ASPECTS OF THE INVESTIGATION OF THE DYNAMIC BEHAVIOUR OF MACHINE TOOLS BY OPERATIONAL MODAL ANALYSIS

JAN BERTHOLD[1], MARTIN KOLOUCH[2]
VOLKER WITTSTOCK[1], MATTHIAS PUTZ[2]
[1]Chemnitz University of Technology, Institute for Machine Tools and Production Processes, Chemnitz, Germany
[2]Fraunhofer Institute for Machine Tools and Forming Technology IWU, Chemnitz, Germany

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e-mail: jan.berthold@mb.tu-chemnitz.de

There are differences in the dynamic behaviour of a machine tool between standstill and process because of preloads, process damping and gyroscopic moments. The standard method to characterize the dynamic behaviour, the experimental modal analysis (EMA), is performed only in the standstill and neglects these effects. In contrast, operational modal analysis (OMA) makes possible a characterisation of the dynamic behaviour under working conditions. Nevertheless, the performance of OMA is based on some assumptions. In this paper several key aspects considering these requirements regarding to machine tools are discussed. These presumptions affect the time-invariance during the measurement, the suitability of a milling process to excite the machine adequately and the influences of the different identification methods to the results. The obtained results of these investigations will be used in further studies to make OMA applicable for machine tools.

KEYWORDS
machine tool, operational modal analysis, dynamics, excitation, cutting forces, identification

1 INTRODUCTION

The dynamic behaviour of machine tools is usually characterized by the experimental modal analysis (EMA) as standard. The results are the modal parameters (eigenfrequencies, modal damping and mode shapes) [Ewins 1986]. With the modal parameters of the machine tool a weak point analysis, structural dynamic modifications (SDM) or FEM model-updating could be performed. Unfortunately, EMA is performed in the standstill of the machine by shaker or hammer excitation, so all effects are neglected that occurring during the process influencing the dynamic behaviour. These are for example gyroscopic moments of the spindle, preloads of bearings as well as process damping [Özsahin 2011]. So the dynamic behaviour of machine tools under working conditions cannot be estimated reliable by EMA.

However, to overcome this disadvantage, the operational modal analysis (OMA) can be employed. OMA originates from the field of civil engineering where the ambient conditions (wind, water waves and ground vibrations) are used to excite a structure [Cunha 2006]. The excitation is not measured, only the output signals are used to identify the modal parameters.

When transferring this approach to machine tools, the process could be used to excite the machine, there is no need for shaker or hammer excitation. The results will be plausible and relevant because the modal parameters are identified in the working point of the machine with all effects occurring while process.

Nevertheless, the performance of OMA is based on some assumptions. To fulfil these requirements while applying this method to the field of machine tools, several key aspects are considered in this paper. So the system has to be time-invariant during the measurement [Tcherniak 2010]. A machining process, however, causes relative movements of the components and so effects changes in the dynamic behaviour. Therefore, the position-dependent frequency response functions and the mode shapes are evaluated in the working space, to determine a time-invariant tool path. It is also assumed that the excitation has a white noise characteristic [Batel 2002]. Considering a machining process that generates harmonic frequencies by the teeth engagement, this requirement is not fulfilled. However, it could be shown that by changing the cutting parameters during a milling process a broadband excitation could be generated. Since the excitation does not exactly meet the white noise assumption, the influence of different excitation signals onto the resulting modal parameters is investigated and compared by different identification methods of OMA.

2 INVESTIGATION OF A TIME-INVARIANT TOOL PATH

A machining process requires a relative movement of the components because of the necessary feed in combination with the cutting speed. As the dynamic behaviour of the machine depends on the machine positon, it will change during the machining. The subsequently identified modal parameters will represent only an average of the dynamic behaviour along the chosen tool path. So, the aim is to determine a tool path in the working space of a machine tool for a process which provides both, the structure could be excited and at the same time the changes in the dynamic behaviour are insignificant.

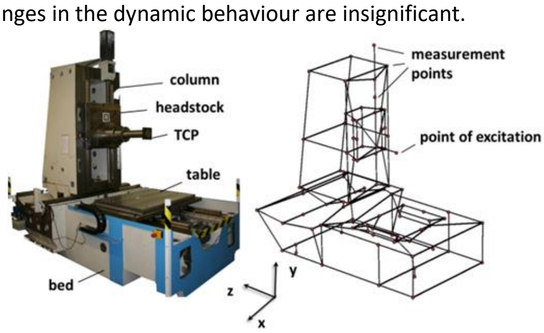


Figure 1. Wire frame model of 3-axis machine tool [Putz 2016].

