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A SEARCH OF AN INDUCER GEOMETRY THAT IS BENEFICIAL FOR LIFTING PARAMETERS OF A LIFTED OBJECT OF A SELECTED SHAPE

POSZUKIWANIE GEOMETRII WZBUDNIKA KORZYSTNEGO DLA PARAMETRÓW UNOSZENIA OBIEKTU O WYBRANYM KSZTAŁCIE

Key words: acoustic levitation, modal analysis, CFD.

Abstract The literature describes acoustic levitation phenomena with the utilization of air squeeze film between the vibrating inducer and the lifted object. The objective of the study is to determine the shape of the inducer with vibration characteristics that would allow the levitation of an object of the assumed geometry. In this paper, the influence of the dimension ratio of the inducer on the frequency of the first mode of vibration was presented. CFD calculations for a selected dimension series were performed with the goal of the determination of lifting conditions. The data obtained from the analysis will be used to manufacture an inducer that will serve as an experimental verification for the fluid dynamics calculation.

Słowa kluczowe: lewitacja akustyczna, analiza modalna, CFD.

Streszczenie W literaturze opisywane jest zjawisko lewitacji akustycznej z wykorzystaniem efektu wyciskania powietrza ze szczeliny między drgającym wzbudnikiem a unoszonym obiektem. Celem badań jest znalezienie takiego kształtu wzbudnika, którego charakterystyka drgań pozwalałaby na lewitację obiektu o założonej geometrii. W opracowaniu określono wpływ wymiarów wzbudnika na kształt oraz częstotliwość jego pierwszej postaci drgań własnych. Dla wybranego przypadku wykonano symulacje CFD w celu określenia warunków unoszenia. Uzyskane wyniki analiz posłużą do wykonania wzbudnika w celu przeprowadzenia weryfikacyjnych badań eksperymentalnych.

INTRODUCTION

One of the most beneficial characteristics of near field acoustic levitation (NFAL) or squeeze film acoustic levitation is a non-contact means of positioning objects with the possibility to work with an atmospheric air acting as a working fluid. The transport systems utilizing the squeeze film effect can find application in the transportation and handling of micro-electromechanical elements prone to adhesion contamination.

The idea of NFAL has been researched for several decades, and experimental and theoretical investigations have been performed. Unfortunately, there is no known paper presenting a general description of dependencies of various factors (e.g., lifted mass, inducer frequency, or amplitude) on the characteristics of the fluid film.

Three methods of inducing NFAL can be distinguished based on the behaviour of the vibrating plate. The first assumes the oscillation of the whole plate acting as a rigid body (piston type inducer) **[L. 1, 2]** **(Fig. 1a)**. In this case, the frequency and the amplitude of the inducer are dependent on the energy source of the system (typically a piezoelectric transducer – PZT).

The second type **(Fig. 1b)** of inducer behaviour is the vibration caused by the effect of resonance. In this case, the vibrating source is deflected according to the mode of vibration at specific frequencies **[L. 3–5]**. This setup can be characterised by natural frequencies which are dependent on setup geometry, used materials, and damping conditions. The change of the amplitude of the vibration can be achieved by changing the supply voltage of the PZT element. The oscillations out of the

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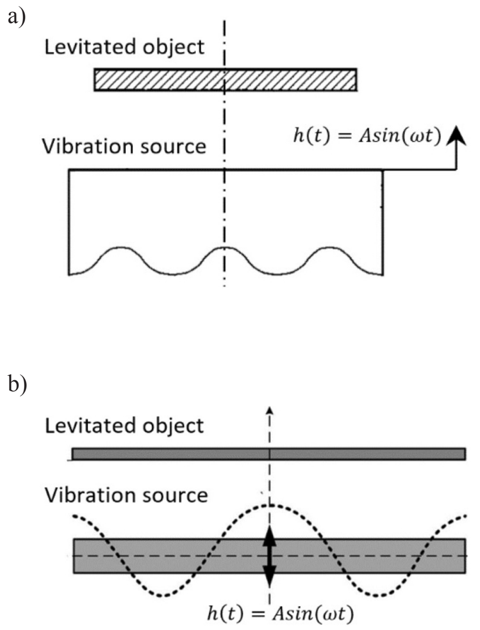

