Ultrasonic Transducer Characterization in Air based on an Indirect Acoustic Radiation Pressure Measurement

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***Abstract*—We present proof–of–concept measurement results from a simple indirect method that allows us to determine the acoustic radiation pressure acting on air coupled ultrasonic transducers in form of acoustic thrust. The simple and inexpensive method utilizes this acoustic thrust, acting on the ultrasonic transducer mounted on a clamped aluminum cantilever ($850 \times 20 \times 2\,\mathrm{mm}^3$). This approach is successful in air, because it exploits resonance amplification in return of a longer measurement time. By using a self–tuning circuit, the beam oscillates at its resonance frequency of approximately 2 Hz with a quality factor of 330. Modeling the system as spring–mass–dashpot system allows using the equations of forced damped oscillation to determine the acoustic thrust of various transducers based on only the measured beam displacement, obtained via e.g. strain gauges or a laser distance sensor. We used two commercially available ultrasonic transducers (MA40B8S and MA40S4S, both from MURATA, Japan) of different size and weight to test the setup. Excited with their specified maximum excitation voltages, acoustic thrust forces of up to 61 µN and 161 µN for the MA40S4S and the MA40B8S, respectively, are measured. Over a wide range these measurements are in good agreement with results from a digital high precision scale. Thus, our results show that the setup is able to measure small values of acoustic thrust in the µN–range. For future work, this approach can be used to compare different types of air–coupled ultrasonic transducers in terms of their efficiency, based on their generated acoustic thrust force.**

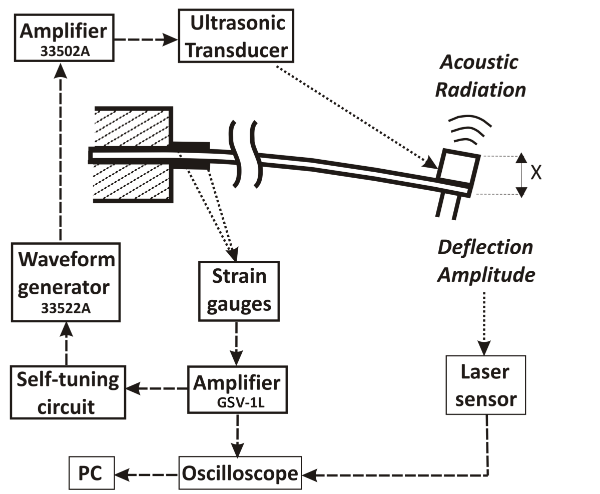

Fig. 1. Schematic view of the indirect measurement system to determine the acoustic thrust force the ultrasonic transducer generates. With the help of a self–tuning circuit the ultrasonic transducer signal (from a waveform generator and then amplified) is turned on and off periodically, so that the beam starts to oscillate at its self resonance frequency. The cantilever displacement amplitude x is measured with strain gauges and a laser sensor (for comparison purpose only) and then the periodic force that is required to excite this beam to this certain amplitude level is calculated as a measure for the acoustic thrust force. Note that the drawing of the beam shows the top view for improved symmetry and that gravity effects are minimized.

I. Introduction

The effect of acoustic radiation pressure is well known from nonlinear acoustics. It originates from the interaction of acoustic energy flow and the surrounding medium. It represents a force which exerts a load on an obstacle placed in the acoustic field [1]. The radiation pressure generated by ultrasonic transducers is used in various applications, for example to drive microscopic small objects in direction of the acoustic wave propagation [2]. In biomedical applications these effects are exploited to build so called acoustic tweezers for microparticle manipulation and trapping [3].

Acoustic radiation, arising in front of an emitting ultrasonic transducer, results in a net force affecting the transducer surface [4]. In water, the resulting force is relatively high in magnitude (mN–range), and, thus, relatively simple to measure, since the acoustic waves in more dense mediums, such as liquids, contain orders of magnitude more energy compared to waves of same amplitude in air. The radiation force can be employed as acoustic thrust to maneuver small vessels, diving in water [4], [5]. In air, however, the resulting force acting on the ultrasonic transducer is about one order of magnitude smaller (µN–range), due to the low density of air compared to water. This makes it difficult to measure the forces.

Typical air–coupled transducers have a mass of several grams corresponding to a weight of some ten mN. A direct measurement would have to find the difference between this weight and the weight plus the µN–thrust force from the acoustic radiation. Therefore, this aggravates a direct measurement on a sensitive scale or in some other form of force measurement setup. Thus, an indirect measurement of the thrust force can be an interesting alternative.

