BROADBAND EXCITATION OF MACHINE TOOLS BY CUTTING FORCES FOR PERFORMING OPERATIONAL MODAL ANALYSIS

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The operational modal analysis (OMA) can be employed in the field of machine tools to measure the dynamic behaviour under operation conditions to observe and assess effects that only occurring during process. However, OMA requires an broadband excitation with preferably white noise characteristic. When assuming that the machining process is the main excitation source in machine tools, this requirement could not be fulfilled because of the great number of harmonic components that result from spindle speed and number of teeth.

In this paper an approach is presented to generate a broadband excitation during a milling process by variating the cutting parameters, for e.g. spindle speed and immersion. Investigations are performed simulative as well as experimental and restrictions of the machine tool and the process are considered. It is shown that an broadband excitation by milling is possible only by varying cutting parameters without using a special designed work-piece.

KEYWORDS

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

1 INTRODUCTION

Investigation of the dynamic behaviour of complex structures (e.g. a machine tool) often employs modal analysis for estimation of the modal parameters. Modal parameters are represented by eigenfrequencies, modal damping values and mode shape vectors. Experimental modal analysis (EMA) consists in the estimation of the modal parameters based on experimental data at which the structure is artificially excited (e.g. by a shaker or an impulse hammer) and the excitation as well as response of the structure are measured. As result the modal parameters could be identified by mathematical estimation from frequency response functions (FRF) [Ewins 1986]. This method is state of the art and the preferred one for machine tools.

However, there are some restrictions for any experimental modal analysis regarding the investigated structure like linearity, causality, stability and time-invariance of its behaviour. Due to nonlinearities (e.g. the static stiffness of guiding ways), non-causality (e.g. not measured additional excitation by the active position control of servo axis) and time-variance (e.g. changing static stiffness and mass in dependence on the position as well as a gyroscopic moment resulting from high speed spindle), some of these restrictions are very difficult to be satisfied when investigating a machine tool [Zagbhani 2009, Özsahin 2014]. The restrictions cause that the modal parameters estimated by EMA might be afflicted with uncertainty and they are valid only for a particular experimental setup and conditions.

Alternatively to EMA, the operational modal analysis (OMA) can be carried out to estimate the modal parameters. OMA only requires measurements of output (response) signals of the investigated structure. Generally, this approach employs the surrounding of the investigated structure for its excitation. The state of the art includes examples for buildings, bridges and wind turbines excited by ambient conditions for e.g. the wind or water waves [Cunha 2006, Tcherniak 2011]. In machine tools, the most intensively excitation is supplied by the manufacturing process. This fact predestines the manufacturing process for excitation of a machine tool when performing OMA. The obtained results would be valid exactly for the process in contrast to EMA, in which the experimental setup and conditions determine the results. This includes the linearization of the nonlinear behaviour for particular process conditions, e.g. a relevant preload of bearings by the static part of the cutting force and/or changing temperature [Li 2013, Mao 2014]. In particular, the experimental effort could be significantly reduced when investigating large machining centres by OMA due to the missing need for an artificially excitation. Nevertheless, OMA can intensify the issue of time-invariance, if the manufacturing process is designed in an inappropriate manner [Putz 2016].

When performing OMA, an excitation of the investigated structure with constant broadband spectrum is assumed [Batel 2002, Jacobsen 2008]. In this case all modes of the structure in the frequency range of interest are excited equally and an identification of the modal parameters is clearly possible [Raineri 2014]. Such excitation corresponds for example to a stochastically random signal, e.g. white noise. In case of buildings and bridges, the environmental excitation by wind or water waves mostly meets such assumptions.

However, a manufacturing process, the focus of this paper lays on milling, causes an excitation of a machine tool with frequency spectrum dominated by many harmonic spectral lines. Therefore, this paper aims at an appropriate modification of the milling process to generate an excitation with a constant broadband spectrum without using a special designed workpiece [Öszsahin 2011, Cai 2015]. The presented approach consists in varying cutting parameters like spindle speed and immersion.

In order to set an appropriate variation of the cutting parameters, its influence on the broadband spectrum is theoretically investigated in simulations by a cutting force model. The investigation considers some restrictions resulting from the dynamical limitation of a real machine tool (e.g. the finite dynamics of the spindle drive). Furthermore, milling experiments are performed in that the excitation of the machine tool, represented by cutting forces, is measured. The generated force spectra's are evaluated in terms of their usage for performing OMA on machine tools during the process.

