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Fundamental experiments as benchmark problems for modeling ultrasonic micro-impact processes

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Abstract Many ultrasonic processes are based on the mechanical contact of oscillating parts. Within ultrasonic machining (drilling, milling, grinding) micro impacts lead to abrasion at the processed workpiece and hopefully do not damage the tool. In ultrasonic motors ideally neither part gets worn. Thus the appropriate design of contact partners as well as their kinematics is a substantial task during the development of such devices. A first step to optimize contact mechanics is to understand their behavior and dependencies on parameter variations, such as vibration amplitude and pre-stress of the impacting parts. For a detailed understanding models validated with convincing experimental data from measurements are absolutely essential. This paper focuses on simple vibro-impact experiments which can be used as benchmark data for future models. The setup of the experiment and first experimental investigations are described in detail.

Keywords Contact measurements · Vibro-impact · Ultrasonic application

1 Introduction

Contact mechanisms are a major part in various ultrasonic applications, such as ultrasonic motors or ultrasonically assisted machining. Even where some of such systems are already commercialized, the contact mechanism is neither fully understood nor modeled in a sufficient manner. Mostly only input to output relations are grasped by simple testing without understanding the vibro-impact process in detail.

Obviously there is a lack of knowledge concerning impact modeling in ultrasonic applications. The classical approach for rigid body impacts, i.e. neglecting the contact duration and describing the energy loss by means of a coefficient of restitution fails, because one important requirement is not met: Impacting bodies are not allowed change their positions or orientations during the impact, see e.g. Wittenburg [1]. This assumption seems to be incompatible with one of the bodies vibrating in the ultrasonic frequency range. This mathematically simplest form of dealing with impact as a nonlinear incidence also does not come into consideration because displacements and forces during the contact period—normal forces as well as tangential forces due to friction—are not included in the model formulation.

Much effort has been taken in analyzing different time continuous spring-dashpot models, simple linear models (e.g. Butcher and Segalman [2] and Babitsky [3]) as well as nonlinear models with hysteresis damping (e.g. Hunt and Crossley [4] and Pust and Peterka [5]) and models including remaining indentations due to plasticity, e.g. Lankarani and Nikravesh [6]. For rigid body collisions a lot of experimental data is available from Goldsmith [7] and more or less all these models have proven its applicability, but for superimposed ultrasonic vibrations experimental data and validated models are rare. One application specific experiment for ultrasonic motors can be found in Sashida and Kenjo [8].

Another class of models uses spatial discretization of the impacting bodies. Either in a simple Galerkin

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approach for the whole body, as done by Sattel and Brökelmann [9], or piecewise with the finite element method. The latter is rather popular for analyzing piezoelectric devices of all kinds. Regarding impact problems the finite element method is mostly used for analyzing single impacts with great accuracy (e.g. Wu et. al. [10], Zhang and Vu-Quoc [11], Seifried and Eberhard [12]). The analysis of a complete actuator with many impacts as in Frangi et. al. [13] remains the exception up to now. This is not least because of the vast computation time. Another finite element approach as well as a time continuous model of a piezoelecrtric vibro-impacting tool can be found in Potthast et al. [14].

In this contribution we focus on an experimental setup for the validation of contact models. The experimental results may been seen as a benchmark problem for any kind of impact model.

2 Experimental setup

The main criteria, which are important for an experimental setup are the following: Firstly the ultrasonic contact process must be performed in a stable and repeatable manner. Secondly the setup should be as simple as possible to focus directly on the contact process. The third requirement is measurability of all important measurable quantities. Those are for example the contact times (start and end of contact), the velocity or displacement of the contact point, and the operation parameters of the ultrasonic oscillator.

A picture and a schematic view of the experimental setup is given in Fig. 1. The main holding part of the test bench is a massive and heavy platform. The top steel plate is 20 mm thick and mounted on solid feet. The surface of the steel plate is the fixed contact region. On top of this platform a holding mechanism for an ultrasonic transducer is fixed. Which allows an axial movement of the oscilator using a linear guide. Also the holding mechanism also enables the user to chose a additional normal force, in the range from minus the weight of the actuator to approximately 50 N. As actuator a piezoelectric sandwich transducer with a stepped horn for a high amplitude at the tip is selected. The dimensions are: 8 mm diameter at the contact tip, 27 mm diameter at the free end, and about 113 mm in total length. Further, the transducer contains four prestressed piezoceramic rings. The resonance frequency of the first longitudinal mode is around 20 kHz. The actuator can perform an amplitude up to 20 μm at the contact tip, while it is driven in resonance.

