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ScienceDirect
Procedia CIRP 46 (2016) 400 – 403
www.elsevier.com/locate/procedia
7th HPC 2016 – CIRP Conference on High Performance Cutting

Investigation of the time-invariance and causality of a machine tool for performing operational modal analysis

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Abstract

The dynamic behaviour of machine tools affects the work-piece quality and productivity. Generally, the difference between the dynamic properties at standstill and during machining is neglected by the commonly applied assessment methods for production systems. Operational modal analysis takes into account these cutting- and operation-dependent influences. However, operation conditions might cause violation of the common measurement assumptions regarding time-invariance and causality. The investigations consider the time-invariance by the measurement of frequency response functions over the working space including the evaluation of mode shapes. The causality is evaluated by dynamic measurements at TCP excited by feed motions.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz

Keywords: Machine tool; Dynamics; Operational modal analysis

1. Introduction

The experimental modal analysis (EMA) is a widely used method for investigation of the dynamic behavior of machine tools. The results also called modal parameters show the mode shapes with corresponding modal damping for excited natural frequencies [1]. Generally, the investigated machine is excited by a shaker or impulse hammer. The excitation represents the input signal and measured vibrations of the structure bring out the output signals. In the machine tool industry, EMA is mostly applied with single input and many output signals at which the excitation point is located at the tool center point (TCP). Performing EMA involves an investigation of the dynamic behavior during the standstill of the machine. However, there is generally a difference between the dynamic behavior of a machine tool during machining and standstill due to the pre-loading by the static cutting forces or the weight of the work-piece and the cutting tool, stiffening by the gyroscopic effect resulting from high speed revolution of the spindle as well as the process damping [2, 3]. Unfortunately, the actual dynamic behavior under operation of a machine tool cannot be evaluated by EMA.

Beside EMA there is another type of the modal analysis namely the operational modal analysis (OMA). OMA consists in measuring only output signals. This implies that there is not a need for a shaker or impulse hammer like in case of EMA. Instead of that the machine is excited by actual dynamic loads arising during operation. The issue for OMA in machine tools lies in generating a broadband excitation by the machining process, as addressed in [4]. In general, performing every modal analysis assumes a linearity, time-invariance and causality of the investigated machine.

OMA originates from the civil engineering where it is used for investigation of large structures like e.g. buildings and bridges [5]. In the machine tool industry the application of OMA firstly aims at investigation of large machines, which are difficult to excite by a shaker properly. Furthermore, OMA can yield better results in cases of investigation of machine tools with a nonlinear behavior. In such cases, due to the assumption regarding the linearity, the modal parameters

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz
doi:10.1016/j.procir.2016.04.052

stand for linearized behavior indeed. However, the linearization within OMA is performed for real level of dynamic loads resulting from the machining process and other excitation sources like not constant feed forces/moments, changing acceleration, unbalanced inertial masses, gears, vibration of the ground floor etc.

A machining process requires relative movement between several machine parts. The changed position of those parts can cause a changed dynamic behavior of the machine. If OMA were performed over various positions involving the changing dynamic behavior, the extracted modal parameters would represent an averaged dynamic behavior over these positions and thus they would be less meaningful. Therefore, the tool path for the machining process should be planned in term of minimal changes in the dynamic behavior.

This paper aims at determining such a tool path when conducting OMA. Thus the focus is brought to the changed dynamic behavior in dependence on the machine part position. A three axis milling machine was chosen as test stand for investigations. For better understanding, the changes of the dynamic behavior are also analyzed by mode shapes, extracted by EMA.

The most significant excitation in a machine tool is the machining process. Nevertheless, there are other excitation sources as mentioned above. If OMA is performed, these excitation sources are included in the evaluation of the modal parameters and thus they do not affect the results in term of violated assumption of causality. However, the level of vibrations at TCP caused by these excitation sources should be known in order to properly design the operational conditions for OMA. Thus, this paper further presents measured vibration at TCP during movements along NC-axes.

2. Modal parameters of investigated machine

The modal parameters of the investigated machine tool, a 3-axis milling machine shown in Figure 1, are extracted by using EMA. For this purpose, the machine was excited by an electro-magnetic shaker at the point of excitation located closely to TCP (see Figure 1).

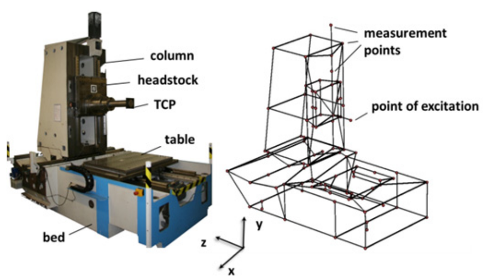

Figure 1 Machine tool and wire frame model used in EMA

The exciting force lied on the x-y plane diagonally. The responses of the machine on the excitation were captured by tri-axial acceleration transducers at 95 locations (see Figure 1). This experimental setup allows estimating totally 285 Frequency response functions (FRF), which were used for mathematically identification of the modal parameters by a curve fitting. The results for the investigated frequency range from 7 to 400 Hz yield 21 mode shapes.

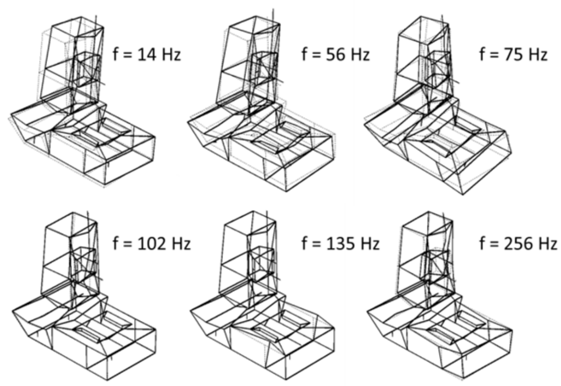

Figure 2 Mode shapes at several eigenfrequencies

The mode shapes being relevant for further investigations are listed in Table 1 including the natural frequencies, modal damping ratios and briefly description. The description supplements the Figure 2. The first mode shape at 14 Hz is a rigid body mode of the machine. All other mode shapes result from deformations of machine parts.

Table 1. The extracted mode shapes

#	Freq. [Hz]	Damp. [%]	Characteristics of the components
1	14	2,97	tilting of the whole machine around z
2	56,2	0,81	bending of column around z, translation table, elliptic movement of TCP in x,y - plane
3	74,6	3,89	torsion of column around y, torsion of the bed around z, TCP moves elliptic in x,y and x,z plane
4	102	3,89	bending vibration of ball screw drive of the y-axis, torsion of column around y
5	135	0,27	bending of the bed in x-direction
6	256	0,77	headstock tilts around y, torsion of the column around y, bending of the bed

3. Experimentally investigation of the time-invariance

In order to investigate the changed dynamic behavior in dependency on position of machine parts, FRF are experimental estimated at different TCP positions. The TCP positions are located on the x-y plane. The plane is divided into a 5×5 matrix. Figure 3 depicts all these TCP positions including their x and y coordinate in mm according to the machine coordinate system. The point and direction of the excitation correspond to those from EMA. The response on the excitation is captured by a tri-axial accelerometer directly at the excitation point in all three coordinates of the machine coordinate system which leads to 75 experimentally estimated FRF. Due to the high number of the FRF the machine was excited by an impulse hammer.