2 SIMULATIVE INVESTIGATION OF BROADBAND EXCITATION BY CUTTING FORCE

2.1 Cutting force model

In order to investigate the influence of the cutting parameters on the frequency spectrum of the excitation signal during a milling process, cutting forces are modelled in the time domain. The model considers a real milling process realized in experiments presented in the following section.It is a matter of a face milling with the immersion of two-thirds of the tool diameter D_{Tool}, the feed rate per tooth c, the depth of cut a_p and the entering angle κ = 90°, as shown in Fig. 1. The chip thickness h_i at the i-th tooth of the tool is a function of the corresponding immersion angle φ_i and the feed per tooth c

$$h_i(t) = c\sin(\varphi_i(t)) \tag{1}$$

with

$$\varphi_i(t) = \begin{cases} \varphi_i(t) & \text{if } \varphi_i(t) \in \langle \varphi_{st}\ \varphi_{ex} \rangle \\ 0 & \text{otherwise} \end{cases} \quad \text{for } i = 1,(1),\ldots,z_{Tool} \tag{2}$$

where φ_{st} and φ_{ex} is the immersion angel at the entry and the exit of a tooth, respectively. z_{Tool} represents the number of teeth. The tangential, radial and axial cutting forces on the i-th tooth of the tool, denoted by $F_{t,i}$, $F_{r,i}$ and $F_{a,i}$, respectively, are expressed in a coordinate system located at the i-th tooth of the tool in accordance with the Kienzle's force model [Kienzle 1951] as follows

$$\begin{aligned} F_{t,i}(t) &= K_t a_p h_j(t) \\ F_{r,i}(t) &= K_r F_{t,i}(t) \\ F_{a,i}(t) &= K_a F_{t,i}(t) \end{aligned} \tag{3}$$

wherein K_t, K_r and K_a are the specific cutting force coefficients in the tangential, radial and axial direction, respectively. Generally, those coefficients are functions of the cutting speed, the rake and relief angle and the tool wear as well. In order to compute the exciting forces in the machine coordinate system, the cutting forces are transformed by a transformation matrix $\boldsymbol{T}$ [Kienzle 1951].

$$\begin{aligned} \boldsymbol{F}_i(t) &= \begin{Bmatrix} F_{x,i}(t) \\ F_{y,i}(t) \\ F_{z,i}(t) \end{Bmatrix} = \boldsymbol{T}(t) \begin{Bmatrix} F_{t,i}(t) \\ F_{r,i}(t) \\ F_{a,i}(t) \end{Bmatrix} \\ &= \begin{bmatrix} -\cos(\varphi_i(t)) & -\sin(\varphi_i(t)) & 0 \\ \sin(\varphi_i(t)) & -\cos(\varphi_i(t)) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} F_{t,i}(t) \\ F_{r,i}(t) \\ F_{a,i}(t) \end{Bmatrix} \end{aligned} \tag{4}$$

After the summation of the cutting forces over all teeth, the resulting cutting forces in machine tool coordinate system are calculated by:

$$\begin{aligned} F_x(t) &= \sum_{i=1}^{z_{Tool}} F_{x,i}(t); \\ F_y(t) &= \sum_{i=1}^{z_{Tool}} F_{y,i}(t); \\ F_z(t) &= \sum_{i=1}^{z_{Tool}} F_{z,i}(t) \end{aligned} \tag{5}$$

Considering the machine tool as a dynamic system excited by the cutting forces, the chip thickness h_i also depends on the relative displacement between the tool and the work-piece Δ, [Altintas 2012], so Eq. (1) turns into

$$\begin{aligned} h_i(t) &= c\sin(\varphi_i(t)) + \Delta \\ &= (c + u_x(t) - u_x(t - T_d))\sin(\varphi_i(t)) \\ &\quad + (u_y(t) - u_y(t - T_d))\cos(\varphi_i(t)) \end{aligned} \tag{6}$$

$u_x(t)$ and $u_y(t)$ being the current relative displacements between the tool and the work-piece in the machine coordinate system. $u_x(t-T_d)$ and $u_y(t-T_d)$ represent the relative displacements of previous teeth at the same position but at time delayed by T_d. The calculation of the dynamic relative displacements from Eq. (6) implies a use of a dynamic model of the machine tool.

In this paper, a model based on measured data is preferred. For this purpose, a matrix of frequency response functions (FRF) between the tool and the work-piece $\boldsymbol{G_{rel}}$ is experimentally estimated. In such case, the estimation yields absolute FRF, from which the matrix $\boldsymbol{G_{rel}}$ is calculated by the following expression [Kolouch 2012]

$$\begin{aligned} \boldsymbol{G_{rel}}(j\omega) &= \begin{bmatrix} G_{rel,xx} & G_{rel,xy} \\ G_{rel,yx} & G_{rel,yy} \end{bmatrix}(j\omega) \\ &= (\boldsymbol{G_{11}} - \boldsymbol{G_{12}} - \boldsymbol{G_{21}} + \boldsymbol{G_{22}})(j\omega) \end{aligned} \tag{7}$$

In this expression, indexes 1 and 2 denote a measurement point on the tool and on the work-piece, respectively. The curve-fitting of the measured data is performed to estimate the modal parameters.

Furthermore, the structural matrices of mass, viscous damping and stiffness, denoted by **M**, **C**, **K**, respectively, are identified from the estimated modal parameters as suggested in [Richardson 1977].