Fig. 1. Chosen methods of the NFAL inducting by vibrating: a) rigid body (piston type inducer) [L. 1], b) elastic circular membrane inducer under chosen resonant frequency [L. 3]

Rys. 1. Wybrane metody uzyskiwania efektu NFAL poprzez drgania: a) sztywnej powierzchni (tłoczyska) **[L. 1]**, b) elastycznej kołowej membrany w wybranej częstotliwości rezonansowej **[L. 3]**

range of natural frequencies are possible, but higher power demand is required.

A setup capable of not only supporting but also transporting elements is based on using a traveling wave. Several experimental devices with both linear and rotational bases were constructed and proved the concept **[L. 6–8]**. In this case, the lifting conditions may be less possible to control; therefore, it is not considered in this article.

ASSUMED SHAPE OF THE INDUCER

For the purpose of the analysis, the shape of the inducing element was assumed as a thick plate with a circular membrane (as presented in **Fig. 2**). In concept, the plate will utilize the second type of behaviour, i.e. a resonant vibration plate **(Fig. 1b)**.

The membrane thickness, *g*, is not the focus of this study. The more slender membrane allows for the higher oscillation amplitudes and frequencies with the use of an extorting element of the same power, which is beneficial for the lifting height. The membrane thickness is limited by the manufacturing technology of the inducer. Therefore, the calculations were performed for the constant dimension of the thickness of the membrane $g = 1\ mm$, which is possible with available manufacturing methods.

Beyond the aforementioned dimension, other varying aspects of the plate are the membrane diameter (*D*), the thickness of the plate (*h),* and the dimension of square flange of plate (*LW*). Four values of its height were considered: 8, 10, 15, and 20 mm. Calculated cases assumed the bore diameter in the range of 35–60 mm with 5 mm increments. The dimensions of the square base presented in the paper refer to the assumed diameter of the membrane in a manner that the length of the plate was increased by 10, 15, 20, and 25 mm with regard to the diameter. Modal analysis for all combinations was performed.

MODAL ANALYSIS OF THE INDUCER

Apart from the shape of the studied body for the modal analysis, relevant aspects are the material data of the element and constrains given for the model. The relevant material data assumed for the case are typical for steel: Young's modulus $E = 215\ GPa$, Poisson's ration $\nu = 0.3$, density $\rho = 7850\ kg/m^3$. Constrains imposed on the model are limited to fixed constrains on the two opposing walls of the plate (**Fig. 2**). They represent the planned position of the mounting of plate.

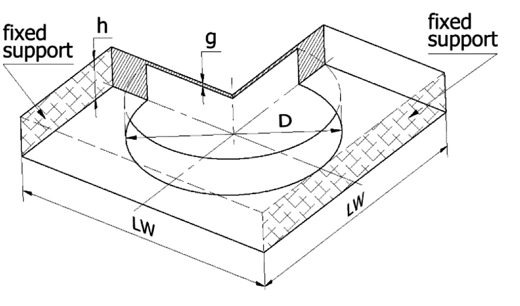

Fig. 2. Bottom view of fundamental geometry of the plate presented with constrained walls

Rys. 2. Widok od spodu głównej części geometrii płyty z oznaczeniem jej ścian mocujących

Performed analysis gave multiple normal modes of vibration of the plate. **Fig. 3** shows the modes of vibration for one of the cases of their fundamental geometry (with dimensions: $h = 10$ mm, $D = 50\ mm$, $LW = 70\ mm$ *and* $g = 1\ mm$). Vibrational modes of the circular membrane and correlation between frequencies of the modes were previously described **[L. 9]** creating labelling nomenclature for the modes. The designations of the two nodal numbers are *d*, which is the number of nodal diameters, and *c*, which is the number of nodal circles.

