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BEM-FEM Simulation of Acoustic Levitation Dynamics with Phased Arrays

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***Abstract*—We present a simulation model that can be used to study the movement of an object in an acoustic levitator. The model uses the boundary element method (BEM) to compute the levitator's acoustic field, and the finite element method (FEM) to compute the movement of the levitating object.**

The model was built to act as a virtual tool for testing how objects move in acoustic pressure fields generated by phased array transducers (PATs). This was demonstrated by comparing object dynamics for different PAT optimization methods. We studied the stability of the levitation in fields created by two optimization methods. The fields were optimized to levitate an ellipsoid in the middle of our PAT geometry. By slightly displacing the levitating object from the intended levitation spot, we were able to show that the levitation became unstable and that the object would drop out from the trap.

The results demonstrate that the model can be used to rapidly validate optimizers instead of having to run long experiments.

***Index Terms*—Acoustic levitation, FEM, BEM, Nonlinear acoustics**

I. Introduction

Significant progress has been made in acoustic levitation over the past decade. Phased array transducer (PAT) based levitators have opened the way for movement and orientation control of the levitating objects [1]. However, the modelling and understanding of levitation dynamics, especially of non-spherical objects, is still lacking [2], and tools for dynamic levitation control are being actively researched. This effort is focused on computational methods for optimizing the PAT's parameters to create dynamically changing levitation traps, such as those presented in [1] and [3].

We previously presented a custom-built PAT levitator [4], as well as a simulation model for calculating the forces and torques experienced by an arbitrarily shaped object in a levitator field [5]. However, the simulation model only computes the static forces and torques acting on the object, and has no time dependent dynamics included.

To study how the levitating object moves in the levitator field, we improved our previous model by adding a time-domain calculation. Levitation dynamics have earlier been studied with the finite element method (FEM) in water [6]. We now propose a boundary element method (BEM) model for computing the acoustic field, based on [5], while using FEM for the object dynamics. The simulation model uses results from field optimization algorithms as an input to create the levitation fields. These algorithms are a promising tool for creating fields tailored for orientation and position control of arbitrary-shaped objects.

Often, like in our previous method for field optimization [4], the optimization is designed for small, non-scattering objects, and the force expression is based on pressure gradients. More involved methods are emerging which account for the scattering from larger objects in the optimization [7]. The simulation model presented here accounts for the effect of scattering *post-hoc* for optimization algorithms which do not account for it, and acts as a general tool for studying levitation stability through the time dependent computation of levitation dynamics.

II. Methods

A. Simulation model

A COMSOL Multiphysics [8] model was built to study the movement of an object in the levitator field. The model uses BEM to compute the levitator acoustic field, making the calculation efficient as meshing is only required on the object boundary. FEM was used for the time domain simulation of the dynamics of the levitating object. COMSOL's *Pressure Acoustics*, *Boundary Mode* module was used in the field computation and the *Solid Mechanics* module was used for the levitating object.

The model geometry corresponds to our PAT levitator consisting of 450 transducers ($f = 40\,\mathrm{kHz}$) arranged in two hemispheres (Fig. 1). The phase and amplitude of each transducer can be controlled individually to create complex field shapes. In the simulation model, each transducer is modelled as a point source. The phases and amplitudes for each transducer are obtained from an optimization algorithm, as described in the next section.

The levitating object was chosen to be an ellipsoid of dimensions (*x, y, z*) $= (1.75, 2.25, 0.75)$ mm. For simplicity, the object was assumed rigid, no elastic deformations, and acoustically hard, i.e. zero normal velocity on the surface of the object. The object is allowed to move freely under the influence of gravity and acoustic radiation force. The acoustic field strength was chosen to correspond to our levitator pressure, $\sim 12\,\mathrm{kPa}$ peak pressure, and the object density was adjusted such that the object levitates in the field, $\rho = 900\,\mathrm{kg/m^3}$.

