Investigation into Squeeze-Film Induced Levitation of Light Objects

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ABSTRACT

The performance of a system consisting of a thin rectangular plate under plane stress due to the action of PT actuators, thus subjected to the Poisson's contraction effect, and a light circular object freely floating over it was studied both numerically and experimentally. The results show that performance of the system is influenced by a few factors, including the magnitude of elastic deformation of the plate and the electrostatic action of the PZTs attached to the plate, which combine to form oscillating dimples created by the Poisson's effect to separate the object from the plate with a film of compressible fluid. The importance of operating frequency of PZTs, shape and size of the dimple, offset and amplitude voltage under which PZTs operate, and distribution of PZTs on the plate's surface were all examined theoretically and verified experimentally. The plate was made of aluminium and stainless steel in order to find out the importance of the material's energy absorption rate for the effectiveness of squeeze-film induced levitation. The agreement between theoretical models and experimental measurements proved to be quite satisfactory.

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Keywords: air squeeze-film, levitation, Poisson's effect, FSI model.

1   INTRODUCTION

Frictionless or non-contact transportation is essential for manufacturing ultra-precision products in micro-fabrication and nanotechnology, for example, silicon wafers and integrated circuits, where tiny flaws, infinitesimal scratches and contamination must be avoided. Techniques such as air–bed flotation and magnetic levitation, have been utilised for frictionless, non-contact production–line transportation. However, air–beds require huge amounts of clean air at high cost due to exterior equipment, e.g. piping and pumps and magnetic levitation only works for ferrous material [1–3].

The literature review reveals that levitation comprises three main categories, namely: Standing Wave Levitation (SWL), Near-Field Acoustic Levitation (NFAL) and Squeeze film levitation (SFL). SWL lifts tiny particle substances placed between two structures (reflector and radiator) due to the reflection of a standing pressure wave. In a near-field acoustic levitation (NFAL) system, there is no need for the reflector as it is represented by the floating item itself.

Squeeze-film levitation (SFL) relies on a similar working principle to NFAL, occurring when the object to be floated is located adjacent to a vibrating structure. However, it is the viscosity and compressibility of a thin film of air (squeeze-film) that is trapped between the two surfaces (vibrating surface and floating object) that is the basis of SFL rather than sound pressure.

There is some confusion in the associated literature with the SFL term being used interchangeably with NFAL. While there is some similarity between NFAL and SFL, they differ as mentioned above and this paper is concerned with the SFL effect.

1.1   Squeeze-Film Levitation (SFL)

The squeeze-film levitation (SFL) occurs when a flat item is located above an oscillating structure. A basic physical realisation of SFL comprises an elastic plate, piezoelectric actuators and a levitated object with air gap. Throughout a compression stroke, a comparatively high overpressure will be generated that attempts to thrust the air out of the boundaries (Fig. 1). On the other hand, the air-film will turn out to be very small, and only a little air flow takes place. Conversely, throughout decompression cycle, the air-film will come to be much bigger than before, so that a comparatively small under pressure will already be adequate to pull sufficient air back into the system to recompense for the losses throughout the compression stroke. Salbu [4] used the nonlinear equation of Reynolds to explain the steady-state sinusoidal squeeze film action. This equation was used in different papers [5,6] to analyse the SFL dynamics. SWAL has a different design to the NFAL method, whereas the former is only utilised for tiny particles, the latter can be used for a heaver floating object. However, the principle underpinning both methods (SWAL and NFAL) is based on sound radiation. In contrast, the squeeze film levitation method is

