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Model-Based Feedback Control of an Ultrasonic Transducer for Ultrasonic Assisted Turning Using a Novel Digital Controller

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Abstract

Ultrasonic turning has time variant parameters due to temperature effects and changing load conditions during the process. This results in a change of the resonance frequency and vibration amplitude. To realize constant vibration amplitudes it is necessary to control the ultrasonic transducer by a suitable feedback controller. One approach to drive such a system is to use the resonance frequency as operating point in connection with an amplitude feedback controller. The advantages of resonant driven low damped systems are low voltages and high values of effective power. This paper presents a digital system used for parameter identification and model-based feedback control of the ultrasonic turning tool. During the turning process the system load depends on several factors like chip formation, material inhomogeneity, warming and tool wear. To achieve a stable process and a uniform surface of the work piece the feedback controller has to guarantee constant vibration amplitudes of the ultrasonic tool. The controller used in this paper consists of a digital resonance controller and a current amplitude controller with a frequency of 500 Hz. The current amplitude and phase between the excitation voltage and current are determined by phase sensitive demodulation (PSD). To determine the feedback parameters a model-based approach is used.

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Keywords: Resonating Systems; Feedback Control; Model-based; Averaging Model

1. Introduction

Many ultrasonic applications have time variant load behavior which leads to lower vibration amplitudes and frequency shift with increasing load. Other reasons for resonance frequency shifts are temperature changes and nonlinear effects. Hence, to guarantee constant vibration amplitudes and stable operating a feedback control is required. Many publications discuss the realization of feedback controllers. Those typically use a phase feedback control for

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resonance frequency tracking and a current amplitude feedback control to stabilize the current amplitude at a constant level. Another approach for stabilization of the operating point is the autoresonant control which feeds back the amplified current signal positively in a control loop which generates an excitation voltage with a zero phase shift to the current. This approach is used and explained by Mojrzisch and Twiefel [8] or Voronina et. al. [9]. Approaches to drive forced excited ultrasonic systems are introduced by Kuang et. al. [5], Smith [6] and Maruyama et. al [7]. However, there are no publications focusing on a model-based method to parameterize a feedback controller for ultrasonic systems. Mojrzisch et. al. [1] introduced an experimental approach to determine the parameters for the control loop. Littmann et. al. [3] utilized the slope of the phase response at resonance to initialize a load-adaptive phase controller.

In this contribution a model-based approach to determine the parameters for the phase and amplitude controller is introduced for the first time. The model is based on the work of van der Pol [4] which suggests describing the system by an averaging model using the imaginary and the real part of the vibration. Twiefel et. al. [2] used phase sensitive demodulation to determine the phase and the amplitude for feedback control of an ultrasonic transducer and explained how to compensate the influence of the parallel capacitance C_p. This method and the phase sensitive demodulation are also used in this contribution. A model, which is linearized around the operation frequency, is derived with the desired state and control variables. This model forms the basis for the parameterization of the applied feedback control.

2. Model Description

To realize a model-based feedback control, an electrical equivalent model (Butterworth-van Dyke Model) and the tool for ultrasonic assisted turning are shown in Fig. 1. The circuit consists of an oscillating circuit and a parallel capacitance. The differential equation describes the high frequency behavior of the oscillating circuit. Typically, an ultrasonic transducer is controlled by frequency and amplitude of the excitation voltage. Changing the frequency influences the phase between the voltage and the current. The amplitude of the excitation voltage controls the current which is proportional to the vibration amplitude in resonance. Concluding, for the control algorithms only phase and amplitude information in driving frequency are necessary. Due to this reason, it is convenient and efficient to describe the system using an averaging model.

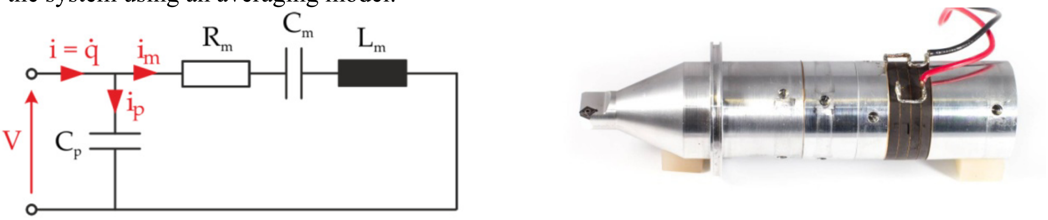

Fig. 1. Electrical equivalent model of an ultrasonic transducer (left) and tool for ultrasonic assisted turning (right)

The averaging model derived from the RLC-oscillating circuit is described by Eq. 1. The Cp term will be compensated during data acquisition. Hence, it can be neglected for the controller design. It describes the phase and current amplitude behavior. The actuating variables are, as desired for feedback control, the angular frequency difference Δω and the amplitude of the excitation voltage v.

