LOAD-ADAPTIVE PHASE-CONTROLLER FOR RESONANT DRIVEN PIEZOELECTRIC DEVICES

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Abstract

In ultrasonic processing tools (e.g. for sonochemistry, ultrasonic machining, bonding or cleaning), as well as in piezoelectric motors and transformers, rod- or plate-shaped structures are excited with piezoelectric elements. Most often, resonant vibrations are required to achieve maximum energy transformation and efficiency. This work presents a simple structured load-adaptive phase-controller for resonant driven piezoelectric devices. The newly developed controller, which is an extension of the well-known "phase-locked-loop"- concept (PLL) considers that the fundamental characteristics of the ultrasonic vibrators depend strongly on their loading conditions, which can be mechanical (e.g. in ultrasonic processing) or electrical (e.g. in piezoelectric transformers).

Introduction

Several driving electronics that try to keep ultrasonic vibrators in resonance have been proposed [1], [2], [3]. But at high power levels and in applications where loading conditions – either mechanical or electrical – vary strongly over time, many of those fail. Non-resonant drives are rather bulky and consume much power due to dissipation of reactive power. In the following, a new phase controller will be explained. It is capable of driving piezoelectric devices in resonance even at strongly varying loading conditions.

Modeling of ultrasonic actuators

A typical tool for an ultrasonic process consists of two basic parts: The converter, a composite of a stack of piezoelectric rings and several metallic components, is rigidly connected to a metallic part ("horn") which is used to amplify the vibration amplitude of the piezoelectric elements (figure 1). The lengths of both parts have to be matched to the resonant frequency, so that their particular longitudinal vibration modes appear at the desired frequency (e.g. 20 *kHz*).

Near resonance the vibrational behaviour of the system can be analysed using electromechanical circuit models, see figure 2. The electrical and mechanical properties of the tool are represented by a capacitor C_P and a resonant circuit (damping d, stiffness c, mass m). Load effects resulting from the process can as a first approximation be represented by a load stiffness c_L and load damping d_L. The electromechanical coupling can be displayed as an ideal transformer n.

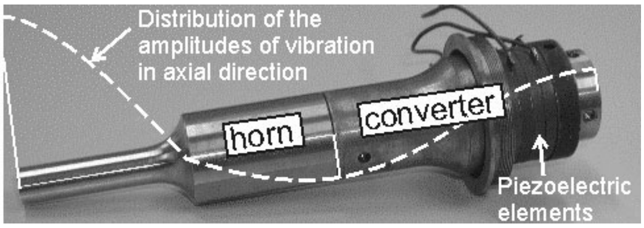

Figure 1: Tool for ultrasonic processing.

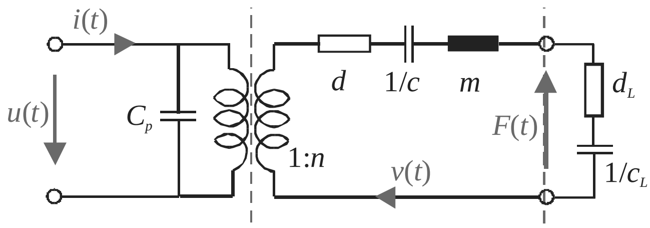

Figure 2: Electromechanical circuit model.

Applying Kirchhoff's laws, the complex input admittance for harmonic excitation $\underline{u}(t) = \hat{u} \cdot e^{j\Omega t}$ is calculated as

$$\underline{\tilde{Y}}(\Omega) = \frac{\underline{i}(t)}{\underline{u}(t)} = \tilde{Y}(\Omega) \cdot e^{j\tilde{\varphi}(\Omega)} = \frac{n^2}{\underline{\tilde{Z}}_m(\Omega)} + j\,\Omega\, C_P \quad (1)$$

with $$\underline{\tilde{Z}}_m(\Omega) = (d + d_L) + j\,\Omega\, m + \frac{1}{j\,\Omega (c + c_L)} \quad (2)$$

being the impedance of the mechanical system part in the loaded case, and $\Omega = 2\pi f$. The tilde symbol (~) denotes the loaded state. The parameters of this model can be identified by admittance measurements for the free and loaded state [1], [4].

