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Measurement and identification of dynamic translational stiffness matrix on machine tools under static preloads

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Abstract

Dynamic stiffness is an important characteristic of production machinery, as it contributes to its ability to maintain the position of the tool centre point accurately and precisely under loads. For machine tools, it directly affects the geometric dimensions and surface properties of produced parts. This work presents a measurement procedure for identification of the full translational dynamic stiffness matrix for a single configuration of a machine tool under loaded conditions. The measurement procedure consists of inducing a static baseload with superimposed dynamic loads, which were controlled in magnitude and direction, at the tool centre point of the machine tool. The measurement procedure uses the Loaded Double Ball Bar and measures the dynamic displacement with three Non-Contact Capacitive Probes. The measurement procedure is implemented in a case study on a 5-axis machining centre.
Finally, the manuscript concludes with a discussion on the utility value of the translational dynamic stiffness matrix for the design and operation of machine tools as well as the possibility to expand the measurement procedure to capture the dynamic stiffness using quasi-static movements of the machine tool.

Keywords: Machine tool, measurement, stiffness, performance

1. Introduction

Machine tools' accuracy enables machining complex products of tight geometric dimensions and tolerances. One of the main design criteria of machine tools is stiffness as it affects their performance under load. Several works exist which focus on the stiffness evaluation and identification at the Tool Centre Point (TCP) of a machine tool. There are a priori modelling approaches, which employ finite element analysis [1], and a posteriori experimental approaches, which can be sub-divided into machining tests [2] and experiments [3]. Analogously for dynamic stiffness, one refers to operational modal analysis [4] and experimental modal analysis [5] which commonly employ impact hammers and shakers for the excitation, as well as accelerometers and lasers for response measurement. These measurements can usually neither apply a load between the spindle and the workpiece or any machine component (e.g. table and spindle), as recommended by ISO230-1:2012 for static stiffness, nor measure directly the displacement. Laser vibrometers measure velocity and require single integration, while accelerometers measure acceleration and require double integration. This is troublesome as also the noise is integrated. This research work is a first step towards expanding the capabilities of the Loaded Double Ball Bar (LDBB) proposed by Archenti and Nicolescu [6] to identify the dynamic translational stiffness matrix K_t represented in terms of its Frequency Response Function (FRF) from displacement measurements.

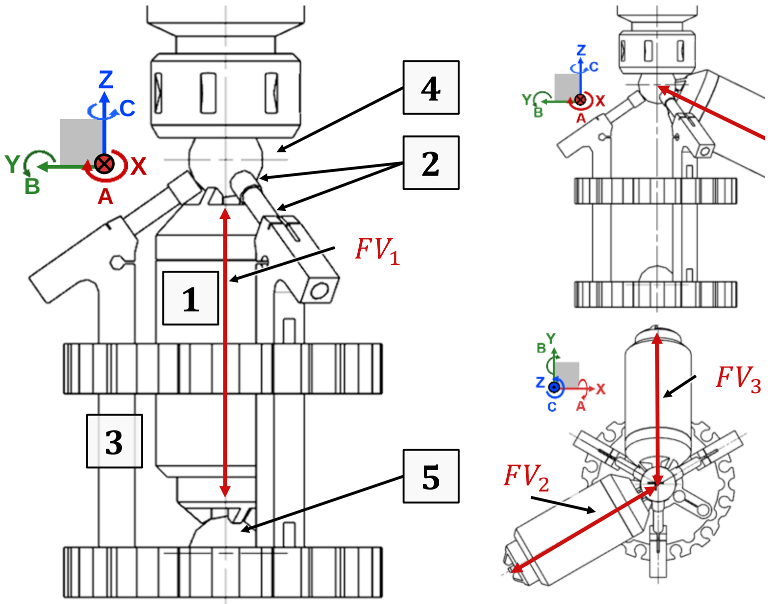

Figure 1. Schematic measurement setup.