When analysing the shape and frequencies of the occurrence of the specific modes, we can group modes of similar shape. The second and third modes occur in similar frequencies and depict similar deflection shapes of the membrane (mode (1,1) – i.e. one nodal diameter, *d*, and one nodal circle, *c*), altering the arrangement of the deformation relative to the constraint faces. A similar case can be observed in the sixth and seventh mode (the (2,1) mode – two nodal diameters and one nodal circle). The order of the modes concerning the membranes is predetermined and their frequency is dependent on the fundamental frequency of the membrane.

Two of the presented modes of vibration do not correspond to cases of sole oscillation of the membrane. Modes 4 and 5 illustrate the deflection of the whole plate.

For the reason of researching the behaviour of the membrane, it is beneficial to avoid the overlap between the modal frequencies of the membrane (where deflection of the flange is negligible) and the modal frequencies with recognizable movement of the rim.

The first mode of the vibration provides the highest amplitude of oscillation with the same amount of energy provided to the system. Moreover, the shape of the membrane during the oscillation is axisymmetric, which should allow for a stable air film between the object and the inducer. Therefore, the frequency for the first mode is further considered.

The fundamental frequencies for constant values of the thickness of the plate are presented in **Fig. 4**. It can be observed that the frequency value is similar for the cases with the same size of the membrane and that the value of the frequency decreases with its diameter. The impact of the base plate dimension for a specific membrane can be observed in **Fig. 5.** The assumed range of the flange dimension allowed the minimization of the relative difference between the highest and the lowest frequencies for a specific membrane size. The relative percentage change is lower than 1% for any investigated case group.

