A strategy for experimental investigation of machine tool dynamics

Carsten Schedlinski [1], Paul Dieter Scharpf [2], Matthias Weber [2]
[1] ICS Engineering GmbH
Lortzingstr. 20
D-63225 Langen, Germany
email: **info@ics-engineering.com**

[2] MAG IAS GmbH
Stuttgarter Str. 50
D-73033 Göppingen, Germany

Abstract

In this paper a three step strategy for experimental investigation of machine tool dynamics is presented that is based on dynamic flexibility measurements, experimental modal analysis, and output only modal analysis. By example of a large scale combined outer diameter milling/turning machine it will be shown that valuable insight into the dynamics of the machine can be obtained which can subsequently be used for machine performance optimization.

1 Introduction

For today's machine tools the demands with respect to cost effectiveness, performance, and flexibility are steadily increasing. Consequently, proper dynamic design of the machine becomes a key issue. Since the excitation characteristics of the finally driven processes are mostly unknown a priori, a thorough experimental investigation of the first machine prototype is all important.

In this paper a strategy is presented that is based on dynamic flexibility measurements, experimental modal analysis, and output only modal analysis. It will be shown that the integrated application of the above techniques aids in understanding both, the principal dynamic behavior of the machine and the excitation characteristics due to the driven process. Moreover, potential weak spots of the machine design or the selected process parameters may be identified.

The strategy will be highlighted by example of a large scale combined outer diameter milling/turning machine. It will be shown that it can provide valuable insight into the dynamics of the machine which can subsequently be used for machine performance optimization.

2 Strategy

The accuracy of a cutting machine is mainly determined by the deviation from the predefined motion of the tool relative to the work piece. Detrimental deviations can be caused by either static or dynamic forces acting on the individual components of the machine. For the latter, the induced machine vibrations can in principle be subdivided into the following two categories according to [1]:

First, machine vibrations stimulated by external excitation, that can be traced back to excitation forces generated outside the machine (and transferred via the foundation into the machine) or within the machine itself (e.g. aggregates, unbalance forces, intermitted cut forces). Here, potential adverse vibration behavior may occur when the external excitation frequencies coincide with resonances of the machine (increased flexibility of the machine).

Second, under unfavorable phase position conditions between tool and work piece (< –90°), the risk of self-excitation arises. This so called regenerative chatter is not induced by external forces, but is driven by the interaction of the dynamic flexibility of the machine and the machining forces. The flexibility behavior of the machine either leads to a decay or built-up (instability) of unwanted vibrations.

In order to thoroughly investigate the dynamics of machine tools a three step strategy is applied:

1. dynamic flexibility measurements
2. experimental modal analysis
3. output only modal analysis

At first, absolute and relative dynamic flexibilities (inverses of the dynamic stiffnesses, i.e. displacement frequency response functions) between work piece and tool are determined. The dynamic flexibility measurements aim at pinpointing critical frequency ranges where an increased flexibility of the machine tool may lead to degraded results or even instabilities of the machining process.

In a second step, an experimental modal analysis is conducted in order to obtain detailed insight into the machine’s dynamics. Furthermore, the vibration behavior in the critical frequency ranges determined in the first step can be studied in detail, and the active parts of the machine can be identified. For the experimental modal analysis measurement locations on the relevant machine components are selected such, that an animated wire frame model of the machine can sufficiently represent the relevant modes of vibration. Subsequently, frequency response functions are measured and the modal parameters (natural frequencies, modal mass, modal damping, and mode shapes) are identified.

Finally, an output only modal analysis is conducted for the relevant maneuvers of the machine based on time data sampled during the machining process. Here, the frequency content of the machining process becomes visible. Also, critical interactions between process and flexibilities of the machine can be revealed.

With the knowledge from all three steps effective counter measures may be developed later on if problems arise during operation.

3 Example

The application of the strategy shall be presented by means of an example of the large scale combined outer diameter milling/turning machine shown in figure 1. The main machine data are summarized in tables 1 and 2.

For this machine it was found during first operational runs that, in some cases, the results of the machining process were not fully satisfying. First tests then showed that the degraded results could be traced back to the first and second orders of the milling cutter at about 30 Hz and 60 Hz, respectively.

With the help of the strategy outlined above the critical features of the machine shall be revealed. Furthermore, the modes of vibration and the machine components contributing the most to the observed phenomena are to be marked out in order to develop appropriate counteractions.

