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Machine Resonance Map Generation using the Machining Spindle as controlled Vibration Source

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Abstract

The knowledge of natural frequencies of machining or measurement systems is essential to avoid resonances at which the frequency of an external vibration is equal or close to a system natural frequency. In such a resonance case, vibration levels significantly increase what again would likely affect the machining or measurement result. Looking at a machining system, this problem becomes complex and multi-dimensional. Where components like bearings, structures or motors represent stiffnesses and thus natural frequencies, other components like drive clock cycles, spindles and pumps could excite these. The spindle speed, for example, changes to follow the machining process. Natural frequencies on the other hand change with axes positions or thermal conditions.

A simple method is described to create a machine resonance map without any modifications to the machining system to give the machine builder or user the possibility to optimize the machining process and thus the machining results.

Assuming the machining system contains of a motor spindle, this motor spindle would excite the machine natural frequencies with its spinning frequency and the residual shaft imbalance. Slowly increasing the spindle speed from standstill to top speed would generate a controlled vibration at the current spinning frequency and its harmonics. Using an accelerometer at different places inside the machining system would allow to create a 3D waterfall natural frequency map by continuously taking FFT readings and lining these up sorted by the spinning frequency. This not only allows to clearly identify resonances, but also natural frequencies and their change with spindle speed or other conditions. The 3D waterfall map further allows a sound way of predicting areas and operating points which need to be avoided and an excellent method of tweaking a machine towards better dynamics and machining results. To determine the source of a specific natural frequency, the examiner can either just turn on or off the machine component in question and compare the results.

As an outlook and for a continuous machine optimization, this measurement could be integrated in the machining system for a continuous in-process monitoring. Using additional vibration sensors at critical machine components would further allow a multi-dimensional monitoring, what, on the other side, would also require a multi-objective and multi-dimensional evaluation.

machine; dynamics; resonance; fft; analysis; spindle; ultra-precision

1. Nomenclature

a - acceleration [m/s²]
f - spinning frequency (spindle speed) [Hz]
r - cylindrical vibration mode amplitude [m]
s - displacement [m]
t - time [s]
C - radial bearing damping [N s/m]
I_θ - transverse rotor moment of inertia [kg m²]
I_0 - polar rotor moment of inertia [kg m²]
A - Amplitude [m]
J - distance between shaft center of gravity and journal bearing center [m]
K - radial bearing stiffness [N/m]
M - spinning mass [kg]
U_s - static imbalance [kg]
U_d - dynamic imbalance [kg]
ε - relative static shaft eccentricity [-/-]
υ - velocity [m/s]
ω - shaft angular frequency [1/s]
ω_r - cylindrical resonance angular frequency [1/s]
ω_θ - conical resonance angular frequency [1/Hz]
θ - conical vibration mode amplitude [m]

2. Preface

A machining or measurement system contains of structures and components that can be reduced to spring-mass-damper systems. The goal of a machine designer is to maximize damping and to design the stiffness of single components not to influence the machining or measurement result. However, most important goal is to avoid any resonances where one component excites the natural frequency of another what again could lead to a cascade. Looking at the number of electric and mechanical components in a machine tool makes clear that this can only be done to a certain extend. Therefore, it is important to do a machine dynamics analysis and to tweak system parameters like control loops or pressures towards a further optimization. To check a certain frequency band for resonances, the machining spindle can be used. Its speed is controllable and thus known, and it can excite other components not only with the spinning frequency (fundamental), but also with its harmonics. Air bearing spindles are perfect for this, because they don't contain of parts like cages or roller elements that have different spinning frequencies. In the following a method is described to create a machine resonance map using the machining spindle as a controlled vibration source without any modification to the machining system.

3. Understanding natural frequencies of machining spindles and FFT basics

The shaft-bearing system of a machining spindle itself has natural frequencies that change with speed and temperature. Therefore, and to be able to distinguish between exciting and excited frequencies, it is essential to know their position in the frequency band.

A simple, but very accurate method is to reduce the spindle shaft to a rigid mass-less beam with the shaft mass *M* concentrated in the centre of gravity, its moments of inertia I_ϑ and I_0, a static imbalance U_S acting at the centre of gravity and dynamic imbalances U_D at both ends. The two radial bearings are reduced to their stiffness K_i and damping C_i values which change with the spinning frequency (speed) f and shaft deflection ε. Considering a concentric spinning shaft (ε = 0), the natural frequencies of this shaft-bearing system can be reduced to a conical vibration caused by the dynamic imbalances U_D and a cylindrical caused by the static imbalance U_S.