2. Methodology

2.1. *Measurement*

The schematic experimental setup is displayed in Figure 1. It consists of the LDBB (1), three Non-Contact Capacitive Probes (NCCPs) Lion Precision CPL290® (2) fixed on a Metrology Frame (MF) (3), a Tool Adaptor (TA) (4), which consists of a sphere of radius 15 mm attached to a shaft of diameter 25 mm, and a set of Table Link (TLs) (5), which feature another steel sphere of radius 15 mm. The LDBB is equipped with a helical coil spring to create the static preload, a Cedrat PP40L® Piezo-Electric Actuator (PEA) is used to exert dynamic loads, and a Dytran1053V2® force sensor to measure the force. The PEA is excited with a sine-sweep from 10 to 210 Hz, generated in a BK Precision 4062 B® and amplified via a Cedrat LA75B®. The force and displacement spectra are acquired using an NI cDAQ-9178® equipped with a NI-9234, to supply the excitation power for the IEPE force sensor, and a NI-9215, which supports ±10 V input signals. In addition to that the dynamic stiffness of the component k_{yy} was measured in a single point using a PSV-500 Scanning Vibrometer® and a Kistler 9726A5000® impact hammer. The bandwidth of the excitation spectrum has been selected to be much lower than the first eigenfrequency of the LDBB which is close to 500 Hz. Furthermore, the metrology loop [7] is decoupled from the force loop [7], which should separate influences from the LDBB in the displacement spectrum. The measurement procedure consists of the following three principal steps: 1) Locating the metrology frame in the Machine Base Coordinate System (MBCS), 2) Transforming data from NCCP coordinate system into MBCS (for more information see [3]), and 3) Measuring the deflections under combined static and dynamic loads. These three steps are repeated for a combination of at least three non-linear Force Vectors (FV). The three FVs used in the case study are displayed in Figure 1. The static loads depend on the compression of the helical coil spring and ranged around 500±50 N for the three FVs. This has been calculated from the distance between the TA and the TLs. For each FV five independent measurements have been conducted. Each independent measurement captures 60 recurring excitation signals. The data of the NCCPs has been acquired using the high sensitivity setting resulting in a measurement range of 50 µm for each of the linear distance sensors.

2.2. *Data analysis*

Models of the dynamic deflections of machine tools describe the spatial deflections ($\Delta x(f)$) of the loaded TCP compared to the unloaded TCP due to the finite stiffness ($K_t(f)$) of the structural members which are in the flow of forces ($F(f)$) considering the dependency of the magnitude of these parameters depending on the frequency (f). For conciseness and as all herein referenced quantities dependent on frequency, this dependency is omitted in their representation.

$$\begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{xy} & k_{yy} & k_{yz} \\ k_{xz} & k_{yz} & k_{zz} \end{bmatrix} \times \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} - \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} \tag{1}$$

The full dynamic translational stiffness matrix is identified as the solution to:

$$\left| |K_t \otimes \Delta\mathrm{x} - \mathrm{F}| \right|^2 \tag{2}$$

For the dynamic translational stiffness matrix K_t, it is assumed the off-diagonal elements are equal, i.e. $k_{xy} = k_{yx}$, $k_{xz} = k_{zx}$, and $k_{yz} = k_{zy}$. The operator $\otimes$ represents the Kronecker product. There are 6 unknown quantities, 9 measured deflections (three for each FV), and 9 measured wrenches (also three for each FV). The FVs allow for a linear least-squares as well as for analytic identification of the components of the stiffness matrix.

