EFFECTS OF DIFFERENT EXCITATION MECHANISM IN MACHINE TOOLS WHEN PERFORMING OUTPUT-ONLY MODAL ANALYSIS

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Output-only Modal Analysis makes possible to investigate the dynamic behaviour of machine tools especially under process conditions. The differences between standstill and process state, which are important to consider, result from process damping, gyroscopic moments of the rotating spindle and changes in preloads and clearance in bearing and joints. Output-only Modal Analysis assumes a complete excitation of the structure by white noise characteristics. There are several mechanism in a machine tool under process conditions that could cause a vibration response. Beside the cutting process itself, the movement of the NC-axes as well as rotating fans of control system and auxiliary units can be excitation sources. This paper investigates to what extent several excitation mechanism in machine tools fulfil the analysis assumption and in which way the identified modal parameters depend on the boundary conditions of the excitation characteristics.

KEYWORDS

Output-only Modal Analysis, machine tool, dynamic behaviour, excitation mechanism, white noise

1 INTRODUCTION

The evolution in production technology from the classic machine tool to the cyber-physical production system, the use of digital twins, and the general focus on product virtualisation offer enormous opportunities for understanding, designing and optimising machines and processes. These methods and tools are even more dependent on measured values that describe the systems under the right boundary conditions and can be determined continuously and reliably. This paper deals with the determination of modal parameters for the description of machine tool structures. The focus is placed on the influence of different excitation mechanisms on the identification results when the system behaviour is determined only from response measurements with Output-only Modal Analysis.

2 STATE OF THE ART

The dynamic behaviour of machine tools is crucial for the resulting workpiece quality, the limits in manufacturing because of chatter, the commissioning of the drives, as well as wear of tool and machine tool components. For these reasons this topic receives increased attention [Altintas 2012].

Modal analysis is used to describe the dynamic behaviour of a machine tool by parameters like eigenfrequencies mode shapes and modal damping [Ewins 1986]. The general experimental approach for obtaining modal parameters consists of the excitation of the structure with a shaker or impulse hammer, the measurement of the response to this excitation, estimation of a transfer function from these measurements, and derivation of the modal parameters using a curve fitting technique. This procedure is also known as Experimental Modal Analysis.

Alternatively, the Output-only Modal Analysis can be performed for modal testing [Allen 2011, Batel 2002]. Only the responses to an acting excitation are measured and the modal parameters are determined. For this method, an important assumption is excitation by white noise. It is assumed that the structure is excited completely and uniformly and the measured responses thus contain only parts of the structure and are not weighted by the character of the excitation itself. The measurement concept originates from the investigation of large structures like buildings, planes, ships and wind turbines, where an artificial excitation is not suitable [Chauhan 2011, Magalhaes 2012]. With regard to the assumption of white noise, excitation by ground vibrations, water waves or wind corresponds very well to this requirement as load cases on this kind of structures.

Due to the fact, that only the response to an assumed but not known excitation is measured and analysed, many identification techniques have been developed and are applied for different use cases. A review of the most common methods is found in [Masjedian 2009]. A general subdivision could be made in identification techniques working in frequency domain and on the other hand techniques in the time domain. A common method in frequency domain is the Frequency Domain Decomposition (FDD). This method, which experiences constant further development, is characterised as robust and easy to use [Gade 2005]. The Curve-Fit Frequency Domain Decomposition (CFDD) makes possible to identify values of eigenfrequencies and damping more exactly, also in the case of presence of deterministic parts in the excitation, by executing the curve fitting directly in the frequency domain [Jacobsen 2008]. As representative of the time domain techniques, the Stochastic Subspace Identification (SSI) is mentioned. This method could be described as mathematically elegant, make possible the identification of coupled modes and offer, trough different weighting options, the reaction to challenging boundary conditions and disturbances in the measured responses [Rainieri 2014]. The technique uses mathematically projection of the raw time data and estimate a subspace description of the investigated system with stochastic inputs. Again, there are several subtypes regrading to the kind of weighting. Mentioned should be the SSI by weighting with Canonical Variate Analysis (SSI-CVA) that makes possible handling of unequally distributed excitation levels [Brincker 2015].

In machine tools, Output-only Modal Analysis is used, mostly to describe the dynamic behaviour exact at working point under process conditions and identify modal parameters that represent these boundary conditions exactly [Gupta 2020, Ahmadi 2014, Berthold 2019].

When performing Output-only Modal Analysis on machine tools, some aspects like the position dependent behaviour in the working space of the machine as well as adequate excitation have to be considered [Berthold 2017]. Especially the excitation regarding to the white noise assumption has to questioned and investigated in machine tools. Several mechanism could lead to an excitation of the structure.

The main sources of excitation of machine tools during cutting can be seen as the process with the recurring cuts itself, the traversing movement to ensure the necessary relative movements between cutting and feed movement and excitations by rotating components such as the main spindle but also fans and pumps of auxiliary units.

Due to their harmonic character, these mechanisms are in strong contrast to the assumption of an excitation with the character of white noise.

Nevertheless, ways of stimulating the machine in line with assumptions are generated, for example, in modifying the cutting process, but also in influencing the axis movements to generate an excitation with stochastic characteristic. The cutting process can be modified by using special prepared workpieces [Mao 2016, Cai 2015], special cutters with unequal tooth pitch angle or modifying technology parameters like spindle speed during cutting [Berthold 2016]. The aim is always to modify the chip thickness to create a stochastic character.