fundamentally based on compressing an air. It should be noted that in some studies it is assumed that there is a similarity between NFAL and SFL [7,8] but in reality there are significant differences regarding the two as aforementioned. Stolarski and Woolliscroft [9] examined levitation features for lightweight objects placed on a vibrating plate which was excited by actuators bounded underneath the plate. The study was based on the SFL phenomenon and it was found that the actuators position governed its effectiveness. Wang and Wei [10] studied the SFL generated by a mixed-modal disk excitation utilising a horn transducer design. The physical studies identified the modal shapes of the disk that produced levitation. The current investigations will focus on the conditions that the design can create a non-contact pressure capable to carry lightweight and delicate items.
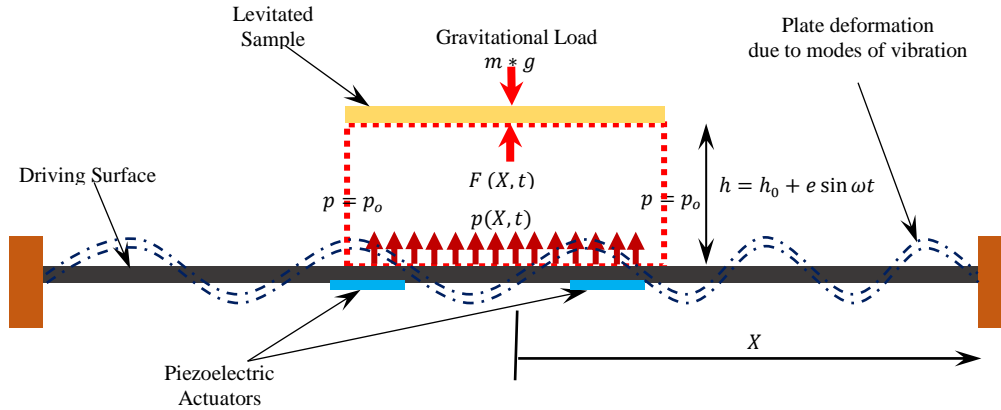

Fig. 1: SFL schematic design (side view).

1.2 Statement of the problem

Figure 1 presents a freely suspended flat item being raised as a result of the boosted average pressure formed by a vibrating surface, which is a thin flat rectangular plate clamped at both ends. A group of single layer hard piezoelectric actuators are mounted onto the lower surface. The plate can oscillate excited by the piezo actuators and a number of parameters affect the load capability: the excitation frequency, the plate boundary conditions and the materials and plate dimensions. Driving the actuators at similar resonance frequencies to the plate can lead to effective levitation [11,12]. Moreover, the attached piezoelectric actuators on the underside of the vibrating plate at a suitable location can further enhance the design's performance [13].

2 NUMERICAL SIMULATION

The coupled system: plate and fluid film, was modelled using ANSYS Workbench. The design consists of a thin flat plate and four rounded piezoelectric actuators bonded onto the plate, exciting the plate at various vibrational frequency. The dynamic response of the plate was determined when driving piezoelectric actuators by an AC voltage with a sine - waveform signal [11,13,14]. The piezoelectric actuator was simulated with the SOLID227 element with ten nodes with up to five degrees of freedom per node (UX, UY, UZ, VOLT and TEMP), which can be used for elastic, plastic and large strain deformations. The piezoelectric properties matrices have been included in the simulation throughout using the Piezo ACT (ANSYS Customization Toolkit). The SOLID187 element has been used to model the plate finite element. This is a higher order 3-D with 10-nodes and three degrees of freedom (3-DOF) at each node (UX, UY, and UZ). The material properties used for two different designs of the plate are presented in Table 1.

Table 1: Plates design configurations [18,19]

Design No.	Plate size [mm]	Material	Modulus of Elasticity [GPa]	Density [kg/m^3]	Poisson's Ratio
A	200*100*2	Aluminium	69	2676	0.31
B	200*100*2	Stainless Steel	193	7781	0.33