The desired vector of relative dynamic displacements $\boldsymbol{u}(t)$ from Eq.(6) represents the solution of the following equation of motion

$$\mathbf{M}\ddot{\boldsymbol{u}}(t_s) + \boldsymbol{C}\dot{\boldsymbol{u}}(t_s) + \boldsymbol{K}\boldsymbol{u}(t_s) = \boldsymbol{F}(t_s) \tag{8}$$

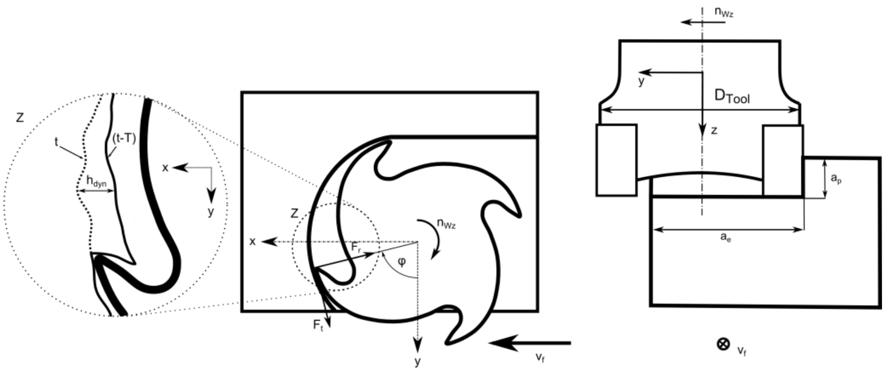


Figure 1. Investigated face milling process

Assuming known initial conditions, the numerical solution of this non-linear equation system can be generally calculated for a fixed time step by using the Newmark algorithm combined with the Newton-Raphson-method, also used in [Li 1992]. For this purpose, Eq. (3-6) are substituted into equation (8). The dynamic cutting forces in the machine tool coordinate system are obtained after substituting the computed ***u(t)*** for the fixed time step.

2.2 Estimation of modal parameters and identification of cutting force coefficients for the cutting force model

The model for the simulation is designed in accordance with the equations presented in the previous section. The formulation of the structural matrices in Eq. 8 is based on measured FRF as already described above. For this purpose, the FRF were measured by using an impulse hammer and accelerometers. Fig. 2 shows the placement of the acceleration sensors on the work-piece and on the tool.

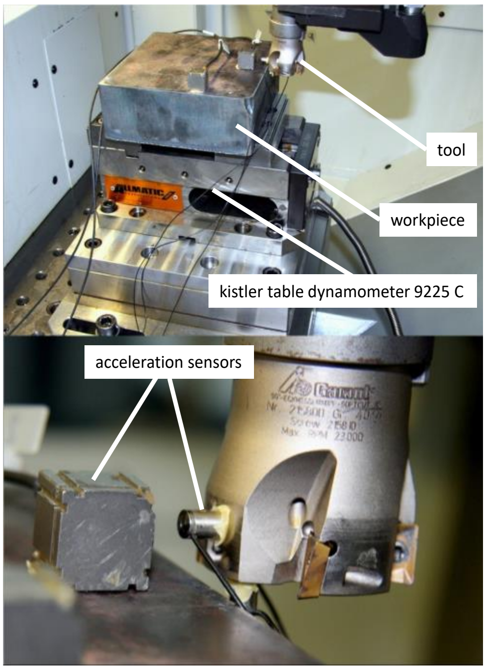


Figure 2. Experimental setup for measurement of FRF and cutting forces

The matrix of relative FRF (between the tool and the work-piece) is computed form the measured FRF by using Equation (7). Fig. 3 shows the relative FRF for the excitation and response both in x and in y direction, denoted by $G_{rel,xx}$ and $G_{rel,yy}$, respectively.

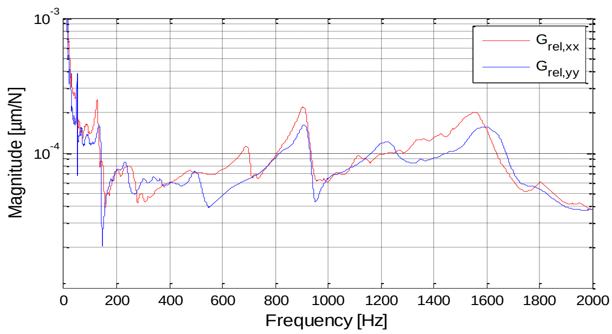


Figure 3. Example of estimated relative FRF between tool and work-piece

The dynamometer shown in Fig. 2 is only used for the measurement of the cutting forces in the machine coordinate system and not for the estimation of FRF. Generally, the intentioned simulation of the milling process requires input parameters like the specific cutting force coefficients and the run-out of the inserts, which describes the deviation of the really position of every insert from the theoretical tool diameter [Yao 2013].