The excitation of the machine tool by axis movements results from mainly two effects. On the one hand, from the inertia forces of moved components during acceleration and deceleration on the other hand, in the case of ball screw drives, the collision of the balls in the ball screw [Li 2019]. Again, the aim is to modify the process motion of the species to influence the time course in order to generate a broadband excitation as far as possible [Li 2013].

Another way to excite the machine with white noise characteristic arises from the control system of the NC-axis of the machine tool. These systems mostly provide the possibility the switch on Pseudo Random Binary Sequence (PRBS) onto current or moment timelines to obtain transfer functions for system identification [Isermann 2011]. This opportunity is used as suitable excitation input in the state of commissioning the controller of the NC drives to identify transfer functions in order to tune the parameters of the control system [Schöberlein 2020].

The presented possibilities for the excitation of machine tools are based on different operating principles and can be applied in different operational conditions (cutting, traverse motion, commissioning). Since different boundary conditions apply to some of these different operational conditions, the modal parameters determined could depend on these boundary conditions.

3 MOTIVATION, RESEARCH QUESTIONS AND PROCEED

There are partly different excitation sources in machine tools that partly are controllable and thereby have characteristics of white noise and are suitable to excite the machine for proper analysis. The research question is, to what extent do the identified modal parameters dependent on these excitation methods? Which influence do excitations properties (source, time course, location) have?

Therefore, a machine tool is excited by several excitation sources and mechanism at various locations and the modal parameters are identified by Output-only Modal Analysis from the measured responses. Exaction will be generated in different cases by:

- Relative and/or absolute excitation by electromagnetical shakers at Tool Center Point (TCP) and/or machine bed
- Movement of NC-Axis with random changing feed velocity and machine positions
- Movement of NC-Axis with additionally PRBS exaction of motor current
- Modified cutting process with random changing spindle speed

Whereby the excitation by shaker is used to get reference values with a well known method from Experimental Modal Analysis. The results are discussed by comparing the differences of eigenfrequencies and modal damping as well as the mode shapes by Modal Assurance Criterion (MAC) [Allemang 2003].

4 REALIZATION OF DIFFERENT EXCITIONS

4.1 Investigated machine and measurement procedure

The investigations are carried out on a three-axis machining centre, controlled by a SINUMERIK with SINAMICS drive components. In Figure 1 a CAD model of the machine is shown. Important structural units could be seen in the machine bed, machine table, a base frame under the X-slide, the X-slide itself, the Y-slide and the Z-slide including the main spindle. The possible positions inside the working space are marked with a blue cuboid. This cuboid depicts distances in X_{NC}, Y_{NC} and Z_{NC} direction, they are about 800 mm, 400 mm and 400 mm in length.

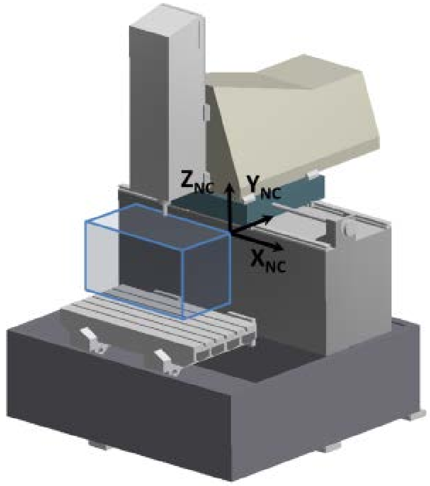


Figure 1 CAD model of the three-axis machining centre

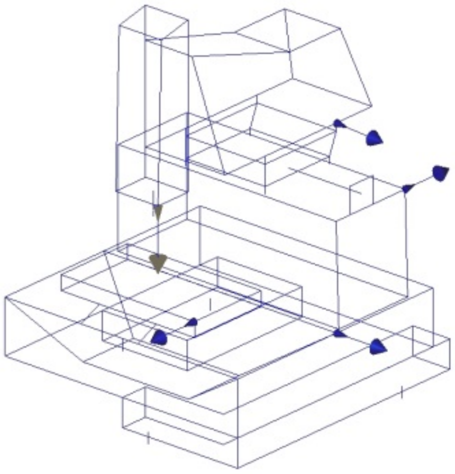


Figure 2 Wire frame model as discretization of the machine tool, (reference sensors are marked with arrows)

For the Output-only Modal Analysis the structure has to be idealized and depict by a wire frame model. Figure 2 depicts this wire frame model.

Acceleration sensors, mounted at node points, depict in the wire frame model, measure the responses to several generated excitations. The measurement procedure is divided in sequences, the necessary reference sensors are depicted in Figure 2 by arrows. There are five reference sensors, which remain at the same positions at all sequences, located at the most important points of the substructures of the machine tool.

4.2 *Excitation by electromagnetical shaker*

The machine tool is excited by electromagnetical shakers relative and/or absolute in three measurement setups. In the first setup, a shaker is mounted between machine table and a dummy tool in the spindle for relative excitation, see Figure 3. This arrangement could be seen as very similar to process excitation.

