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A control system for ultrasound devices utilized for inactivating *E. coli* in wastewater

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ABSTRACT

Sonochemical processes applied to wastewater treatment have an influence on the behavior of ultrasonic systems. This is especially due to the load characteristic of the sonochemical process itself and the temperature increase caused by internal damping within the converter. Hence, a controlling device is needed to guarantee the operation in resonance and to keep the vibration amplitude constant. This paper presents a digital control system for the operation of weak to strong damped ultrasonic devices and its application for inactivating *Escherichia coli* in wastewater. In an experimental investigation, the electric data during a sonochemical process to inactivate *E. coli* in wastewater is taken into account to analyze the efficacy of the treatment process and the reaction of the vibration system to the process. Frequency response measurements depict that the resonance frequency changes with the sonicated medium and the vibration amplitude decreases with driving current. In addition to a common continuous operation of the system, different pulsed modes are investigated. The experiments prove the common dependencies between inactivation and power level or treatment time. Additionally, it is pointed out that the control of the sonochemical device is of utmost importance to guarantee an efficient treatment of water, because fast process changes, especially in pulsed operation modes, need to be controlled to a steady state as fast as possible. Although a water treatment efficiency increase using pulsed modes was not proved, it is shown, that the performance of the control unit is capable of using different driving modes in water treatment.

1. Introduction

Water scarcity in many regions around the globe forces municipalities to consider water reuse options to gain potable water. In the chain of processes involved in the treatment of wastewater, the removal of fecal pollution by disinfection processes is imperative. One of the most used disinfection methods is ultraviolet light (UV), which damages the DNA of the microorganisms thus preventing its multiplication [1]. However this method has two well-known disadvantages: the DNA damage is reversible and UV does not inactivate microorganisms enmeshed in small flocs and adsorbed on the inner surfaces of solids. Furthermore, chemical disinfection methods are frequently associated with the formation of undesirable disinfection byproducts. A promising technique to disinfect water and to overcome these disadvantages is the ultrasonic water treatment process. When introducing ultrasound to water, high mechanical stress arises and cavitation bubbles are formed. On a certain pressure level these cavitation bubbles implode and high local temperatures (up to 5000 °C [2]) and local pressure (up to 500 atm [2]) occur. The high local temperature leads to a pyrolytic reaction that enables the formation of free radicals that can attack biological contaminants [3]. With the mechanical forces and chemical reactions, a huge bandwidth of pollutants can possibly be destroyed. The feasability has already been proven by various scientists [4–6].

Furthermore, pulsed modes have already been investigated by Antoniadis et al. [7]. They used long pulse durations of 9 s on – 1 s off and 5 s on – 5 s off. The results show that the continuous mode leads to a faster *Escherichia coli* reduction than the pulsed modes, even when only considering the on-time. Al-Juboori et al. [8] treated water with shorter pulsed duration of 0.1 s on – 0.6 s off and 0.2 s on – 0.1 s off. They used a statistic model to predict the total coliform reduction and they came to the conclusion that pulsed ultrasound has a negative effect on total coliform reduction and this negative effect can even offset the effects of higher power or longer treatment time.

Neither of these studies took into account that the pulsed operation could lead to different behavior of the vibration system as well as a different behavior of the control unit. But, if the control unit is too slow or not optimally adjusted for the mode, the pulsed mode can negatively affect the procedure. For this reason, in this work, both the *E. coli*

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reduction as well as the electric behavior of the vibration system will be taken into account to emphasize the importance of the control unit.

In the present study, *E. coli* was used as an indicator of faecal pollution in wastewater because it is found exclusively and in large numbers in faeces from human and warm-blooded animals, it does not multiply in the environment and it can be detected by simple and inexpensive methods [9]. However, this indicator does not reveal the total spectrum of water borne pathogens, namely virus and parasites.