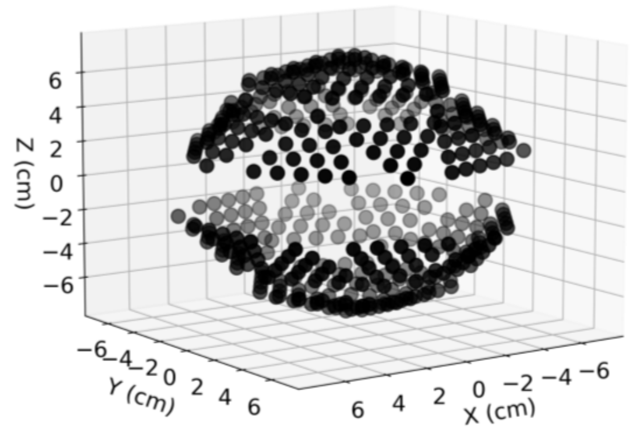

Fig. 1. Levitator geometry. The dots represent ultrasound transducers facing towards the center of the levitator device.

The acoustic radiation force, defined on the object boundary, is [9]:

$$\bar{F} = -\bar{n}\left(\frac{1}{2\rho_0 c_0^2}\langle p_1^2\rangle - \frac{\rho_0}{2}\langle \bar{u}_1 \cdot \bar{u}_1\rangle\right), \qquad (1)$$

where $\bar{n}$ is the normal vector of the object surface, ρ_0 is the density of air, c_0 is the speed of sound in air, p_1 is the acoustic pressure field on the object surface and $\bar{u}_1$ is the acoustic velocity field. By assuming that the object is acoustically hard, the second term of the equation reduces to zero in this simulation.

The acoustic field, using BEM, was calculated in the frequency domain, whereas the object movement, using solid mechanics in FEM, was calculated in the time domain. The velocity of the object was set to be zero at $t = 0\,\mathrm{s}$, and the initial position of the object was chosen in a predefined manner. In the time domain simulation the acoustic field is calculated first at each time step, after which the force on the object surface is estimated and the new position and orientation of the object are calculated accordingly. The acoustic field is assumed to vary much faster than the movement of the levitating object which allows us to separate the frequency- and time-domain computations. The *Solid Mechanics* module uses a geometric nonlinearity formulation meaning that the mesh displacement is also included. This affects the acoustic field computation such that at each step, the field scatters from the object residing in its new position/orientation.

Damping for the object movement was considered to demonstrate stable levitation for initially unstable field configurations. The damping was implemented with an arbitrary damping force (given by a viscosity, $1 \times 10^{-4}\,\mathrm{Ns/m}$) within the rigid object. The chosen value was such that the motion of the object dampens in a suitable, $200\,\mathrm{ms}$, timescale.

B. Optimization algorithms

A singular value decomposition (SVD) based method was previously developed to optimize the levitation field to achieve orientation control of ellipsoidal objects [5]. The field is created by setting zero pressure at the desired levitation location and by aligning the pressure gradients along the z-axis and x-axis with different amplitudes, resulting in an asymmetric acoustic trap. A new method was recently introduced that solves for amplitude and phase via the gradient optimization (Amplitude and phase gradient optimizer, APGO) [10]. The output of these algorithms is a list of values assigning an amplitude and a phase value to each of the individual transducers in the levitator. These values are then transferred to the simulation model.

III. Results and discussion

The capabilities of the model were demonstrated by comparing object dynamics in two generated acoustic fields. Fig. 2a shows the fields obtained by the two optimization algorithms, corresponding to the SVD-based method and to the APGO-based method. The fields were optimized to levitate an ellipsoid-shaped object at the levitation spot (*x, y, z*) = (0, 0, 0). A difference in the field shapes is seen, especially further away from the device center. Fig. 2b depicts the simulations of the same fields with the levitated object in place, showing how the sound scattered off the object surface affects the field, most notably at the object boundary.

For the first simulation the ellipsoid was placed in the intended levitation spot. The ellipsoid began to oscillate vertically at $\sim 95\,\mathrm{Hz}$, but there was no significant translational movement (Fig. 3).

