly

After each component had been modelled separately an assembly model was constructed from the individual members to give the machine configuration as shown in figure 1.

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3 Loads and constraints

3.1 Loads

For both the static and dynamic analyses the loads were applied to the face of the spindle nose as shown in figure 4 below in the 'X', 'Y' and 'Z' directions respectively.

In the static analysis the load applied in each case was 10,000N along the respective axes.

For the dynamic analyses the value of the applied load was 10,000N peak to peak, applied along each axis respectively and varying sinusoidally throughout the specified frequency range.

3.2 Constraints

The model was constrained in the same manner as the machine is intended to be, by specifying no movement to take place at the underside surface of the foundation connectors, either translational or rotational.

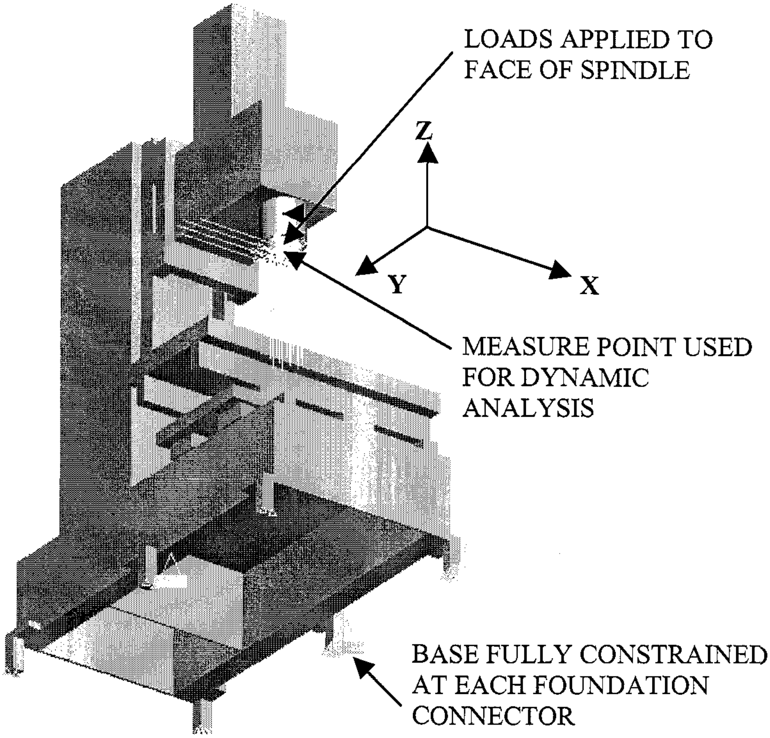

Figure 4: Applied loads and constraints

4 Analyses

4.1 Static

The static analysis calculated the magnitude and direction of the deflections of the structure due to the applied loads and thus enables the static stiffness of the machine to be determined.

4.2 Modal

The modal analysis calculated each natural frequency within a specified range and also the modal shape corresponding to each frequency. The resulting information from this analysis can be used to determine where any particular weaknesses lie within the structure and where to carry out remedial work to improve the design.

4.3 Dynamic

The dynamic analysis calculated the frequency response curve for the structure in the specified direction of the applied load up to a specified frequency thus enabling the dynamic stiffness of the machine to be determined.

5 Results

5.1 Static deflections

The figures below show the static deflections of the structure due to the applied loads with the corresponding static stiffness values shown in table 1.