Figure 1: Survey of NG650 machine

Working range	Overall Travel left/right [mm]
X travel	378/410
Z travel	3126/3026

Table 1: Travel paths of machine

Parameter	Spindle	Cutting tool, left
Torque [Nm]	4533	10400
Speed [min^{-1}]	up to 2000	up to 207
Drive Power [kW]	71 (at 60% DC)	68 (at 60% DC)

Table 2: Machine parameters (at work piece)

3.1 Dynamic Flexibility Measurements

Absolute dynamic flexibilities were determined for the following components:

- Milling cutter (X1, Z1)
- Work piece, middle of (X2, Z2)

The positions and measurement directions are highlighted in figure 2. The excitation was applied with a special mid sized 1.1 kg heavy impulse force hammer (shown with red cap in figure 2). The response of the machine was measured with highly sensitive accelerometers, and the determined frequency response functions were integrated twice in the frequency domain to obtain the dynamic flexibilities.

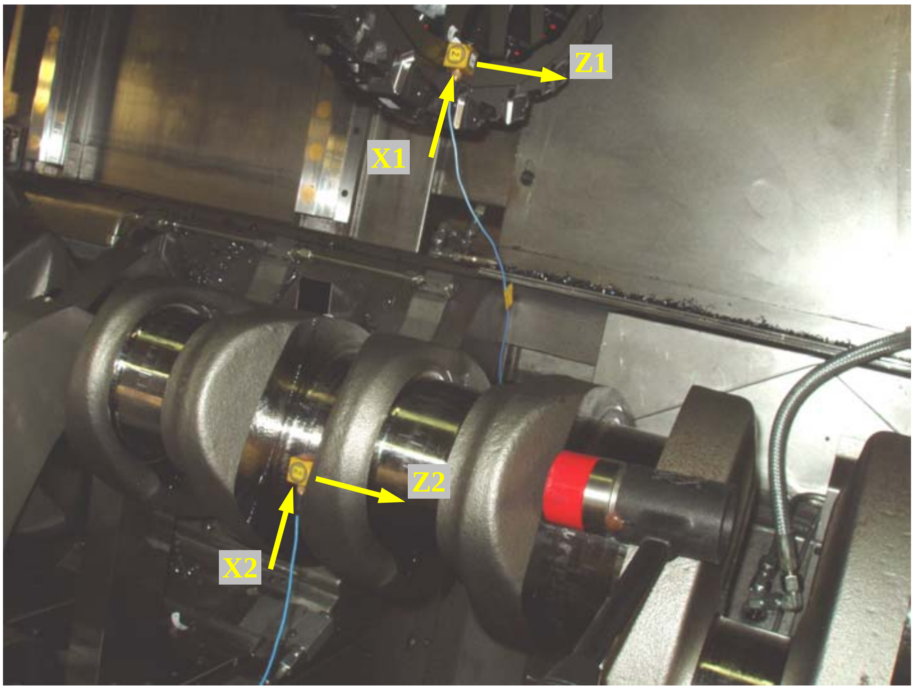

Figure 2: Dynamic flexibility measurement

Figure 3 shows a typical example of a normalized dynamic flexibility result at the milling cutter in Z1 direction. The increased dynamic flexibilities below about 25 Hz are primarily driven by rigid body modes of the complete machine and are not critical.

Above this frequency range a rather constant behavior can be observed, however, some peaks – especially at 35 Hz and 75 Hz – are close to the first and second order frequencies of the milling cutter.

Figure 3: Typical normalized absolute dynamic flexibility – milling cutter Z1

For the accuracy of the machining process itself the relative dynamic flexibilities between tool and work piece are most relevant. Thus, relative dynamic flexibilities were determined based on the measured absolute dynamic flexibilities by proper summation/subtraction of the absolute point and cross dynamic flexibilities (eccentricities were neglected) according to equation (1). A typical normalized result is shown in figure 4, again for the Z direction of the machine.

$$h^{rel} = h_{11}^{abs} - h_{12}^{abs} - h_{21}^{abs} + h_{22}^{abs} \qquad (1)$$

with

h^{rel} relative dynamic flexibility

h_{ij}^{abs} absolute point and cross dynamic flexibilities (i, j = 1,2)

At first, it can be noted that in the frequency range of the rigid body modes no increased flexibilities are found anymore. They have canceled out for the relative dynamic flexibilities (no relative motion between tool and work piece). The increased dynamic flexibilities in the critical frequency ranges around 30 Hz and 60 Hz are still present and rather prominent indicating that an excitation of these frequency ranges may lead to degraded machining results.