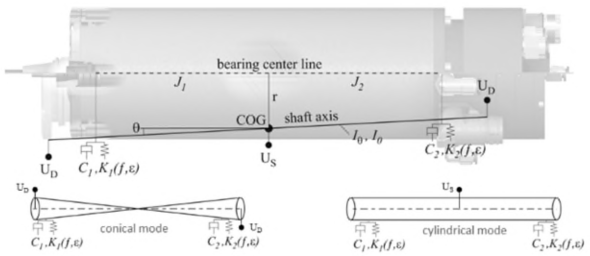


Figure 1: Shaft rigid-mode criticals

Knowing of the change in stiffness with spindle speed allows to calculate both, the cylindrical and conical mode, with spindle speed using equations (1) and (2).

$$(1)\quad \omega_r(f,\varepsilon)^2 = \frac{K_1(f,\varepsilon)+K_2(f,\varepsilon)}{M}$$

$$(2)\quad \omega_\theta(f,\varepsilon)^2 = \frac{K_1(f,\varepsilon)\cdot J_1{}^2+K_2(f,\varepsilon)\cdot J_2{}^2}{(I_\theta - I_0)}\quad [2]$$

Plotting these natural frequencies and the fundamental (spinning frequency) with speed generates the theoretical natural frequency map of the spindle.

The theoretical values can be verified using an accelerometer at the spindle or a capacitive distance sensor measuring the change in distance to the shaft or a tool. Both need to have a bandwidth of at least 2.5 times the natural frequency you want to detect [5]. The sensitivity of the accelerometer should be not less than 1 *V/g* or a resolution not under 5 nm for the capacitive sensor.

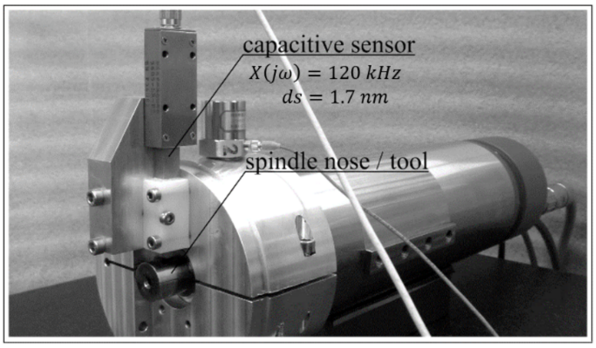


Figure 2: Set up to determine spindle natural frequencies

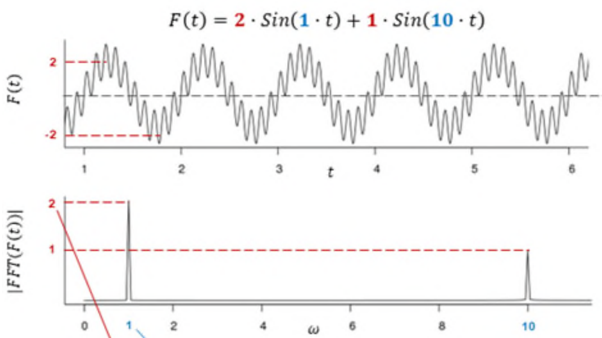
Should the real acceleration be of any interest, this can easily be derived from the change in distance using the equations of motion (3).

$$(3)\quad s(t) = \hat{A}\cdot \sin(\omega\cdot t)$$

$$\vartheta(t) = \frac{ds(t)}{dt} = \hat{A}\cdot\omega\cdot\cos(\omega\cdot t)$$

$$a(t) = \frac{ds^2(t)}{dt^2} = -\hat{A}\cdot\omega^2\cdot\sin(\omega\cdot t)$$

A Fourier Transform is an integral function that transforms a signal from its time domain into either a real or complex frequency domain, representing the frequencies present in the original signal. In other words, any time-based signal can be re-assembled by summing up a fundamental sinus signal and its harmonics with different amplitudes (Fourier Coefficients). The Fast Fourier Transform (FFT) is a discrete Fourier Transform and thus ideal to be handled by computers.



$$f(t) = A_0 + A_1\cos(\omega t+\varphi_1) + A_2\cos(2\omega t+\varphi_2) + \cdots + A_N\cos(N\omega t+\varphi_N)$$
$$= \sum_{n=0}^{N} A_n\cos(n\omega t+\varphi_n).$$

Figure 3: FFT principle – Re-assembling a time-based signal using a fundamental frequency, its harmonics and the Fourier Coefficients (amplitudes)

Accelerating the spindle slowly from standstill to top speed (or the other way around), taking an FFT measurement at small speed steps and lining the single FFT diagrams up in the order of the spindle speed gives a 3D waterfall frequency diagram of the spindle itself. The speed can either be evaluated with an external tacho (phase sensor) or just using the zero flag of the spindle's rotary encoder.