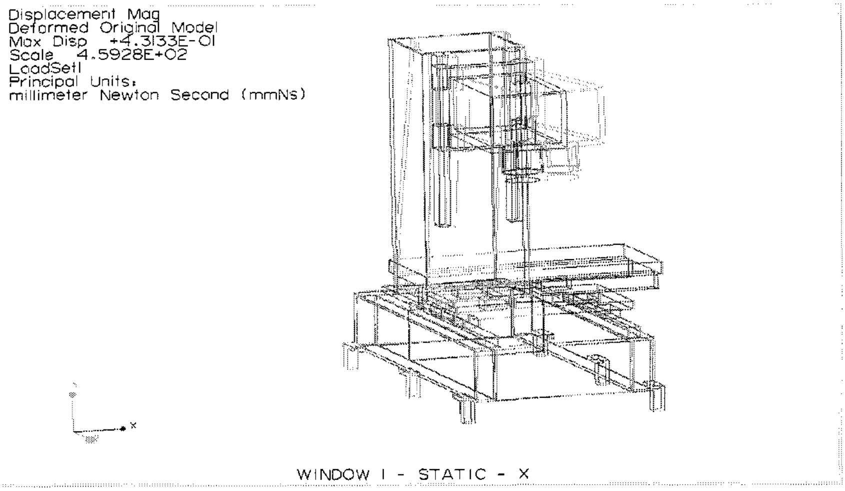

Figure 5: Deflection due to load in 'X' direction

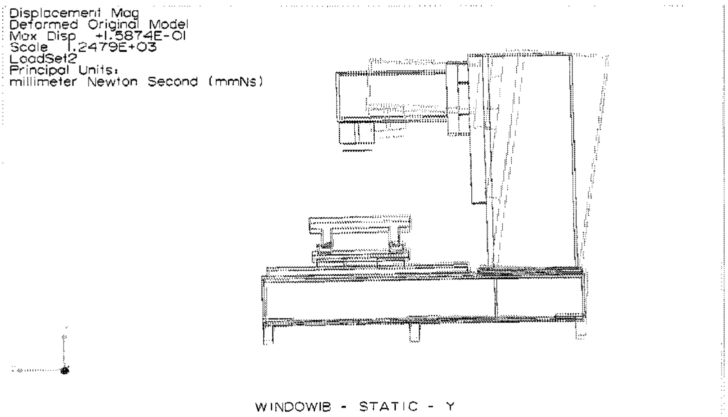

Figure 6: Deflection due to load in ‘Y’ direction

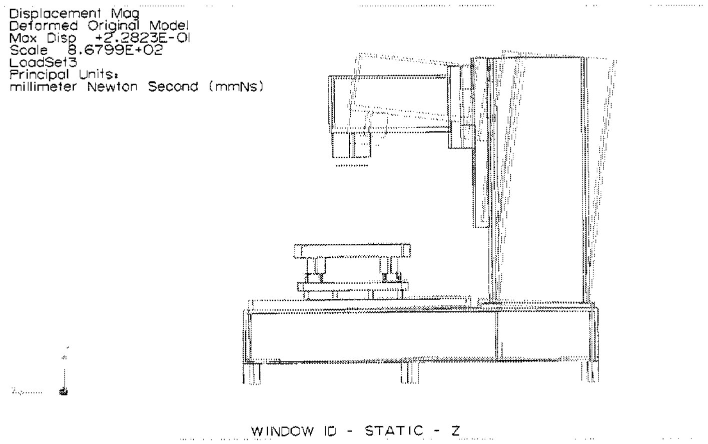

Figure 7: Deflection due to load in ‘Z’ direction

Table 1: Static stiffness results

Load	Direction	Stiffness (N/micron)
10,000 N	X	23
10,000 N	Y	62
10,000 N	Z	43

5.2 Modal shapes and frequencies

The figures below show the first three modes of vibration and the corresponding natural frequencies.

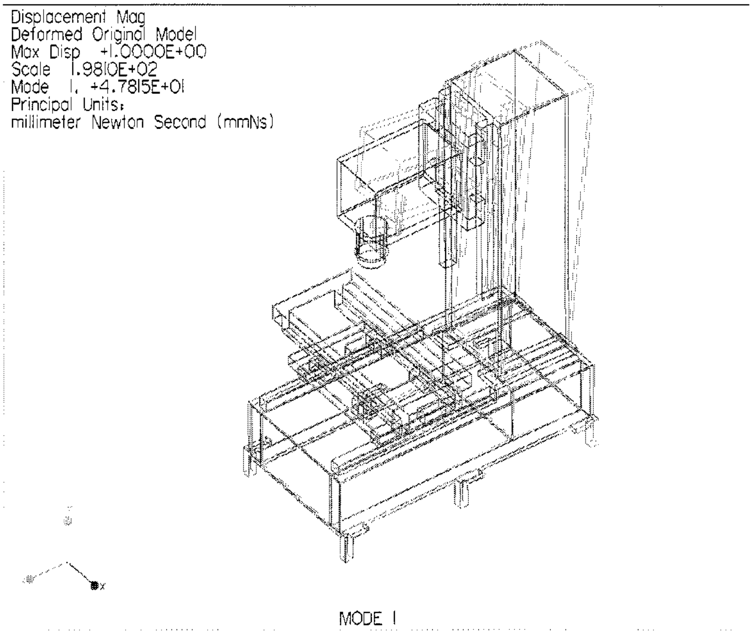

Figure 8: Mode 1 (48 Hz)