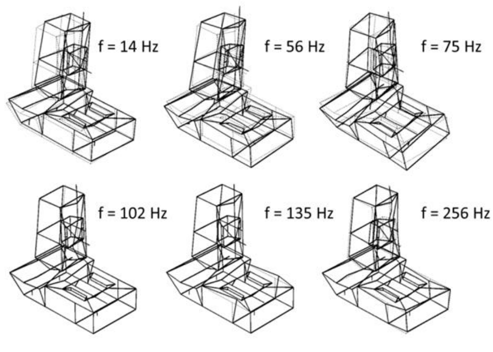


Figure 2. Selected mode shapes at several eigenfrequencies [Putz 2016].

The investigations are carried out on a 3-axis milling machine [Putz 2016]. The dynamic behaviour is characterized by an EMA, exciting the machine tool with an electro-magnetical shaker diagonal in the x-y-plane near the TCP. Therefore, the machine is depicted as a wire frame model with 95 measurement points (see Fig. 1). The response to the excitations was measured with acceleration sensors in every point. In the range from 7 to 400 Hz 21 modes were identified. Several representative modes are shown also in Fig. 2.

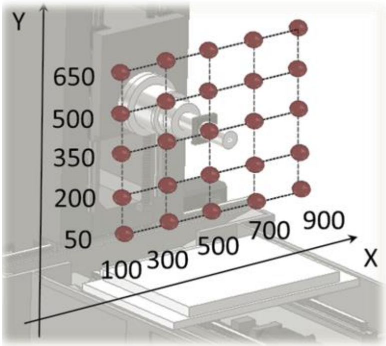


Figure 3. FRF measurement points in the X_{NC}-Y_{NC}-plane [Putz 2016].

In addition to the EMA, Frequency Response Functions (FRF) are measured in varying machine positions in the working space at the TCP. The investigations are performed in the X_{NC}-Y_{NC}-plane by changing the column or headstock position, respectively. The plane was divided in a 5x5 matrix and the response to an impulse hammer excitation was measured at the TCP in x,y,z-direction (see Fig. 3).

As result, there are occurring 75 FRF's. In a first analysis the FRF's are compared to each other as shown in Fig. 4. In the upper part the influence of changing the Y_{NC}-position (at central X_{NC}-position) could be seen. Considering the range from 7 to 150 Hz there are only rarely changes between the particular FRF's. This is different to the higher frequency range above 150 Hz, here the curves and also the modes are significant changing. It is the same when looking at the change of the X_{NC}-positon (at central Y_{NC}-position). As the comparison of the different FRF's has a subjective character, the Frequency Response Assurance Criterion (FRAC) [Chen 2003] is employed to get more convinced comparison results. If two compared FRF's showing perfect accordance, the FRAC is equal to 1. Otherwise, if there is no accordance at all the FARC is 0. Figure 5 shows the FARC values for the investigated machine positions in the X_{NC}-Y_{NC}-plane. The reference, to which all FRF's are compared, is set in the middle of the plane (X=500, Y=350, Z=200).

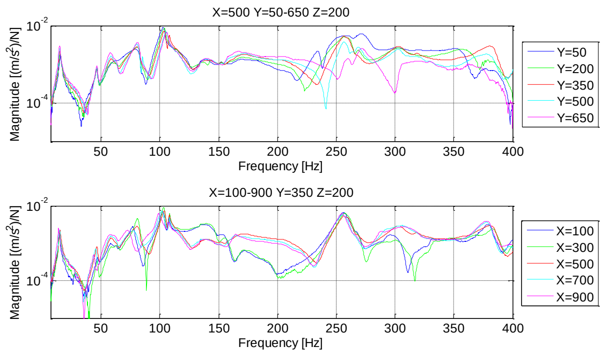


Figure 4. Measured FRF in the x-direction for several machine positions [Putz 2016].

The FARC results are depicted in Fig. 5, they are broken down in different frequency ranges (the three columns in Fig. 5) and in x- and y-direction (the two rows in Fig. 5). When looking at the frequency range from 7 to 100 Hz, it could be seen that the results are nearly unaffected by the change of the Y_{NC}-position but by the X_{NC}-position. In this range the modes are dominated by rigid body modes of the bed and the column. In the higher frequency range, for e.g. 200 to 400 Hz, the changes along the X_{NC}-axis are smaller than in the Y_{NC}-axis. Here the mode shapes are dominated by the movements of the headstock and local deformations of bed and column.