For measurements of displacement and velocity a laser doppler vibrometer from Polytec (Controler: OFV-3001 Vibrometer: OFV-512) is used. In the fixed contact region on top platform is a small hole (2 mm in diameter) for measuring displacement and velocity of the transducer tip as near as possible to the actual contact point. An electrical circuit, a DC voltage source between transducer and surface, enables determination of contact duration, since the holding mechanism for the actuator is electrically insulated against the platform surface. The measured voltage level is used to decide if the contact is open (higher voltage level) or closed (low voltage level).

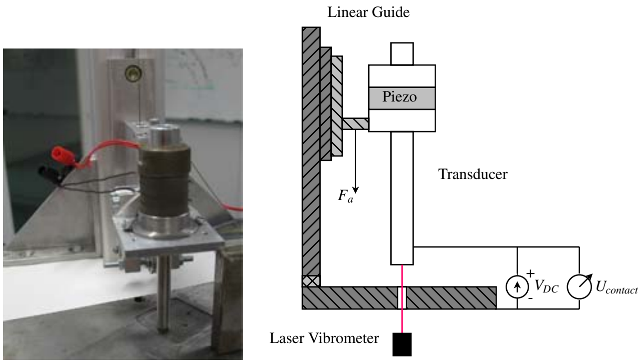
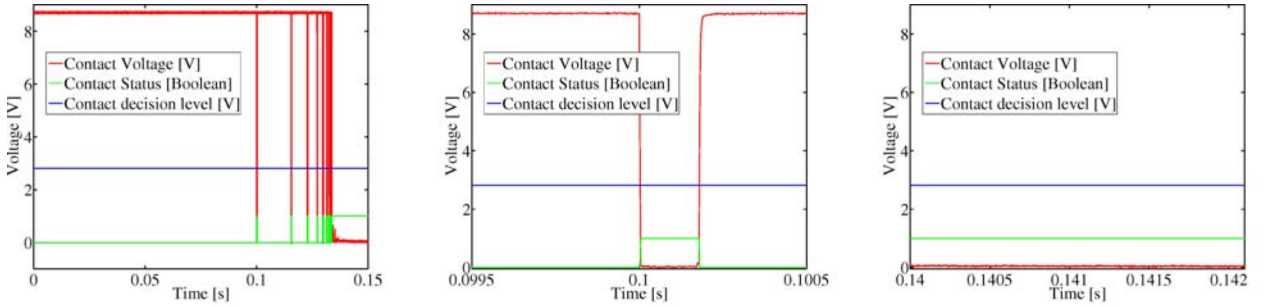


Fig. 1 Experimental setup

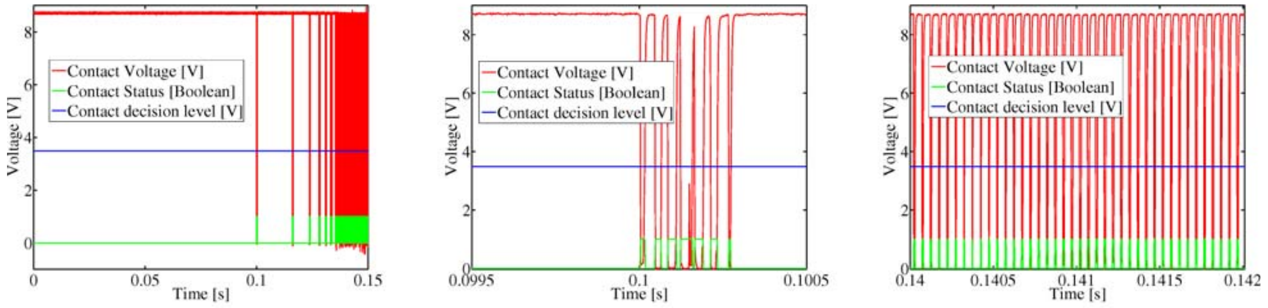
3 Measurements

The introduced test bench is used at first to prove its possibilities and usability. The transducer is dropped from a fixed height of 3 mm applying an additional normal force of 5 N during the whole time. The height is adjusted with an isolating spacer between platform and support of the transducer. In the beginning of the test the transducer rests on the spacer, then the spacer was smoothly removed and the actuator dropped on the platform. The measurements of contact voltage, tip displacement and velocity were performed, the signals were recorded with a Yokogawa DL706 oscilloscope. The drop tests are performed with two different starting conditions: at first the actuator is not powered, in the second test the actuator is driven with fixed frequency and approximately 250 V_{p-p} slightly below the resonance frequency. The frequency is chosen to avoid the strong non-linearity of the transducer in resonance. For the test with ultrasonic actuation the transducer is in a free-free steady state at the beginning of the recording.