In addition to the analysis of the water quality the impact of the process on the control unit will be evaluated. A continuous operation mode will be compared to different pulsed modes. The desired benefit of a pulsed operation is a more energy efficient process. Since the cavitation bubbles do not disappear as soon as the ultrasound is turned off, but stay a short time longer, there is always cavitation inside the medium, although the ultrasound is turned off, or the energy is reduced for a short period.

2. Materials and methods

2.1. Experimental setup

For the *E. coli* inactivation experiments a commercial sonifier (Branson Sonifier W-250) is used. The vibration system consists of a converter with a disrupter horn and a microtip attached. The tip diameter of the microtip is 6.4 mm and it is placed 3 cm under the surface of the water where it creates cavitation bubbles. The polluted water is sonicated inside of a rosett cell that is cooled with water in a cooling vessel. The commercial control unit is replaced by the phase-locked loop control system DPC500/100k that has been developed at the Institute of Dynamics and Vibration Research [10,11]. The control unit controls the phase between current and voltage, as well as the current amplitude with a control cycle of 500 Hz. To operate the vibration system in resonance, the desired phase value is set to $\varphi = 0°$. In resonance the current amplitude is proportional to the vibration amplitude, so the vibration system is controlled to a defined displacement amplitude. The inputs for the control system are the current and voltage signals from the transducer that are measured by a current probe (Tektronix TCP A300 Amplifier and Tektronix TCP312A) and a voltage probe (Hameg Hz100 1:200). The control unit then generates the sinusoidal driving signal for the transducer that is amplified by the power amplifier (QSC RMX-4050), see Fig. 1. Additionally, the voltage is increased by a transformer with a ratio of 2.5:1.

In order to run a pulsed operation, a new mode for the DPC500/100k has been designed. The mode switches the target value of the current amplitude between 2 adjustable values. This means there are no classic off and on states, but two states with different amplitudes. This method makes it easier to control the phase than it would be with off-states between the on-states. Each target value is then set for a defined number of cycles.

For the data acquisition, an USB oscilloscope (Picoscope 5203) is used and connected to a notebook running a Labview program that visualizes and saves the calculated current amplitude, voltage amplitude, frequency, phase between current and voltage as well as power over the whole process in defined cycles. Additionally, segments of the time data of the current and voltage are logged. For the time data a 200 ms and 1000 ms sequence for short and long pulse modes, respectively, are logged with 250.000 samples per second. This system makes it possible to evaluate the data over the whole process as well as the high frequency data during the process.

In preliminary experiments the cavitation activity is observed. To visualize and quantify the occurring cavitation, a high-speed camera (Phantom v710) is used, which is focused on the part of the rosett cell in which the highest cavitation activity is expected.

2.2. System identification

The characteristics of the system are determined utilizing frequency response measurements. To illustrate the influence of the water and the cavitation to the vibration system, frequency response measurements for different power levels and media are performed. For the response the driving frequency is increased by 0.5 Hz steps and in every step the measured values are averaged over 100 cycles.

To measure the dependency between driving current and vibration amplitude, a fiberoptic laser-doppler-vibrometer in in-plane configuration is used. First, the vibration amplitude at the tip of the sonotrode and at a further spot in the middle of the vibration system is measured in air to discover the transmission ratio between these two points. In the next step, the system is driven with its tip in water at different controlled current amplitudes. Meanwhile, the amplitude at the spot outside the water is measured. From this data the vibration amplitude per ampere can be calculated.

The control parameters are then calculated using an approximation formula, based on an equivalent model of the piezoelectric system [11]. The required equivalent model parameters are calculated from the measured data. The parameters are then used to estimate the settling times for the phase and current controller using the following equations:

$$\tau_{\varphi} = \frac{1}{k_{\mathrm{p}}}, \tag{1}$$

$$\tau_{\mathrm{c}} = \frac{2L_{\mathrm{m}}}{k_{\mathrm{pc}}K}, \tag{2}$$

where τ_{φ} and τ_{c} are the estimated settling times for phase and current,

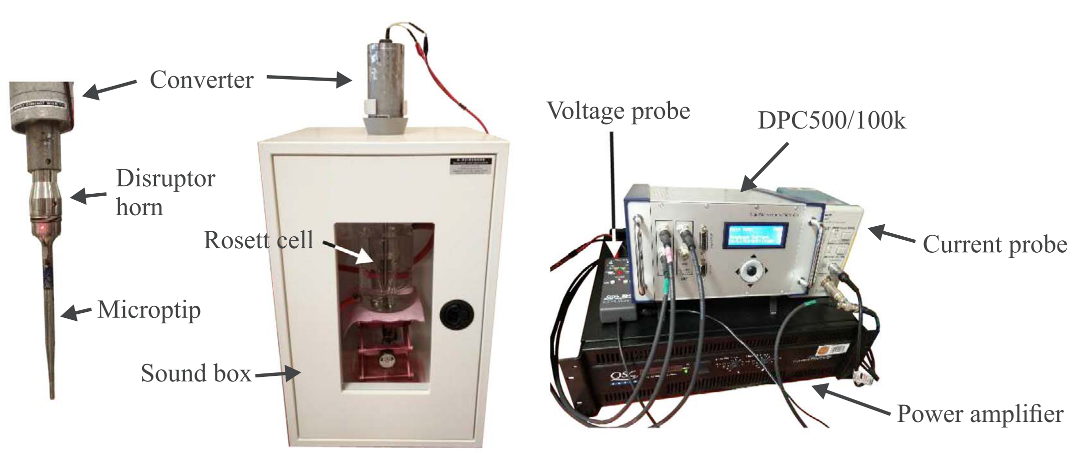

Fig. 1. Setup for *E. coli* inactivation experiments.

respectively, k_p and k_{pc} are the parameter for the PI-controller for phase and current control, L_m is the equivalent inductance and K is the amplification factor of the power amplifier.

2.3. Wastewater samples and method to quantify E. coli

Wastewater samples for the ultrasound experiments were collected from the Herrenhausen municipal wastewater treatment plant with a capacity of about 500.000 population equivalents. Wastewater samples collected after the primary clarifier and diluted 1:10 were used in the present study. Samples were taken before and after the ultrasound treatment for the quantification of *E. coli* following the Colilert method. This method utilizes a nutrient indicator that produces fluorescence when metabolized by *E. coli*. Results were expressed in Most Probable Number (MPN) of viable cells in 100 mL of sample. The analyses were done by the Public Health Office of Lower Saxony (NLGA) in Hannover.

2.4. Experimental procedure

In each experiment, 50 ml of polluted water is filled into the rosett cell. The cell is then lifted to a certain height, so the depth of the microtip is equal for all experiments. Subsequently, the data acquisition system and the control and driving units are started, after the new parameters are set up in the control unit. In all parameter sets the low level to high level pulse duration ratio is 1, so the low level duration equals the high level duration. For every parameter set the experiment is executed for 5 min and 10 min. After the desired time, all devices are turned off and the treated water is instantly filled into a sterile bottle. Every experiment is repeated twice to examine the replicability. The pulse durations, desired current values and desired mean power of the different experiments are listed in Table 1.

The high and low level desired values of the current are chosen in a manner that the maximum vibration amplitude of the sonotrode remains below its named limit and the mean power is similar to the power of the corresponding continuous mode. Since the settling time of the current (Eq. (4)) is much higher than the pulse duration of the fast pulses, it is expected that the desired values will not be reached and a triangular behavior of the current amplitude should be present.

3. Results and discussion

In the present study the electric measurements as well as the *E. coli* quantification are taken into account. The dependency between the behavior of the vibration system and the *E. coli* inactivation is analyzed.