In order to ensure a high confidence level of the simulation results, these input parameters are identified by measured cutting forces for the presented milling process. For this purpose, the face milling process with spindle speed of 800 min^{-1}, feed rate 300 mm/min, 30 mm immersion, cutting depth of 1 mm and shoulder milling cutter with tool diameter of 40 mm and 4 teeth is considered. The material of the work-piece is S235JR. In the first step of the identification, the cutting forces are calculated. The specific cutting force coefficients are assumed to be static and then adopted for the work-piece material and the tool geometry from the literature [Degner 2015]. The run-out of all inserts is assumed to be zero. After the measurement of the cutting forces with dynamometer, a residuum between the calculated and measured results is defined. This residuum is minimized by the nonlinear last square method, in which the optimization parameters are the cutting force coefficients and the radial as well as axial run-out of all inserts.

Fig. 4 shows the comparison of the measured and computed cutting forces after the optimization of the input parameters. It is obvious that measured and calculated results show good conformity. The difference might result from the fact that only translational displacements of the tool and the work-piece are considered. However, the ignored tilting of the tool can also cause additional non-considered displacements.

As expected, the used milling process leads to an excitation of the machine tool with dominating harmonic and high-order harmonic signals, as shown in the right part of Fig. 4. The most dominating harmonic frequencies are the spindle speed at 13.3 Hz and the tooth pass frequency at 53.3 Hz. The frequencies lying below the tooth pass frequency result from the run-out. Beside the two harmonic frequencies, there are high-order harmonic frequencies, which generally arise due to the deviation of the real force signal form the ideal harmonic signal.

2.3 Variation of cutting parameters to generate broadband excitation

In order to achieve a broadband excitation, the variation of cutting parameters like the spindle speed n and the immersion a_e is investigated in this paper. All other cutting parameters are assumed to be constant. This includes the feed rate v_f = 300 mm/min, the depth of cut a_p = 3 mm, the tool path in X direction over 200 mm, which implies the simulation time of 40 s. Other cutting parameters (like tool diameter, number of teeth, work-piece material, etc.) are naturally adopted from the identification procedure inclusive the identified cutting force coefficients and the run-out. Due to the constant feed rate over all simulation runs, a varying spindle speed causes an inevitable variation of the feed per tooth c according to

$$c(t) = \frac{v_f}{z_{Tool}\, n(t)} \tag{9}$$

and consequently a variation of cutting force amplitudes, as well. Generally, the variation of a cutting parameter is defined

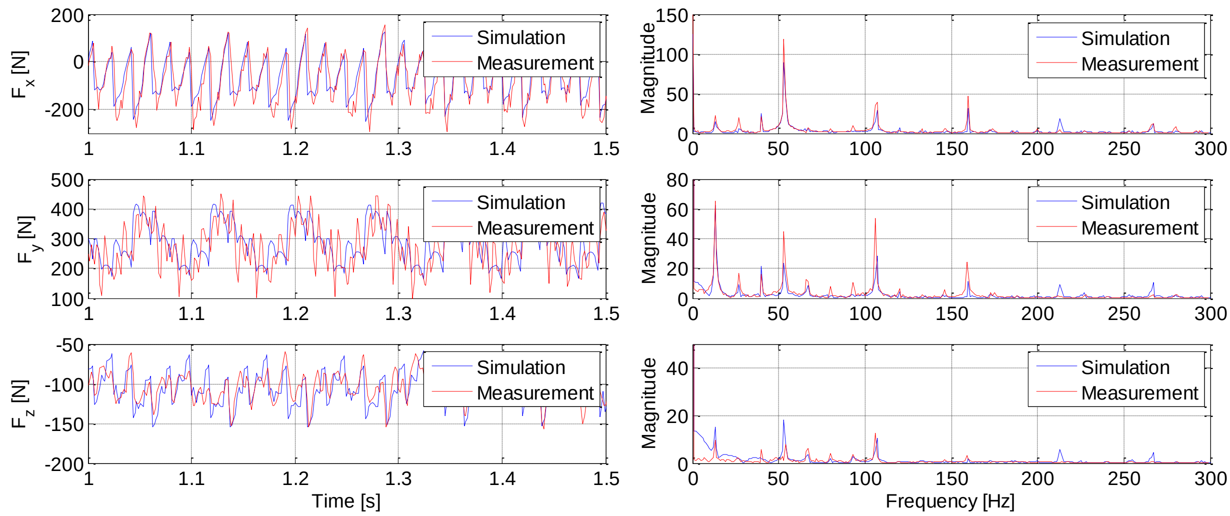


Figure 4. Comparison of calculated with measured cutting forces in the time and the frequency domain

by a function and the corresponding function parameters. Tab. 1 shows all investigated configurations of the cutting parameters including the type of used functions and the limits for the function parameters. Additionally, Tab. 1 also contains a diagram of the magnitude of the resulting cutting force in the frequency domain.