To introduce some instability in the system, the ellipsoid was placed $0.5\,\mathrm{mm}$ off the levitation spot along the x-axis. In the time domain simulation, the object begins to oscillate along the x-direction, with smaller oscillations in the z-direction. The trajectories for the first horizontal oscillation, i.e. from the starting point back to the starting point, are shown in Fig. 4.

The object behaved differently in the two fields. The horizontal oscillation amplitude was similar between the fields, however the frequency was more than two times higher in the SVD field ($f = 40\,\mathrm{Hz}$) compared to the oscillation in the APGO field ($f = 16\,\mathrm{Hz}$). The vertical oscillation amplitudes and frequencies ($f = 96\,\mathrm{Hz}$ for SVD and $f = 88\,\mathrm{Hz}$ for APGO) were comparable.

A method for achieving orientation control and controlled movement of a levitating object would be to apply a dynamic feedback loop that receives information on the movement and position of the object and then adjusts the field accordingly. This concept is partly demonstrated here by adding an arbitrary damping force to the simulation.

Two longer simulations were run to see how the damping force affects the object dynamics. The ellipsoid was again placed $0.5\,\mathrm{mm}$ off the levitation spot along the x-axis as in the

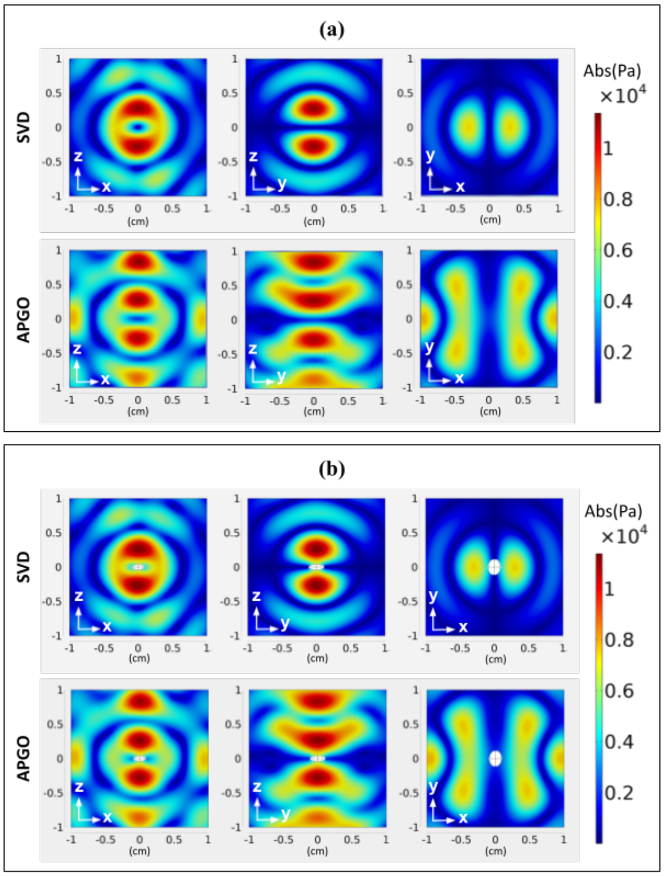

Fig. 2. a) Comparison of two levitator fields, upper row corresponding to an SVD-based algorithm and lower row to an APGO-based algorithm. b) A simulation of the two fields, including the scattered field from the levitating object.

previous simulation, but now only the APGO-field was used. The trajectories for the two cases, one with and one without a damping force, are shown in Fig. 5.

In the case without the damping the ellipsoid continues to oscillate in the x- and z-directions, until it drops out from the levitation trap. The fall is due to a gradual drift in the y-direction. When the damping force was added to the system the amplitudes of the oscillations decline, and over time the object settles in the intended levitation spot. Based on this simulation, we expect the levitation field, which was optimized for levitation at the origin, to be unable to handle displacements on the order of the object dimensions. This exercise demonstrates how the model can be used to give feedback to the algorithm development instead of having to run experiments with the real levitator.