The plate dynamics must be optimised in order to maximize the vibration amplitude and minimisation of pressure leakage of air trapped between the two surfaces of the vibrating surface and floating object, which will lead to increased levitating loads. The squeeze film action takes place in an air film with a floating height at micrometre scale and the dynamics is governed by the Reynold's equation, in this complex case, a numerical solution of a 2D coupled model being determined with the air film modelled using CFX. The following conditions are assumed: air considered as an ideal gas, the flow being laminar and isothermal, the plate and load have smooth surfaces and the air layer thickness is much smaller than the size of the plate surface. The velocity gradients in the normal direction are more significant than those in the radial and tangential path, so the latter two can be ignored [11,15]. The studies revealed that the effect of the boundaries on the flow cycle show that, throughout the compression step, the growth in pressure creates an outward flow and at the same time, the air-gap between the planes reduces, permitting only little airflow to take place. On the contrary, throughout the decompression the pressure drops and the flow alters its path to being an inward flow. At this step, the air-gap rises, permitting a greater flow amount to pass in at a fairly slow velocity [16,17]. The levitated object (freely suspended rigid mass) has only one degree of freedom in the vertical direction. The instantaneous location of the floating object is calculated by balancing of its inertia, gravity and the fluid flow force, which is induced by the air pressure. An air film that is squeezed between a lightweight object (a disc of mass 5 g) and an aluminium vibrating plate (Design A) is considered. In order to study the levitation performance, first, an air film of 20 µm thickness, which represents the clearance between the floating object and the vibrating plate is simulated. The area of the air film modelling is same as the floating object area. Three boundary conditions introduced are: at the top related to the levitating load surface, at the bottom modelled as a deformed boundary with an amplitude obtained from the dynamic deformation of the plate and the lateral boundary considered an open boundary allowing unrestricted flow.

3 EXPERIMENTAL ANALYSIS

A plate with dimensions 200×100×2 mm, clamped at both ends was excited by four foil type PZTs of circular shape (dia. 28 mm and thickness 0.5 mm) attached to the bottom of the plate's surface. PZTs were driven by a power supply unit together with a sine wave signal generator. Floating objects, in the form of a light disc, were monitored utilising a Digital Image Correlation (DIC) system (Fig.2). The experimental apparatus enabled direct observation of the localised elastic deformations of the plate for comparing them with that generated by the plate's finite element computer model. Moreover, it was also possible to measure the floating height of the object and corroborate it with the prediction of the fluid-solid interaction (FSI) model presented in the previous section. For example, for a given plate design, frequency of PZTs operation, and object mass of 5 g, the floating height was around 70 µm.
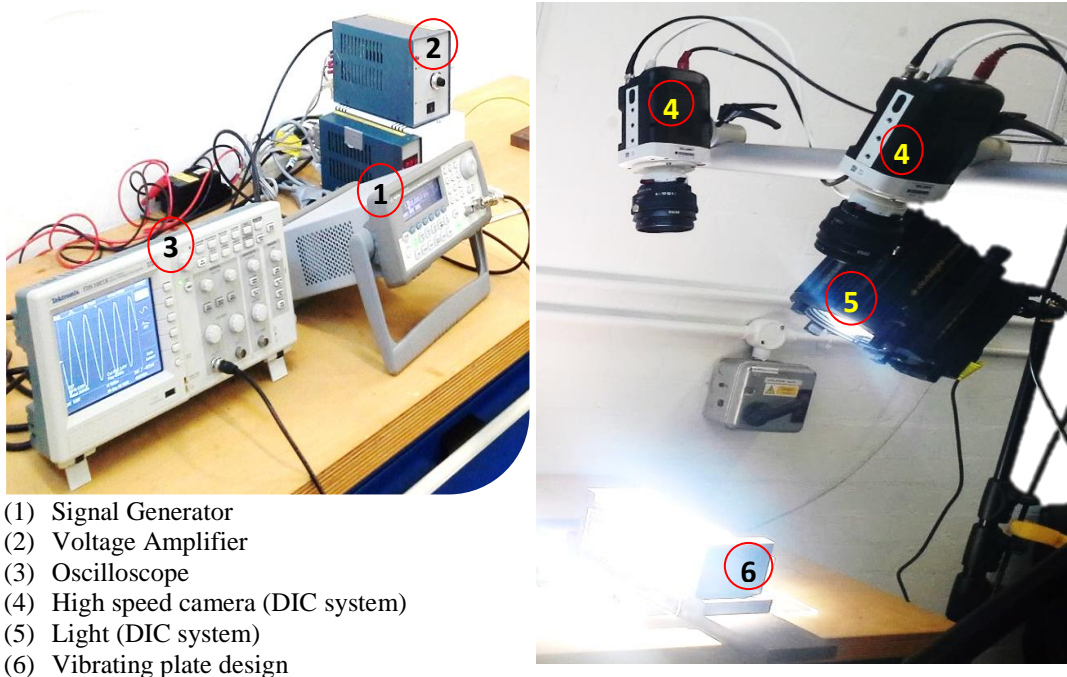
(1) Signal Generator
(2) Voltage Amplifier
(3) Oscilloscope
(4) High speed camera (DIC system)
(5) Light (DIC system)
(6) Vibrating plate design