Mode 1 – mainly a rocking and bending motion of the column in the 'Y-Z' plane causing vertical movement of the spindle

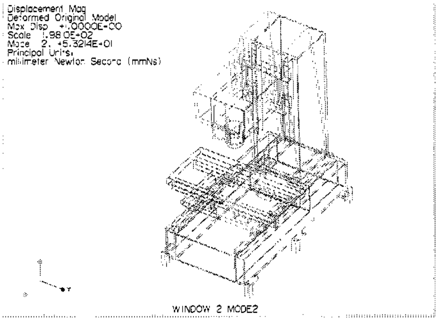

Figure 9: Mode 2 (53 Hz)

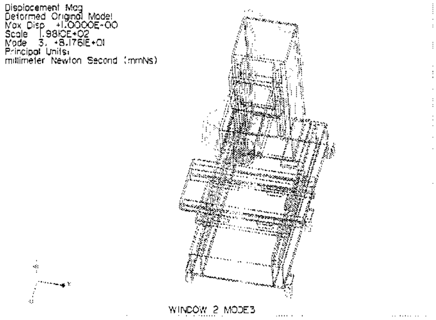

Figure10: Mode 3 (83 Hz)

Mode 2 – mainly a rocking and bending motion of the column in the 'Y-Z' plane causing horizontal movement of the spindle.
Mode 3 – mainly due to twisting of the column in the 'X-Y' plane causing horizontal movement of the spindle.

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5.3 Frequency response

The figures below show the frequency response curves for the 'X', 'Y' and 'Z' directions respectively.

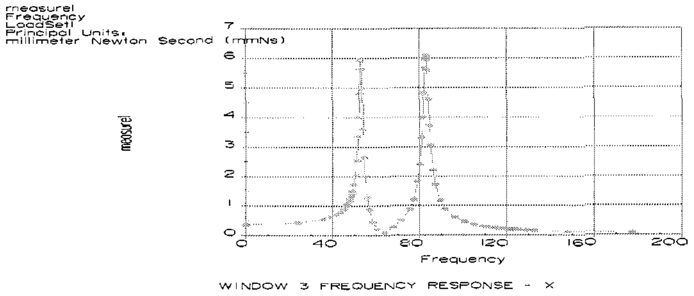

Figure 11: Frequency response due to 'X' direction force

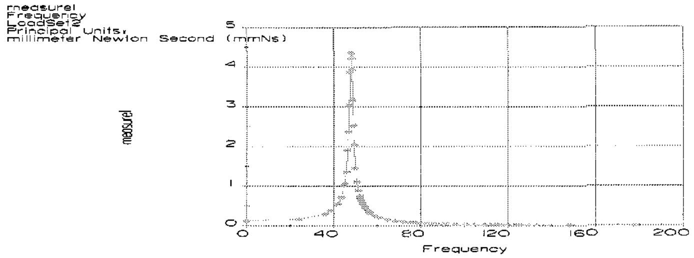

Figure 12: Frequency response due to 'Y' direction force

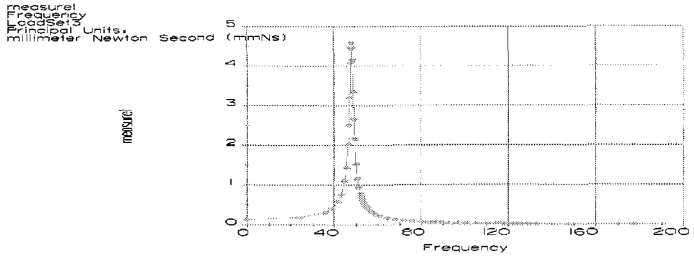

Figure 13: Frequency response due to 'Z' direction force

The above graphs show clearly that the highest deflections occur at frequencies which correspond to the natural frequencies obtained in the modal analysis results shown in figures 8, 9 and 10 for the first, second and third modes respectively.

6 Conclusions

The use of Finite Element Analysis as a tool for determining the static and dynamic stiffness characteristics for a machine tool structure can be seen to have a number of advantages in terms of time and accuracy of results over more traditional methods such as using classical theoretical calculations etc.

This paper shows that it is now possible to carry out exhaustive analyses of relatively complicated machine tool structures by use of desktop computers and the appropriate software. The depth of analyses gives access to information that will allow the machine tool designer to optimise structures with respect to weight and size such that maximum stiffness and minimum mass can be achieved, thus improving component precision in terms of size, form and surface finish whilst at the same time maximising metal removal rates.

7 Acknowledgments

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