The load impedance influences the system behaviour in different ways: Compared to free vibration, damping reduces the peak value of the magnitude curve and reduces the maximum slope of the phase. A load stiffness leads to a shift in frequency (figure 3).

Since both voltage and apparent power reach their minimum at resonance, it is desirable to drive the system in its actual resonance $(\tilde{\varphi} = 0)$. However in case of variable load stiffness this requires a specific control strategy.

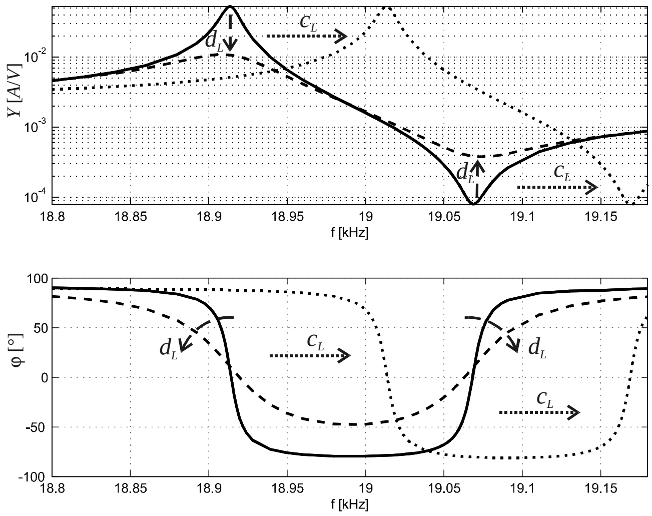

Figure 3: Effect of load stiffness c_L and damping d_L on the admittance of a typical ultrasonic tool.

Self-oscillating concept vs. phase controller

Two basic ideas for controlled resonant operation are known in ultrasonic technology: The “self-oscillating” concept [5] uses the tool itself as a frequency generator similar to a quartz oscillator: Once being activated (e.g. by means of an on-off switch) the system starts oscillating at its natural frequency. For compensation of damping, the oscillation gets amplified and is sent back to the vibrator in a positive feedback-loop. It is pleasantly easy to implement this concept in practice [6], but it shows several disadvantages regarding robustness in presence of strongly variable loads [1].

The second concept is the “phase-locked loop” concept (PLL) which has been adopted from communications engineering where it finds application for synchronisation of two electrical signals [7]. The basic idea of a phase controller is as follows: If the phase between current and voltage (e.g. at the piezoelectric actuator) is positive, the driving frequency is increased, otherwise decreased. In [8] the concept is analysed in terms of standard control theory. The main difference compared to the self-oscillating concept is that the driving frequency is excited by an external frequency generator.

In commonly-available PLL systems, so-called voltage-controlled-oscillators (VCO) are applied. They use a linearised approximation for the phase of the transducer’s admittance (figure 4): The frequency distance Δf between the actual driving frequency f and the resonance frequency f_0 is derived from the measured electrical phase angle φ by

$$\Delta f = K \cdot \varphi \ . \tag{3}$$

The controller’s optimum amplification factor K corresponds to the slope of the phase [9]. It can be determined at the free vibrating tool by measurement of frequency and phase angle at two different sampling points, e.g. at (f_1, $\varphi_1 = \pi/4$) and at resonance (f_0, $\varphi_0 = 0$) leading approximately to

$$K = \frac{f_0 - f_1}{\varphi_1} \ . \tag{4}$$

The PLL-concept is state-of-the-art for many ultrasonic application such as ultrasonic bonding [10].

PLL controller for systems with high damping

Ultrasonic actuators for processes with very high damping (e.g. welding of plastics) sometimes cannot be driven using the proposed PLL-concept: If the minimum phase value of the admittance between resonance and antiresonance stays far beyond the zero-phase line, it is not possible to detect the resonance frequency based on phase-measurements only (figure 4). Alternatively, a non-zero phase value could be chosen as the target frequency.

