Measurement techniques for determining the static stiffness of foundations for machine tools.

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Abstract. The paper presents a novel technique for accurately measuring the static stiffness of a machine tool concrete foundation using various items of metrology equipment. The foundation was loaded in a number of different ways which simulated the erection of the machine, traversing of the axes and loading of the heaviest component. The results were compared with the stiffness tolerances specified for the foundation which were deemed necessary in order that the machine alignments could be achieved. This paper is a continuation of research previously published for a FEA of the foundation [1].

Introduction
To perform satisfactorily a machine tool must be both statically and dynamically rigid. Its static stiffness determines its ability to produce dimensionally accurate parts and its dynamic stiffness affects the quality of the component’s surface finish and the maximum metal removal rates that can be achieved. Virtually all medium to large machine tools, such as the one shown in Figure 1, rely upon a concrete foundation to provide adequate structural support in-order that the machine is sufficiently rigid to enable it to perform satisfactorily.

Large machine tools are used typically for producing component parts for the aircraft and automotive industries and the accuracies to which the many different configurations are built are specified in a wide range of ISO and other standards. The typical tolerance specified for axes straightness for such machines is 5 microns per metre of traverse and since the machine might typically weight as much as 100 tonnes with a foundation weighing 500 tonnes, the stiffness of the concrete base must be extremely high to minimise non rigid errors [2].
To illustrate how exacting the requirements are, it is interesting to observe that for machines of extremely long traverse the earth’s curvature can be a significant proportion of the allowable tolerance. A machine 40metre long might have a ‘X’ axis straightness tolerance of 160 microns and the earth’s curvature over this distance is 32 microns.

**Foundation specification**

It is essential therefore to be able to specify and subsequently measure the static stiffness of machine tool foundations, such as the one shown under construction in Figure 2, in order to ensure that the correct level of support is provided and that the machine tool alignment accuracies are achieved [3, 4].

![Fig.2 Foundation being constructed for a gantry milling machine](image)

For a satisfactory machine installation the foundation stiffness must first be specified based upon the required alignment tolerances for the machine, as specified in the appropriate ISO standard for the particular machine configuration e.g. ISO 3070 Part 2 for a large Moving Column, Horizontal Ram Type milling machine and ISO 8636 Part 2 for a Moving Gantry Vertical Ram Type milling machine. The stiffness specification for the foundation must state a number of criteria and the associated tolerances.

For the above gantry machine with ‘X’ traverse of 14 metres and ‘Y’ traverse of 4 metres the values were as shown below: -

a) Maximum bending deflection in longitudinal and transverse planes (typically 5 microns per metre of the corresponding traverse of the machine ‘X’ and ‘Y’ axes due to firstly the moving weight of the machine (30 Tonnes) and secondly the maximum weight of component (5 Tonnes) ).
   - ‘X-Z’ plane maximum deflection 70 microns.
   - ‘Y-Z’ plane maximum deflection 20 microns.

b) maximum acceptable rigid body rotation of the foundation in both the longitudinal and transverse planes (typically10 microns / metre of the corresponding tranverse of the machine ‘X’ and ‘Y’ axes due firstly to the moving weight of the machine and secondly the heaviest component).
   - ‘X-Z’ plane maximum deflection 140 microns.
   - ‘Y-Z’ plane maximum deflection 40 microns.

c) maximum vertical deflection that can occur at the boundary between the machine support area and the work support area. (10 microns due to machine movement or loading of heaviest component)

The bending stiffness (a) affects the accuracy of the component since any error would be machined into the part.

The rigid body rotational stiffness (b) does not affect component accuracy but will cause difficulties with the machine installation since movements of the foundation during erection of the machine need to be monitored and taken into account.

The foundation was designed, built and subsequently tested to confirm it met the above specification requirements.
Test procedure
A technique has been developed using a combination of metrology equipment, as shown in Figure 3, comprising water level units, electronic levels and dial test indicators that enabled the deflections, distortions and stiffness of the concrete foundation to be measured to the accuracy necessary to satisfy the tolerances stated above.

The procedure involved placement of the required equipment on the foundation surface such that measurements could be taken at sufficient points to enable the distorted shape to be subsequently described by graphical means. This meant taking readings at approximately 20 locations on the foundation surface.

Eight water level units were placed around the foundation periphery and linked by transparent hose filled with water with a wetting agent added. Adjacent to six of the water level units three steel beams were placed transversely across the foundation and mounted on single point supports. Steel tubes are suspended from the beams and dial test indicators (DTI) were placed beneath each tube. Each DTI was attached to a plate grouted to the concrete surface. Additional information was obtained from electronic levels placed onto steel plates mounted directly onto the concrete surface at various positions to suit the loading conditions.

The foundation was loaded in a sequential manner with weights that were approximately equal to the various weights of the machine moving elements. The procedure was such that it firstly simulated the erection of the machine, the subsequent traversing of the machine through its critical axes and finally the weights are removed to monitor that the base returned to its original shape in order to confirm its elasticity.

The measurements at the water units were achieved using traditional depth micrometers. The repeatability of the reading taken at the water level units was +/- 10 microns. This enabled the vertical deflections and distortions the base to be determined over its entire surface to an accuracy of +/-20 microns, a difficult task to achieve with any other type of metrology equipment e.g. laser / trackers etc.

Results
The results, shown in Table 1, were plotted 3 dimensionally, see Figure 4, to graphically show the distorted foundation shapes under the various loaded states. The results were analysed and compared with the specification to confirm whether or not the distortions and deflections of the base would cause an impediment to either the erection or the subsequent use of the machine.

Table 1. Maximum distortion values of the foundation

| Criteria                  | Foundation deflections                     | Tolerance  |
|---------------------------|--------------------------------------------|------------|
| Max. bending              | 40 microns (‘X-Z’ plane – central load)    | 70 micron  |
| Max. rigid body rotation  | 100 microns (‘X-Z’ plane – load at negative X posn.) | 140 micron |
The above results were subsequently compared with a Finite Element Analysis (FEA) of the concrete foundation and which is the subject of another paper [1].

Conclusion
The test was carried out successfully and enabled the stiffness the foundation to be measured to the level of accuracy that was required. The results showed that the foundation met the tolerances laid down in the ‘Foundation Specification’ thus confirming that the gantry machine tool could be installed to the high level of precision specified by the alignment test sheets and that it would function correctly when in use.

The test procedure took a total of three days to carry out, one day to set up the equipment and two days to carry out the loading and measurements. The equipment used, though relatively inexpensive, met the necessary accuracy requirements.

By testing a foundation in this manner before a machine is installed it is possible to determine whether or not subsequent machining problems will occur after installation and establish where the responsibility lies.

It is envisaged that by comparing the results from these and future tests on other foundations, with the results obtained by FEA, that the accuracy of FEA prediction will be further enhanced to give even higher levels of certainty.

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