Several of the described test are preformed and the recorded data is analyzed in the next paragraphs. At first the contact status is depicted in Fig. 2. The diagrams (a)–(c) show the behavior without ultrasonic movements, the lower row (d)–(f) depicts the test with



(a) Without ultrasonic actuation **(b)** Zoom on the first contact in (a) **(c)** Zoom in steady state in (a)

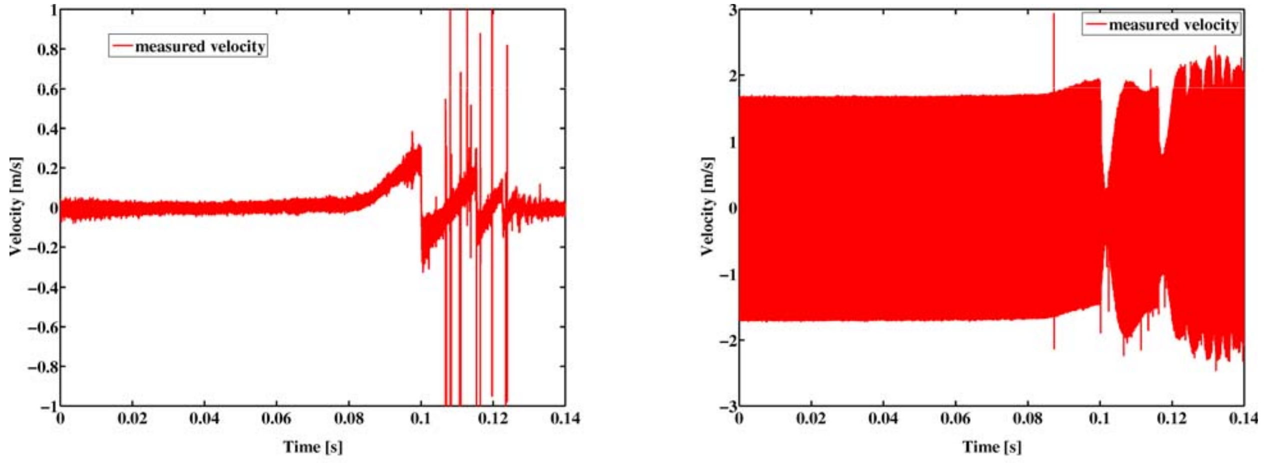


(d) With ultrasonic actuation **(e)** Zoom on first contact in (d) **(f)** Zoom in steady state in (d)

Fig. 2 Contact status during drop test with and without ultrasonic movements

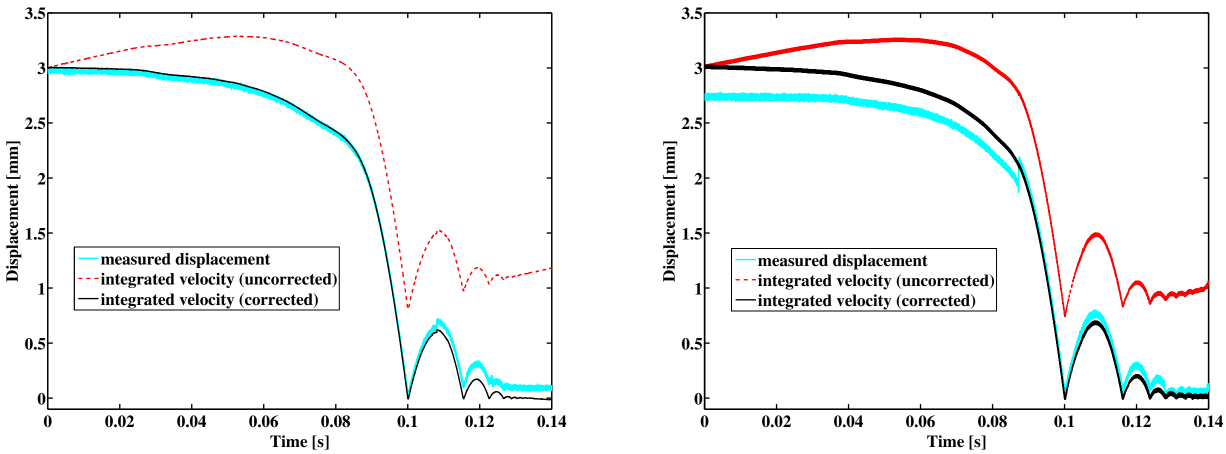
actuation. The measured voltage from the contact detection circuit (red line) is used to calculate a contact status signal. A threshold value (blue line) is used to define the status (green line). The diagrams show the expected behavior: The transducer hits the surface, bounces back after a short contact duration and so on. In the steady state the actuator rests upon the surface. In the actuated tests, the first macroscopic contact already contains multiple microscopic contacts. In the steady state the transducer finds and loses contact in the actuation frequency. Summarizing this, the contact detection shows its ability to identify contact status changes with ultrasonic frequencies.