A different approach is based on the auxiliary admittance curve

$$\underline{\tilde{Y}}_a(\Omega) = \underline{\tilde{Y}}(\Omega) - j\Omega C_P = \frac{n^2}{\underline{\tilde{Z}}_m(\Omega)} \tag{5}$$

which is directly proportional to the kernel admittance $\underline{v}(t)/\underline{u}(t)$, see figure 4. Since the phase $\tilde{\varphi}_a(\Omega)$ of the auxiliary admittance crosses the zero-phase line independently of the load damping, it is always possible to drive a PLL-controller based on the auxiliary phase curve. To this end however the capacitance C_P has to be identified in advance.

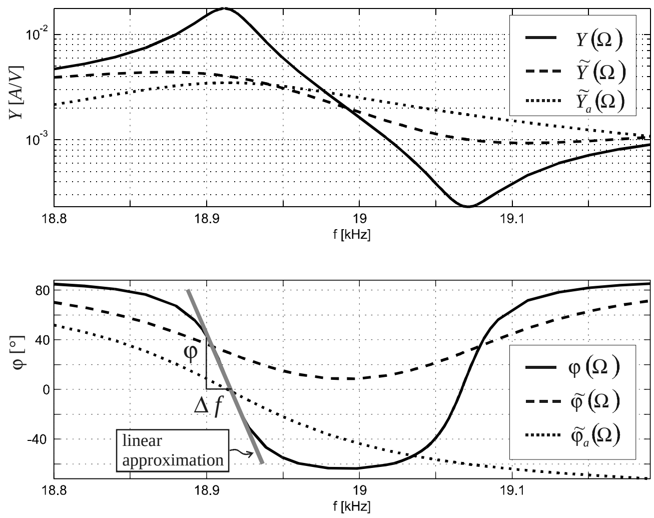

Figure 4: Admittance curves: free, strongly damped, and corresponding auxiliary admittance.

Frequently, a tuning inductor is placed in parallel to C_P [1]. It lowers the phase minimum far below zero for a rather large range of damping. Optimum matching will be achieved by tuning the inductor to the resonance frequency ω_0 of $\underline{Y}_a(\Omega)$ using the matching condition

$$L_P = \frac{1}{\omega_0^2 \, C_P} \ . \tag{6}$$

A major advantage of this solution is the reduced requirement of energy since the inductor cancels out the reactive power which allows to use smaller components in the power electronics.

Adaptive phase-locked loop controller

Different from the case with high damping, in applications with strongly varying damping, the described PLL phase controller does not work stable: Due to change in damping, the slope of the phase-curve is altered (see figure 3) and consequently, the amplification factor K ought to be adapted. Unfortunately, it is not possible to measure the actual “load-slope” corresponding to formula (4) as in the freely vibrating case since the load may change during the measurements.

A solution for this problem based on the electromechanical circuit model of figure 2 is as follows: The slope of the auxiliary phase curve $\tilde{\varphi}_a(\Omega)$ is expressed in terms of the circuit parameters, and the amplification factor is derived from

$$\tilde{K} = -\frac{1}{2\pi \cdot \tilde{\varphi}_a'(\tilde{\omega}_0)} = \frac{1}{4\pi} \cdot \frac{d + d_L}{m} \tag{7}$$

where $\tilde{\omega}_0 = \sqrt{(c + c_L)/m}$ (8)

is the resonant frequency in loaded condition.