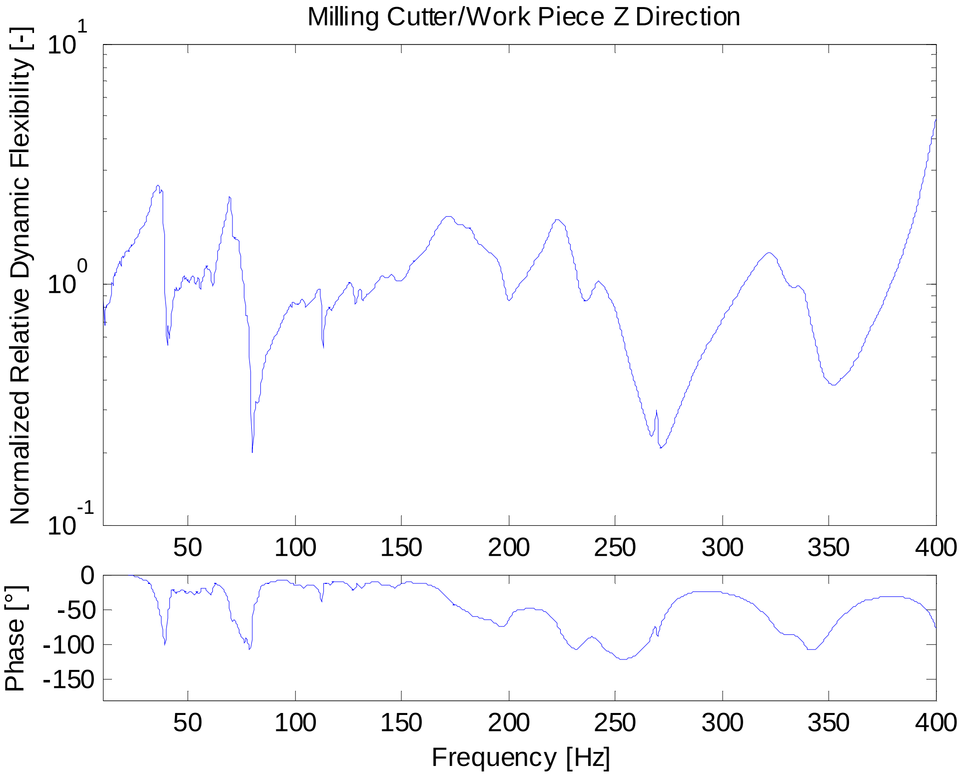

Figure 4: Typical normalized relative dynamic flexibility – Z direction

3.2 Experimental Modal Analysis

For experimental modal analysis 52 measurement nodes were selected according to the wire frame test model shown in figure 5. Excitation was applied at four different locations (references) with the modal hammer already used for the dynamic flexibility measurements (see also figure 2). The responses were measured with a roving set of highly sensitive triaxial accelerometers in a frequency range up to 400 Hz with a frequency resolution of 0.25 Hz.