Such an indirect approach, based on acoustic thrust force measurement with the help of a pendulum setup, is for example described in [6]. Another interesting example is given in [7]. On top of an atomic force microscope (AFM) cantilever, a capacitive micromachined ultrasonic transducer (CMUT) was placed. The goal of this work was to excite the AFM cantilever by the acoustic thrust force of the CMUT. Due to the radiation pressure force generated by the CMUT, it was possible to deflect the small cantilever (weighing several micrograms) in a micro scale range.

In this work, we present our approach to measure the acoustic thrust force of far larger commercially available air–coupled ultrasonic transducers, mounted on a clamped aluminum cantilever ($850 \times 20 \times 2\,\mathrm{mm}^3$). Assuming the beam is deflected with small amplitudes only, one can expect a linear relationship between the acoustic thrust and the displacement amplitude of the beam. Since the geometry and dynamics of the beam are well known, it is sufficient to measure only the beam displacement to determine the periodic force that is required to excite this beam to this certain amplitude level. The approach trades measurement sensitivity for measurement time, i.e. it exploits resonance amplification to measure small forces in the µN–range (Fig. 1).

In the next section, all assumptions and equations used are described. Then the experimental setup is described in detail before two results for two different ultrasonic transducers are given and discussed.

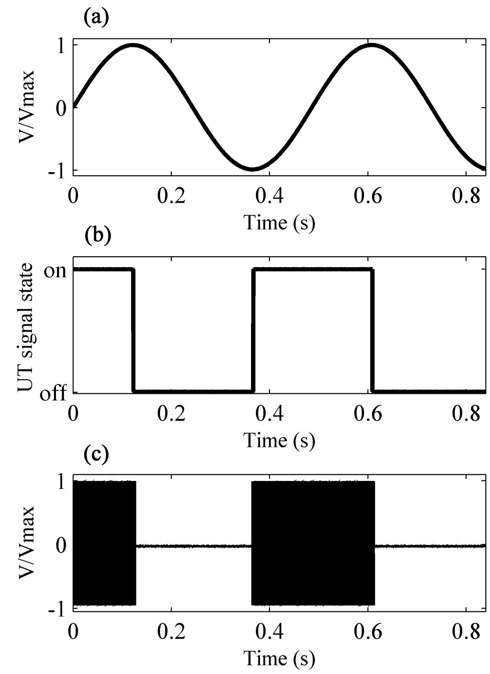

Fig. 2. A self–tuning circuit ensures that the cantilever is operated at its maximum amplitude for a given acoustic thrust, i.e. the system benefits from resonance amplification: (a) normalized strain–gauge bridge voltage after stationary oscillation has been reached; (b) output signal of the self–tuning circuit that triggers the waveform generator (Fig. 1); (c) gated excitation signal that drives the ultrasonic transducer after amplification.

II. Methodology

A cantilever under periodic force can be described using the model of a simple linear damped oscillator (spring–mass–dashpot system). The underlying assumption is that the cantilever deflection is small, which has to be considered when dimensioning the cantilever.

Thus, to estimate the system parameters, we apply the equations of mechanical theory describing the forced damped oscillation [8]. The equation of motion for a damped mechanical system is

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t), \tag{1}$$

where x is the deflection of the beam at its free end (Fig. 1), F is the driving force and m, c and k are the system parameters, corresponding to effective mass (modal mass), damping and spring constant, respectively.

The spring constant for the bending stiffness of a clamped cantilever can be calculated using

$$k = \frac{3EI}{l^3}, \tag{2}$$

where E is the Young's modulus of the corresponding material and the beam length is represented by l. In case of a rectangular beam cross section, the moment of inertia I can be estimated from its width b and thickness h using $bh^3/12$.

The effective mass (modal mass) of the system can be estimated from its damped natural frequency ω_r. The damping parameters can be obtained from the free vibration of the beam, where $F(t) = 0$ after an initial stimulus of the system. The logarithmic decrement of decay δ of free oscillations, is related to the damping ratio ξ by

$$\delta = \frac{1}{N} \ln \frac{x_1}{x_{N+1}} = \frac{2\pi\xi}{\sqrt{1-\xi^2}}, \tag{3}$$

where x_1 and x_{N+1} are consecutive amplitudes corresponding to instants of time t_1 and t_{N+1}, separated by a number of complete cycles N. After both ξ and ω_r are estimated from free oscillation, the effective mass (modal mass) can be obtained from

$$m = \frac{k}{\omega_r^2}(1 - \xi^2). \tag{4}$$

Similarly, we calculate the value of the damping constant using

$$c = 2\xi\sqrt{mk}. \tag{5}$$

Based on the envelope of the gated ultrasonic signal, as shown in Fig. 2, we assume that the external force is periodic, unipolar and square–shaped, with a duty cycle of 50 %. Thus, a Fourier series can be employed to express the force function. The equation of motion for the second–order system becomes