Furthermore, the ratio α of the amplification factors in loaded and unloaded state is equal to

$$\alpha = \frac{K}{\tilde{K}} = \frac{\tilde{Y}_a(\tilde{\omega}_0)}{Y_a(\omega_0)} = \frac{d}{d + d_L} \ . \tag{9}$$

Here $\tilde{Y}_a(\tilde{\omega}_0)$ and $Y_a(\omega_0)$ are the maximum absolute values of the admittance in loaded and in unloaded condition, respectively. Accordingly, the amplification factor $\tilde{K}$ can permanently be adapted to the load state using the actual maximum absolute value $\tilde{Y}_a(\tilde{\omega}_0)$ of the auxiliar admittance. If the phase controller is able to keep the system perfectly in resonance, this value can be derived online by measurements (formula 5). Allowing small deviations, the actual measured complex admittance is used to calculate the maximum value at resonance (figure 5)

$$\tilde{Y}_a(\tilde{\omega}_0) = \frac{\tilde{Y}_a(\Omega)}{\cos(\tilde{\varphi}_a(\Omega))} \ . \tag{10}$$

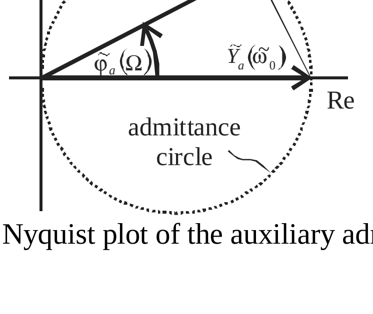

Figure 5: Nyquist plot of the auxiliary admittance.

This leads to the final result for the amplification factor for the loaded case

$$\tilde{K} = \frac{K}{\alpha} = K \cdot \frac{Y_a(\omega_0)}{\tilde{Y}_a(\Omega)} \cdot \cos(\tilde{\varphi}_a(\Omega)) \tag{11}$$

An adaptive PLL was developed and is presently validated experimentally.

Adaptive PLL for piezoelectric transformers

The simplified circuit model of a piezoelectric resonance transformer is similar to that of an ultrasonic actuator if both energy conversion steps on the input and output side are combined into one ideal transformer (figure 6). The main difference appears in the circuitry at the load side: While load stiffness and damping of an ultrasonic tool form a series circuitry, the load resistance R_L of a transformer is parallel to the transformer’s output capacitance C_B.

The input admittance curves of a typical piezoelectric transformer show a strong dependence on the load resistance (figure 7).

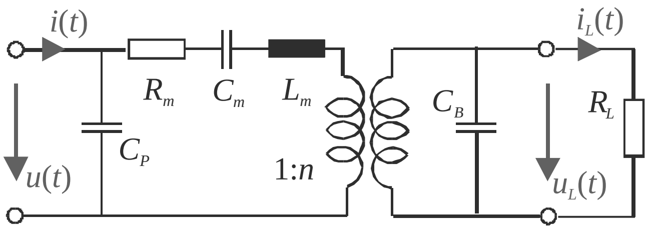

Figure 6: Circuit model of a piezoelectric transformer.

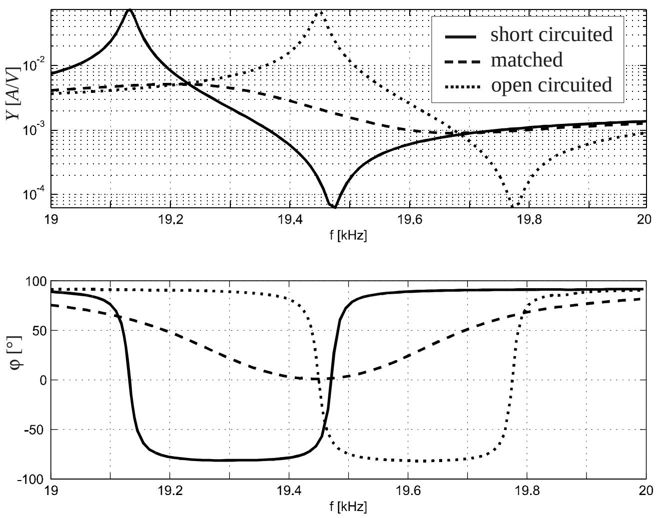

Figure 7: Input admittance of a transformer at different loading conditions.