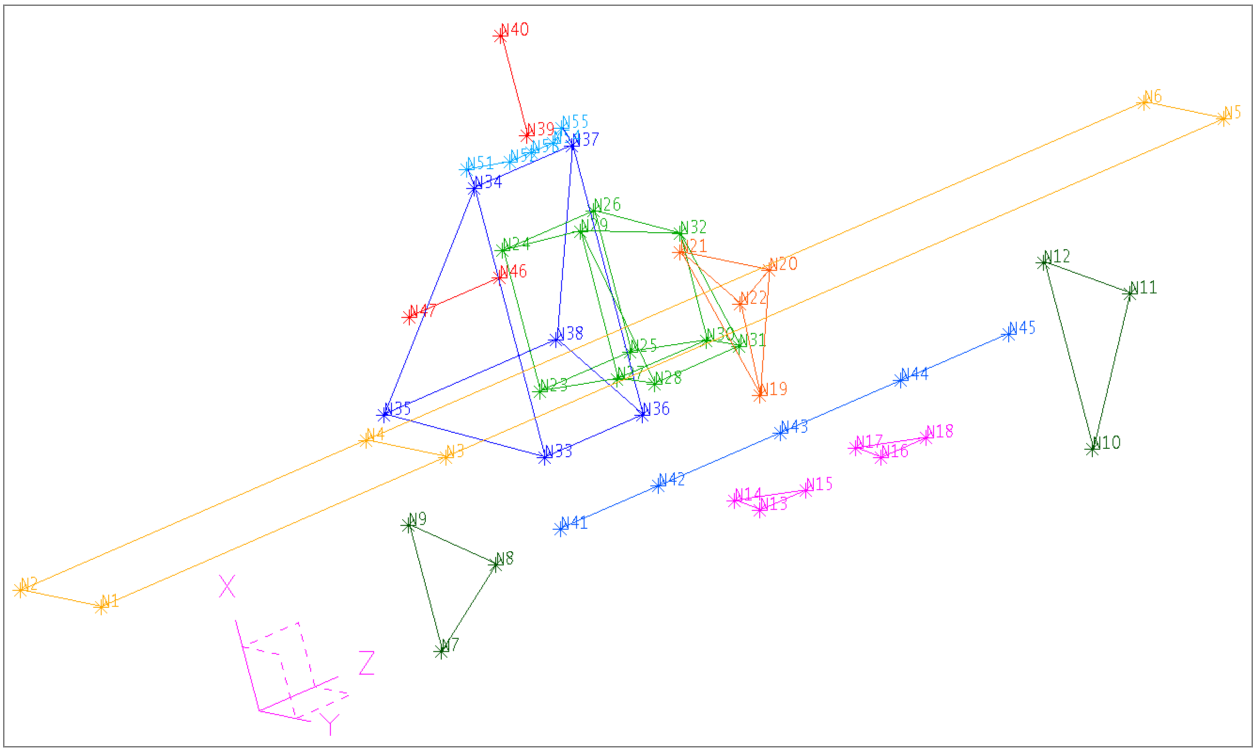

Figure 5: Test model for experimental modal analysis

Typical frequency response functions (FRFs) are shown in figure 6 (imaginary parts of acceleration FRFs) in the most relevant frequency range up to 100 Hz. A rather high modal density and partly high damping can be observed.

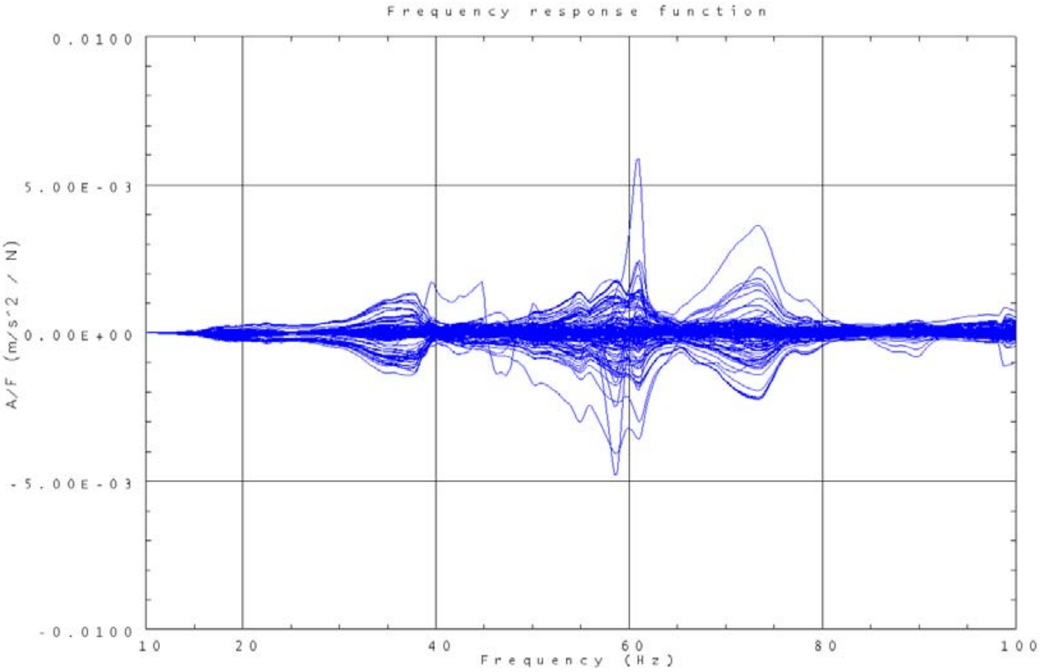

Figure 6: Typical frequency response

The experimental modal analysis provided 17 modes up to about 80 Hz. Table 3 lists the results and figure 7 shows the Auto-MAC of the mode shapes. Because of the rather high modal density only those results were retained that could be identified in a stable and reliable manner. The corresponding mode shapes can be regarded as representative for the respective frequency ranges.