Fig.2: Experimental measurements.

4   RESULTS AND DISCUSSION

A correlation analysis of the plate modal shapes was initially carried out between the finite element model and the experimental rig. Three types of modal shapes were observed and considered for model correlation: flexural modes in the X and Y directions and mixed wave shapes with diverse wave numbers alongside the X and Y directions coordinates (Fig.3). For load capability analysis, the plate was excited at 1.4 KHz close to a resonance frequency and the corresponding dynamic response measured using the DIC system (Fig.2). In addition, the plate deformation on the X and Y directions are compared in Fig.4 and Fig.5 showing a good correlation.
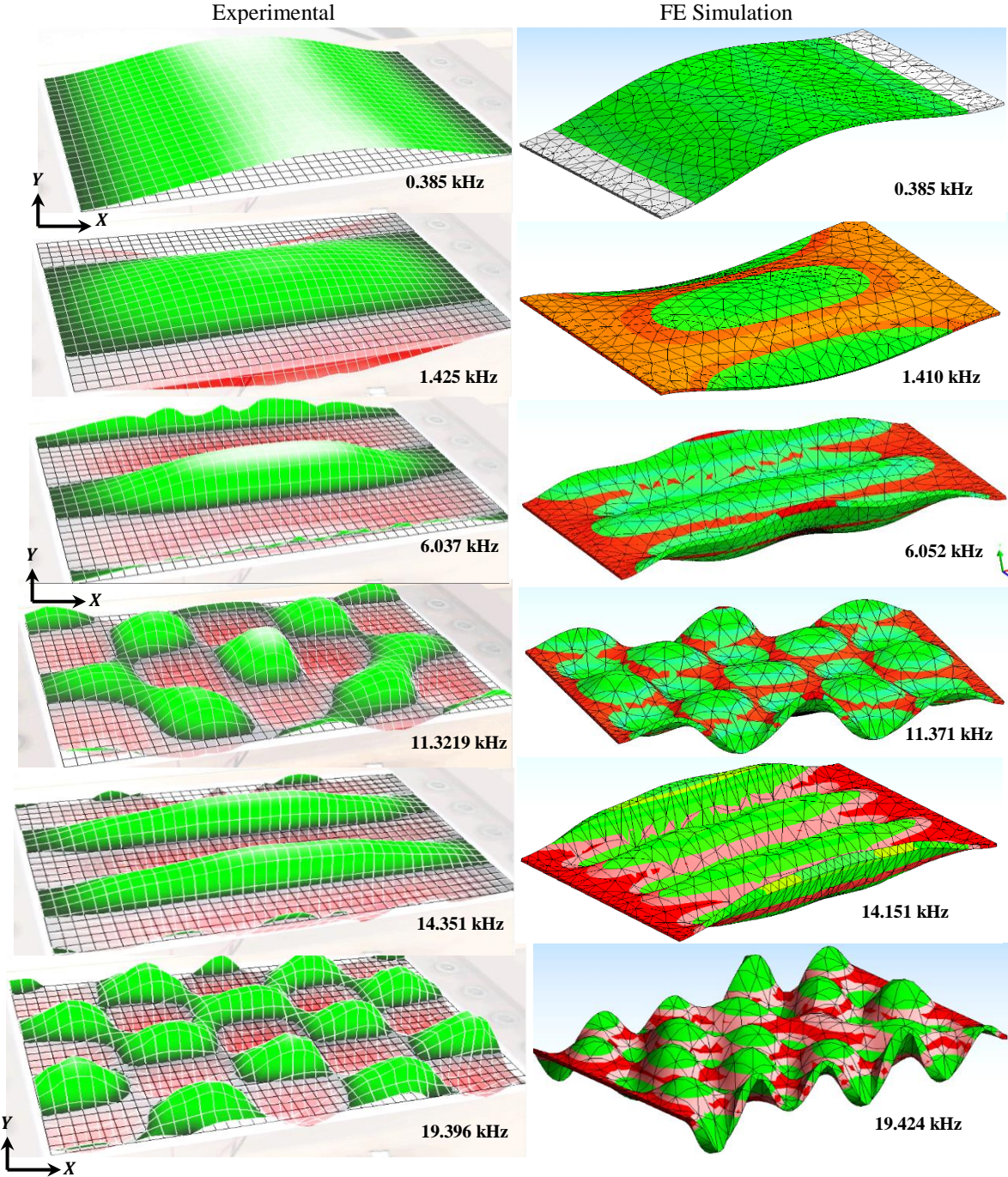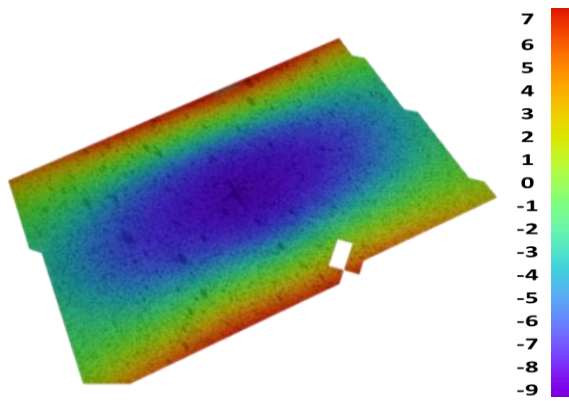