Considering the determination of a time-invariant and appropriate tool path for performing OMA and looking at the whole frequency range from 7 to 400 Hz, it can be seen, that the dynamic behaviour is very sensitive to the machine position. For the investigated machine, a possible tool path should not exceed a length of 200 mm from a start point and the feed motion should take place only along one axis.

x-Direction, Frequency range 7-400 Hz

Y_{NC} ↑ / X_{NC} →	100	300	500	700	900
650	0.32	0.29	0.43	0.43	0.27
500	0.51	0.45	0.80	0.43	0.64
350	0.52	0.51	1.00	0.85	0.73
200	0.46	0.45	0.87	0.69	0.57
50	0.40	0.38	0.58	0.42	0.39

x-Direction, Frequency range 7-100 Hz

Y_{NC} ↑ / X_{NC} →	100	300	500	700	900
650	0.72	0.81	0.91	0.80	0.49
500	0.69	0.85	0.95	0.80	0.46
350	0.69	0.83	1.00	0.86	0.44
200	0.65	0.82	0.98	0.80	0.36
50	0.62	0.81	0.89	0.74	0.28

x-Direction, Frequency range 200-400 Hz

Y_{NC} ↑ / X_{NC} →	100	300	500	700	900
650	0.25	0.23	0.24	0.21	0.16
500	0.60	0.52	0.83	0.21	0.79
350	0.62	0.55	1.00	0.92	0.87
200	0.54	0.43	0.84	0.72	0.66
50	0.47	0.33	0.49	0.41	0.43

y-Direction, Frequency range 7-400 Hz

Y_{NC} ↑ / X_{NC} →	100	300	500	700	900
650	0.45	0.46	0.73	0.71	0.69
500	0.39	0.45	0.79	0.71	0.78
350	0.46	0.51	1.00	0.86	0.83
200	0.51	0.56	0.90	0.73	0.64
50	0.59	0.59	0.80	0.60	0.49

y-Direction, Frequency range 7-100 Hz

Y_{NC} ↑ / X_{NC} →	100	300	500	700	900
650	0.78	0.87	0.95	0.79	0.68
500	0.76	0.88	0.92	0.79	0.67
350	0.81	0.87	1.00	0.81	0.64
200	0.82	0.87	0.96	0.80	0.61
50	0.87	0.87	0.91	0.79	0.58

y-Direction, Frequency range 200-400 Hz

Y_{NC} ↑ / X_{NC} →	100	300	500	700	900
650	0.35	0.34	0.65	0.66	0.64
500	0.29	0.29	0.75	0.66	0.81
350	0.41	0.41	1.00	0.91	0.88
200	0.54	0.55	0.89	0.76	0.77
50	0.60	0.60	0.79	0.59	0.61

Figure 5. FARC values (also highlighted by colours) in x- and y-direction for different frequency ranges at various machine positions. The reference point for comparison is at Z_{NC}=500, Y_{NC}=350, Z_{NC}=200 [Putz 2016].

3 BROADBAND EXCITATION BY CUTTING FORCES

Generally, when performing OMA, the excitation is assumed to have a white noise characteristic or is broadband in frequency spectrum of interest. All modes of the structure are excited with the same force level and an exact separation and identification of the modes is clearly possible.

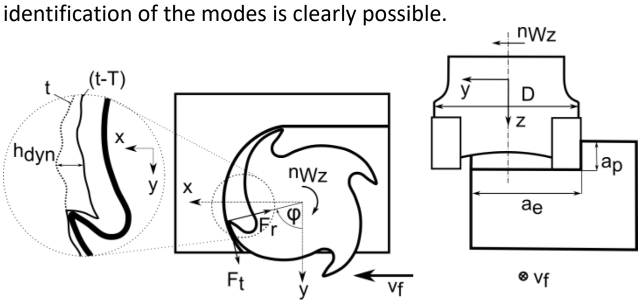


Figure 6. Scheme of the investigated face milling process [Berthold 2016a].

When a cutting process is considered, e.g. milling, the spectrum of the cutting forces consists of many spectral lines because of the tooth pass frequency and the number of tooth. The aim is to achieve a broadband excitation of the machine by cutting forces through changing the cutting parameters, especially the spindle speed and the immersion during the process without using a special designed workpiece [Cai 2015].