In the scope of the presented investigations, the variation of the spindle speed is based on three functions, in fact a linear, an exponential and a harmonic function. The linear function corresponds in principle to a sine-swept excitation.

the dynamic of the spindle drive of the used machine tool limits the maximum value of the changing rate r = 0.1 (see Tab. 1). The start value of the spindle speed is defined to $\bar{n}$ = 1000 min^{-1}. This value of spindle speed always represents the default value, if there is not another definition. In the same manner, the default value for the immersion $\bar{a}_e$ is equal to 30 mm. The harmonic function describes a variation of the spindle speed of $\bar{n}$ according to a sine function with the frequency f (in other words the varying speed of the revolution) and the amplitude b$\bar{n}$. It is obvious that b = 1 would lead to milling without cutting speed. In contrast, a too low value of b would cause too low variation of revolution. Hence, the limits of b are defined in the range from 0.5 to 0.9. The frequency f is again limited by the dynamic of the spindle drive and thus the maximum value amounts to 0.08 Hz.

As another function the spindle speed is variated as sine swept function, which is a standard excitation signal in experimental dynamic investigations. The spindle speed start value is also defined by $\bar{n}$ = 1000 min^{-1} and amplitude is set to 20 percent by b = 0.2. By variating the parameter p from 0.1 up to 0.5 the end frequency of the sine swept function is investigated in the range from 4 to 20 Hz.

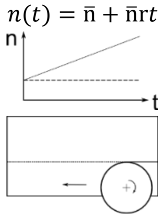
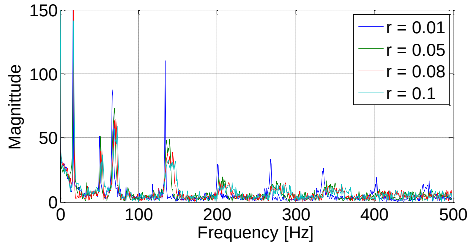
The last investigated function of spindle speed variation is an exponential function with only one function parameter q and the default value $\bar{n}$. The setting of the parameter q is again restricted by the dynamic of the spindle drive. Thus the maximal value of q amounts to 0.0003. In this case, the default simulation time 40 s would lead to too high spindle speed. Therefore, the simulation time was reduced to 30 s. The results for the spindle speed variation yields that the most appropriate function for a broadband excitation is represented by the sine function with the parameters b = 0.9 and f = 0.08 Hz. The sine function also yields better results for the remaining function parameters b and f than the linear and exponential function.

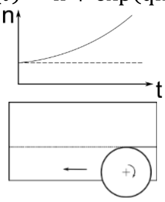
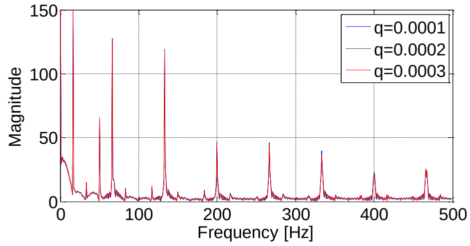
The limitations by the spindle drive dynamics can be clearly seen in the case of the linear function. Theoretically, this function should lead to a broadband excitation like a sine-swept signal. However, the spindle drive dynamics reduces the necessary rate r to a value that is insufficient for a broadband excitation.

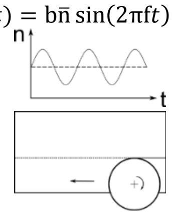
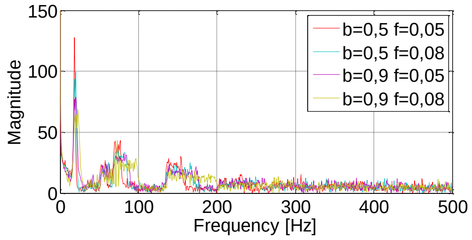
The variation of the immersion is performed according to a linear and an exponential function for the default spindle speed. The parameter a_{e0} in the both functions represents an initial immersion value. The varying immersion changes the form of the periodic cutting force signal. For very low immersion values, the corresponding cutting force signal is akin to an impulse with a low force value. Increasing the immersion increases the force amplitude until a maximum value corresponding to the maximum chip thickness, which is equal to the feed rate per tooth, if run-out is neglected. This implies that a varying immersion affects only the high-order harmonic frequencies and the force amplitude at all frequencies. The simulation results for the varying immersion reproduce exactly these effects. For the purpose of a broadband excitation, the varying immersion according to the linear function with r = 0.75 mm/s and a_{e0} = 5 mm yields the most appropriate result due to the relatively low differences in force amplitudes at harmonic and high-order harmonic frequencies.

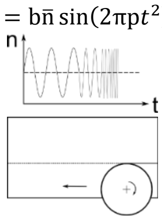
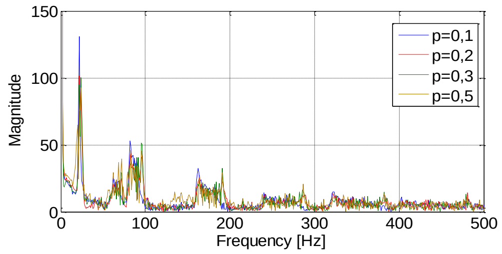
In the last row of Table 1, results for the combination of the spindle speed and the immersion variation according to a harmonic and linear function, respectively, are presented. The best broadband excitation is reached by the harmonic function with $\bar{n}$ = 5000 min^{-1}, b = 0.9 and f = 0.08 Hz in combination with the linear immersion with parameters r = 0.75 mm/s and a_{e0} = 0 mm.