$$\begin{pmatrix} \dot{\hat{i}}_m \\ \ddot{\hat{i}}_m \\ \Delta\dot{\phi} \\ \Delta\ddot{\phi} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ (\omega^2-\omega_0^2) & -D\omega_0 & 2D\omega_0\bar{\omega}\bar{\hat{i}}_m & 2\bar{\omega}\bar{\hat{i}}_m \\ 0 & 0 & 0 & 1 \\ -\dfrac{2D\omega_0\bar{\omega}}{\bar{\hat{i}}_m} & -\dfrac{2\bar{\omega}}{\bar{\hat{i}}_m} & \bar{\omega}^2-\omega_0{}^2 & -2D\omega_0 \end{pmatrix} \begin{pmatrix} \hat{i}_m \\ \dot{\hat{i}}_m \\ \Delta\phi \\ \Delta\dot{\phi} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 2\bar{\omega}\bar{\hat{i}}_m + \dfrac{v\sin(\bar{\phi})}{L_m} & \dfrac{\bar{\omega}\sin(\bar{\phi})}{L_m} \\ 0 & 0 \\ 0 & \dfrac{\bar{\omega}\cos(\bar{\phi})}{L_m\bar{\hat{i}}_m} \end{pmatrix} \begin{pmatrix} \Delta\omega \\ v \end{pmatrix} \quad (1)$$

Using this averaging model, it is possible to derive the transfer functions. Those are fundamental for the design of a fast and stable control loop. These transfer functions can be linearized arround the operating angular frequency which is the resonance of the investigated transducer. The bar above a variable indicates values in the operating point of the linearized system. The variables ΔΦ and Δω are the differences between the actual phase and the phase in the operating point and the angular excitation frequency and the angular frequency in operating point. The value v is the amplitude of the excitation voltage.

$$G_1(s) = \frac{\Delta\Phi(s)}{\Delta\Omega(s)} = \frac{-4\omega_0{}^2 s - 4D\omega_0^3}{s^4 + 4D\omega_0 s^3 + (2\omega_0^2(1+2D^2) + 2\omega_0)s^2 + 8D\omega_0^3 s + 4D^2\omega_0^4} \quad (2)$$

$$G_2(s) = \frac{I_m(s)}{V(s)} = \frac{2\omega_0{}^2 s + 2D\omega_0^3}{L_m(s^4 + 4D\omega_0 s^3 + (2\omega_0^2(1+2D^2) + 2\omega_0)s^2 + 8D\omega_0^3 s + 4D^2\omega_0^4)} \quad (3)$$

Both transfer functions have two dominant poles and two poles which affect the system by a high frequency vibration of small amplitude. Due to the weakly damped system ($D^2 \approx 0$) the poles can be simplified, as shown in Eq. 4 and Eq. 5. Those will be used for the further considerations. In regard to the pair of the dominant poles, it is a PT1-system. The dynamics of the system is given by the product of the angular resonance frequency ω_0 and the damping ratio D.

$$s_{1/2} = -D\omega_0 \pm j(\omega_0\sqrt{1-D^2} - \omega_0) \approx -D\omega_0 \quad (4)$$

$$s_{3/4} = -D\omega_0 \pm j(\omega_0\sqrt{1-D^2} + \omega_0) \approx -D\omega_0 \pm j2\omega_0 \quad (5)$$

3. Design of the Feedback Controller

The PT1 behavior is due to the compensation of one of the dominant poles by the system itself in resonance, as Eq. 6 shows.

$$\frac{\Delta\Phi(s)}{\Delta\Omega(s)} = \frac{-4\omega_0{}^2(s + D\omega_0)}{(s + D\omega_0)^2(s^2 + 2D\omega_0 s + D^2\omega_0^2 + 4\omega_0^4)} \quad (6)$$

Therefore, it is convenient to use a PI-controller to compensate the second dominant pole. The transfer function of a PI-Controller is given by Eq. 7. The controller has one root, which is used to compensate the pole of Eq. 6 and one pole in the origin. Due to this reason, the parameter T_N is defined to be equal to the reciprocal of the product of the angular resonance frequency ω_0 and the damping ratio D.

$$G_R(s) = k_R \frac{T_N s + 1}{T_N s} = k_R \frac{s + \frac{1}{T_N}}{s} \quad (7)$$

In regard to the closed loop of the system, the dynamics is given by the gain of the feedback controller k_R. To be able to design a quasi continuous controller the dynamics of the closed loop has to be much slower than the sampling time of the control system. A common approach is to set the settling time of the controlled system thirty times larger than the sampling time. A simple approach to determine the parameters of the feedback controller is given by the following equations.

$$T_N = \frac{1}{D\omega_0} \quad (8) \qquad \omega_{pcs} \approx k_R \quad (9) \qquad \omega_{ccs} \approx \frac{k_R 2L_m}{\kappa} \quad (10)$$

The poles of both transfer functions are at the same position. Therefore, the parameter T_N for the phase and current controller is defined by Eq. 8. The angular frequency ω_{pcs} of the closed loop of the phase controlled system is given by Eq. 9 and the angular frequency ω_{ccs} of the closed loop of the current amplitude controlled system by Eq. 10, where κ is the gain of the amplifying stage.