The investigations consider in a first step the simulation of a milling process (see Fig. 4) to get to know the influence of the variation of the cutting parameters and in a second step the experimental verification by cutting force measurements.

The regarding cutting force model presented in [Berthold 2016a] describes the face milling process. The machine tool is considered as dynamic system, so there will be displacements during the process between the tool and the workpiece. These displacements are calculated by measured FRF between the two by using the modal parameters [Richardson 1977]. This is based on a first estimation of the cutting forces to calculate the displacements by numeric solution with the Newmark algorithm combined with the Newton-Raphson-method [Li 1992] and in a second step the more precise calculation of the cutting forces including these displacements, these steps are repeated until a stop criterion.

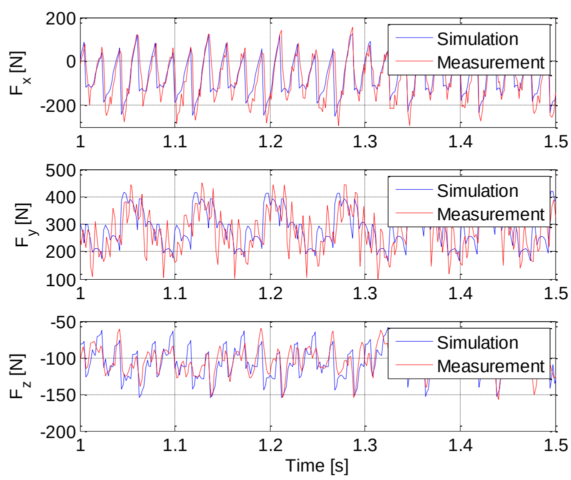


Figure 7. Comparison of calculated and measured cutting forces in time domain [Berthold 2016a].

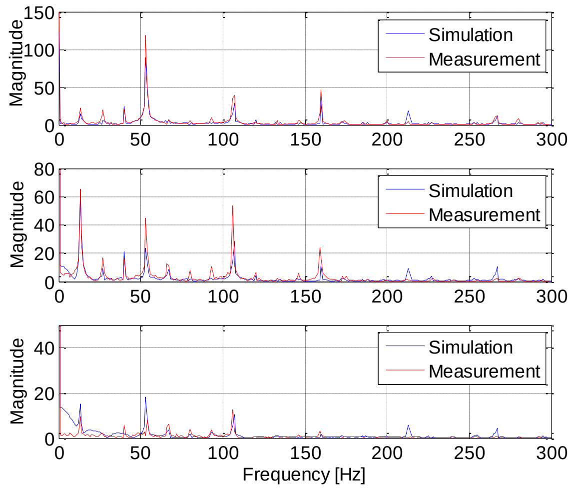


Figure 8. Comparison of calculated and measured cutting forces in frequency domain [Berthold 2016a].

The simulated cutting forces are compared with measurements in time and frequency domain, see Fig. 7 and Fig. 8, which shows a good accordance. In the frequency domain, especially the harmonic parts of the cutting forces can be seen, which is the spindle speed at 13,3 Hz (800 min^{-1}) and the tooth pass frequency at 53,3 Hz (4 tooth miller). Differences may caused by the missing consideration of the tilting of the tool in the simulation.

To achieve a broadband excitation the influence of the spindle speed and the influence to the spectra is investigated by the presented cutting force model. All other parameters are assumed to be constant. With the constant feed rate in combination with changing spindle speed, the feed rate per tooth variates, which leads to a change in the cutting force amplitude.

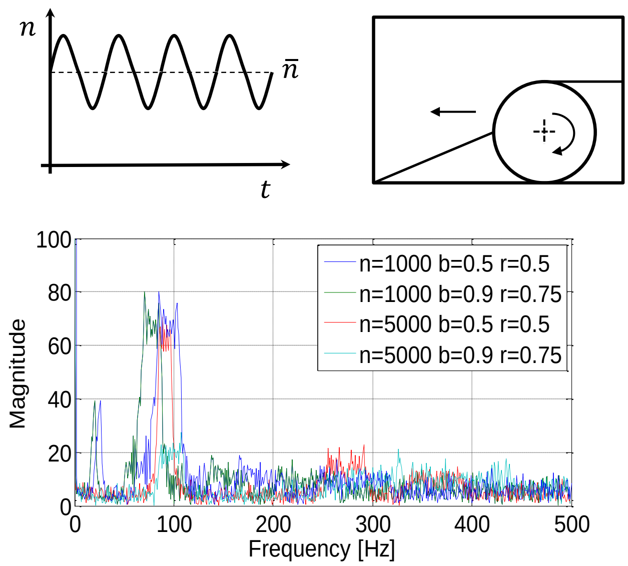


Figure 9. Simulation results for varying the spindle speed as a harmonic and the immersion as linear function for several parameters [Berthold 2016a].