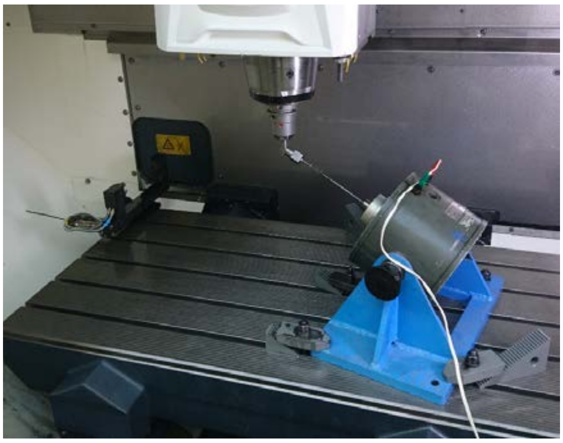


Figure 3 Electromagnetical shaker mounted for relative excitation between machine table and spindle

The second setup uses also an electromagnetical shaker but in this way coupled to machine bed and mounted at the hall floor, resulting in absolute excitation (see Figure 4).

The third measurement setup results in the combination in of the first and second setup, which means a simultaneously excitation at two points.

Figure 4 Electromagnetigal shaker mounted at hall floor and coupled to machine bed for absolute excitation

The excitation signal has white noise characteristic provided by a signal-generator, which fulfils the excitation assumption for Output-only Modal Analysis very well. Measurement time was 100 s with 50 averages, which results in a time sample of 2 s.

In all setups the acting forces, exciting the structure, are measured by force sensors. The timelines are shown for overview over a range of 10 s as well as detailed section and the resulting spectrum of the measurement time of one sequence are presented in Figure 5. It could be seen, that the amplitudes in the timeline have random character. The force level of both shakers is in the same range. In the spectrum, the excitation is constant in a wide range up to 300 Hz, above this range the shaker between machine bed and TCP shows relevant frequencies, which result from the mounting and the dynamic behaviour of the shaker itself.

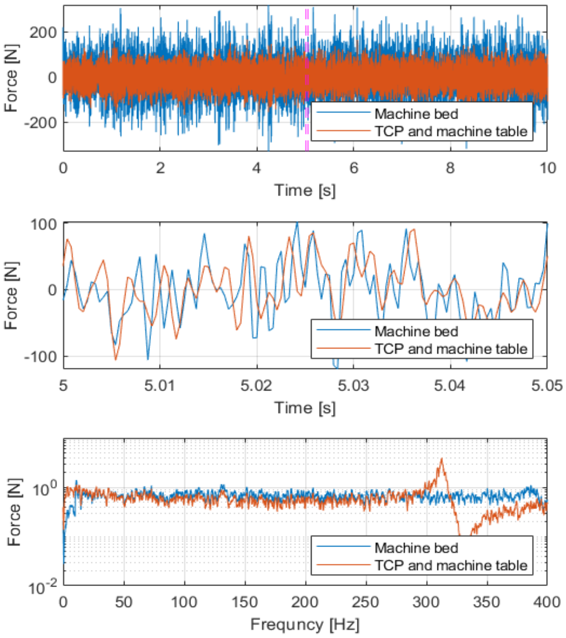


Figure 5 Measured Forces during excitation by electromagentical shakers. Setup 1: Shaker between TCP and machine bed active. Setup 2: Shaker at machine bed active. Setup 3: Both Shakers active simultaneously.

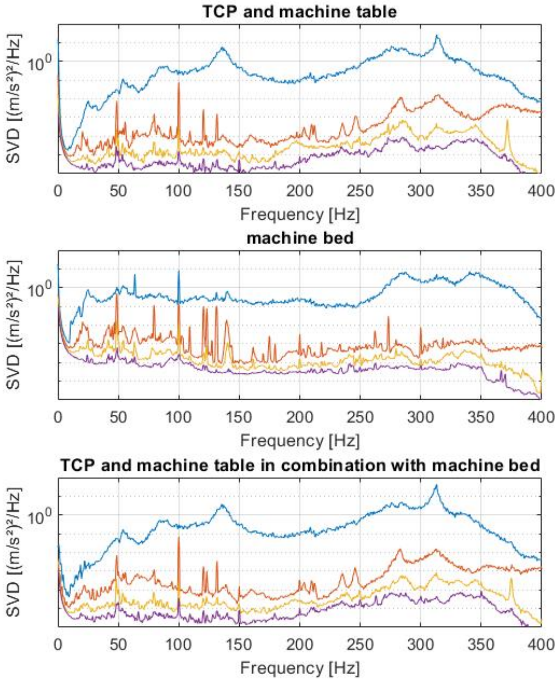


Figure 6 SVD plots of measured responses by shaker excitation in several locations (first to fourth singular value line in descending order). Setup 1: Shaker between TCP and machine bed active. Setup 2: Shaker at machine bed active. Setup 3: Both Shakers active simultanously

In Figure 6 the responses presented as Singular Value Decomposition (SVD) plots are shown. The first setup, excitation between TCP and machine table leads to responses, which are suitable for analysis, no harmonic parts in the first singular value curve and clearly distinct peaks that probably show eigenfrequencies. It is interesting that the setup 2, excitation only at machine bed, points to frequencies in the range from 15 to 25 Hz as well as in the range from 340 to 350 Hz, which are not to that extent characteristic in setup 1. On the other hand, relevant frequencies from 70 to 250 Hz are not seen in setup 2 like in setup 1, also, there are more harmonics in setup 2. The combination of setup 1 and setup 2 leads to setup 3, with excitation between TCP and machine table as well as machine bed. In this case mostly the curve of setup 1 is found again.