4. Experimental Setup

The setup of the ultrasonic assisted turning and the digital phase controller are shown in Fig. 2. The control system was developed by the Institute for Dynamics and Vibration Research and introduced for the first time by Mojrzisch et. al. [1] in 2012. Here, an experimental approach was introduced to parameterize the feedback controller.

Fig. 2. Ultrasonic assisted turning (left) and digital phase controller (DPC 500/100k) (right)

The digital phase controller is suitable for frequency and step response measurements and for phase and amplitude feedback control. It is a compact and multifunctional system for analyzing and driving of ultrasonic systems which needs solely an amplifying stage as external hardware. To determine the phase and the current amplitude phase sensitive demodulation is used. To compensate the influence of the parallel capacitance the term $v\omega C_p$ is subtracted from the imaginary part of the measured current. Hence, the controller sets the amplitude of the velocity proportional current i_m. The DPC determines the phase and amplitude within a time of 500 µs and controls an ultrasonic transducer with a frequency of 500 Hz.

5. Experimental Results

The transient behavior of the controlled unloaded system is shown in Fig. 3. In this case, the damping is much lower as in regard to the loaded transducer. Thus, the slope of the phase response is lower in resonance. Therefore, the unloaded transducer is the most critical case for the feedback controller. As Fig. 3 shows, the settling time of the controlled system is within approx. 40 ms. Utilizing the determined parameters, neither undesired oscillations nor high overshoots appear.

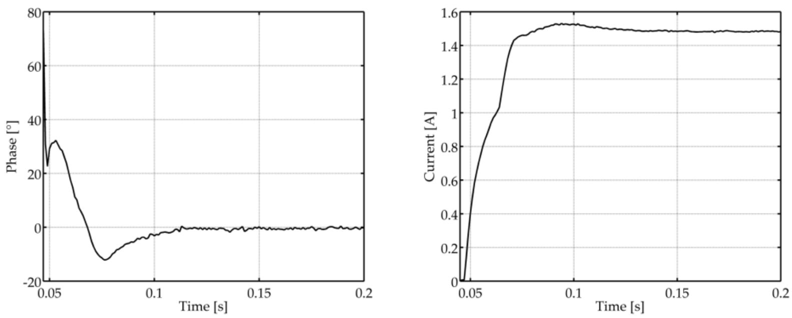

Fig. 3. Transient behavior of the unloaded controlled system

In Fig. 4 two process examples of ultrasonic assisted turning for cutting of aluminum and steel are shown. As the figure shows, the current amplitude and the phase are constant in the cutting process of aluminum. During the increase of the load, the excitation voltage rises as well as the frequency due to the phase feedback control. Similar behavior can be observed during cutting of steel. In this case the process forces and dynamics are higher. However, the phase and the current amplitude still show the desired stable and convenient behavior. During the cutting of steel there are some ripples due to low frequency vibrations of the ultrasonic tool.

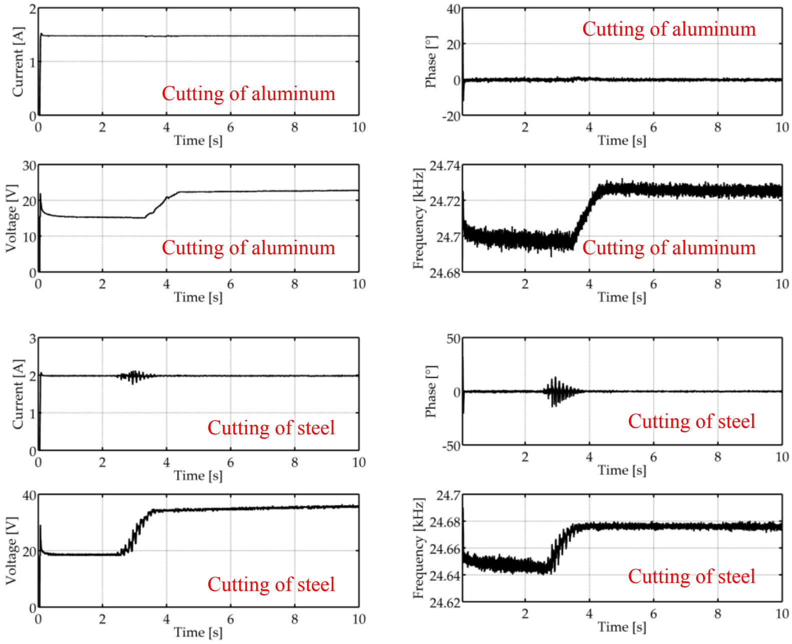

Fig. 4. Measurements for ultrasonic assisted turning using the introduced digital phase controller for aluminum and steel cutting

6. Conclusions

A model-based approach for feedback control of ultrasonic systems is given by this paper. Using the model, it is possible to predict the systems behavior and estimate the limits of the feedback controlled transducer. If these limits are known, the parameterization of the feedback controller is more efficient. Thus, it is possible to optimize the settling time and the stability. The measurements, using the introduced digital phase controller, show a stable and fast behavior of the controlled system without undesired oscillations and high overshoots.

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