$$n(t) = b\bar{n}\sin(2\pi f t) + \bar{n} \quad (1)$$

$$a_e(t) = rt \quad (2)$$

Theoretically, the variation of the spindle speed with random values will lead to a broadband excitation, which would be very preferable but is practically not feasible. As the spindle drive is limited considering the changing rate of the spindle speed by the inertia and the control unit cycle time (IPO). So the spindle speed is changed with three functions, linear, exponential and harmonic (sine-function). The immersion is variated according to a linear and an exponential function. In case of small immersion values, the effect to the cutting force is similar to an impulse with low force level. Increasing the immersion leads to higher force amplitude with longer period. So by immersion mostly the higher order harmonics could be influenced. The best simulation results considering a broadband excitation are generated by a harmonic spindle speed variation (sine-function) combined with a linear change of the immersion. The results are shown in Fig. 9 for several parameter configurations (regarding Eq. 1 and 2).

Subsequently to the simulation, milling experiments are performed to proof the calculated results. Linear and exponential changes of the spindle speed showing no satisfactory effect to the spectra, only the variation as sine-function results in broadband excitation from 80 to 120 Hz.

Due to extend the broadband part of the spectra, the spindle speed variation is combined with the linear change of the immersion. The results can be seen in Fig. 10, the cutting forces are broadband in the range from 0 to 250 Hz which is a clear improvement regarding to the initial condition considering the harmonics. This excitation can be employed for performing OMA on machine tools by process excitation. Nevertheless, attention should be paid to the non-constant amplitude of the cutting force spectra, especially in terms of identifying the modal parameters.

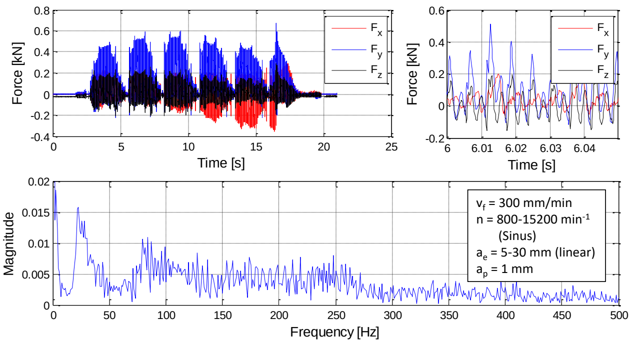


Figure 10. Measured cutting forces in time (overview and detail) and frequency domain as result of alternating spindle speed and linear changed immersion [Berthold 2016a].

4 IDENTIFICATION OF MODAL PARAMETERS

Even tough, a process can be designed to generate a broadband excitation by cutting forces, the results don't exactly get the assumption of white noise characteristic. Furthermore, the excitation only takes place at the TCP, which affects mostly the tool, workpiece and adjacent component but not all structural components.

Therefore, the influence of the excitation signal to the identified modal parameters by different OMA-methods has to be investigated and compared with results gained by the classical EMA.

In the context of OMA many methods have been developed to identify the modal parameters. A general differentiation can be made between methods working in the frequency- and in the time-domain. Well-known methods in the frequency domain are the Peak-Picking (BFD), the Frequency Domain Decomposition (FDD) and the Least Squares Complex Frequency (LSCF) method. On the other hand methods in the time domain include the Eigenvalue Realization Algorithm (ERA), the Ibrahim Time Domain (ITD) and the Least Squares Complex Exponential (LSCE) method, to name just a few. Another big group in the time domain, which becomes more and more popular, are the Stochastic Subspace Identification methods (SSI) [Zha08]. The several methods are pursuing different strategies in the procedure to estimate the modal parameters, considering especially the handling of noisy data or the separation of coupled modes.

The investigations are performed on a test rig with different excitation signals and the analysis is done by EMA and OMA [Berthold 2016b]. The simple design and the clearly definable boundary conditions in the test rig allow a comparison of the results. Conclusions could be drawn regarding to the influence of the excitation to results. The investigations are carried out on cardan joint element of parallel kinematic machine tool (see Fig. 11).