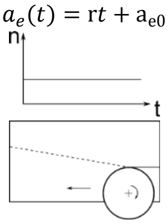
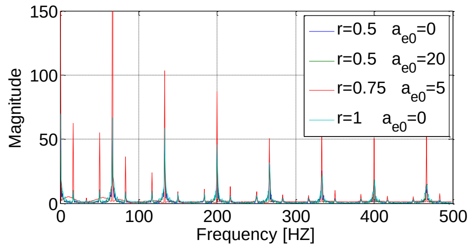
Table 1. Investigated types of cutting parameters variation and the corresponding cutting force in frequency domain

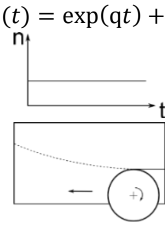
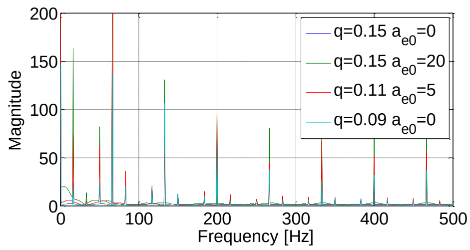
<table>
<tr><th>Parameter</th><th>Parameter function</th><th>Cutting force in frequency domain</th></tr>
<tr><td rowspan="4">spindle speed
n(t)</td><td>$n(t) = \bar{n} + \bar{n}rt$

</td><td>

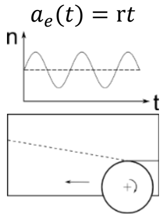
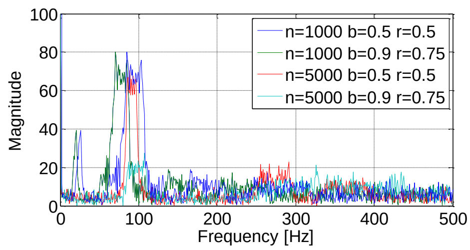
</td></tr>
<tr><td>$n(t) = \bar{n} + \exp(q\bar{n}t)$

</td><td>

</td></tr>
<tr><td>$n(t) = b\bar{n}\sin(2\pi ft) + \bar{n}$

</td><td>

</td></tr>
<tr><td>$n(t) = b\bar{n}\sin(2\pi pt^2) + \bar{n}$

</td><td>

</td></tr>
<tr><td rowspan="2">Immersion
$a_e(t)$</td><td>$a_e(t) = rt + a_{e0}$

</td><td>

</td></tr>
<tr><td>$a_e(t) = \exp(qt) + a_{e0}$

</td><td>

</td></tr>
<tr><td>spindle speed
and immersion
n(t) and $a_e(t)$</td><td>$n(t) = b\bar{n}\sin(2\pi ft) + \bar{n}$
$a_e(t) = rt$

</td><td>

</td></tr>
</table>

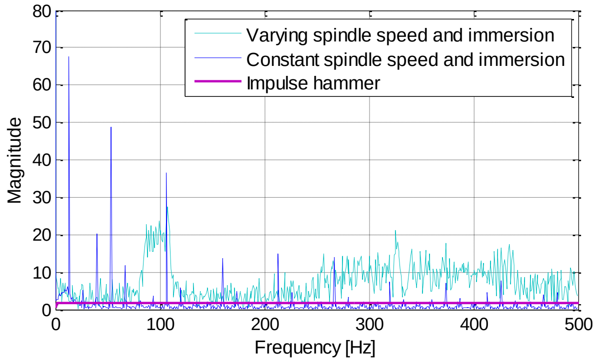


Figure 5. Comparison of simulation results of sinusoidal varying spindle speed and linear immersion with an excitation by impulse hammer and constant spindle speed and immersion

Fig. 5 shows a comparison of the promising results supplemented by a force spectrum of a milling process with constant parameters and an excitation with impulse hammer of force amplitude about 2000 N and frequency range from 0 to 500 Hz. It is obvious that the combination of the spindle speed and immersion variation achieves the best results, which are comparable with an excitation by impulse hammer.

Based on these simulation results, milling experiments are performed for the most suitable parameter settings in the following section.

3 EXPERIMENTAL REALIZATION OF BROADBAND EXCITATION BY CUTTING FORCE

The experimental setup is the same as in the case of the above presented experiment for the identification of cutting force coefficients. As already mentioned in the previous section, the ideal excitation signal could be a random signal in the time domain. In order to use such a signal, the spindle speed is numerically generated as a pseudo-random function in the time domain with limits between 500 min^{-1} and 1500 min^{-1} resulting from the used work-piece and cutting material [Li 2013]. The realization of the milling process with this function leads to a stopping of the feed rate. As the spindle speed cannot be reached in the control unit cycle time (IPO) due to the finite dynamic of the spindle drive, the control system stops the feed until reaching the programmed spindle speed. This fact excludes the usage of the pseudo-random function for the broadband excitation by cutting forces in machine tools.