4.3 Excitation by movement (random feed and postions)

Another way to excite the machine arises from the movement of components by the NC-axes. To give these movements a stochastic character, the feed rate as well as the NC position to be achieved are varied with random numbers regarding the technological limits. Starting from a reference point (corresponds to TCP position during the shaker test) the axis are moved sequentially in the order X_{NC}, Y_{NC} and Z_{NC}. The feed velocity varies in the range from 1000 to 5000 mm/min, the possible motion distance varies in the range -4 mm to +4 mm from the reference point. The variation of feed rate and motion distance is independent of each other the values vary randomly. In this way, 100 different positions are moved to one after the other. A small section of the important parameters of the NC-data is shown in Table 1.

An illustration of the successive points in the working space of the machine tool resulting from this random data is possible through the Figure 7.

The resulting responses to this excitation are shown as SVD plot in Figure 8. On the one hand, the results are very noisy, but on the other hand, the level of the singular values in the range up to approx. 115 Hz shows an adequate excitation. Possible eigenfrequencies can be detected in the lower frequency range, but an exact identification probably could be difficult due to the noise components. Likewise, the range above 115 Hz is not characterised by clear, well excited peaks, but from the knowledge of the shaker excitation, relevant eigenfrequencies should also occur in this range. The response suggests that there was insufficient excitation in this frequency range.

Table 1 NC Data for excitation with feed motion with variating positions and rate

Set	Coordi-nate	Value [mm]	Feed [mm/min]
N10	X	0.689	3671
N20	Y	-1.903	4378
N30	Z	-3.644	2378
N40	X	2.039	4122
N50	Y	-2.058	3702
N60	Z	-0.461	1026
N70	X	0.689	3671

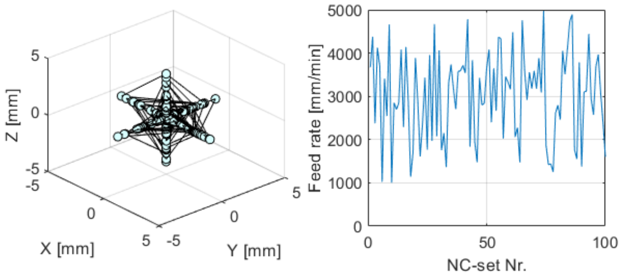


Figure 7 Random positions and feed rates in the working space

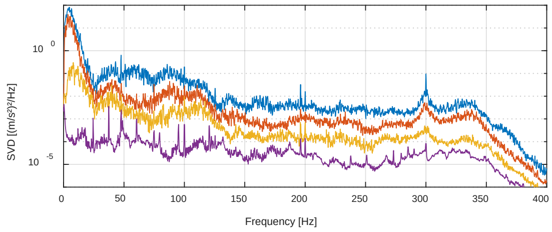


Figure 8 SVD plot of measured responses by feed motion excitation with variating feed rates and NC-positons (first to fourth singular value line in descending order).

4.4 Excitation by movement with PRBS

The PRBS excitation is switched onto the current setpoint of the motor by means of the function generator of the control system during a travel movement. The axes move one after the other in X_{NC}, Y_{NC} and Z_{NC} at a feed rate of 1000 mm/min for a travel distance of 10 mm each.

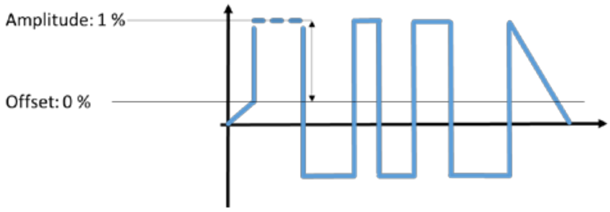


Figure 9 Parameters of PRBS excitation in Simotion (simplified)

The parameters of the generated PRBS are shown in Figure 9, the defined bandwidth for frequencies of interest is set to 500 Hz. The results regarding the actual motor current is shown in Figure 10. The first part of the timeline shows the actual current for the programmed movement of the several NC-axes, the second part shows the current if additionally the PRBS is switched on. The diagram in the middle of the figure depicts the detailed curve of the motor current. Since the motor torque is moment-forming, the course of the excitation can be seen as equivalent to the inertial force acting on the respective axis. This allows to draw conclusions from the course of the motor current to the excitation of the machine. The curve of the whole part with PRBS switched on is transferred in to frequency range and shown in the bottom diagram. There are no harmonic parts left. The excitation itself has a constant level.

The measured responses regarding to the excitation by PRBS are shown in Figure 11. Compared with shaker excitation, the course of the curves are constant regarding the response level. From 50 Hz on to higher frequency ranges, peaks are clearly identifiable, no harmonics remaining (regarding first singular value) and no disturbance is recognizable, the curve is smooth. On the other hand, at 40 Hz there is a strong excitation influence. In addition, the simultaneously traverse motion leads to higher response in the low frequency range up to 20 Hz.

