PARTICLE TRANSPORT WITH CONTINUOUS FREQUENCY SWEEPING AND ACOUSTIC RADIATION FORCES

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Summary A device and design study with a planar device for the transport of particles suspended in fluid with continuous frequency sweeping is introduced here. With a numerical simulation as well as in experiment the important role of damping has been shown. The choice of material for the mechanical structure, PMMA and Al, as well as the location of the transducer have been shown to be critical. The wave coupling into the fluid appears to be a mixture of direct coupling and plate vibrations.

INTRODUCTION

Transport and agglomeration of cells or micrometer-sized particles in suspension have a major area of application in life-sciences and biochemistry, such as drug screening or purification of nucleic acid solutions for sensitive molecular analysis. These applications are often sensitive to sample contamination which could be reduced to a minimum with non-contact handling techniques, examples of which are electrophoresis, optical tweezers, utilizing gravitational, magnetic or acoustic radiation forces. The later forces act on particles in an acoustic field typically taking high values within a standing pressure field. Particles which are denser and stiffer than the surrounding medium are driven towards the pressure nodes. The acoustic radiation force is modelled with Gorkov's theory [1]. There are different techniques utilizing acoustic radiation forces to move particles over a larger distance, e.g. amplitude modulation of two transducers, or by shifting boundaries, or by changing the frequency [2, 3, 4]. The advantage of the latter is, that it can be easily used with a closed chamber that could be built independently of the transducer. The frequency can be changed in different ways. If the frequency is changed in discrete steps, only using the resonances, in 1D, particles can be moved either to the centre, or equally to the left and right boundaries. On the other hand if the frequency is changed continuously particles can be moved towards or away from the transducer, that is e.g. from the left boundary to the right or vice versa. For this aim, the damping present in the system as well as the coupling mechanism of ultrasonic waves to the fluid domain are of essential importance. There is an optimum of damping for a given device size. Here, numerical and experimental work on a device designed to investigate this coupling and damping or the influence of a reflector for the design of devices based on continuous frequency sweeping is presented.

DEVICE

The fluid chamber is built up from three layers as shown in Fig. 1. The cover plate (top layer 1) is a 250 µm PMMA foil which allows visual inspection. Using GBL (gamma-Butyrolactone), the foil is bonded to the middle layer (2) which is laser cut from a 1 mm PMMA sheet. The base layer (3) has been varied in both, thickness and material. It is either a 250 µm or 0.5 mm PMMA sheet, or a 0.5 mm Al plate with and without a cut. The Al parts have been glued to the top layers using epoxy. To fill the chamber with water and particles two 1 mm openings have been added in the cover plate in opposing corners. As transducers 1 mm thick piezoelectric elements with a length and width of 2 mm x 12 mm have been used. They are attached to the chamber using conductive epoxy and are placed either below the base plate or on top of the cover plate as indicated in Fig. 1. The dimensions of the fluid chamber are 1 mm x 10 mm x 3 mm and it is placed in the centre of the device which has an outer length and width of 40 mm x 12 mm. The cut in the Al plate is placed close to one transducer and separates the base layer into two parts which are 100 µm apart from each other leaving a free water surface which is kept in place by its surface tension. This separation heavily reduces plate vibrations and thus the effect of coupling waves into the fluid by them.

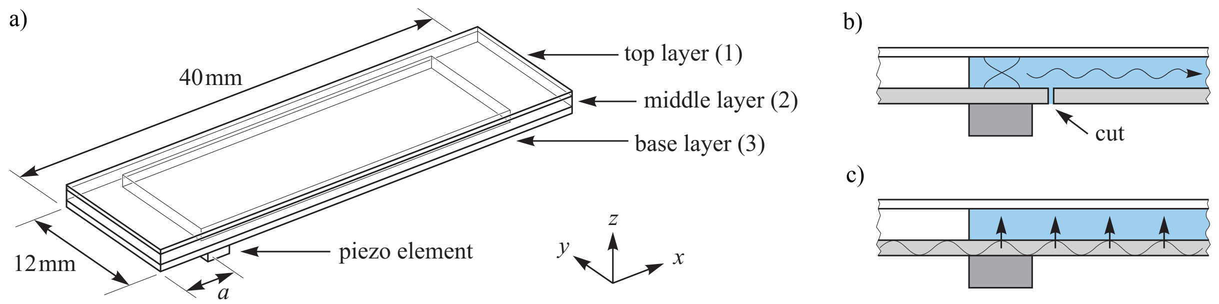

Fig. 1 Schematic of the device with dimensions a) and illustration of wave coupling over fluid b) and via plate vibrations c).