For very low and very high loads the admittance is only slightly damped and has its resonance frequency near one of the extreme values for short-circuited ($R_L = 0$) or open-circuited ($R_L \to \infty$) state,

$$\omega_{sh} = \sqrt{\frac{1}{L_m C_m}} \text{, and } \omega_{op} = \omega_{sh} \cdot \sqrt{1 + \frac{C_m}{n^2 C_B}} \ . \tag{12}$$

In contrast, the system is strongly damped if the load resistor R_L is chosen according to the matching condition

$$\tilde{\omega}_m C_B R_L = 1, \tag{13}$$

where $\tilde{\omega}_m \approx \sqrt{\omega_{sh} \cdot \omega_{op}}$ is the resonant frequency at matched state. The strong variation of the load dependent amplification factor $\tilde{K}$ may be estimated by the more common quality factor of the admittance curve

$$\tilde{Q} = \frac{\tilde{f}_0}{2 \cdot \left(\tilde{f}_0 - \tilde{f}_1\right)} = \frac{\tilde{f}_0}{2\tilde{K}} \tag{14}$$

which finds its minimum value also for the matched case (figure 8).

For any given value of the load resistor R_L both maximum voltage step-up (α) and maximum efficiency (η) will appear at the appropriate resonance frequency $\tilde{\omega}_0(R_L)$. Their values are plotted over the load for a given transformer in figure 9.

Since maximum step-up and maximum efficiency do not appear at the same load resistance, it would be desirable to drive the transformer in resonance for the whole load range shown in the graphics. This task is solved by the adaptable PLL-controller explained in the previous paragraph: Since it is possible to replace the parallel circuitry at the load side by a series RC-circuitry for any given frequency, the amplification factor $\tilde{K}$ of a transformer may be adapted to the actual load resistance based on the auxiliary admittance $\underline{\tilde{Y}}_a(\Omega)$ in similar manner as shown before.

All measurements of figures 8 and 9 have been executed on a piezoelectric transformer using the adaptaptive PLL controller for excitation in resonance. Solid lines are calculated from circuit parameters which have been identified from measured admittance curves in advance.

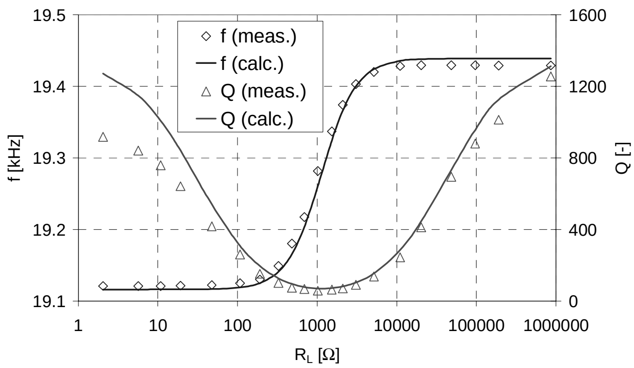

Figure 8: Resonant frequency (f) and quality factor (Q) over load resistance (R_L).

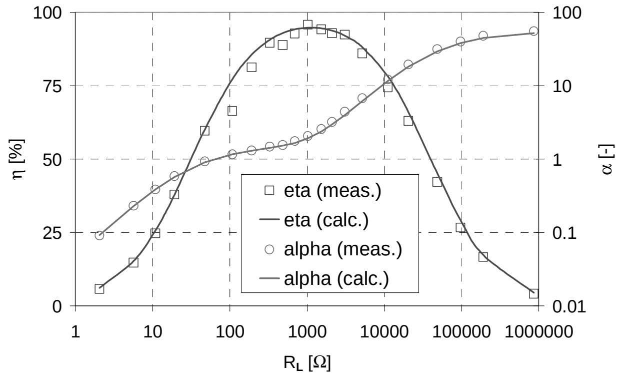

Figure 9: Voltage step-up (α) and efficiency (η) over load resistance (R_L); measured in resonance.

Conclusion

A new adaptive phase controller for driving piezoelectric actuators as well as transformers in resonance has been developed. It is capable of adapting to the actual load state of the ultrasonic system on its own. Theoretical investigations have been confirmed by measurements on a piezoelectric transformer.

Aknowledgement

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