The mode shapes can be subdivided into five categories:

1. rigid body motion
2. translation of Z slide in Z direction, tilting of X slide motor about Z
3. tilting of X slide motor about Z (in Y direction)
4. rotation of X slide/cutter about X
5. rotation of X slide/cutter about Y

Potentially critical are categories 2 to 4 since they lie well within the frequency range excited by the cutter.

Nr.	**Freq. [Hz]**	**Damp. [%]**	**Description**
1	13.02	3.32	rigid body motion
2	14.96	9.52	"
3	17.16	2.80	"
4	18.49	7.66	"
5	20.10	2.72	"
6	22.57	2.47	"
7	33.25	1.85	translation of Z slide in Z direction, tilting of X slide motor about Z
8	34.72	4.95	"
9	37.93	2.06	"
10	45.37	1.33	tilting of X slide motor about Z (in Y direction)
11	46.90	1.18	"
12	48.27	0.61	"
13	54.89	2.09	rotation of X slide/cutter about X
14	58.57	1.66	"
15	60.84	1.52	"
16	70.86	1.61	rotation of X slide/cutter about Y
17	80.13	1.27	"

Table 3: Results of experimental modal analysis

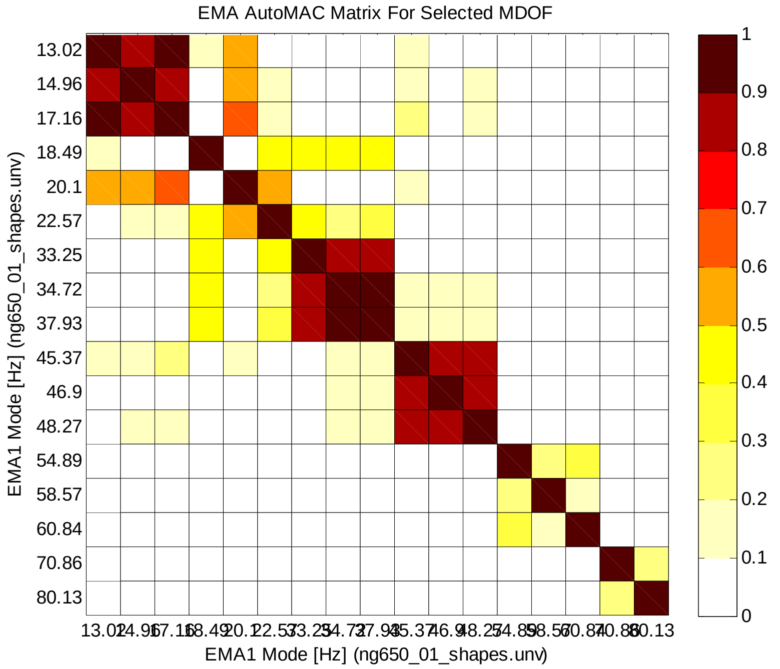

Figure 7: Auto-MAC of identified mode shapes

3.3 Output Only Modal Analysis

For the operational analysis the test model was reduced to nine triaxial and six uniaxial measurement nodes according to figure 8. Multiple milling runs were performed with a dummy work piece applying different parameters for the milling process (figure 9), and time data were sampled (figure 10).