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) = \sum_{n=1}^{\infty} b_n \sin(n\omega t). \tag{6}$$

For this force function the Fourier coefficient is

$$b_n = \frac{2F_0}{n\pi}, \tag{7}$$

for odd $n = 1, 3, 5, \ldots$ and $b_n = 0$ otherwise. F_0 represents the amplitude of the force required to obtain the measured beam deflection amplitude. The value for the amplitude of the force F_0 can then be evaluated from the steady state solution of (6), which is given by

$$x(t) = \sum_{n=1}^{\infty} \frac{b_n}{\sqrt{\left(k - m(n\omega)^2\right)^2 + c^2(n\omega)^2}} \sin(n\omega t - \phi_n). \quad (8)$$

III. Experimental Setup

The main part of the characterization setup is an aluminum cantilever with the dimensions $l = 1000\,\mathrm{mm}$, $b = 20\,\mathrm{mm}$, $h = 2\,\mathrm{mm}$. Over a length of 150 mm it is clamped and the remaining 850 mm–long portion is free to vibrate. The Young's modulus was determined experimentally to be $E = 64\,\mathrm{GPa}$. This value is lower as expected because of the fact that an aluminum alloy was used. The corresponding spring constant of this setup was determined to be $k = 3.97\,\mathrm{N/m}$.

The ultrasonic transducer, weighing up to several grams, is mounted at the tip of the free end of the cantilever (Fig. 1). In case several transducers with different weights are used, counterweights must be used so that the total mass loading at the tip of the cantilever is identical during all measurements.

In order to resonate the cantilever at its self–resonance, the following approach is used. Four strain–gauges are glued to the top and bottom surface of the cantilever. Two of the four strain–gauges are used only for thermal compensation. The output of this Wheatstone–bridge is an alternating signal that can be amplified (GSV–1L, ME–Meßsysteme GmbH, Germany) and fed into the self–tuning circuit.

For a given acoustic thrust of an ultrasonic transducer, maximum cantilever displacement amplitude will occur only when the ultrasonic transducer is turned on and off properly. That means the only purpose of the self–tuning circuit is to turn the excitation signal of the ultrasonic transducer on when the cantilever swings in one direction and off when it swings in the other direction. In other words, the ultrasonic transducer is turned on until the cantilever tip reaches a maximum displacement point. Then, it is turned off and the cantilever tip moves back. When it reaches minimum displacement, the ultrasonic transducer is turned on again. This configuration allows us to benefit from resonance amplification, since the natural frequency of the cantilever will control its forcing frequency and a small radiation force is sufficient to force the beam into steady–state oscillation after a long transient start–up phase. The feedback from the strain–gauge signal to the driving force of this system will ensure that the cantilever oscillates at its resonance frequency. As soon as the system is turned on, the system slowly ramps up to full displacement amplitude and reaches steady–state oscillation. Then, the strain gauge output [Fig. 2(a)] is phase–locked to the gate signal [Fig. 2(b)], and, thus, also to the driving signal envelope [Fig. 2(c)]. The approach trades measurement sensitivity for measurement time and allows to measure small forces in the µN–range without any expensive measurement equipment.

The self–tuning circuit is a key component as well. It consists of two main components: First, the signal obtained from the strain gauges is differentiated by a standard opamp–circuit. Then, the output of this differentiator is fed into a comparator that produces the signal, as shown in Fig. 2(b). This signal acts as a gate circuit for the waveform generator, i.e. turning on and off the waveform generator output providing the excitation signal for the ultrasonic transducer.

In order to determine the deflection amplitude of the cantilever tip, we used a commercially available laser distance sensor (LAS–T5-40, WayCon Positionsmesstechnik GmbH, Germany), which is based on the triangulation principle. It allows to measure the varying distance between the cantilever surface and the sensor mounted on the opposite side of the ultrasonic transducer, which requires a free field in front of it. The electric output signal is converted into the corresponding distance in millimeter range.

For all measurements described in this paper, we used a vibration–isolating table (CleanTop II, TMC, USA) to avoid any outside influence and vibrations. In addition, the setup was operated remotely to ensure that the user is not affecting the results.

IV. Results and Discussions

The system is designed for low damping ratio ($\xi < 0.002$) to ensure large peak amplitudes at resonance frequency, even when excited with small acoustic thrust values. Therefore, the high quality factor of approximately 330 is essential for resonance magnification. The natural frequency of the cantilever was identified to be 2.06 Hz. The drawback of the narrow bandwidth of the system is that the transient startup phase takes approximately 200 s, before the system reaches a stable stationary oscillation.