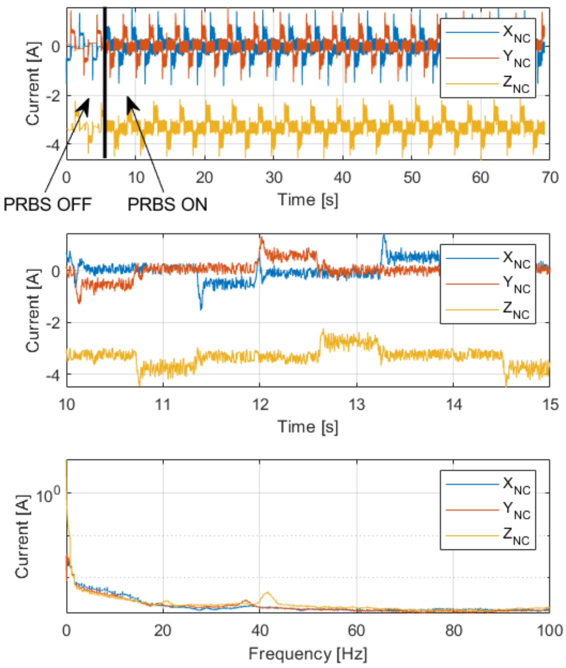


Figure 10 Motor current of NC-axis with PRBS switched on

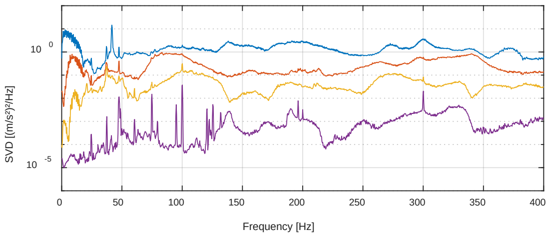


Figure 11 SVD plot of measured responses by PRBS excitation (first to fourth singular value line in descending order).

4.5 Excitation by cutting process

In order to adequately excite the machine through the cutting process, the technological parameters in the process must be changed in order to achieve broadband excitation and avoid harmonics. This is ensured by controlling the spindle speed in the process with random speed values in the range from 600 to 1400 min^{-1}. The spindle speed is changed every millimeter of the traverse path along the workpiece, during a constant feed rate of 300 mm/min. The workpiece itself has a length of 300 mm. A detailed explanation of the procedure is found in [Berthold 2018]. In order to be able to analyse the acting forces, the forces on the workpiece are measured with a force measuring platform Kistler 9255C in the modified process (see Figure 12).

In Figure 13 the measured forces are shown. There are three force curves in every diagram, the indices corresponds to the machine coordinate systems. The curves depicts an excerpt of ten seconds for an overview and a detailed view of 0.2 seconds. The random character resulting from the randomly changed spindle speed is not immediately visible in the time lines. It is rather possible to recognise the occurrence of the tooth engagements.

In the resulting responses, depicted in Figure 14, it can be seen that in the lower frequency range up to 25 Hz a very noisy and unclear response is measured. Above this range the SVD lines are very clear and show distinct peaks. It is interesting that the peak at 250 Hz, which is prominent in the measured cutting force, does not show up in the responses of the machine structure.

Figure 12 Workpiece mounted on force measurement platform, for analysing of process excitation with modified cutting parameters

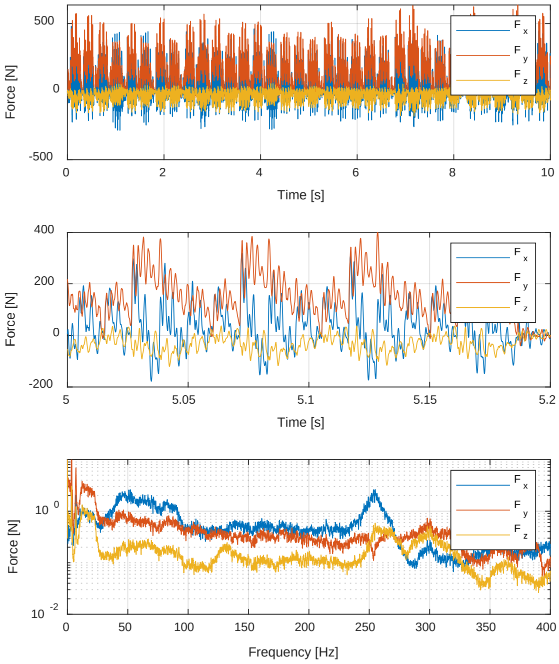


Figure 13 **Measured forces by excitation with modified cutting process**

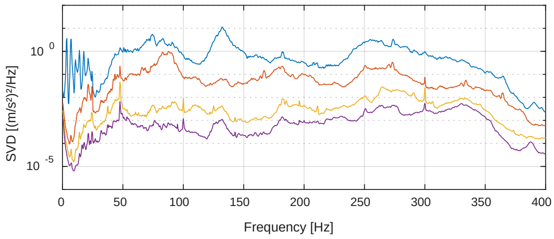


Figure 14 SVD plot of measured responses by modified cutting process excitation (first to fourth singular value line in descending order).

5 IDENTIFICATION OF MODAL PARAMETERS

The several excitation forms all result in responses suitable for analysis and identification of modal parameters. To discuss their influence onto the identification process they are compared. In Figure 15 the SVD plots of all presented and discussed excitation principles are shown overlaid. For better understanding, only the first singular value is depict. Although the structure is the same and is investigated in the same position with the same analysis methodology, the measured responses vary greatly depending on the different excitation method with the respective valid boundary conditions.