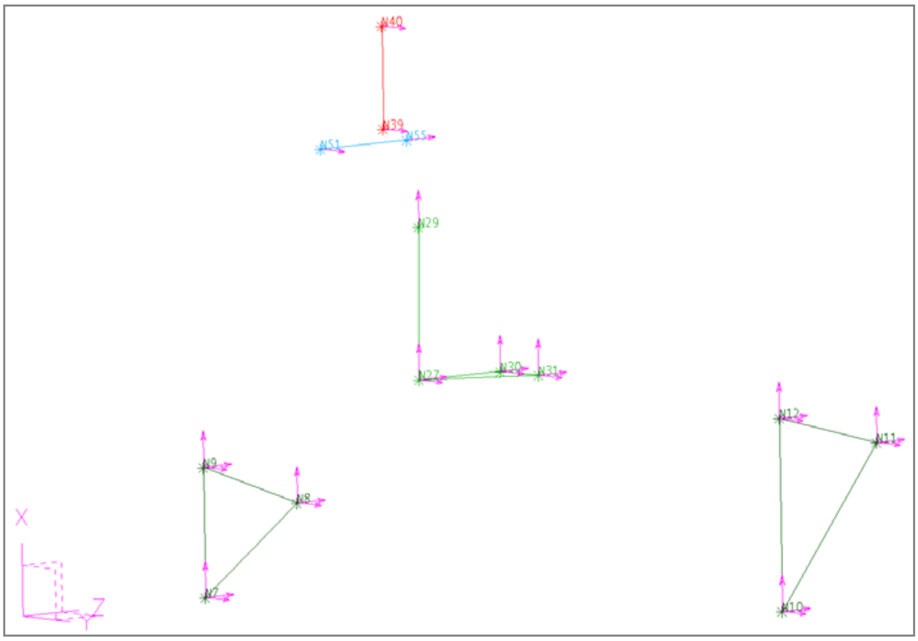

Figure 8: Reduced test model with measured directions

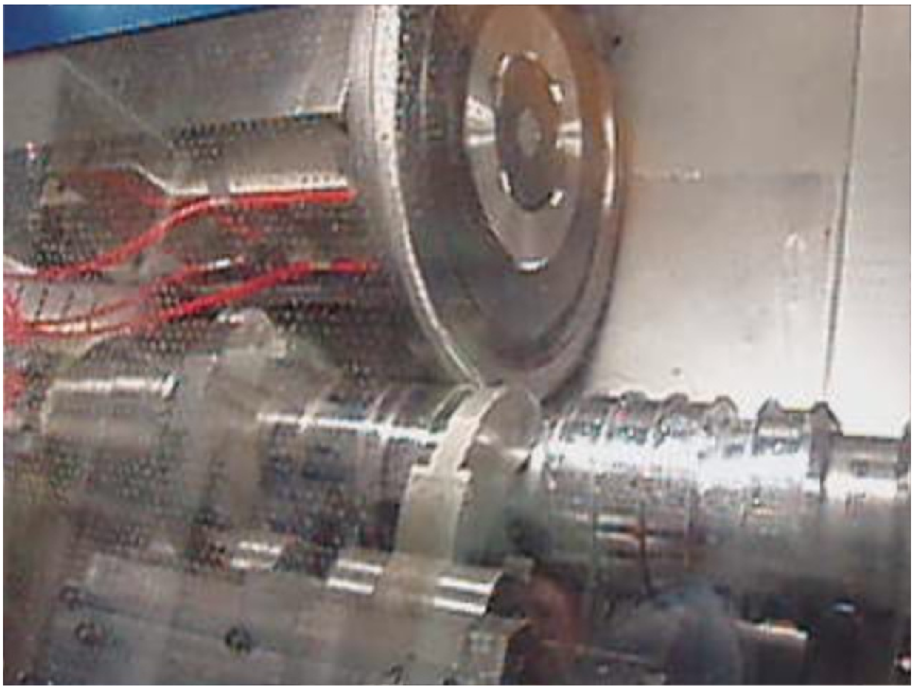

Figure 9: Survey of operational test

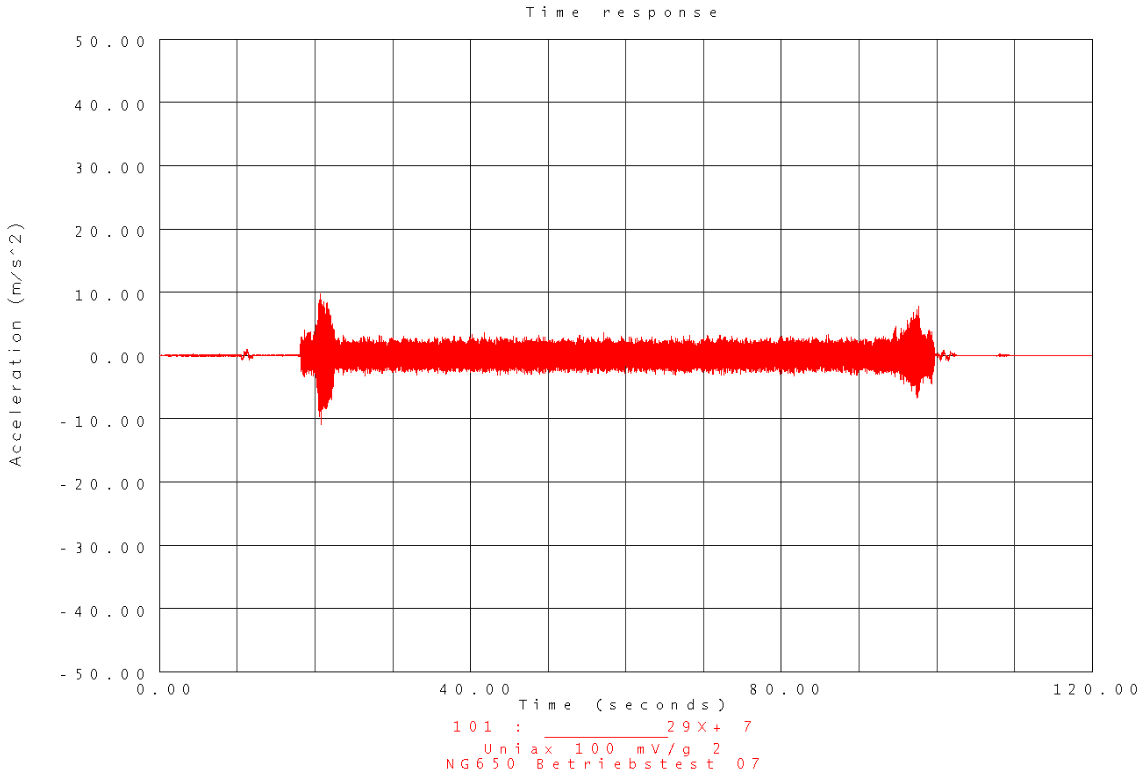

Figure 10: Typical time record, X slide

At first, spectra were estimated for the measured accelerations. The spectra were then integrated to displacements in the frequency domain. A typical result is shown in figure 11 for the X slide up to 100 Hz. It can be noticed that only the first and second orders of the milling cutter excitation (≈31 Hz and ≈62 Hz) are relevant. The peaks below 20 Hz fall well in the range of the rigid body modes and are not critical for the machining result.