As the amplitude of the vibration is of less importance at this point and for better visibility, the 3D waterfall diagram is reduced to a 2.5D chart where dark areas represent higher amplitudes and light areas lower. In this context 2.5D means looking top-down on a 3D diagram as shown in Figure 4.

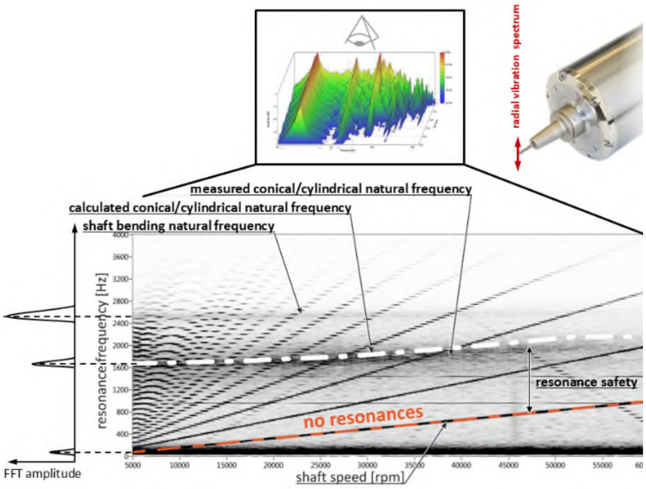


Figure 4: 2.5D view of a 3D chart and spindle natural frequencies

The fundamental (synchronous) speed as well as its harmonics can clearly be identified. The conical and cylindrical are very close together and are a single horizontal band that slightly bends upwards with speed due to the change in bearing stiffness. Also, the bending critical can be seen as another dark band above the cylindrical/conical. As the fundamental never reaches or crosses the conical, cylindrical or bending critical, there are no resonances over the entire speed range of the spindle used for the tests.

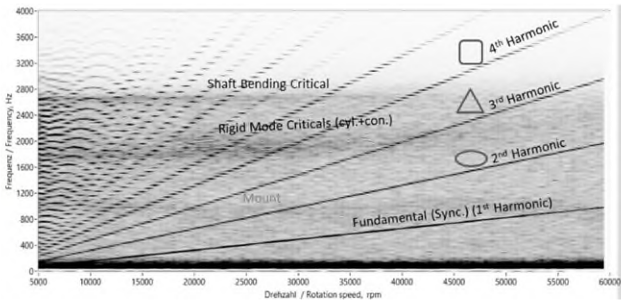


Figure 5: Spindle natural frequencies over spindle speed

4. Set up and Measurement

With the spindle natural frequencies known, the accelerometer is now placed at the machine component or area of interest instead of the spindle. This can be axes, the machine bed or the machine housing e.g. With the machine now being switched on, the same measurement as in section 2 is done. Slowly ramping the machining spindle up or down now excites the machine or component natural frequencies with the spindle natural frequencies, the fundamental (spinning frequency) and its harmonics.

In the following example, the accelerometer was placed in the direction X of a linear axis featuring a linear motor and oil-hydrostatic guides (Figure 6).

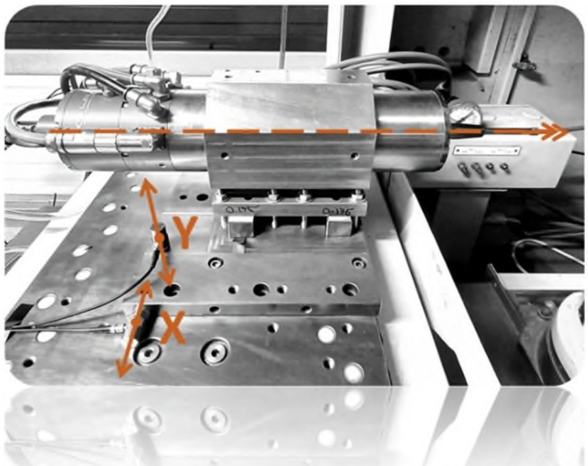


Figure 6: Measurement set up to determine machine natural frequencies using the machining spindle as vibration source

The analyzer system [3] uses an accelerometer with 1 *V/g* sensitivity and 10 *kHz* bandwidth, a DAQ sample rate of 400 *MS/s* and an in-house developed software to create resonance maps based on FFT readings. As described in Sec. 3 and in Figure 4, 2D FFT data and charts are continuously recorded, then rearranged with spindle speed and displayed as a 2.5D waterfall chart.

Figure 7: Dynamics analyzer system

The accelerometer reads the reactions of the axis when excited by the spindle on it, and the results show that now many more natural frequencies become visible compared to the ones that can be seen in Figure 5.