The velocity of the actuator tip is shown in Fig. 3. Diagram (a) depicts the velocity without ultrasonic actuation, where the general behavior is like expected: The velocity increases until the first contact is reached, then the direction changes. This process repeats until the transducer rests on the surface. The noise in the signal is due to the measurement technology. Figure (b) depicts



(a) Without actuation **(b)** With ultrasonic actuation

Fig. 3 Measured velocity during drop tests

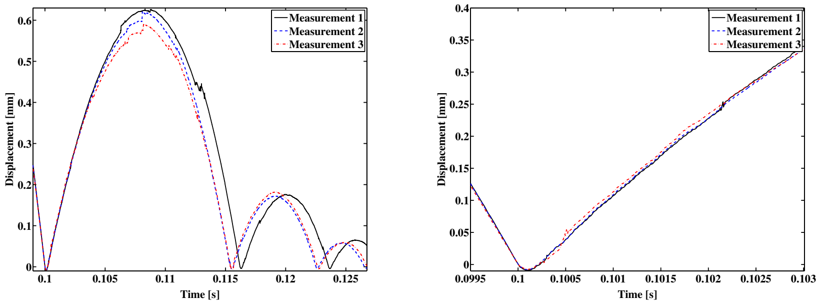


(a) Without actuation **(b)** With ultrasonic actuation

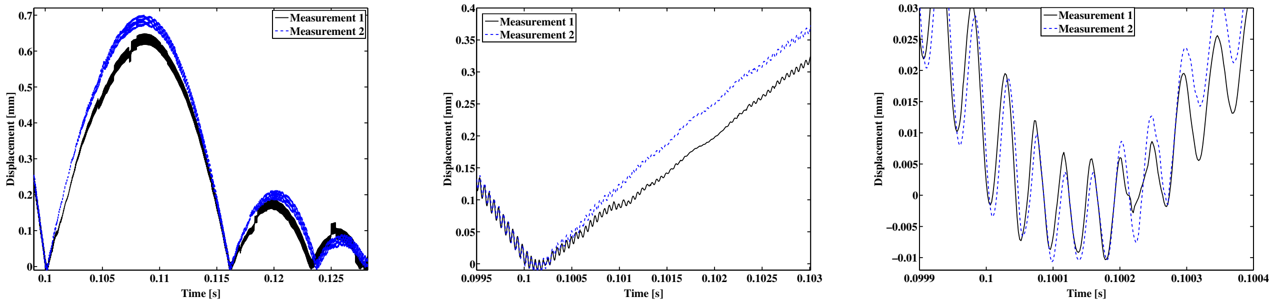
Fig. 4 Evaluation and comparison of displacement measured and calculated from the measured velocity

actuated test: Before the first contact the actuator is in a steady condition, the average velocity is increasing while falling down and at each contact, especially after each macroscopic contact a new transient effect started.

Besides the velocity the displacement of the tip is the most interesting signal. Figure 4 shows the measured displacement for both, the actuated and the not actuated experiment. The light (cyan) lines in the diagram are directly measured using the displacement decoder of the laser vibrometer, which is utilizing the information in the phase of the receiving laser signal. Due to the measurement method there can be jumps in the output signal. Ignoring those jumps the measurements showed the desired behavior. For a long-time measurement the velocity measurement, utilizing the doppler effect, of the laser vibrometer is more robust. Therefore, is it interesting to integrate the velocity to calculate the displacement. The dashed red lines in both diagrams