First, the vibration is analyzed using the frequency and phase response of the system. Fig. 2 shows the results of this measurement. In Fig. 2a) the electrical admittance is depicted, Fig. 2b) shows the corresponding phase, in each case for a frequency range of 200 Hz between 19,800 Hz and 20,000 Hz. The response when operating the system in air with a low amplitude looks like an usual response of an ultrasonic vibration system, where a clear resonance and antiresonance can be observed in the peaks of the admittance as well as in the zero-crossings in the phase. When operating the system in water with the same parameters, the resonance frequency shifts to lower frequencies because of the change in the load impedance. At the low level operation there is no cavitation during the measurement. With increasing power nonlinearities arise, represented by jump phenomena in admittance and phase. Additionally, the damping increases with the amplitude, which can be seen in the gradient of the phase near the resonance.

Table 1
Parameter set for *E. coli* inactivation.

Set	t_{pulse}	$i_{high-level}$	$i_{low-level}$	P_{mean}
	Const.	750 mA	750 mA	40 W
1	10 ms	1300 mA	200 mA	40 W
	20 ms	1220 mA	200 mA	40 W
	Const	625 mA	625 mA	30 W
2	100 ms	1085 mA	200 mA	30 W
	200 ms	1085 mA	200 mA	30 W

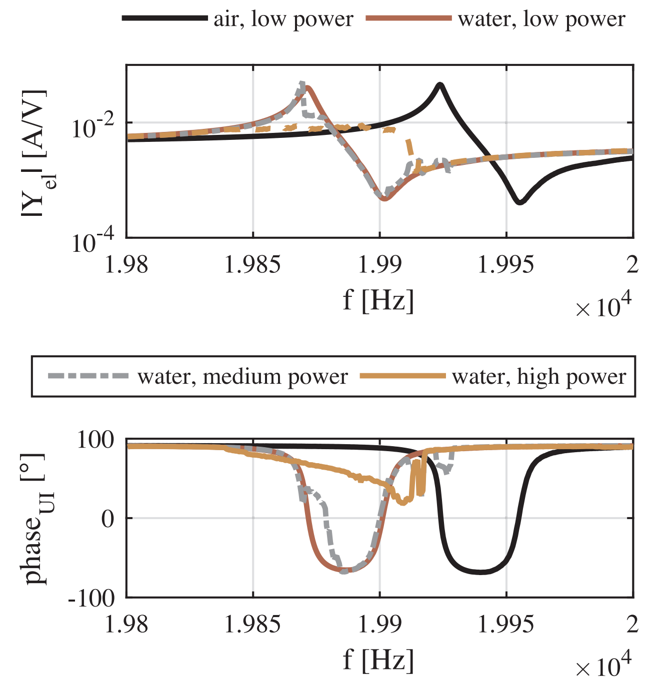

Fig. 2. a) Frequency response functions and b) phase response functions at different power levels in air and water.

Furthermore, the phase does not reach $\varphi = 0°$ with increasing damping, so the usual phase zero control will not work without any further modification. The frequency responses demonstrate that the system is markedly dependent on the process itself and is nonlinear, thus leading to a challenging control task.

The vibration amplitude per ampere is calculated with the transmission ratio to

$$\hat{x}(\hat{i}) = 112\frac{\mu\text{m}}{\text{A}}\hat{i}, \tag{3}$$

where $\hat{x}$ is the vibration amplitude and $\hat{i}$ is the current amplitude. With this equation a linear system in the operation range is assumed. Since the maximal permissible vibration amplitude given by the manufacturer is $\hat{x}_{max} = 123.5$ μm, the current amplitude should remain below $\hat{i}_{max} = 1.1$ A for a resonant operation.

For the used PI-controller parameter set, the settling times are calculated with Eq. 1 and Eq. 2 to

$$\tau_\varphi = 11.6 \text{ ms} \tag{4}$$

$$\tau_c = 68 \text{ ms}. \tag{5}$$

In a preliminary experiment the temperature of the sonicated medium is measured during a sonication process. Therefore a PT100 sensor measures the temperature at the bottom of the rosett cell and the data are logged every second. The measurements show that the temperature rapidly increases within the first 2.5 min and then stays at the saturation temperature of 29 °C. This temperature is below the inactivation temperature of *E. coli* so the reduction in the following experiments can be ascribed to the ultrasonic effects.