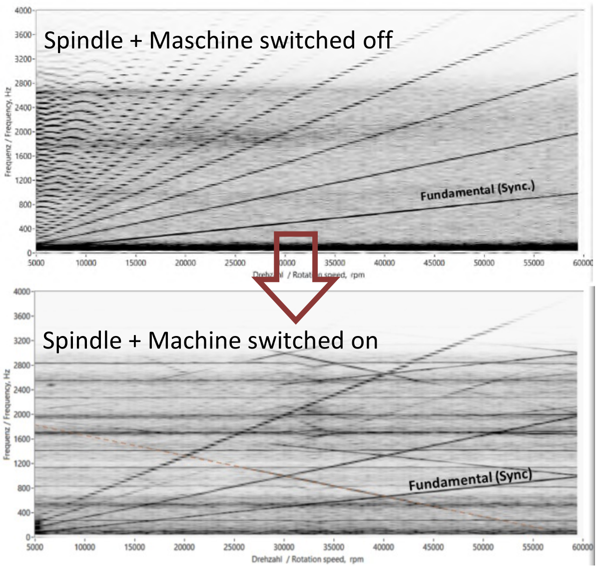


Figure 8: Machine Resonance map created with machining spindle as vibration source – Machine switched off (top) and on (down)

5. Evaluation and Interpretation

As it can be seen in Figure 8, when switching the machine on, the natural frequencies of the spindle become almost invisible, because the amplitude level of the axis response is significantly higher. Nevertheless, it is still fact that the frequencies of the spindle excite natural frequencies of the axis (resonances) and need to be avoided. To find out what machine component is influenced and what natural frequency belongs to what component or parameter, the test can be repeated by switching components like hydraulics or drives on and off. In the test set up for this presentation the following unfavourable machine components and spindle speeds could be identified.

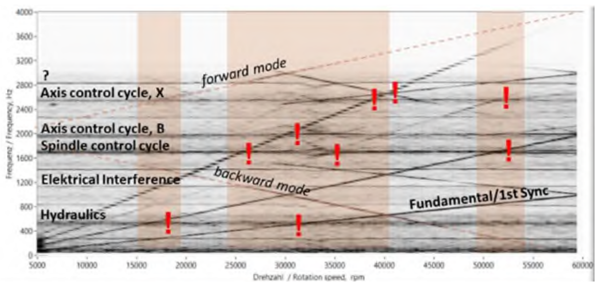


Figure 9: Machining conditions to avoid due to resonances with the fundamental/harmonics of the machining spindle

The second harmonic of the spindle resonates with the machine/axis hydraulics at spindle speeds of 15,000-19,000 *rpm*. So does the fundamental (sync) spinning frequency at 30 krpm. Where the 3rd harmonic of the spindle seems to be suppressed, the 4th harmonic is amplified and resonates with the spindle amplifier control cycle, the B-axis control cycle and the X-axis control cycle at spindle speeds of 25,000-40,000 *rpm*. The second harmonic and spindle drive control cycle resonate at 49-53,000 *rpm*. Looking at the results, the spindle should not be used at these speeds.

Some axis control cycles also lead to forward and backward mode sub-criticals which increase or decrease linearly. This is caused by phase changes between the exciting and the affected frequency. A forward mode increases the system stiffness, a backward mode decreases the system stiffness and should be avoided.

6. Counter measures and optimization

The user or machine builder now has the option to either not to use the spindle in the speed ranges

- 15,000 - 19,000 *rpm*,
- 25,000 - 40,000 *rpm* and
- 49,000 - 53,000 *rpm*

or to tweak components or parameters so that the speed range that is required can be used. This can be simple measures like changing to a different PWM frequency or oil pressure or redesigning and replacing machine components.

7. Summary and Outlook

The described method to identify process-critical resonances and to optimize machining parameters and components towards better machining results is quick and efficient and does not require any modification to the machining system.

However, such an optimization requires time and is always based on a system that already needs to be optimized. In the future such a system could be integrated in the machining system itself to continuously optimize machine and machining parameters to get better machine dynamics and thus better machining results. Using multiple accelerometers in critical areas of the machining system could offer a multi-dimensional, continuous and automated optimization linked with machine parameters like PWM frequency, oil pressure or temperature control.

For online condition monitoring there are analyzer systems available [4] that could provide the data. However, the closed-loop control of machining parameters still must be tailored to the machining system, which targets more on the machine builder to provide the machine user with better machining results or on research facilities.

The automated identification of critical conditions and a multi-dimensional evaluation would require sophisticated algorithms and high computing power. This would be a very suitable case for quantum computing and its physical principle of searching for all possible solutions at once and looking at the highest probability.

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