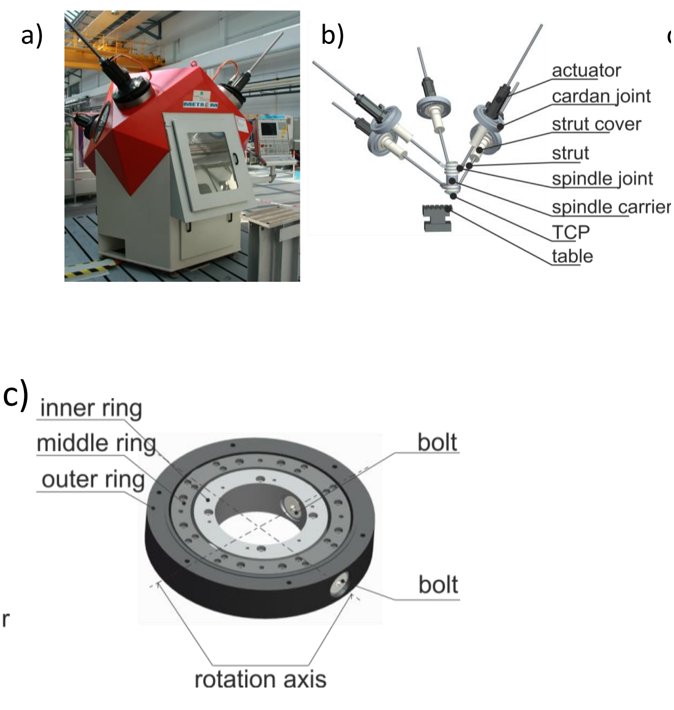


Figure 11. Parallel kinematic machine (a) tool with kinematic model of the spindle and the struts(b), cardan joint element(c)

The spindle of the machine tool is mounted to the spindle carrier which is moved by five struts. Each strut is connected to the machine frame by the cardan joint element. It consists of three rings, an inner ring, a middle ring and an outer ring. The structure is excited by an electro-magnetic shaker mounted in the middle (similar to real excitation) and driven by a signal generator to configure several excitation signals. The applied force is measured by a force transducer.

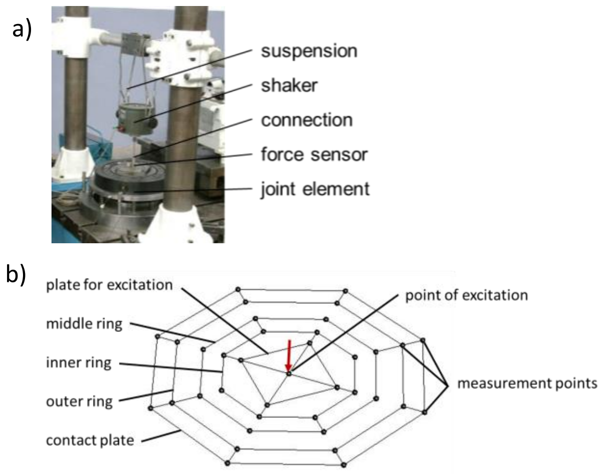


Figure 12. Test rig, (a) element mounted in test rig, (b) wire frame model [Berthold 2016b].

The joint element described by 37 measurement points is shown in Fig. 12. The response to the excitation is measured by tri-axial acceleration sensors. The structure was excited by a random burst signal. In a first step, to get basic values considering a comparison, the modal parameters are identified using the EMA with the Rational Fraction Polynomial Method, which yields to 8 eigenfrequencies in the range from 7 to 800 Hz. An overview of these results can be seen in Fig. 13 by looking at the Complex Mode Indicator Function resulting from EMA.

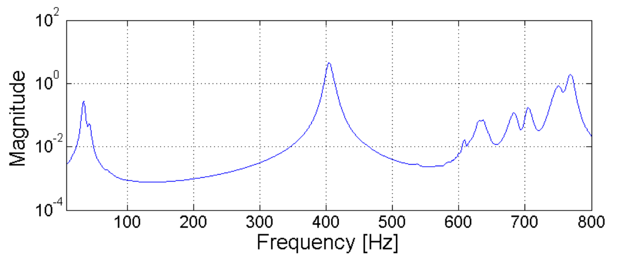


Figure 13. Complex Mode Indicator Function (CMIF) for EMA of cardan joint in test rig [Berthold 2016b].