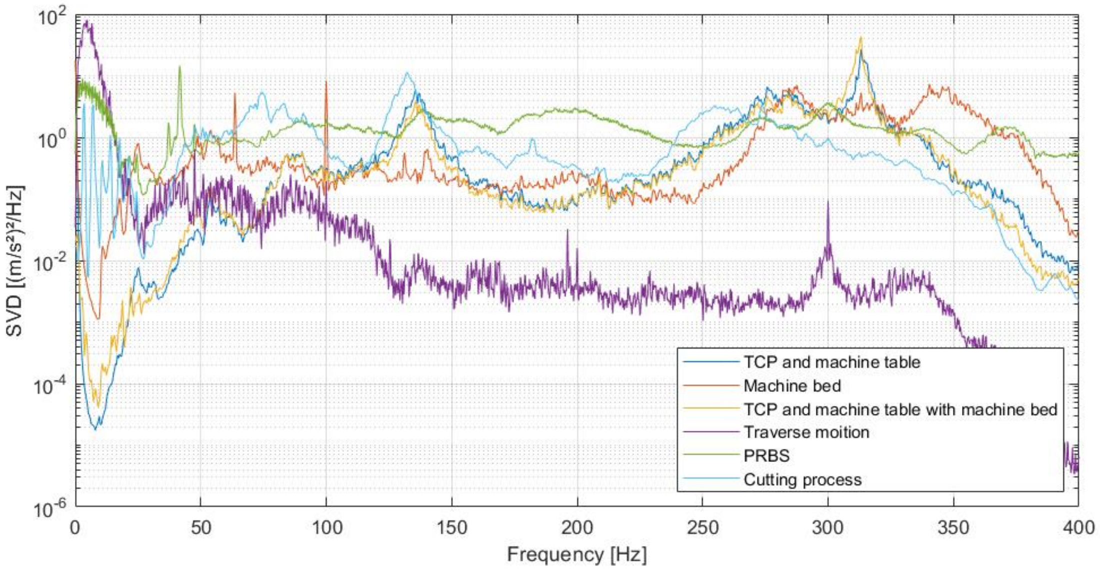


Figure 15 SVD plot of responses resulting from different exciation principles

Table 2 Modal Parameters of several excitation forms

Shaker									Traverse motion			PRBS			Modifed Cutting Process		
Setup 1			Setup 2			Setup 3											
#	EF [Hz]	DMP [%]	#	EF [Hz]	DMP [%]	#	EF [Hz]	DMP [%]	#	EF [Hz]	DMP [%]	#	EF [Hz]	DMP [%]	#	EF [Hz]	DMP [%]
									1	5,8	32,1						
1	23,4	27,1	1	24,3	16,5	1	24,9	25,2									
												1	40,0	27,0			
2	50,5	1,3	2	48,1	7,9	2	47,9	5,8	2	47,0	2,5				1	47,3	7,1
3	55,9	12,1	3	53,5	11,5	3	53,8	11,2									
						4	62,5	17,8									
4	77,2	2,6	4	76,9	10,0	5	76,7	6,4				2	77,0	17,7	2	72,4	3,9
						6	85,4	6,2							3	83,5	9,8
															4	89,2	6,2
						7	99,7	0,6				3	104,0	21,0			
									3	119,9	5,9						
			5	130,9	2,9												
5	135,0	5,1	6	139,9	0,9	8	135,8	3,2	4	136,0	4,5	4	136,6	4,2	5	132,8	2,6
															6	182,4	3,2
						9	157,9	1,4									
6	197,2	3,8	7	196,7	6,8	10	203,1	2,1	5	197,2	1,1	5	199,2	4,4			
7	207,9	3,5				11	210,7	1,0							7	210,5	3,3
8	236,4	2,4				12	234,8	0,9	6	233,4	2,5						
9	242,9	4,1				13	247,1	1,4							8	250,1	2,5
10	263,1	1,1				14	257,5	3,3				6	254,9	5,8	9	254,3	2,1
															10	262,0	2,2
11	274,6	1,5	8	275,6	2,6	15	275,4	2,3	7	270,9	3,2	7	271,2	3,3	11	273,8	1,5
12	282,8	1,6	9	287,9	3,0	16	284,1	0,9									
13	286,8	3,2															
									8	298,0	1,3	8	298,5	1,9			
14	301,1	2,0				17	305,4	2,4	9	299,8	0,6				12	301,4	2,2
15	314,9	0,8	10	311,7	2,5	18	312,7	0,6							13	315,1	2,4
16	318,4	1,2	11	322,8	1,7	19	320,0	2,0				9	322,4	4,1			
			12	331,3	4,1				10	327,4	2,1						
17	336,0	1,2	13	338,8	1,4	20	336,4	2,1	11	338,7	2,3	10	339,3	3,4	14	332,7	2,7
			14	346,8	2,0	21	345,9	3,2									
															15	351,3	2,7
18	358,7	2,3	15	360,5	2,1	22	363,1	2,4	12	366,3	2,4				16	368,0	2,0
			16	375,5	2,0	23	376,0	0,9				11	373,7	2,3			
			17	388,5	1,5												

What is very interesting is that setup 2 (only one shaker on the machine bed) shows a different curve, especially the lower frequencies show a better response and a higher dynamic range. Also at 300 Hz, frequencies emerge that are not visible with the other excitation setups. In the combination of both excitations by the two shakers, however, this improved dynamic range is no longer visible. Possibly the same excitation level of both shakers in combination with each other is too low with regard to the excitation at the machine bed to have a significant influence.

The traverse motion with randomly character of feed rate and NC-positon results in a low response level, is distorted and contents harmonic parts. If the shaker excitations are considered, there are hardly any differences found between setup 1 (one shaker relative on the TCP) and setup 3 (one shaker relative on the TCP and another on the machine bed).

The excitation by PRBS shows an adequate response level in comparison to the other excitations forms, on the other it is important to recognize, that the dynamic range is low, also the peaks are different compared to shaker excitation.

Regarding to the excitation by cutting process with modified technology parameters it is seen, that dynamic range is higher than in PRBS excitation, also the peaks, compared with shaker and also PRBS excitation, occur a little shifted to smaller frequency values.

