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Closed loop cavitation control – A step towards sonomechatronics

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ABSTRACT

In the field of sonochemistry, many processes are made possible by the generation of cavitation. This article is about closed loop control of ultrasound assisted processes with the aim of controlling the intensity of cavitation-based sonochemical processes. This is the basis for a new research field which the authors call "sonomechatronics". In order to apply closed loop control, a so called self-sensing technique is applied, which uses the ultrasound transducer's electrical signals to gain information about cavitation activity. Experiments are conducted to find out if this self-sensing technique is capable of determining the state and intensity of acoustic cavitation. A distinct frequency component in the transducer's current signal is found to be a good indicator for the onset and termination of transient cavitation. Measurements show that, depending on the boundary conditions, the onset and termination of transient cavitation occur at different thresholds, with the onset occurring at a higher value in most cases. This known hysteresis effect offers the additional possibility of achieving an energetic optimization by controlling cavitation generation.

Using the cavitation indicator for the implementation of a double set point closed loop control, the mean driving current was reduced by approximately 15% compared to the value needed to exceed the transient cavitation threshold. The results presented show a great potential for the field of sonomechatronics. Nevertheless, further investigations are necessary in order to design application-specific sonomechatronic processes.

1. Introduction

Acoustic cavitation, that is the generation of cavitation by sound wave induced pressure changes, is used in many sonochemical processes like mixing or emulsification or for ultrasonic cleaning. Independent of its mechanism of generation, cavitation can be detected by vibrations (oscillation and implosion) caused by cavitation bubbles. Hydrodynamic cavitation in valves [1] or pumps [2] for example can be monitored observing the occurrence of certain frequency components. In acoustic cavitation, the generated frequency components are mostly related to the driving frequency f_0 of the ultrasound transducer [3–10]. Researchers [11–14] have shown that with a so called self-sensing technique, that is using the ultrasound transducer simultaneously as both an actuator and a sensor, indicators for the presence of cavitation can be detected by observing the transducer's electrical signals. By now the transducer data [12,13] have been compared to those of microphones and hydrophones in order to reach a conclusion on the processes in the fluid. With this, the onset of cavitation and the transition between stable and transient or inertial cavitation could be detected but no quantification was possible.

In this contribution, a link is established between the cavitation activity determined from photographs and indicators in the transducer's electrical data (self-sensing). This provides a new possibility for process monitoring. During the investigation of this monitoring technique, it was found that the hysteresis effect of cavitation [10,16–18] – mechanical amplitude can be reduced without affecting cavitation intensity after the threshold for inertial cavitation is exceeded – can also be monitored using self-sensing. The hysteresis effect offers an opportunity to energetically optimize acoustic cavitation generation. Because inertial cavitation is of a transient and chaotic nature, this process undergoes partly violent fluctuations. Therefore, an open loop process control is not sufficient for optimization. The design of a closed loop control is necessary.

Currently, several approaches to active closed loop cavitation control are known. For medical HIFU therapy by tissue heating [19–21] a feedback system has been designed. To monitor cavitation activity during tissue heating, a passive broadband single-element cavitation detector [22] is used as additional sensor. For the application of sonoporation several authors report closed loop concepts with hydrophone measurements to determine cavitation activity [23–26].

In Ref. [27] also a hydrophone is used to monitor acoustic emission of cavitation generated by a plane piezoelectric transducer for sonoporation. A closed loop is established to alter acoustic intensity based on acoustic emissions. These recent publications show that closed loop

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control of cavitation is a valuable target. Additional motivation to implement closed loop cavitation control are high power processes such as ultrasonic assisted hybrid casting [14], there cavitation is utilized to enable a pure metallic bond between aluminum melt and solid copper. The intensity of cavitation is crucial for the quality of the connection. Since the few known implementations of closed loop cavitation control are application focused a transfer to further processes is needed. This encourages to propose a general concept for process control of acoustic cavitation regardless if further sensors can be used or not.

In this contribution the concept of monitoring acoustic emissions for closed loop cavitation control is applied to an exemplary sonochemical power ultrasound process. Instead of using an additional sensor like a hydrophone, the self-sensing concept is implemented for detection of acoustic emissions. In order to be able to generate cavitation application-specific in this contribution, a double set point closed loop control [28] for controlling cavitation intensity for power ultrasonics is presented. As control parameter, an indicator in the ultrasound transducer's electrical signals is used, which makes the application of additional measuring equipment unnecessary. Next, the concept of sonomechatronics is described in detail. Subsequently, the principle of the applied self-sensing technique is explained, the experimental setup is described and the transducer's sensor characteristic is investigated. This is followed by the explanation of the possibility of energetic optimizability and finally the implemented closed loop control is presented.