Fig. 3: Experimental and simulation of modal shapes.

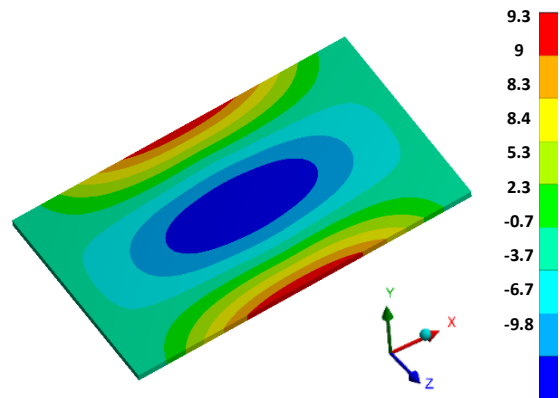Fig.4: Experimental deformation.
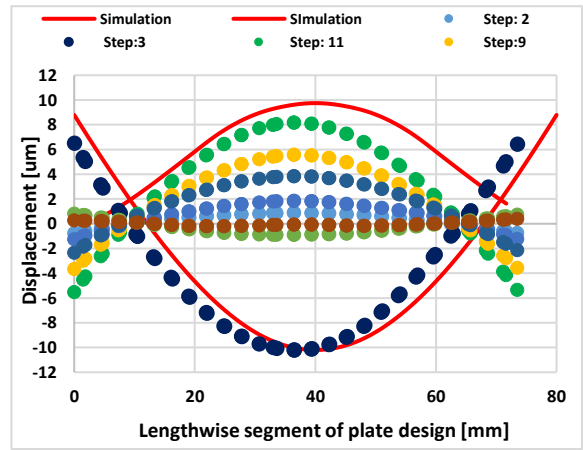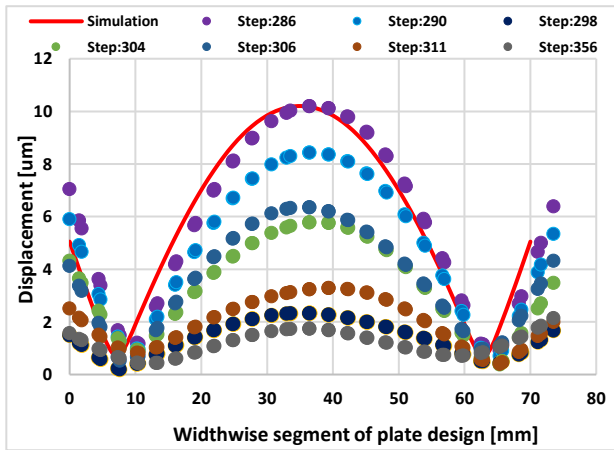