For the *E. coli* reduction experiments, first, the comparability of the wastewater treatment experiments, with respect to the input power, is investigated. Therefore, the measurements of the mean power over the whole process time are considered. The values are calculated from the measured current and voltage data. Both, the results of the 5 min experiments as well as the 10 min experiments show similar results of

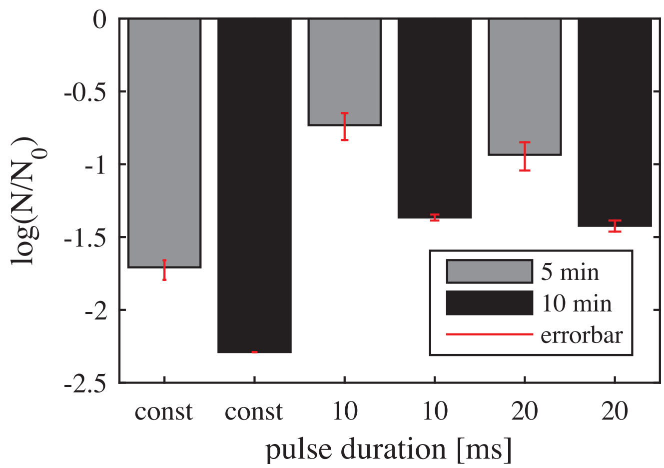

Fig. 3. Results of the first set (errorbar represents minimum and maximum of the repeated experiments).

the power for each set. In the first set the mean power for all modes is around 40 W, in the second set around 30 W. Since the power within each set is quite similar, the power is not regarded as a factor of influence in the presented *E. coli* inactivation experiments.

Fig. 3 shows the corresponding logarithmic *E. coli* reduction of the first experimental set with short pulse durations of 10 ms and 20 ms and a continuous operation with a similar power level. The logarithmic *E. coli* reduction is defined as the logarithmic value of the final *E. coli* MPN normalized to the initial MPN (739900 *E. coli* MPN/100 ml). The errorbars indicate the minimum and maximum of the repeated experiments, the reduction bar shows the mean value. For the 10 min continuous operation the results from the NLGA did not quantify the reduction within upper and lower limits, but only with an upper limit. This means the reduction is probably higher than depicted in the figure. Since both repetitions have the same upper limit, the errorbar has a length of zero.

In all operating modes, 10 min of sonification leads to a higher reduction of *E. coli* than 5 min of sonification. The reduction in the pulsed modes is significantly lower than in the continuous operating mode, although the input power is quite similar and the high-speed videos from the preliminary experiments show that cavitation exists in both excitation levels. To explain this behavior the high-frequency data, shown in Fig. 4 and Fig. 5, is taken into account. These data show a 200 ms sequence of the operation that is measured with 250.000 samples per second. From the high-frequency data the current amplitude and phase between current and voltage are calculated and depicted in the figures. In the continuous operation the control unit is capable to control the current to the desired value. In the pulsed modes

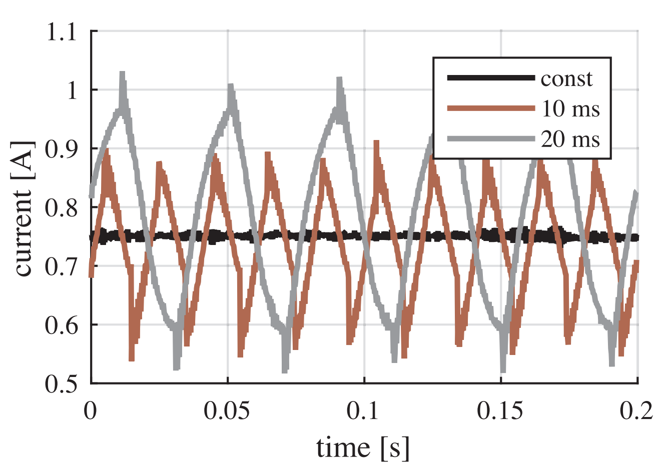

Fig. 4. Current amplitudes of the first set.