In the next step OMA was performed at the same structure. Two additionally sensors, which are used as reference, were mounted on the inner ring and the outer ring for the recording of acceleration signals in the vertical direction. Also the force is measured when exciting the structure, not for calculation but for monitoring. The three different excitation signals could be seen in Fig. 14.

Whereby, the random signal corresponds to the white noise assumption. The random burst, known from EMA, is employed because of its appropriate signal processing properties. The random signal overlaid with harmonics stands for an excitation by cutting forces with dominating frequencies. The modal parameters were identified by the FDD, EFDD and CFDD method in the frequency domain and by SSI methods like UPC, UPC Merged Data Set, PC and CVA in the time domain for each of the three excitation signals [Rainieri 2014]. The results of the random burst excitation identified by EFF Dare shown in Fig. 15. Fig. 16 shows the same measurements but the modal parameters were identified by the UPC Merged Data Sets method. Both figures depict the calculated singular values of the spectral density with regarding frequency.

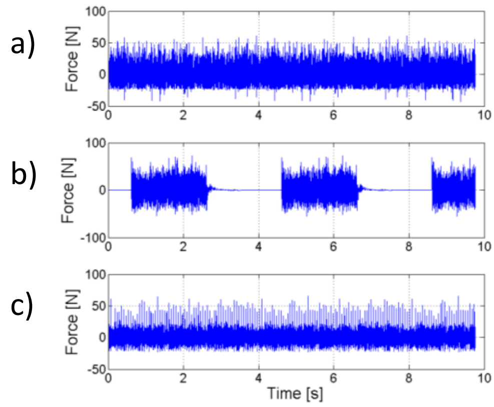


Figure 14. Excitation signals in time and frequency domain: (a) random, (b) random burst and (c) random with harmonics [Berthold 2016b].

For the EFDD the natural frequencies, mode shapes and modal damping values are estimated by single-degree of freedom models for each pole [Jacobsen 2008]. Unlike to EMA, additionally frequencies are occurring at 461 and 499 Hz. These are modes of the shaker, coupled to the cardan joint element excluded in the EMA results because of the force measurement.

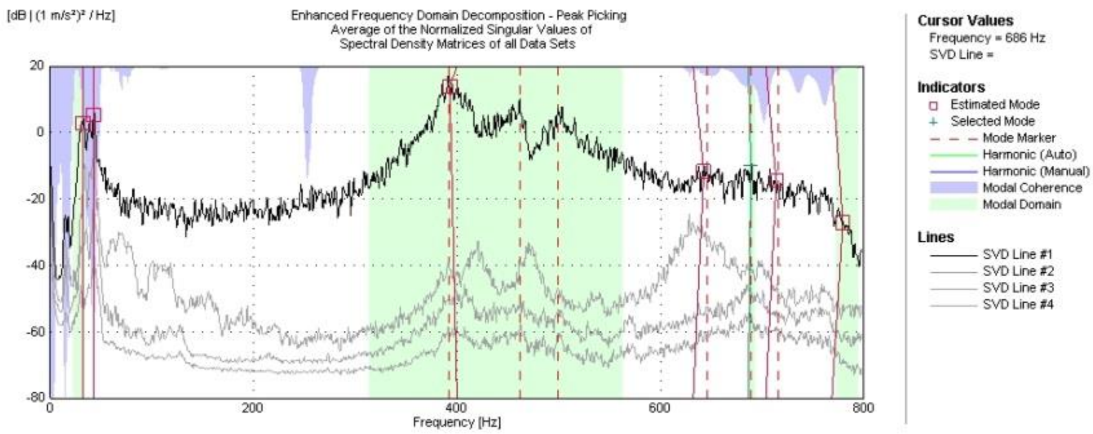


Figure 15. Singular values of spectral density matrices estimated by EFDD [Berthold 2016b]