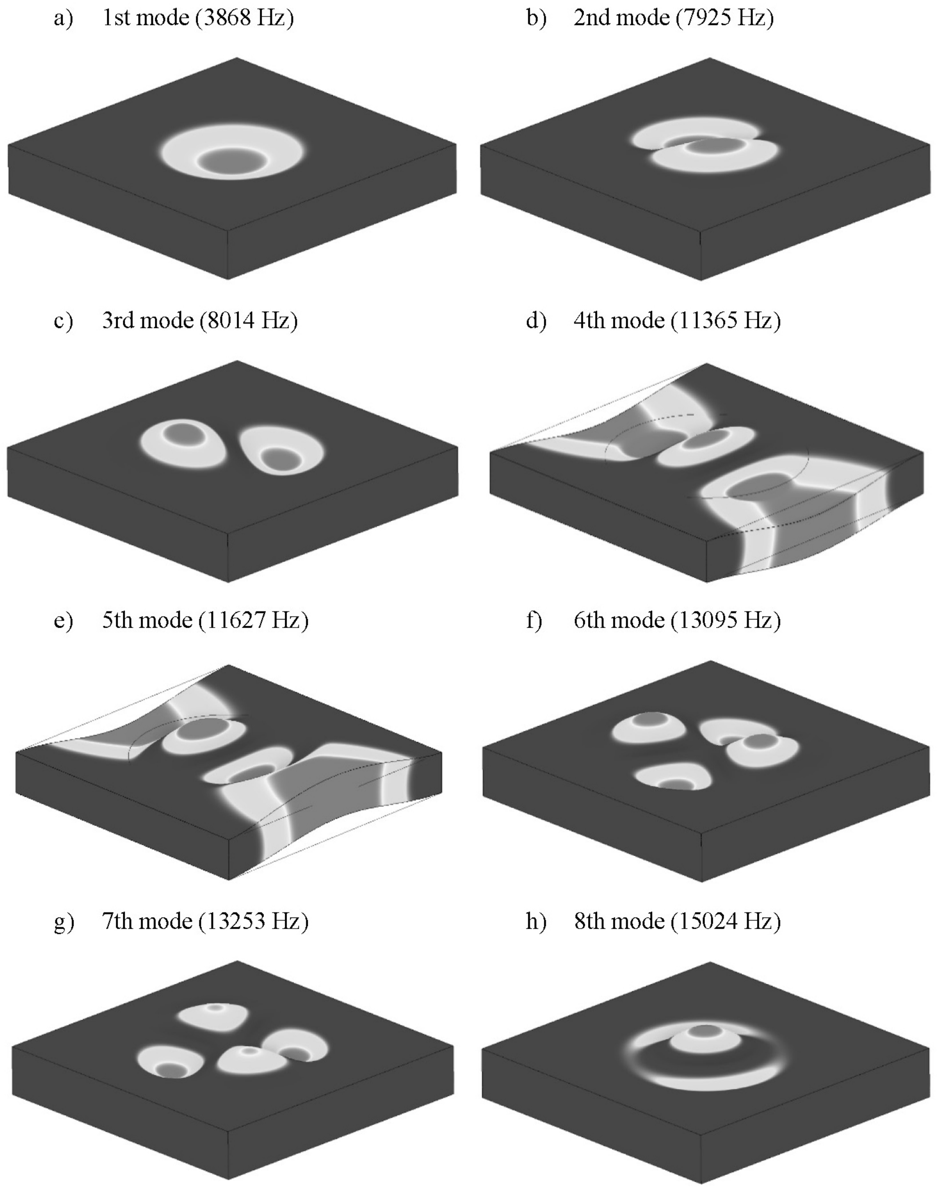

Fig. 3. Modes of vibration of the plate (*h* = 10 mm, *D* = 50 mm, *LW* = 70 mm)
Rys. 3. Postacie drgań własnych płyty (*h* = 10 mm, *D* = 50 mm, *LW* = 70 mm)

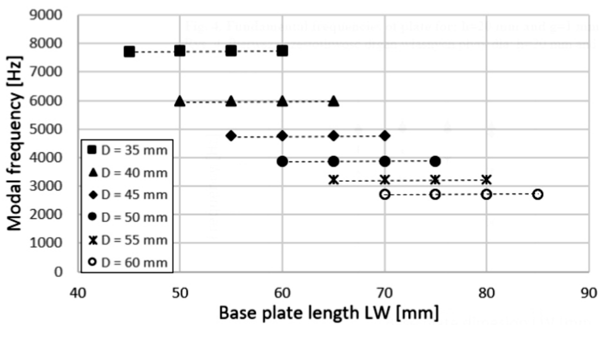

Fig. 4. Fundamental frequencies of plate for: *h = 20 mm* and *g = 1 mm*

Rys. 4. Pierwsza częstotliwość drgań własnych płyty dla: *h = 20 mm* and *g = 1 mm*

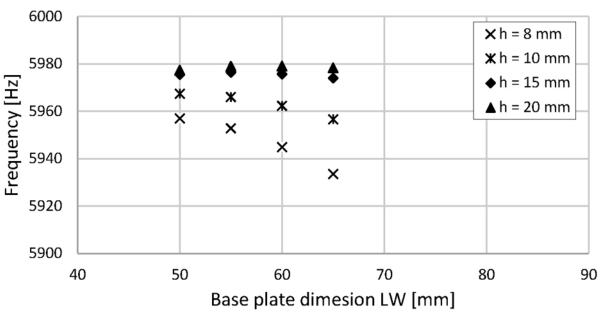

Fig. 5. Fundamental frequencies of plate for *D* = 40 mm and *g* = 1 mm

Rys. 5. Wartość pierwszej częstotliwości drgań własnych płyty dla: *D* = 40 mm i *g* = 1 mm

RESULTS OF THE CFD ANALYSIS – PARAMETERS OF THE LIFTING

The final geometry chosen for the Computer Fluid Dynamic analysis is a cuboid base with dimensions *LW* = 65 mm and *h* = 11 mm and a membrane diameter *D* of 40 mm (and *g* = 1 mm). The resonant frequency related to the membrane first mode is equal to 6015 Hz. In the chosen geometry, the modal frequency related to the base rim is equal to 13785 Hz. The difference is sufficient to avert the possibility an overlap of the cases due to machining inaccuracies or minor changes in mounting setup.

