euspen's 19th International Conference &
Exhibition, Bilbao, ES, June 2019
www.euspen.eu

Acoustic frequency measurement of an ultrasonic actuator designed for the use in a vibration-assisted air bearing spindle for micro machining

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Abstract

Micro machining processes need to be continuously improved in order to fulfil the increasing demand for miniaturization of components and the functionalization of surfaces. One way of increasing micro machining's efficiency is the implementation of vibration-assisted cutting, which also expands the machinable material range to difficult-to-cut materials. Therefore, an ultrasonic actuator that can be implemented into an air bearing spindle was designed. This actuator will be able to generate the tool's ultrasonic movement by using the magnetostricitve effect. In order to qualify the tool's resulting vibration in the ultrasonic range, vibrational frequencies of at least 16 kHz need to be achieved.

The research presented in this paper describes the approach and validation of the acoustic frequency measurement as well as the results of the measurements of the ultrasonic actuator. For this purpose, the background noise was recorded and deducted from the acoustic signal that was measured while operating the actuator. The frequencies of the resulting signal have been analysed by using Fast Fourier Transforms. With this approach, the acoustic frequency measurement was successfully validated and frequencies up to 20 kHz have been measured with high reliability.

Keywords: acoustic frequency measurement, micro machining, vibration-assisted cutting, air bearing spindle

1. Introduction

As miniaturization of components and the use of micro machining processes are increasing, the efficiency of these processes needs to be improved in order to keep up with tighter tolerances, required tool life and to enlarge the range of machinable materials [1]. Applying ultrasonic assisted cutting to micro machining processes promises to fulfill these demands [2]. One way of realizing ultrasonic-assisted cutting is by implementing an actuator into the spindle. In doing so, the conventional rotating cutting motion is superimposed by an ultrasonic oscillation of the tool in axial direction [3].

Currently used micro tools have diameters < 50 µm and thus require high rotational speeds to reach the required cutting speeds [4, 5]. Conversely, existing ultrasonic assisted spindles reach comparatively low rotational speeds of 1,000 rpm at 0.7 µm radial run-out and tool vibration frequencies of 25 kHz [6].

To combine the high rotational speeds and the low radial run-out of air bearings with the benefits of vibration-assisted cutting, an air bearing spindle with an integrated ultrasonic actuator is developed. A CAD-based sectional view of the spindle can be seen in figure 1. The aim of this development is to reach rotational speeds higher than 100,000 rpm, minimal radial run-out and tool vibrations in the ultrasonic range. In order to check the actuators function, the generated vibrational frequency needs to be characterized. Therefore, an acoustic measurement method was applied and validated that can handle frequencies in the ultrasonic range.

The following paper describes the actuators concept and the mechanism which is responsible for the generation of the tool's vibration. The experimental setup is shown and the utilized measurement method is explained in detail. Additionally, the validation of the actuator's functionality as well as the analysis method of the acoustic measurement up to the frequency determination is presented. In the following, experimental results of the acoustic frequency measurement of the ultrasonic actuator are discussed. The paper is closed by a short conclusion, summarizing the conducted research.