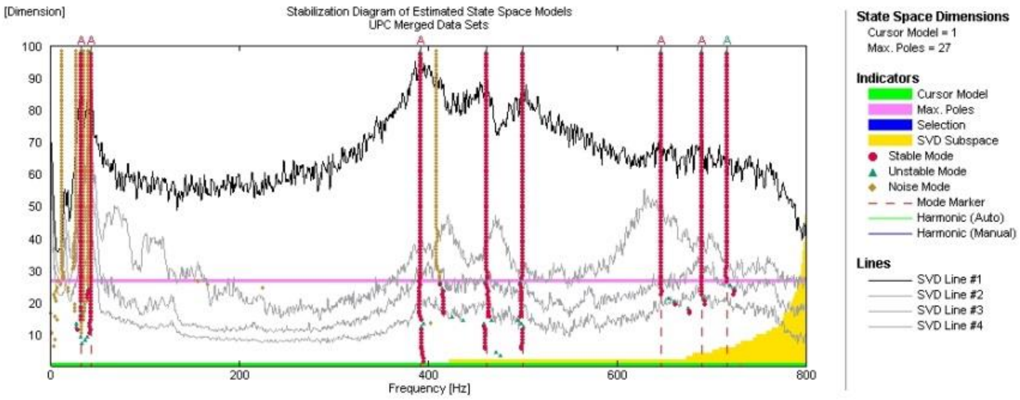
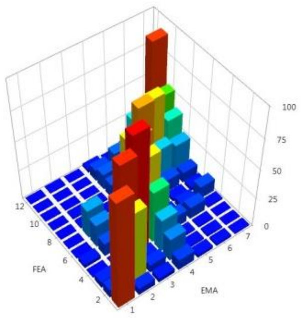


Figure 16 Singular values of spectral density matrices estimated by UPC Merged Data Sets [Berthold 2016b]

In Fig. 16, which presents a stabilization diagram also based on the singular values, 8 modes are clearly found in the range from 0 to 800 Hz, depicted by red spots. The order of the state space model which is achieved is set to 27. There are also found noise modes symbolized by brown rhombus. Equally, the modes of the shaker could be seen.

In the comparison it is obvious that the first three modes are the most distinctive ones, which are clearly identified by EMA as well as OMA. This is shown in Fig. 17 by comparing the mode shapes using the MAC [Allemang 2003]. In the case of random excitation, it is not possible to identify all of the first three modes by all OMA-methods. Furthermore, harmonic parts in the excitation make an exact identification of the modal parameters difficult. To overcome this discrepancy, the analysis must be performed with several identification methods and the results have to be compared and checked regarding their plausibility.



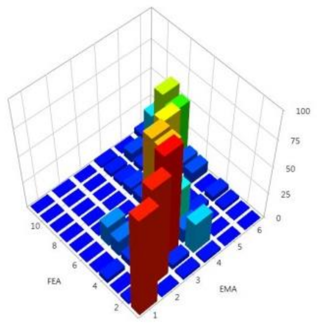


Figure 17 Comparison mode shapes identified by EMA and OMA using the MAC, left: OMA using EFDD, right: OMA using UPC Merged Data Sets

5 CONCLUSION AND OUTLOOK

When employing OMA instead of EMA to characterize the dynamic behaviour of machine tools, it will be possible to detect effects occurring during the process. Nevertheless, this approach is associated with some obstacles. It could be shown that a tool path in the working space could be determined in which the structural changes are small and so the dynamic behaviour could be assumed as time-invariant. By the variation of cutting parameters during a milling process a broadband excitation could be achieved. The analysis of the identification of the modal parameters showed, that investigating the same structure with the same boundary conditions yield to the same results considering EMA and OMA. Nevertheless, the kind of excitation as well as the applied OMA method have influence on the results.

The further objective is to figure out a methodology that allows to perform OMA on machine tools. So the time-invariance should also checkable during machining. Furthermore, the cutting force model must be improved to determine cutting parameters that extend the broadband excitation with constant amplitude. The influence of the excitation characteristic to the results has to be investigated, especially the excitation by the specifications of a cutting process.

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CONTACTS:

Dipl.-Ing. Jan Berthold
Dr.-Ing. Volker Wittstock
Chemnitz University of Technology
Institute for Machine Tools and Production Processes,
Reichenhainer Strasse 70, 09126 Chemnitz, Germany
+49-371-531-33938, jan.berthold@mb.tu-chemnitz.de
+49-371-531-37822, volker.wittstock@mb.tu-chemnitz.de
http://www.tu-chemnitz.de/mb/WerkzMasch

Dr.-Ing. Martin Kolouch, PhD
Prof. Dr.-Ing. Matthias Putz
Fraunhofer Institute for Machine Tools and Forming Technology IWU
Reichenhainer Strasse 88, 09126 Chemnitz, Germany
+49-371-5397-1362, Martin.Kolouch@iwu.fraunhofer.de
http://www.iwu.fraunhofer.de/