Fig.5: FE deformation.

Fig.6: Theoretical and experimental plate deformation (width-wise segment).

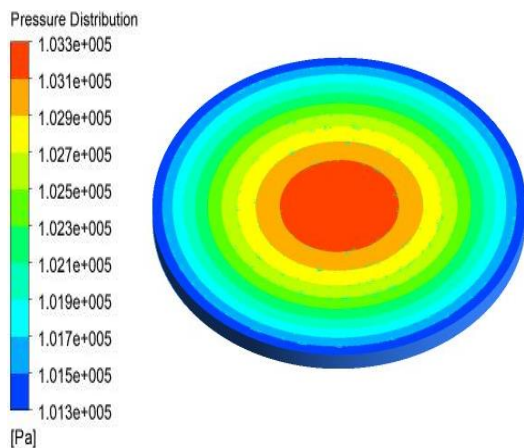Fig.7: Theoretical and experimental plate deformation (Lengthwise segment).

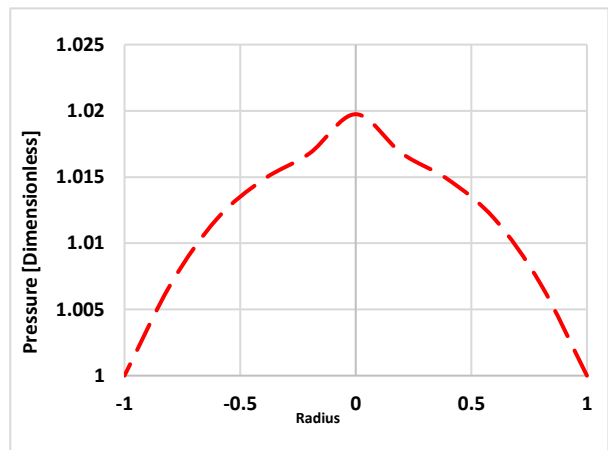Fig. 8: Squeeze air film pressure distribution.

Fig. 9: pressure distribution of the squeeze air film.

Furthermore, the simulated pressure profile and the resulting dimensionless profile of the squeezed air film shown in Fig.8 and Fig.9 confirm that the average pressure is higher than the ambient pressure, leading to the levitating load movement. A significant increase in pressure can be observed in the central area, due to the appropriate vibrational excitation frequency and operational modal shape.

5 CONCLUSION

A coupled fluid-structure interaction model capable of simulating a squeeze film configuration was developed. The levitating capabilities of the proposed system were studied theoretically and experimentally on test rig for different configurations of vibrating plates with an optimization of the excitation piezo actuators location and operational frequency. The results of this investigation clearly demonstrate that the squeeze-film levitation can represent a practical approach for load levitation and transportation. Further studies are required concerning the levitating mechanisms and refinement of the load capability determination. The current assumption that the levitating object (disc) could be assumed to move only in the normal direction (having 1 DOF) should be extended by including the possibility of a rigid rotation while the load levitates vertically.

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