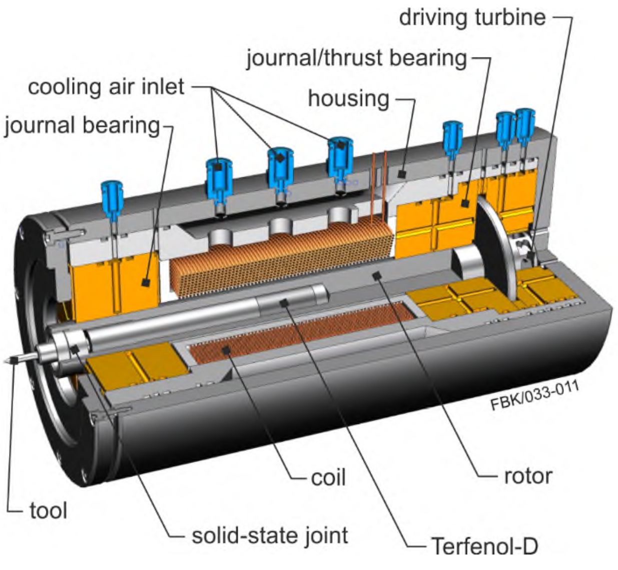

Figure 1. Sectional view of the vibration-assisted air bearing spindle

2. Actuator Concept

In this concept, the actuator is directly integrated into the spindle's rotor, meaning that the actuator needs to generate the periodical displacement of the tool. The implemented actuator concept utilizes the effect of highly magnetostrictive materials which change their geometric properties when being exposed to a changing magnetic field. In this project, the highly magnetostrictive material Terfenol-D is used [7]. The changing magnetic field is established by an electric coil that is connected to an alternating current. All actuator components are located inside the spindle's rotor, whereas the electric coil is installed at the spindles stator. The rotor is supported by one thrust and two journal air bearings and is driven by an air turbine. The spindle is equipped with three air inlets for cooling air supply which is required due to the heat generation of the coil.

To verify the actuators functionality a non rotating prototype was developed and built. The CAD model of this prototype can be seen in figure 2.

The spindle's housing was replaced by an additively manufactured housing using ABS plastic. The rotor with its integrated ultrasonic actuator is fixed to the housing using a fixing screw, preventing rotor movements . As in the spindle concept, the Terfenol-D rod is located in the middle of the electric coil to benefit optimally from the generated magnetic field. The so caused periodic elongation of the Terfenol-D rod is transferred through the upper positioning element to the solid-state joint. The tool, which can be clamped in the solid-state joint by a shrink fit will then execute the movement that is transmitted by the deformation of the solid-state joint. The solid-state joint's stiffness and the expected magnetic field strength, which directly effects the Terfenol-D rod's elongation, have been simulated in previous studies [8].

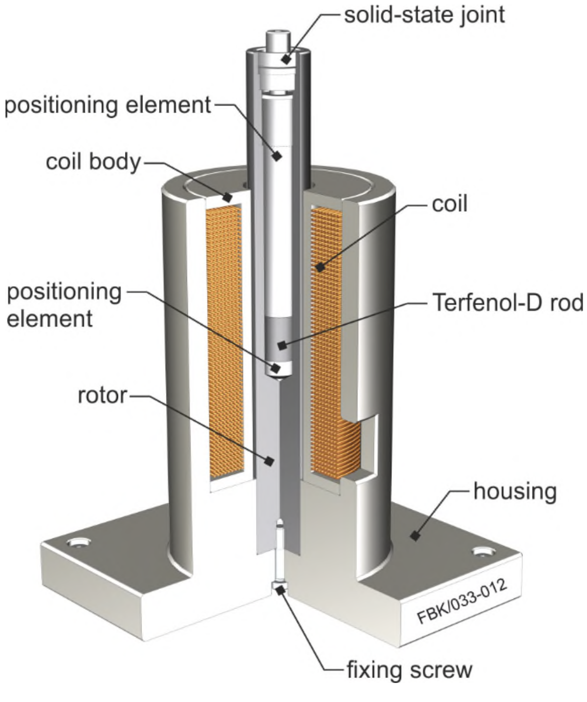

Figure 2. CAD model of the ultrasonic actuator

3. Experimental Analysis

This chapter gives an overview of the experimental setup, including the peripheral devices used to run the actuator as well as the installed measurement technology. In addition, the acoustic measurement method is explained and validated.

3.1. Experimental Setup

Figure 3 shows the experimental setup that is used to carry out the acoustic frequency measurement of the ultrasonic actuator. The frequency generator (Hameg HM 8030-3[1]) creates a sinusoidal signal which is enhanced by the use of an amplifier (the t.amp TA 2400 MK-X[1]). Using clamp connections, the amplified alternating current then flows through the coil, generating a changing magnetic field, causing the Terfenol-D rod's elongation. The microphone (miniDSP UMIK-1[1]) is used for the acoustic measurement of the actuator's frequency and is connected to a sound recording software.