The modal parameters are identified with time domain method by SSI-CVA. Each type of excitation enables the identification of meaningful modal parameters. There are common characteristics between the different types of excitation in the form that certain eigenfrequencies appear with each type of excitation, but there are also very great differences in the sense that certain eigenfrequencies can only be assigned to certain types of excitation.

Table 2 provides an overview of the identified natural frequencies and the corresponding modal damping. For better clarity, the considered equal frequencies are placed on the same line of the table for each excitation.

Excitation with two shakers leads to the most eigenfrequencies, but it is interesting to note that the combination of both types of excitation does not result in all eigenfrequencies of the two individual types of excitations, if they are considered on their own. With regard to the damping values, these seem to be overestimated for the first modes; no such large values (over 10 percent) are expected. This conclusion is derived from the damping values determined in an experimental modal analysis with the same setup (shaker excitation between TCP and machine table), see [Berthold 2019]. Traverse motion yields to 12 modes, the first at 5.8 Hz suggesting an operation deflection shape rather than a structure mode. The same applies to the excitation with PRBS, here too a mode results at 40 Hz, which however is more likely to originate from a process-bending excitation.

Compared to the shaker excitation, the process excitation has the second largest number (16) of identified modes. Also, there result many frequency pairs with the shaker excitation.

As mentioned before, the order in the table is based on the value of similar eigenfrequencies. However, this order does not allow any conclusions to be drawn about the correspondence of the modes. For this reason, the modes are compared by MAC.

The results of this comparison by MAC are shown in Figure 16. Because the largest number of modes is found with two shaker excitation, this is taken as a reference.

The excitation at the machine bed compared to the excitation by two shakers shows only few similarities. Especially the modes at about 54, 135 and 284 Hz stand out in a good agreement. The comparison between shaker excitation at the TCP compared with excitation by two shakers is different. There are many similarities here. Differences occur mainly in the lower frequency range. The reason for this could be the additional excitation of the machine bed (in the case of 2 shakers), which is omitted with the exclusive excitation at the TCP. Apparently, this has a great influence on the modes that occur. Reflecting back on the assumptions of the Output-only Modal Analysis, that a comprehensive excitation of the structure for the identification of plausible modal parameters is pruposeful. The excitation by 2 shakers is accordingly taken as a basis for the comparisons with the traverse motion, PRBS and the modified cutting process.

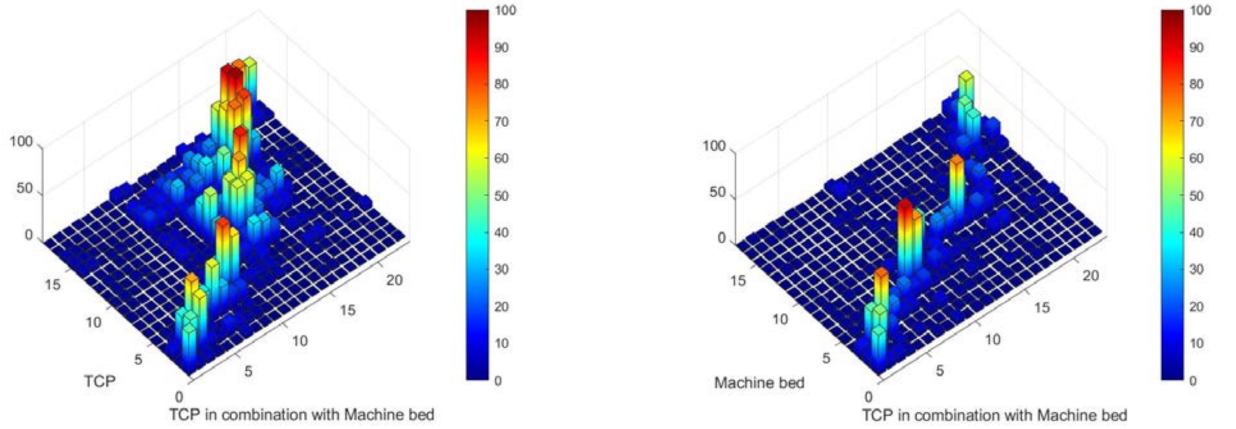
When comparing the Traverse Motion with the 2-shaker excitation, there are only a few similarities, the eigenfrequencies in the range of 135 and 270 Hz stand out. The same applies to the PRBS excitation. In the case of excitation by the modified cutting process, these frequency ranges are also characterised by high MAC values; furthermore, in comparison to the traverse motion and PRBS, there are many smaller similarities along all eigenfrequencies, with MAC values in the range of 30-60 %. These do not indicate the same but similar characteristics, which is unique for cutting process excitation.

If the excitation by PRBS is compared with the excitation by the modified cutting process (the traverse motion is not compared here due to the more disadvantageous SVD diagram), the fewest similarities of all comparisons so far are found. This is very interesting, because these two types of excitation correspond most closely to an excitation during operation of the machine, and both types of excitation would also be conceivable as a description of the machine in the form of a "modal fingerprint" for the continuous determination of the modal parameters. The excitation by the shakers is more like a pseudo-modal analysis in terms of the way it is carried out. As this set-up actually originates from the Experimental Modal Analysis context and is associated with a higher measurement effort and therefore the benefit in terms of time saved from a measurement under operating conditions with the Output-only Modal Analysis cannot be used in a meaningful way. In addition, the effect of mapping operating conditions would still be lost.