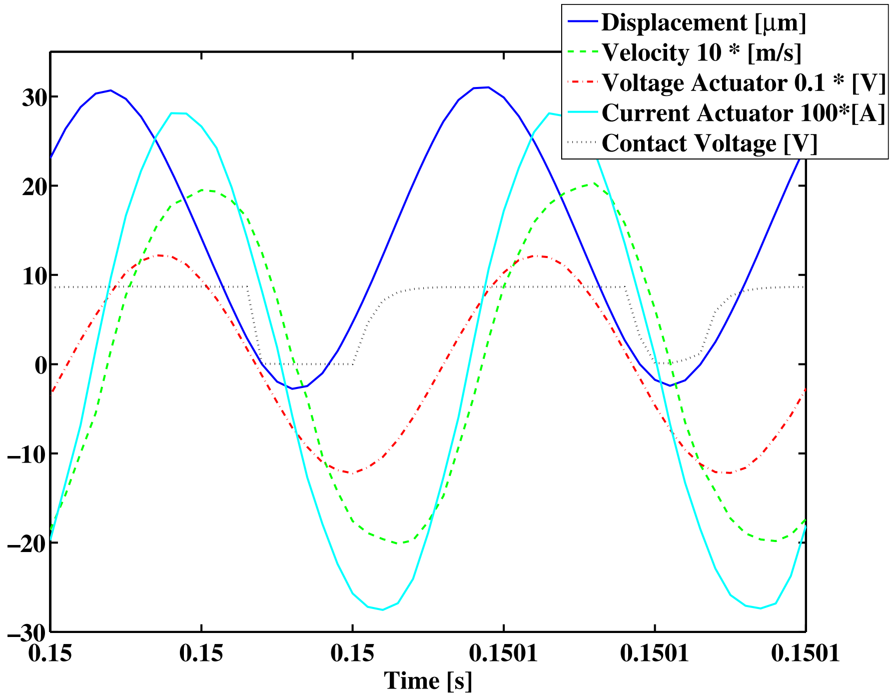
(a) First three contacts without ultrasonic actuation **(b)** Zoom on first contact without ultrasonic actuation



(c) First three contacts with ultrasonic actuation **(d)** Zoom on first contact with ultrasonic actuation **(e)** Close zoom on first contacts with ultrasonic actuation

Fig. 5 Multiple drop test

Fig. 6 Transient behavior of test bench



show the result of integration of the signals from Fig. 3, for both cases the result shows an error. This error is assumed to be linear. Using the information from the contact status measurements and the information about the starting position, one can calculate the slope of the function of the error piecewise between two contacts. Subtracting this function from the integrated signal the solid black lines were gained. The corrected integrated velocity showed, besides the jumps, a behavior nearly equal to the direct measured displacement, which is a good verification that the linear error assumption is correct. Further, it indicates that measurements are correct and the experimental setup is suitable for these contact measurements. For further investigations we use the integrated velocity signal as displacement.

In addition to the macroscopic behavior the microscopic behavior is in the focus of interest. Also, the reproducibility of experiments has to be investigated. Figure 5 gives an insight in both. The first row of diagrams depicts three measurements in the drop test without excitation, all measurements give a similar behavior. In the close up (b) even the displacement during the contact can be evaluated clearly. The second row shows two measurements from the drop test with ultrasonic actuation. Here again a similar behavior can be found. After the first contact the displacement is slightly different but both measurements show a transient effect shortly after losing contact. In diagram (e) the displacement behavior during contact can be seen clearly. For this experiment—operation close to resonance and 5 N additional load—the sinus movement of the tip is nearly unaffected by the contact process. The tests show that the experiments are well repeatable. The results also show that only one parameter is not directly adjustable, which is the phase of the tip-movement for the first contact time.

Besides the contact process parameters, the operational parameters of the piezoelectric transducer are subject of investigations. Figure 6 depicts the transient behavior of all measured quantities. The experiment is again performed as described in the beginning of this section, close to the resonance and with 5 N applied load. All parameters can be seen in the diagram, where the solid heavy blue line is the integrated and corrected velocity. The measurement of the operational parameters enables also the validation of models that include not only the contact behavior, but also the backlash of the contact on the piezoelectric actuator.

4 Conclusion and future work

A simple experimental setup to investigate ultrasonic contact process, is presented. The test bench is capable of recording the displacement at the actuators contact tip. Further the velocity of the contact tip and the contact times can be evaluated. In the performed drop tests the experiment shows a good ability for benchmarking and validation of ultrasonic contact models.

As future work different modeling approaches will be tested on the simplified problem of the bouncing ultrasonically excited actuator. This problem is included, as a major process, in many ultrasonic applications such as ultrasonic motors or ultrasonically supported machining. Examples for promising modeling approaches are time continuous spring-dashpot simulations or finite element simulations.

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