2. Introducing the concept of sonomechatronics

The concept of sonomechatronics is based on a classic mechatronic concept, where mechanics, electronics and information technology are combined in one system. For a sonomechatronic system, the classic mechatronic concept is expanded and includes the chemical domain, see Fig. 1. The combination of mechanics, or in this case acoustics, and chemistry is well known as sonochemistry. The sonomechatronic concept then combines sonochemistry with electronics and information techniques which makes it possible to observe and control sonochemical processes. Most sonochemical processes are not controlled by means of the sonochemical results. For example, the process time or energy are based on experience values. For this reason, it is most probable that the process is unnecessarily long or the energy input is higher than necessary to guarantee a completed sonochemical process. This directly leads to a waste of energy. To overcome this issue, sonochemical processes can be sensed and the sensor data can be used to adapt the ultrasonic system. With this attempt, the transducer can be driven in an operation condition that fits the sonochemical process and stops when the desired processing result is reached. This approach can be reached using two control loops, see Fig. 2. The inner control loop controls the ultrasonic system to drive it in resonance at desired amplitude.

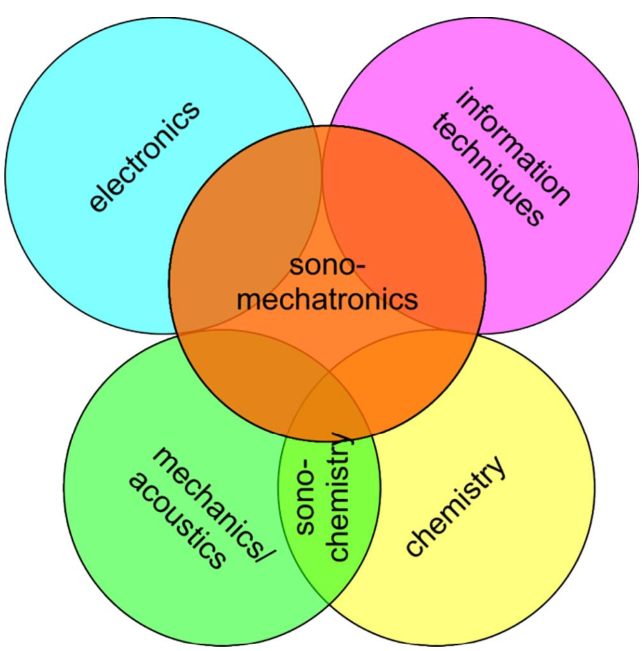

Fig. 1. Concept of sonomechatronics – different disciplines.

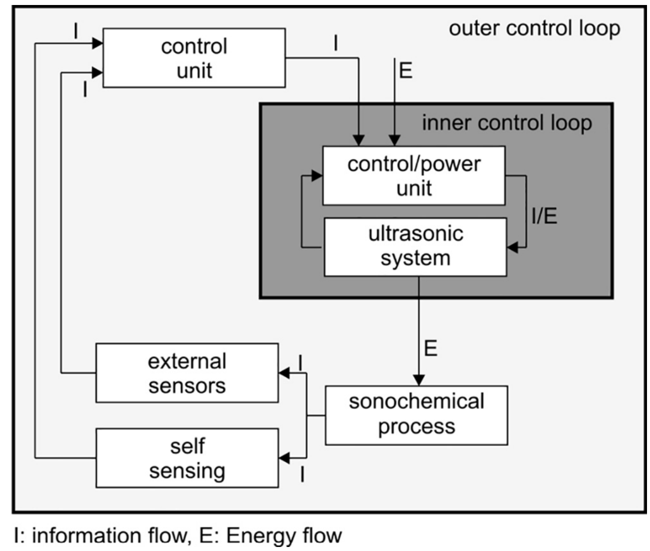

Fig. 2. Inner and outer control loop in sonomechatronical applications.

In order to bring the system in an optimal operation condition for the process, the outer control loop uses the sensor data or self-sensing data to adapt, for example, the desired driving amplitude or power for the inner control unit. The system will be turned off as soon as the desired result is reached and sensed, thus the issue of overprocessing is solved.

3. Principle of self-sensing cavitation detection

For clarification before the experimental setup is described and the results are presented, the principle of self-sensing cavitation detection is now explained in more detail.

The bolt clamped piezoelectric power ultrasound transducer [29], used for this investigation, consists of three different parts. A converter, a booster and a Sonotrode, which is in contact with the process medium. The transducer used for this investigation is an experimental transducer manufactured at Institute of Dynamics and Vibration Research driven at its third longitudinal eigenmode at a frequency of approximately 20 kHz. Driving the transducer in resonance has the benefit that the phase value between the electrical current and voltage at the transducer's terminals is 0°, which corresponds to a purely resistive behavior. For the transducer used in the experiments, as typical for ultrasound transducers driven at resonance, at this driving point the relationship between electrical current and displacement amplitude is linearly proportional. A sketch and a photo of the mounted transducer are shown in Fig. 3.

By applying voltage to the piezoelectric ceramics, the converter is mechanically excited by the inverse piezoelectric effect. The vibration is transferred to the tip of the sonotrode via the geometry. The transducer's transfer function changes when a load is applied to the tip of the sonotrode. These changes include, for example, a shift in resonance frequency, f_0, and the electrical admittance, Y_{el}. The basis of self-sensing cavitation detection is the fact that the converter is able to convert electrical signals in mechanical vibration and vice versa. When