One limitation of the optimization algorithms is that they do not consider the sound field scattered off from the levitated object. Thus, one needs to validate the fields generated by the algorithms, especially for objects approaching the sonic wavelength in size. The presented simulation model permits this kind of validation.

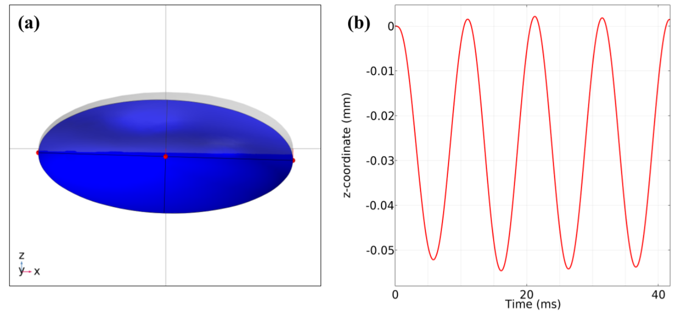

Fig. 3. a) Displacement of the ellipsoid after 6.0 ms corresponding to the maximum displacement of the vertical oscillation. b) Displacement of the object's centre of mass along z-direction over four vertical oscillations.

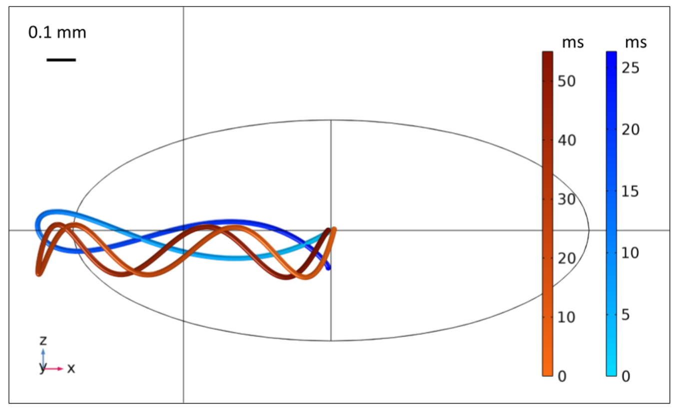

Fig. 4. Trajectory of the first horizontal oscillation of the ellipsoid in an APGO field (orange) and an SVD field (blue). Color gradient represents the elapsed time.

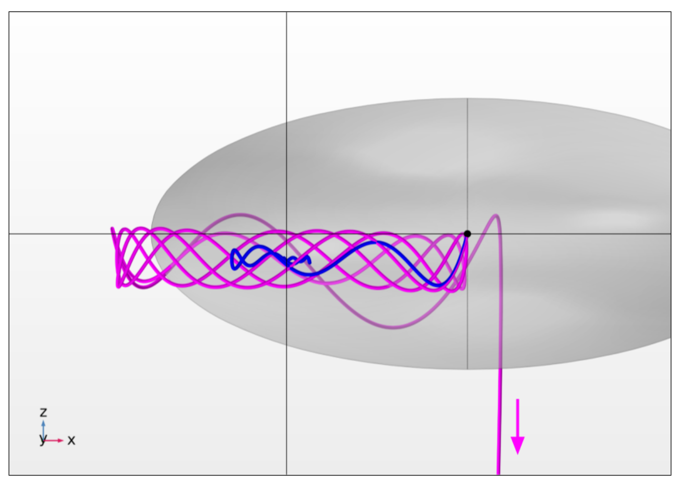

Fig. 5. The trajectory of the levitating ellipsoid in the APGO field with a damping force (blue) and without a damping force (pink). Without the damping force, the object begins to drift along the y-direction, causing it to finally fall out of the levitation spot.

IV. Conclusions

We presented a simulation that models the dynamics of an object in an acoustic levitator. The model was used for comparing object dynamics in two levitation fields generated by field optimization algorithms. This model can aid in developing algorithms to achieve stable levitation of complex-shaped objects.

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