As a conclusion for the PRBS and Cutting Process suggestions, which can be used under operating conditions, it can be said that the results with regard to the modes do not lead to the same results. The differences are due to the different mechanisms that are at work during excitation. What is the same is that the NC axes are in motion with both types of excitation. The excitation is caused by the inertial forces of moving components, just as the excitation is caused by the rolling motion of roller-bearing mounted guideways and ball screws. There is also an influence from rotating components of auxiliary units and fans as well as the control system.

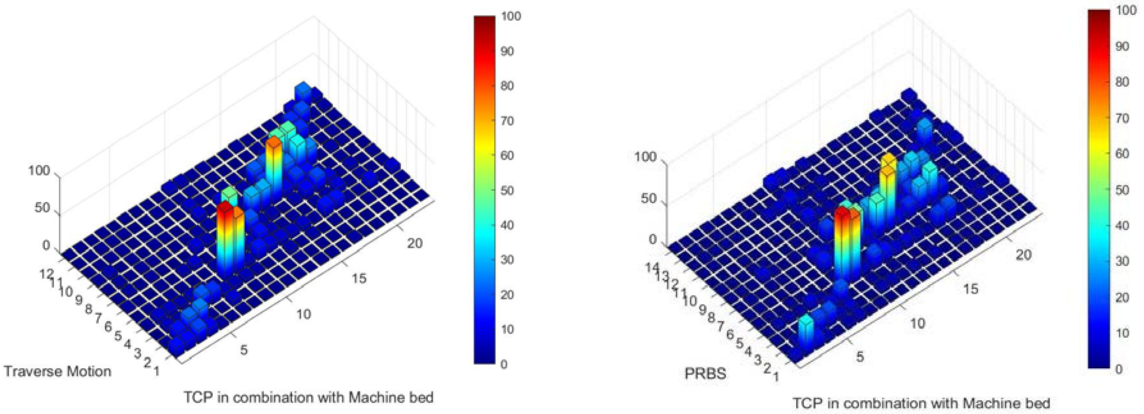
In the case of excitation by the cutting process, the rotating main spindle, the process damping by the cutting process and also the tooth engagement and disengagement impacts are added. In addition, the time invariance in the workspace should be taken into account. Although the investigations of the different types of excitation are carried out in almost the same machine position, it should be noted that, with the exception of the excitation by the shakers, there is always a travel path, the identified modal parameters are then the result of an averaging along the travel positions.

Various kinds of excitation yield to different modal parameters. The results, identified by Output-only Modal Analysis, cannot be transferred into each other.



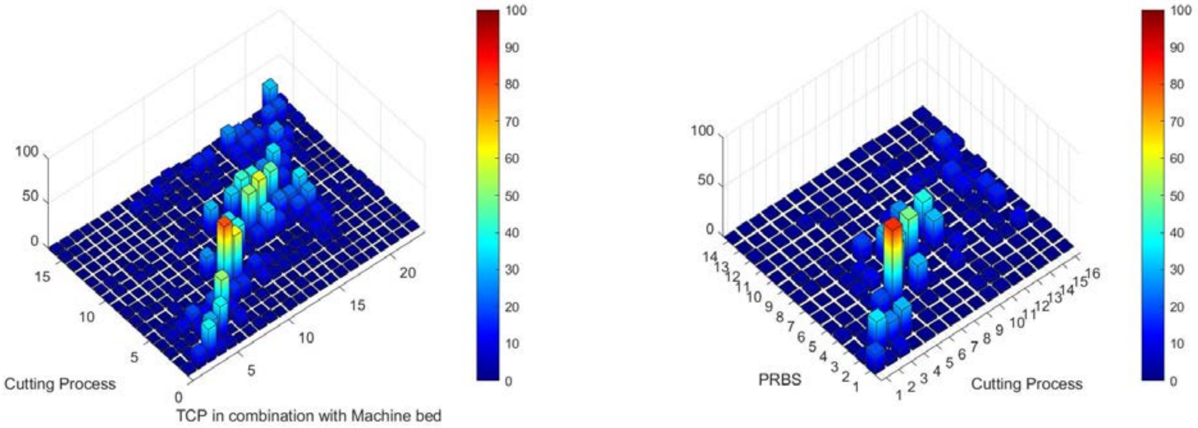
a. TCP versus TCP in combination with Machine Bed

b. Machine bed versus TCP in combination with Machine Bed



c. Traverse Motion versus TCP in combination with Machine Bed

d. PRBS versus TCP in combination with Machine Bed



e. Cutting Process versus TCP in combination with Machine Bed

f. PRBS versus Cutting Process

Figure 16 Comparison of modal parameters resulting from different excitations forms by MAC Diagrams

6 CONCLUSIONS

The research question postured at the beginning, can therefore be answered for the excitation presented and the modal parameters identified. The form of the excitation has a significant influence on the modal parameters, which are found with Output-only Modal Analysis. The eigenfrequencies show high similarities, but the resulting modes differ greatly. This should be taken into account in future analyses.

For a meaningful use of the method of Output-only Modal Analysis, the excitation by means of PRBS and modified cutting process would be the most suitable, because these types of excitation could be realised comparatively quickly in the operation of the machine and enable the determination of modal parameters with plausible boundary conditions in each case.

However, the modal parameters of different excitations are not readily exchangeable and, consequently, the conclusions based on these results are not either. This is particularly relevant for causal conclusions, weak point analyses and design improvements. The subsequent purpose for using the modal parameters should therefore be taken into account when choosing the operating conditions or when designing the excitation.

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