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MODELING

The finite element method simulation presented here was performed in 2D with COMSOL Multiphysics 4. The model geometry is a cut of the device in the *x-z* symmetry plane and thus the model includes three domains: fluid, mechanical structure and piezoelectric element. The fluid is modeled as water with a complex speed of sound and a quality factor of 2000. The PMMA and the Al are modeled with an isotropic loss factor of $\mu_{PMMA} = 0.02$ and $\mu_{Al} = 1*10^{-4}$ [5] and the longitudinal piezoelectric transducer is modeled as Pz26 (ferroperm) with complex damping parameters [6]. Large pressure amplitudes are expected around the first main resonance of the transducer which is at 2 MHz. This value can shift with different device layouts, for this reason a wide frequency band of 1.5 - 2.5 MHz has been investigated.
Fig. 2. shows the pressure distribution in the water along its symmetry line at half water chamber height for a frequency range of 1.8 - 2.2 MHz. In a) the distribution is shown for a device with a base layer of Al and in b) with one of PMMA and the same thickness (0.5 mm). The transducer is placed below the water (a = 5 mm). Good performance of the device is expected with high pressure amplitudes evolving over the whole length of the chamber and a frequency range which covers a node shift of at least one wave length. This is the case for the Al device (a) whereas the high pressure amplitudes frequency band is smaller and decays much faster in a PMMA device (b). For both devices, changing the position of the transducer below the PMMA of the middle layer (2) mainly reduces the overall pressure amplitudes, similar to increasing the damping of the whole device. Placing the transducer on top of the cover plate (1) increases the performance of the devices. On the other hand, introducing a cut in the Al base layer (3) results in a pressure distribution similar to the one shown in Fig. 2 b). Thus the wave coupling appears to be a mixture of different effects, underlining the complexity of the system.

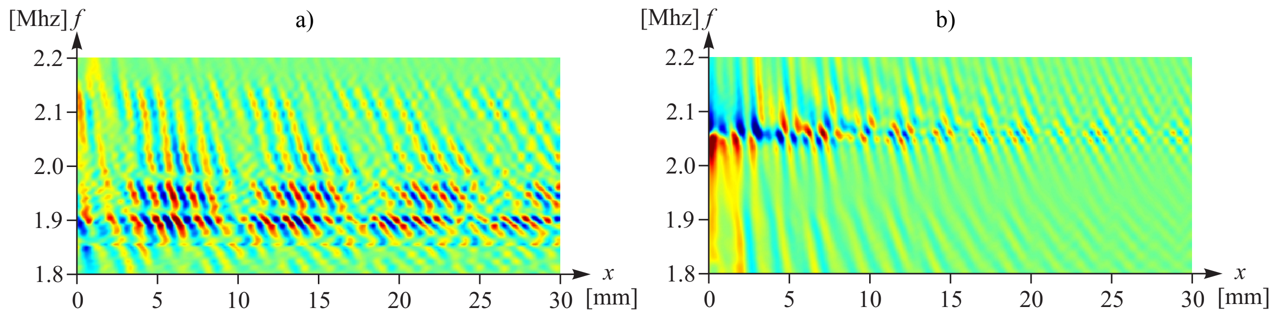

Fig. 2 Computed pressure distribution along the center line of the device for a base layer of Al a) and PMMA b).

EXPERIMENTAL RESULTS

As expected from the results of the numerical simulation, a device with Al base layer and transducer placed below the water, works best, as shown in Fig. 3 with 55 µm copolymer particles. The randomly distributed particles a) are moved away from the transducer on the left boundary towards the right. As indicated by the pressure plots, the particles move faster close to the transducer which results in a distribution shown in b) after 40 sec. Finally, after 80 sec most particles are clumped together at the right boundary.

Fig. 3 Particle transport with continuous frequency sweeping (1.5 - 2.3 MHz). The particles are distributed in the whole chamber a) then with excitation from the left transported to the final position c)

CONCLUSIONS

For particle transport with continuous frequency sweeping damping is an essential requirement. But a device is best designed having low damping along the path of wave propagation in the water chamber. The device can be optimized by using low damping along the water chamber to have sufficiently high amplitudes far away from the transducer and by good power coupling from the transducer into the fluid.

References

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