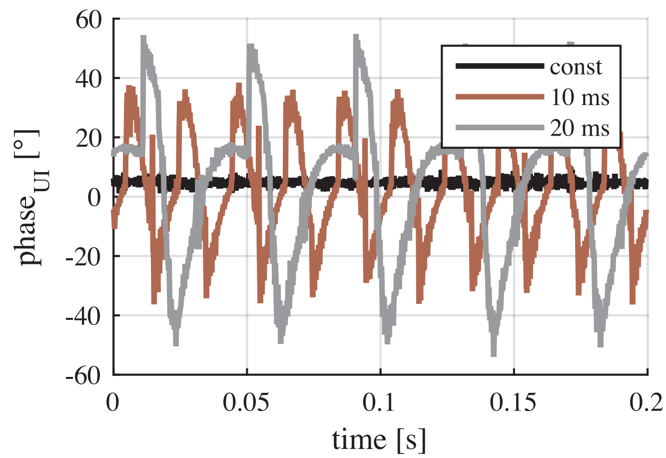

Fig. 5. Phase between current and voltage of the first set.

the current amplitude oscillates between a low and a high level that is different from the desired value. This behavior was also expected, since the settling time τ_c (Eq. (4)) is much higher than the pulse duration. Nevertheless, a defined operation is present, since the necessary desired high and low level values were estimated with preliminary experiments to set up the mean power level. As expected, this parameter set leads to a triangular function of the current that is oscillating around the current of the continuous operation.

It can be observed in Fig. 5 that the phase between current and voltage for the continuous operation is controlled to its desired value. In the pulsed modes the phase is not controlled to a constant value within the pulse duration. Thus, the vibration amplitude is lower than calculated by Eq. (3), because the operation is not exactly in resonance. With smaller vibration amplitudes there is less cavitation in the water and therefore lower *E. coli* reduction. This behavior can explain the lower efficacy of the pulsed operation compared to the continuous operation.

In the second set, where the pulse durations are 100 ms and 200 ms, the positive correlation between sonication time and *E. coli* reduction is proven. Additionally the dependency between mean power level and *E. coli* reduction can be extracted from Fig. 3 and Fig. 6, since the lower power in Fig. 6 leads to a lower *E. coli* reduction. In contrast to the short pulse durations, the inactivation efficiencies of the long pulsed operations are similar to the continuous mode. The desired added value in utilizing the post-cavitation effects in the low excitation cycles do not occur, because the low cycles are too long, so a steady lower cavitation state is reached.

Looking into the converted high-frequency data, a big difference to

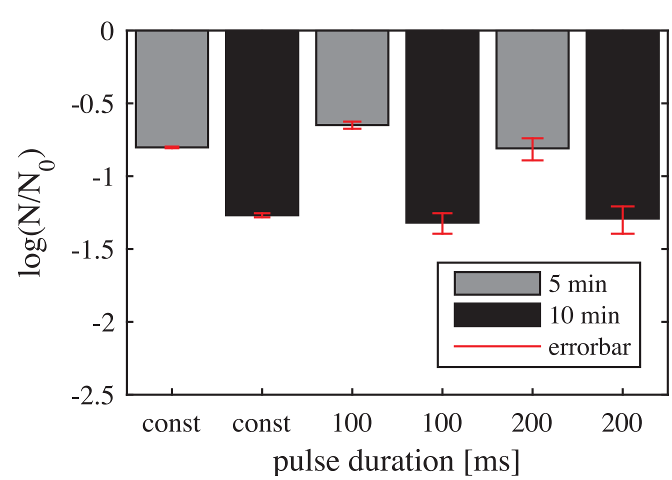

Fig. 6. Results of the second set (errorbar represents minimum and maximum of the repeated experiments).