In order to overcome the stopping feed rate, a variation of the spindle speed according to the IPO has to be carried out. For this purpose, an under-program was developed operating in the background of the NC-code. This approach is comparable to a variation of the spindle speed by the hand-wheel. Nevertheless, the spindle speed can be exactly mathematical programed with parameters depending on variables like time or machine position. In such way, a sine-swept function for varying the spindle speed is implemented. The non-constant frequency of the sine-swept function depends on the position, so that the frequency of the spindle speed variation increases with the increasing traverse path of the tool. Nevertheless, the maximum of this frequency is limited to 20 Hz due to the IPO. This leads to a very low spindle speed variation as shown in Fig. 6. Furthermore, the corresponding frequency spectrum of the cutting force features many harmonics frequencies. A decreased feed rate from 300 to 10 mm/min allows a higher sweep-frequency up to 200 Hz, unfortunately, without having a positive effect on the frequency spectrum of the cutting force.

Another investigated approach consists in variation of the spindle speed according to an exponential function, simultaneously, with increasing immersion. In the experiment, an exponential function with q = 0.000745 (see Tab. 1) for a spindle speed range from 500 min^{-1} to 15.000 min^{-1} over distance of 160 mm. The immersion increases linearly from 5 to 35 mm over the same time as the exponential function. The force frequency spectrum for this experimental run is shown in Fig. 7. It is obvious that there are some frequency ranges featuring broadband excitation as well as harmonic signals. The force spectrum resulting from this experimental part is better than the experiment with the presented sine-swept function but still not usable for a broadband excitation when performing OMA.

The next experimental investigation focuses on the spindle speed variation according to a sine function with a mean value of 7000 min^{-1}, amplitude of 2800 min^{-1} and frequency of 0.21 Hz, with an immersion value of 30 mm is constant along the whole milling distance. This investigation principally corresponds to the third row of Tab. 1. Fig. 8 presents the results of this experimental run. The frequency spectrum does not contain any more parts of significant harmonic signals. There is only a broadband excitation in the range from 80 till 120 Hz. As expected, the spindle speed variation according to a sine function generates the best results in the so far presented experimental investigations.

Nevertheless, the simulation shows a potential by the combination of a sine spindle speed variation with a linear immersion. For this purpose, the parameters of the sine spindle speed variation are set to mean value 8000 min^{-1}, amplitude of 7200 min^{-1} and frequency of 0.24 Hz, respectively. The linear immersion changes from 5 mm to 30 mm over the milling distance. Fig. 7 shows the results of the measured cutting force in the time and frequency domain for this parameter setting. The frequency spectrum of the cutting force features a broadband signal over the whole frequency range (0-250 Hz). Nevertheless, it must be mentioned that this signal is unfortunately non-constant in the amplitude. Furthermore, there are frequency ranges with relative constant amplitude, e.g. 100-250 Hz, which can be employed for OMA.

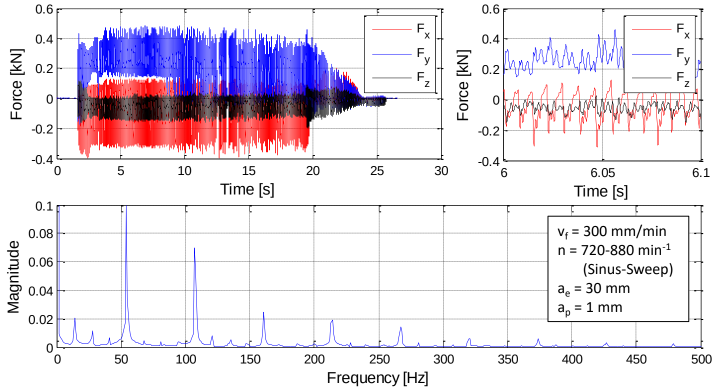


Figure 6. Cutting force in the time and frequency domain for spindle speed sine-sweep changed

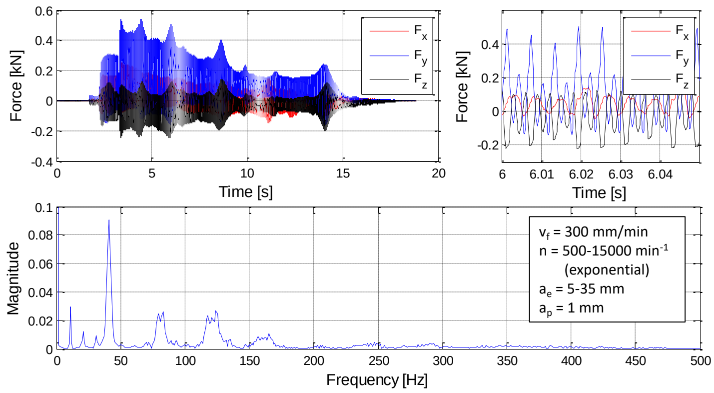


Figure 7. Cutting force in the time and frequency domain for spindle speed exponential changed, immersion linear changed