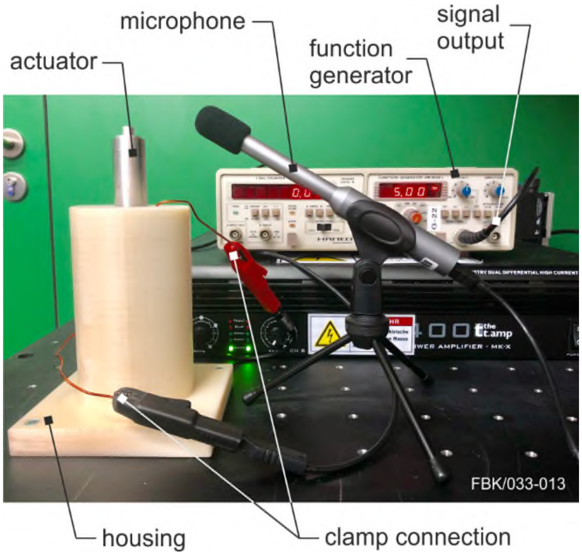

Figure 3. Experimental setup of the acoustic frequency measurement

3.2. Measurement Method

The used microphone is capable of recording frequencies between 20 Hz and 20 kHz. The sampling rate is 44.1 kHz which is, according to the Nyquist-Shannon sampling theorem, sufficient to reliably analyze frequencies in the range specified by the microphone [9].

The acousitic measurement method consists of several stages of signal processing used to identify the actual frequency generated by the designed actuator. First, the background noise of the surrounding environment is recorded while the actuator is not active. This signal will be used later to filter frequencies that are not generated by the ultrasonic actuator. Secondly, the actuator is turned on and its acoustic signal is recorded. This signal can be seen in figure 4.

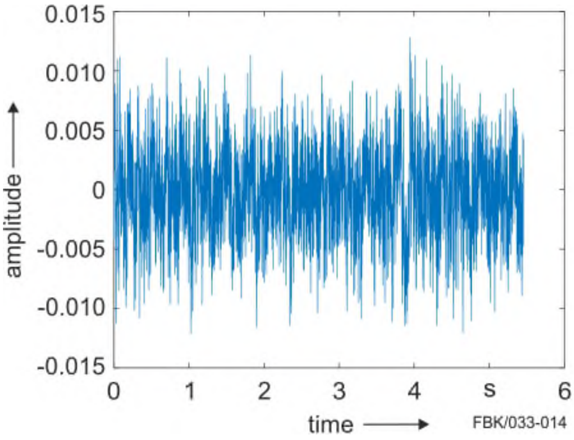

Figure 4. Measured acoustic signal

This unprocessed acoustic signal is a superposition of several acoustic oscillations with different frequencies. In order to obtain information about the measured frequencies, both acoustic signals are transferred into the frequency domain through a Fast Fourier Transform [10]. The resulting signals in the frequency domain, both for the actuator turned off and on, are shown in figure 5.

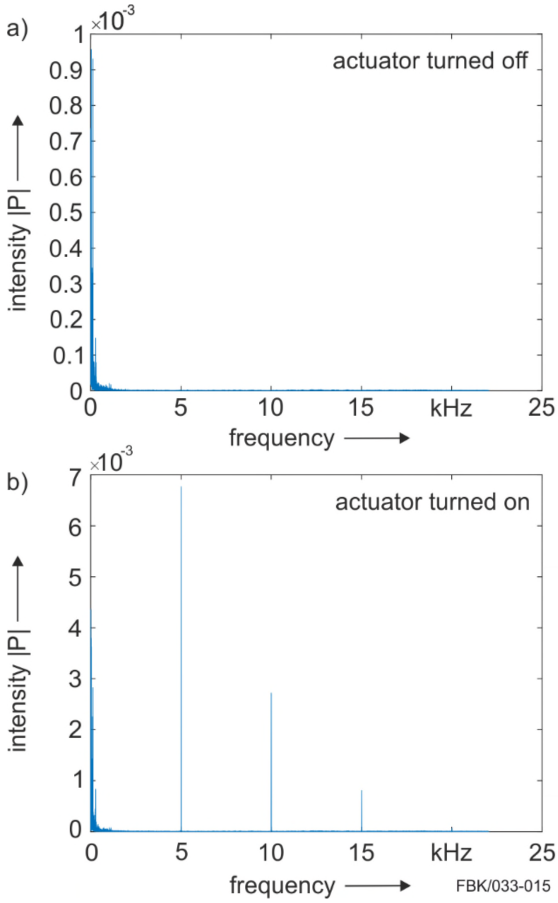

Figure 5. Fast Fourier Transform of acoustic measurements

Although the sample rate of the acoustic recording can detect occurring frequencies of up to 22.05 kHz (figure 5a), the received information is only reliable within the range of 20 Hz to 20 kHz due to the microphone's characteristics. The diagram with the actuator turned on (figure 5b) shows the intensity |P| of several dominant frequencies which appear in the recorded signal of figure 4. Besides the three significant frequencies, background noise in the frequency range of up to 1 kHz can be seen.