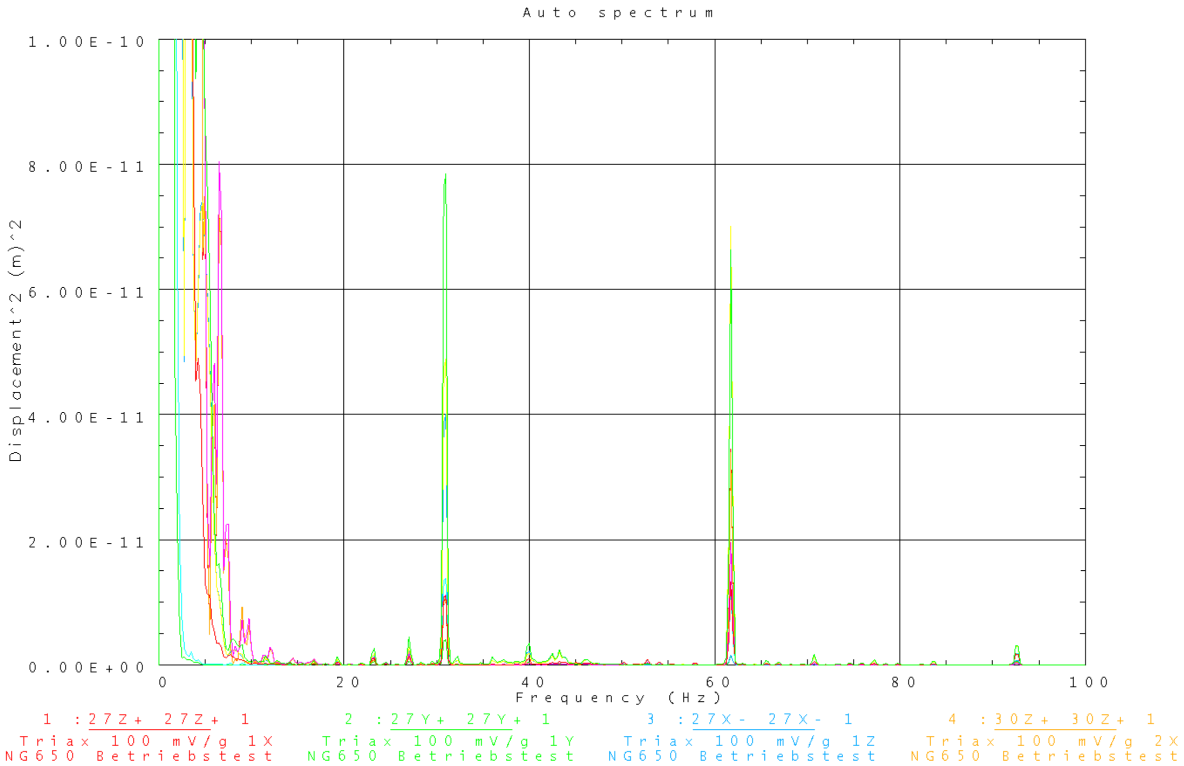

Figure 11: Displacement spectra up to 100 Hz on X slide, 5mm feed

The data were then evaluated with output only modal analysis techniques (see also [2]) in order to identify operational mode shapes. Table 4 lists the results and figure 12 shows the Auto-MAC of the mode shapes. Here, three categories of modes are relevant according to table 4 that correlate well with the findings from the experimental modal analysis.

Potentially critical are categories 1 to 3 since they exhibit the largest contribution according to the displacement spectra shown above.

No.	Freq. [Hz]	Damp. [%]	Description
1	30.90	0.13	motion in X and tilting of X slide about Y
2	40.42	3.62	tilting of X slide motor
3	45.78	0.80	"
4	61.74	0.03	tilting of X slide about Y

Table 4: Results of output-only modal analysis

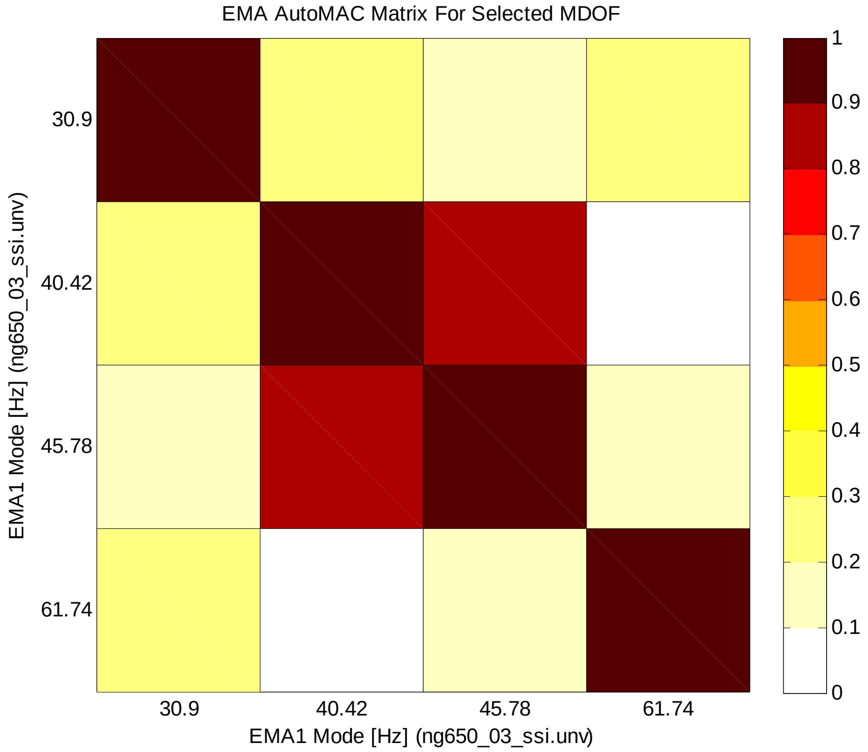

Figure 12: Auto-MAC-Matrix der Eigenformen

4 Summary and Conclusions

In order to analyze and evaluate the dynamic behavior of a large scale combined outer diameter milling/turning machine experimental vibration analyses were conducted. In particular, a strategy was applied incorporating dynamic flexibility measurements, experimental modal analysis, and operational modal analysis.

Especially the operational test revealed that the first and second order frequencies of the milling cutter dominantly (and solely) excite the system. Since these excitations fall well in frequency ranges with increased flexibility of the machine, the observed degraded milling results can directly be explained.

The modal analysis gave additional insight into the motion of the machine in the relevant frequency ranges. With this information specific improvements of the machine can be derived either based on technological changes (e.g. change of process parameters) or modifications of the machine itself (e.g. stiffening).

References

[1] M. Weck, C. Brecher, *Werkzeugmaschinen: Messtechnische Untersuchung und Beurteilung, dynamische Stabilität*, 7. edition; Springer-Verlag, Berlin Heidelberg (2006)

[2] Schedlinski C., Lüscher M., *Application of Classical and Output-Only Modal Analysis to a Laser Cutting Machine*, Proc. of ISMA2002, Leuven, Belgium (2002)