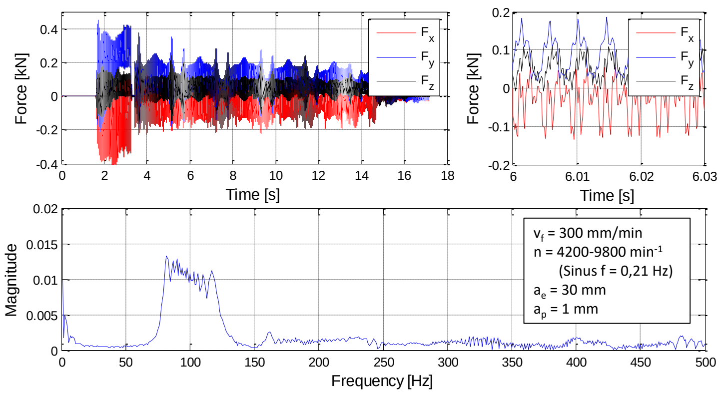


Figure 8. Cutting force in the time and frequency domain for spindle-speed sinusoidal changed

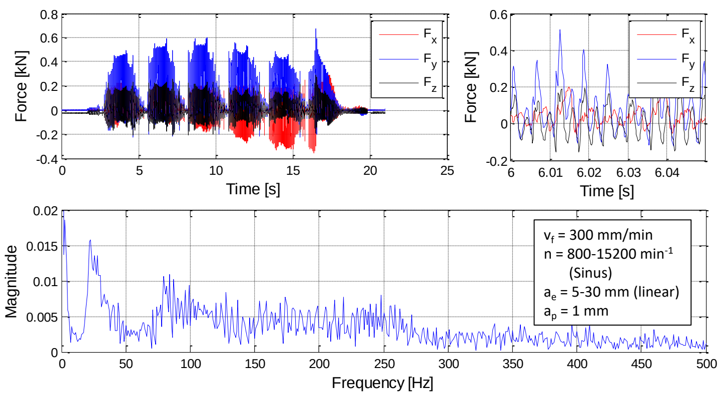


Figure 9. Cutting force in the time and frequency domain by sine alternating spindle speed, immersion linear changed

In Fig. 10 the spectra's of a standard milling process with constant spindle speed and immersion are compared with simulated and measured results of varying sinusoidal spindle speed and linear increasing immersion. As a reference value the spectrum of an impulse hammer excitation is depicted.

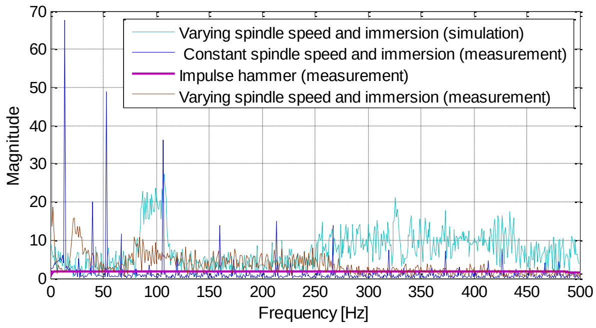


Figure 10. Comparison of simulation and experimental results with impulse hammer

In order to reach a constant value in the lower frequency range (0-100 Hz), either additional optimization of the parameters or a new milling strategy are necessary. Both are the subject of further investigations.

4 CONCLUSION AND OUTLOOK

Generally, machine tools represent a non-linear mechanical system with a time variant behaviour during milling. This leads to the fact that the dynamical behaviour of a machine tool in operation differs from the dynamic behaviour in standstill. Generally, EMA assumes a linear behaviour and it is usually performed on a position and in stagnant state of the machine. In this manner, the influence of a manufacturing process on the dynamic behaviour of machine tool cannot be investigated. In contrast, OMA theoretically allows measuring the dynamic behaviour of a machine tool in operation.

But, performing OMA requires a constant broadband excitation (e.g. by a random signal) which unfortunately does not correspond to a standard milling process. In this paper, approaches for generating a broadband excitation free of harmonic signals by a milling process were investigated by simulation and in experiments. The simulation allows better understanding of the relationship between the immersion, spindle speed and the resulting frequency spectra of cutting forces. The simulation takes into consideration the dynamic behaviour of the machine tool, the work-piece and the tool.

The results show that a milling process with a sine spindle speed variation in combination with linearly changing immersion leads to a broadband excitation without any harmonic signals. This simulation results were also verified in experiments.

The future work on this field concentrates on the further optimization of the setting cutting parameters to extend the broadband excitation to a wider frequency range with a constant amplitude.

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