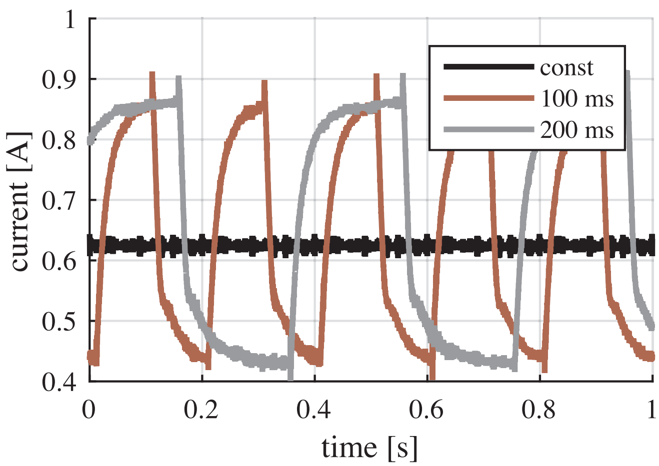

Fig. 7. Current amplitudes of the second set.

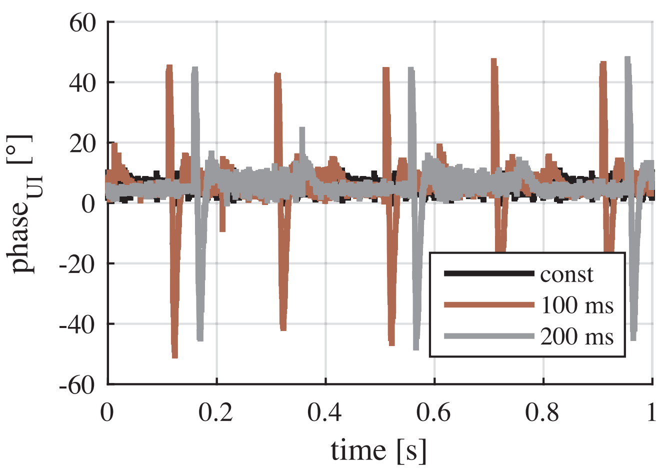

Fig. 8. Phase between current and voltage of the second set.

the short pulse durations is observed. In Fig. 7, it is apparent that the current does not reach its desired value, but stays approximately constant for more than 50% of the cycle. This behavior can occur when the control parameters do not perfectly match the system. In this case the control parameters are estimated for the unloaded system, but during the operation the high amplitude and the cavitation changes the systems behavior, so the control parameters need to be adjusted. This observation demonstrates the importance of taking the systems behavior and control into account. Nevertheless, the operation shows a typical pulsed behavior, so the results can be treated as if different desired amplitudes are set. The phase between current and voltage reaches a constant value within a short period of the pulse duration (Fig. 8). The phase then stays near $\varphi = 0°$, which means a resonant operation is present and the current amplitude is proportional to the vibration amplitude. Therefore, a vibration amplitude higher than that in the short pulsed mode is expected, which leads to sufficient cavitation and *E. coli* reduction.

4. Conclusion

The characterization of the system demonstrated that it is important to have an efficient control unit for water treatment processes, since the system changes with the sonicated medium and the vibration amplitude. The study showed that the pulse durations have little or even negative impact on the efficacy due to the obtained control dynamics. For the long pulses this can be explained by the too long pulses which lead to two steady cavitation states and the effectiveness is similar to the mean power level. The logged data of the short pulses show that the system was not controlled optimal, so the system is operating with a lower efficiency which leads to lower *E. coli* reduction. Nevertheless it has been shown that the control system is capable of driving ultrasonic systems for water treatment purposes in different operation modes. It allows to easy implement new strategies, like the here shown pulsed operation. The presented results also depict the importance of taking the high-frequency electrical data of a vibration system during the process into account to explain the outcoming results.

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