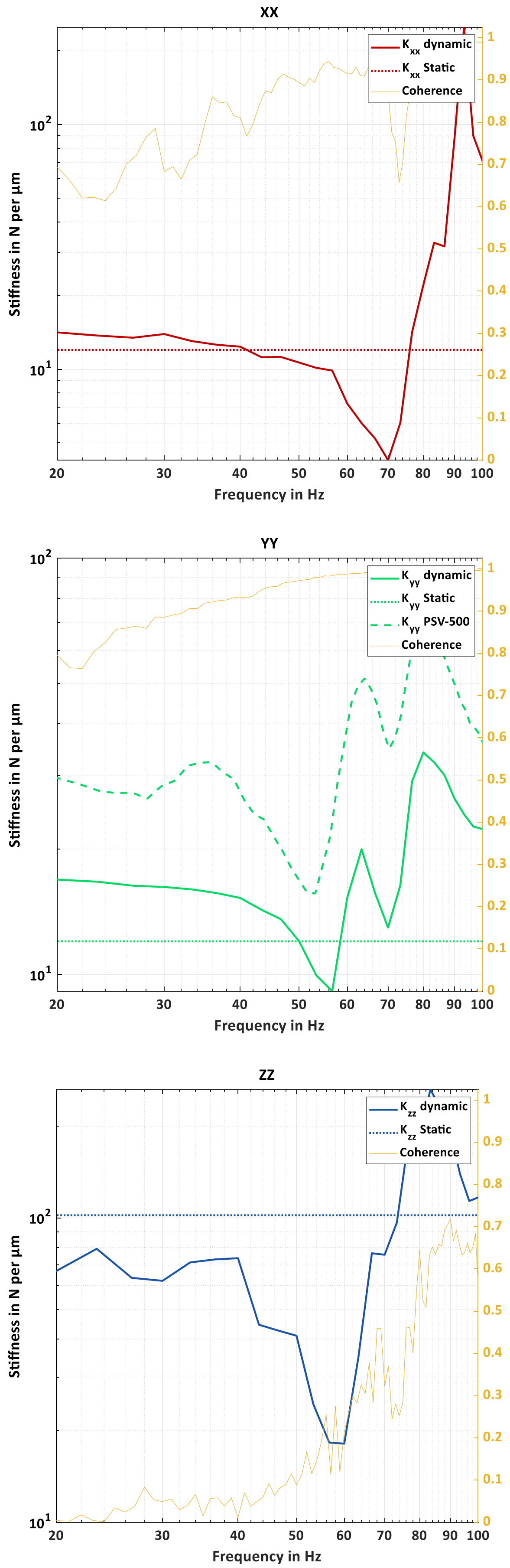

Figure 2. The main diagonal of the dynamic translational stiffness matrix identified from the analytic expression.

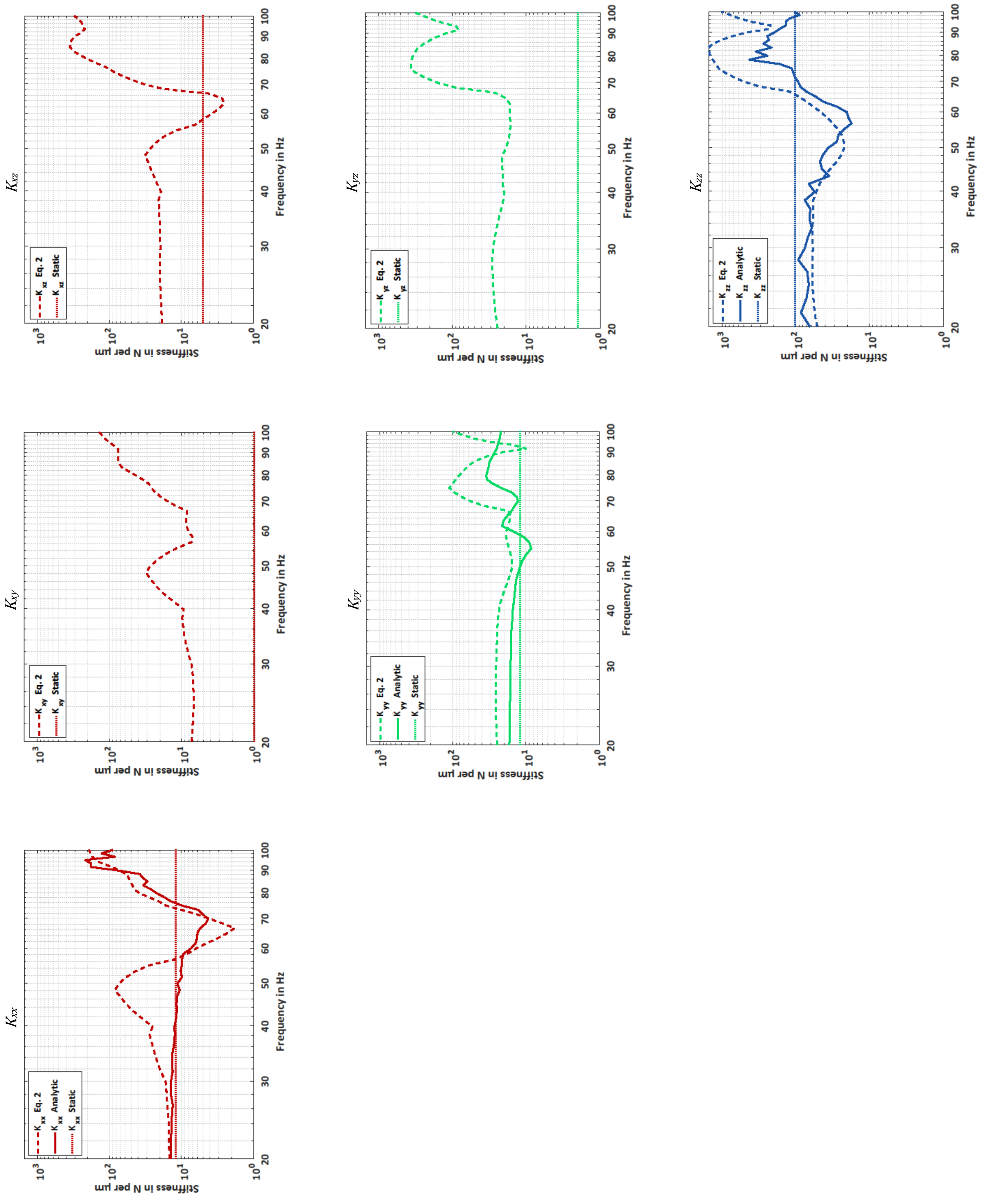

Figure 3. The full translational dynamic stiffness matrix identified from the linear least-squares expression.