The object assumed to be lifted is a circular plate of 40 mm in diameter, which is equal to the membrane diameter *D*, with a mass of 5 g. The lifted object is modelled in CFD environment as a surface of a rigid body; therefore, there is no requirement to assume object material properties. In the system, the object movement is restricted to one degree of freedom with translation along the axis perpendicular to the initial plane of the membrane. Its mean position form the plane of the unexcited membrane (*h* = 0 μm), and it is designated as *hTop* **(Fig. 6)**. The difference of the deflection of the membrane measured along the symmetry planes is limited to no higher than 1%, allowing one to assume axisymmetric conditions. The membrane is modelled as a surface with varying geometry. The geometry movement is time-dependant, and the shape is approximated based on modal analysis and scaled in such a manner that the amplitude of movement of the central point of the membrane h_{max} is equal to 0.5, 1, and 1.5 μm **(Fig. 6)**. The values of the amplitudes *A* were chosen based on the knowledge of values of practicable amplitude values on the systems with use of the power source and PZT elements accessible to the authors.

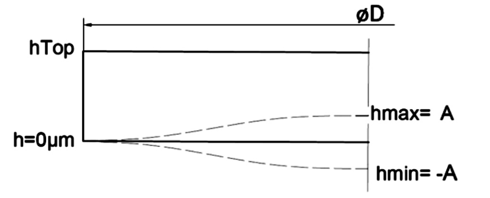

Fig. 6. Scheme of the geometry of assumed axisymmetric CFD model

Rys. 6. Schematyczne przedstawienie geometrii przyjętego osiowosymetrycznego modelu CFD

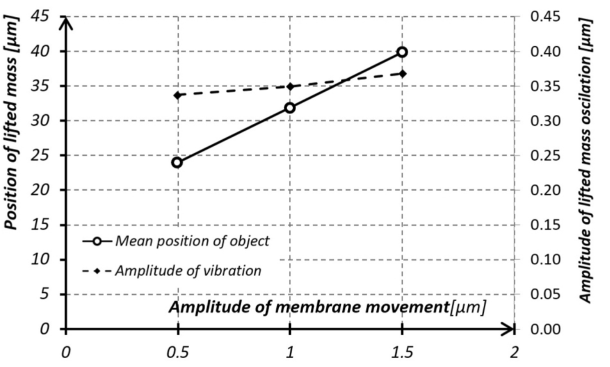

Fig. 7. Mean position (*hTop*) and the amplitude of vibration of the modelled object as a function of amplitude of membrane movement

Rys. 7. Średnia wysokość (*hTop*) oraz amplituda drgań unoszonego obiektu w funkcji amplitudy oscylacji membrany

Figure 7 shows the mean height of the levitation and the value of the oscillation of the lifted body. These two values are the most important in determining the chance of contact occurring between the inducer and the object. According to the calculations, the average levitation height raises with the increase of the membrane amplitude movement, and it is in the range of 23–40 μm. The oscillation of the lifted body is never larger than 0.5 μm, which two orders of magnitude smaller than the average height. The raise of both values may be explained with the increase of the power provided for the system. In literature **[L. 2]**, stable levitation conditions are described having as low as 10 μm film thickness in experimental conditions. With sufficient rigidity of the lifted mass and appropriate surface characteristics of the membrane, the proposed geometry of the setup will allow for experimental study of the near field acoustic levitation phenomena.

CONCLUSIONS

It has been confirmed that initially assumed dimensions of the reinforcing plate allowed us to obtain a few modes of vibration without significant impact of the rim. Assured lack of the influence of the plate periphery supporting the inducer allowed us to simplify further investigation into the geometry of the membrane itself.

The geometry applied for the CFD study allows for the generation of a fluid film with satisfactory thickness. The amplitude of the vibration observed is considerably smaller than the lifting height.

The plate will be used as an experimental verification of used CFD model and provide a tool for NFAL phenomena research. The feasibility of the usage of the plate away from modal frequencies based on energy consumption efficiency should be observed.

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