To focus on relevant information about the frequencies generated by the actuator, the intensity of the frequencies occurring in the recording of the background noise are compared to the maximum intensity of the frequencies of the acoustic recording of the ultrasonic actuator. Frequencies shown in figure 5a with an intensity higher than 1 % of the maximum intensity of the response frequency in figure 5b have been filtered out.

The noise-cancelled result of the Fast Fourier transform of the acoustic signal of the ultrasonic actuator is shown in figure 6.

The noise-cancelled Fast Fourier Transform shows solely frequencies generated by the ultrasonic actuator, implying that the noise occurring in the lower frequency range has been reduced significantly. The intensity of the response and the harmonics remain unaffected by the noise-cancelling since the intensity of the frequencies represented in figure 5a are not high enough in this upper frequency range to be filtered.

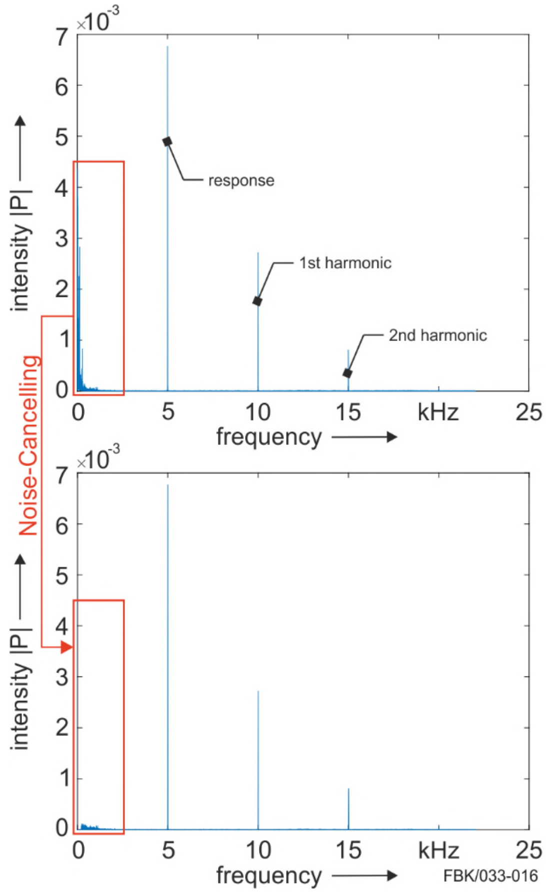

Figure 6. Noise-Cancelling of acoustic measurements

3.2. Validation of the Measurement Method

The described measurement method was validated to ensure its accuracy and functionality. For this purpose, an acoustic frequency generator was used and the emitted acoustic signal was varied between 2 - 20 kHz. The measured frequency was compared to the frequency set by the frequency generator. The result of this comparison can be seen in figure 7, which shows the percentage deviation over the set frequency.

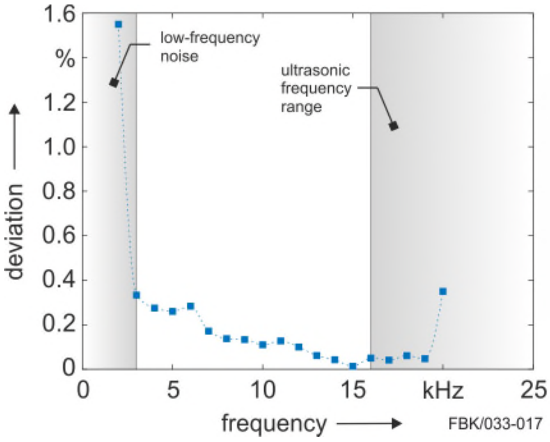

Figure 7. Percentage deviation between set and measured signal

An evaluation script was written in Matlab which determines the values of the dominant frequency and its intensity. It then compares set and measured frequency to provide information about the deviation between those. All deviations are below 1.6 %, the average value of the deviations is 0.22 %. Using the evaluation script for a set frequency of 15 kHz, the dominant frequency was determined at 14,998 Hz, which corresponds to a nearly non-existent deviation of 0.013 %. The remaining deviation between measurement and setting can be explained by the unaccurancy of the used frequency generator and microphone.