3. Results

The case study uses a 5-axis milling machine, kinematic configuration *wC'A'bYXZ(C)t*, with a rotary tilting table, equipped with a tandem drive on the A-axis [8]. Figure 2 displays the analytic solutions for the components k_{xx}, k_{yy}, and k_{zz}. For all three components the dynamic and static stiffness as well as the coherence are displayed in the same graph. For k_{xx}, k_{yy}, and k_{zz} there exist differences of respectively 1 Nμm^{-1} (10%), 4 Nμm^{-1} (30%), and 27 Nμm^{-1} (30%) up to 40 Hz compared to the static stiffness reference. The static stiffness has been measured according to [9]. Then the stiffness drops in the bandwidth of 50 to 70 Hz depending on the direction. This, per theory, is the bandwidth in which the first eigenfrequencies of machine tools can be expected. The coherence functions for the components k_{xx} and k_{yy} are reasonably good, while the coherence for the k_{zz} component is unsatisfactory. It is assumed that this is due to the fact that the Z-axis stiffness is about ten times bigger than for the X- and Y-axis. Nevertheless, the magnitude of the identified k_{zz} component has some relevance with respect to the static stiffness reference. For comparison, the k_{yy} component was additionally measured with a scanning vibrometer and an impact hammer, see Figure 2 PSV-500. The identified FRFs share similar characteristics but are different in magnitude. This is probably due to the fact that the sensitivity of the force sensors in both measurements differ by almost exactly a factor 100 and that the data in the comparative measurement has not been transformed into the MBCS. Furthermore, it should be heeded that the proposed measurement with the LDBB exerts a static base load, which is assumed to result in a change in stiffness, while the comparative measurements with the PSV-500 exert no static base load. The standard deviations are omitted in all plots, as these are always less than 1 Nμm^{-1}, i.e. hard to visualise. Figure 3 displays the full translational dynamic stiffness matrix. The sub figures visualise the identified components as solutions according to Equation 2, as well as the analytic solutions and static references displayed in Figure 2. The components of the main diagonal exhibit the same trend, but k_{xx}, k_{yy}, and k_{zz} differ respectively by 1 Nμm^{-1} (8%), 9 Nμm^{-1} (56%), and 35 Nμm^{-1} (40%) up to 40 Hz compared to the analytic solution. Coincidentally, the linear least-squares solution to k_{yy} is a close match to the comparative measurements up to 55 Hz, i.e. their magnitudes differ on average by 3 Nμm^{-1} (10%). The components k_{xy}, k_{xz}, and k_{yz} differ by 5 Nμm^{-1} (85%), 15 Nμm^{-1} (75%), and 26 Nμm^{-1} (93%) and have the same sign up to 40 Hz compared to the static stiffness reference. The components k_{xz} and k_{yz} exceed the expected magnitudes and are bigger than k_{xx} and k_{yy}. Additionally, above 40 Hz sign changes take place for k_{xy} and k_{xz}. This is signs are omitted in Figure 3 as all quantities are plotted on a logarithmic scale.

4. Conclusion

This work presents a measurement and identification procedure for the full translational dynamic stiffness matrix of a machine tool using the LDBB and additional measurement instruments. As can be observed from the measurement results displayed in Figure 2 and Figure 3, the proposed method yields reasonable estimates for main diagonal entries of the full translational stiffness matrix, but further work needs to be conducted to provide reliable estimates of the off-diagonal elements. A comparison of measured and simulated eigenfrequencies could be considered a prudent validation for the proposed method; however, accurate simulations of machine tools are exclusively reserved to the manufacturers. Additionally, the investments in the measurement instruments used renders the proposed method only applicable to machine tool design rather than machine tool users, e.g. process planning. Future works focus on improving the method to identify the full translational stiffness matrix for a subset of the workspace. Further future work shall focus on providing an uncertainty budget for the proposed measurement procedure, as it is uncertain how the machine tool kinematics and thermal drifts influence the measurement results.

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