We tested two types of air–coupled ultrasonic transducers (MA40B8S with a diameter of 16 mm and MA40S4S with a diameter of 10 mm, both from Murata, Japan). These ultrasonic transducers operate at a resonance frequency of 40 kHz and have a different aperture size, a different weight, and a different maximum excitation voltage that can be applied. Thus, the supply voltage was varied from 2.5 V in 2.5 V steps up to the maximum amplitude according to manufacturer specification of $40\,\mathrm{V_{pp}}$ (MA40B8S) and from 0.5 V in 1.5 V steps up to $20\,\mathrm{V_{pp}}$ (MA40S4S).

The maximum values for the acoustic thrust determined are 161 µN (corresponding to 7.4 mm displacement amplitude) at an excitation voltage of $40\,\mathrm{V_{pp}}$ (MA40B8S) [Fig. 3(a)] and 61 µN (corresponding to 3.3 mm displacement amplitude) at $20\,\mathrm{V_{pp}}$ (MA40S4S) [Fig. 3(b)]. For both measurement, an almost linear curve is obtained beyond a certain excitation voltage of around $5\,\mathrm{V_{pp}}$. The shape of these curves is similar to the one described in [7], i.e. at a certain excitation voltage level a linear relation between generated acoustic thrust force and excitation voltage is obtained.

These results can be validated partially when the ultrasonic transducer is positioned on a digital high precision scale. We used two different models for our measurements, a XA 60/220 from RadWag, Poland and a GEM20 from Smart Weigh, USA.

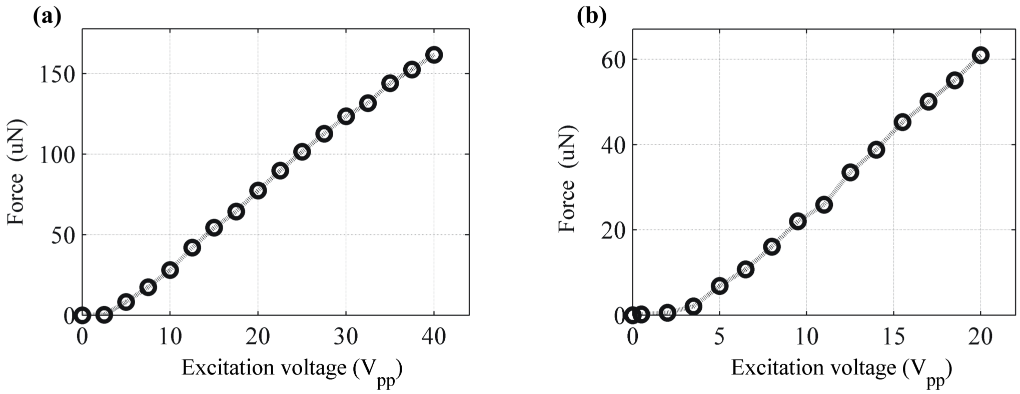

Fig. 3. Excitation voltage of two ultrasonic transducers, i.e. (a) shows the results for the MA40B8S and (b) for the MA40S4S, corresponds to different amount of acoustic thrust, calculated based on the measured cantilever displacement amplitude.

Switching on the excitation voltage results in an acoustic thrust force that acts in addition to the gravitational force of the ultrasonic transducer, i.e. the increase of weight displayed by the scale corresponds to the acoustic thrust force generated by the transducer. However, there are a couple of problems with this setup: first, the digital high precision scale provides a different acoustic boundary condition to the transducer compared to our setup. Second, at higher sound pressure levels, acoustic streaming effects [9] start to affect the digital high precision scale.

Thus, only for excitation voltages ranging from $5\,V_{pp}$ to $20\,V_{pp}$, we observe a match within 5% for both ultrasonic transducers (MA40B8S and MA40S4S) between our setup and the digital high precision scale. In particular, at larger excitation values for the MA40B8S, significant deviations have been observed. Most likely these deviations can be attributed to the difference in acoustic boundary conditions and the parasitic influence of acoustic streaming, affecting the accuracy of the digital high precision scale. This hypothesis, which needs to be tested by performing more scale measurements, is underpinned by the fact that the values for the acoustic thrust obtained by the digital high precision scale show a positive nonlinearity with increasing excitation voltages. This nonlinearity is not visible in the measurement curves obtained with our setup.

V. Conclusion

Our results show that the acoustic thrust force in the μN–range of air–coupled ultrasonic transducers can be measured with a simple cantilever system. The setup delivers reproducible and stable readings for the acoustic thrust force. The sensitivity required is achieved by exploiting resonance amplification in exchange with a longer measurement time. Besides the fact that the system is inexpensive and that it can be optimized for a wide range of ultrasonic transducers, the approach described has the potential to characterize and compare different types of air–coupled ultrasonic transducers in terms of their total efficiency. Thus, for future work, we plan to compare different types of air–coupled ultrasonic transducers in terms of their efficiency.

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