The maximum deviation value occurs at a frequency of 2 kHz. At this value the noise-cancelling is less effective, since the generated frequency lies in the range of the background noise. In this way, the low-frequency background noise distorts the measurement despite the applied noise-cancelling. The slightly increased deviation at a frequency of 20 kHz can be attributed to inaccuracies of the microphone close to its recording ability.

4. Experimental Results

To test the actuator's function, the frequency generator was set to frequencies from 2 to 20 kHz. The vibration generated by the Terfenol-D rod's periodical elongation was measured by recording each acoustic signal for 6 s. The results of the noise-cancelled acoustic frequency measurement can be seen in figure 8.

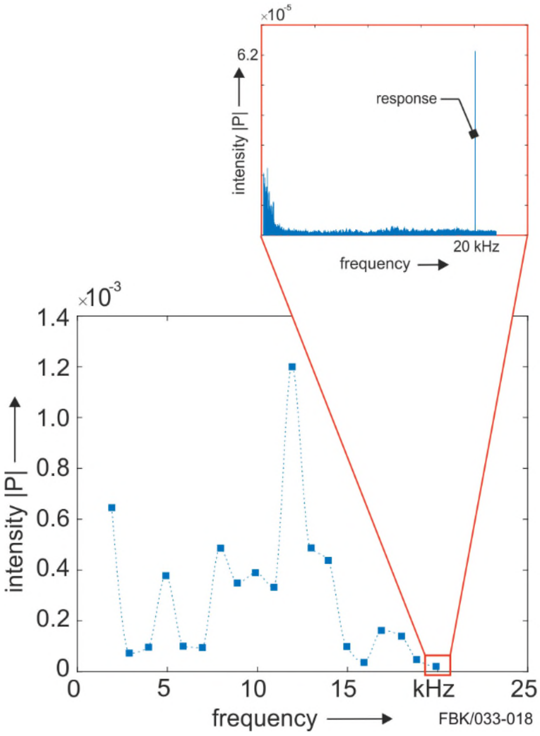

Figure 8. Noise-cancelled response intensity for 2 – 20 kHz

The depicted intensities vary between several orders of magnitude. The highest intensity was measured at 12 kHz, which can be due to the possible excitation of a natural frequency. Although being of a much lower intensity, a dominant vibration was measured at 20.07 kHz, too. This confirms that the developed actuator is able to generate vibrations in the ultrasonic range and to transfer these vibrations as an oscillating motion to the tool with high accuracy.

5. Conclusion

Acousitc frequency measurement is a suitable method to determine high-frequency vibrations with reasonable effort, since the measurement devices can easily be impelented into an existing setup.

This paper described an acoustic measurement method for frequencies of up to 20 kHz, including the analysis which provides information of dominant frequencies in the acoustic recording. In addition, a noise-cancelling procedure was implemented that reduces distracting noise in the lower frequency range. The measurement method was validated at 2 - 20 kHz achieving a very high accuracy between generated and measured signal.

During experimental tests, frequencies up to 20 kHz have been measured with high intensity, qualifying the developed actuator for ultrasonic-assisted cutting.

In the future, acoustic frequency measurements of the running spindle with the actuator turned on and off will be performed in order to clearly separate the spindle's rotational speed and the generated tool vibration. Eventually, the Matlab evaluation script will be modified in order to provide the ability to analyse the measured frequencies in real-time.

Even though the described measurement method and the devices are sufficient to analyse the frequency range used for ultrasonic-assisted cutting, the maximum frequency of the actuator will be determined by a more sensitive microphone and an increased sampling rate. In addition, a measurement method for recording the actuator's vibrational amplitude will be developed and combined with the presented acoustic frequency measurement method.

Acknowledgement

The authors would like to thank the German research foundation (DFG) for the financial support within the project AU 185/57-1 "Ultrasonic air bearing spindle for micro machining" and within the International Research Training Group IRTG 2057 "Physical Modeling for Virtual Manufacturing Systems and Processes".

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[1] Naming of specific manufacturers is done solely for the sake of completeness and does not necessarily imply an endorsement of the named companies nor that the products are necessarily the best for the purpose.