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# THEORETICAL MODELING OF A MECHANICAL NEAR-FIELD ACOUSTIC LEVITATION SYSTEM

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***Abstract.*** *The problem in question permeates the fluid induced acoustic levitation, which consists of the introduction of a large amount of pressure waves, resulting from the sound vibration of a high frequency exciter creating a pressure field from a compression film, as a consequence of an opposing force to gravity. It is possible for objects to be suspended, even if they are large or heavy. Understanding the behavior of this type of model is of paramount importance due to the numerous applications and its versatility. The approach used in the present work is new, as it seeks to describe the pressure field by means of a system of ordinary differential equations solved simultaneously using the method of progressive finite differences. The proposed model consists of a receiving disc and an exciting surface, where both are surrounded by a cylinder so that the system is sealed and that there is no mass flow. In addition, it is necessary to analyze the reliability of the proposed model. For this, at first, the problem is modeled, so that the exciter is static, that is, it is not active. Thus, the focus of the analysis is only on the receiver and its movement from rest. With this simplification, and the introduction of the parameter beta , which depends on the mass and cross-sectional area of the disc, it is possible to compare the numerical model with an analytically predicted response, which validates the hypothesis. Finally, the last case analyzed will be one with a movement imposed on the exciter with known speed, position and frequency and obviously the implications of this for the receiver and the system such as the variation of the specific mass of the film, the internal temperature and the position of the disc over time.*

***Keywords:*** *acoustic levitation, numerical analyses, flow induced-vibration, near-field, theoretical model*

## 1. INTRODUCTION

Levitation is a concept that permeates the human imagination. It can be defined as the suspension of matter via some technique, that is, levitating is possible by applying a counter-gravitational force. Ferreira Júnior (2018) mentions that, in recent years, these techniques have gained the attention of several researchers since they can be applied in the transport and manipulation of bodies without any mechanical contact with it.

Castro (2013) cites the different types of levitation in science, such as acoustics, optics and magnetic ones. For that, acoustic levitation is an interesting application, precisely because it does not take into account the physical properties of a material, as in the case of the magnetic one, in which the object to be levitated must present ferromagnetic properties in some state.

There are essentially two types of acoustic levitation: near-field and plane-wave. The plane-wave approach is one of the simplest used today and, according to Andrade (2010), makes use of two devices, an ultrasonic transducer and a reflector. The waves that are generated by the transducer are reflected by the reflector so that there is destructive interference in some intervals of the space between the devices. Thus, low pressure nodes are created with adjacent high pressure zones, which allows small objects to be suspended. Although effective, the model also has restrictions, now regarding the size of the objects to be suspended, which must have up to half the emitted wavelength.

In the near-field acoustic levitation, high frequency ultrasonic oscillations are used from a vibrating device (exciter) that creates a layer of high pressure gas, called a compression film or because it is an acoustic model also called the Fresnel Zone, as proposes Vandaele *et al.* (2005), between the exciter and the object to be levitated.

The pressure increase is due to the compressibility of the fluid, in this case, the gas between the two surfaces. With this increase, the tendency is to reach pressure values higher than the atmospheric pressure in order to create a force in the opposite direction to the weight. Ilssar and Bucher (2015) proposes that to describe acoustic levitation, one must take into account another force besides weight: the damping force resulting from the viscosity of the gas. For this, they use the model of the Reynolds equation that describes well the pressure field in bearings lubricated with fluid. There are still experimental works, such as of Li *et al.* (2017) , which tried to use this same device to describe both the force due to compression and the viscous dissipation force.

However, the approach used in this work, although similar, presents some differences, mainly in treating the pressure field linked to three other ordinary differential equations (ODEs).

Thus, the work aims to propose a theoretical model of near-field acoustic levitation, and by using numerical methods, to solve it in order to discover how some of the properties of the compression film behave in a given testing time.

## 2. METHODOLOGY

At first, the representation of the physical model of the problem is interesting, as shown in Fig. 1. It is a model very similar to the one proposed by Ilssar and Bucher (2015) and by Ueha *et al.* (2000) , which consists of a disc and a flat surface with the difference that here both are arranged in a closed cylinder and without friction against the walls. Therefore, it is possible to verify that there is no mass flow in the model, only the mass confined between the disc and the exciter surface. Both the surface and the disc have the same radius, coinciding with the radius of the external cylinder.

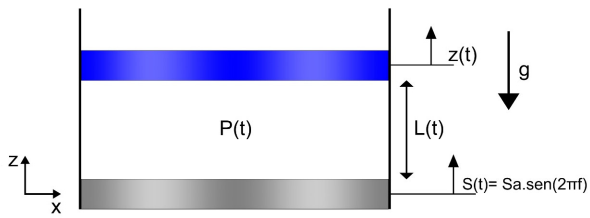


Figure 1. Scheme proposed for the physical model

It is important to note that the exciter does not suffer deformation during its performance. In addition, it is necessary to carry out an initial analysis with the static exciter as in Fig. 2, considering that there is a parameter $\beta$, relevant for understanding the model as a whole. Only afterwards, one should go for the acoustic levitation itself.

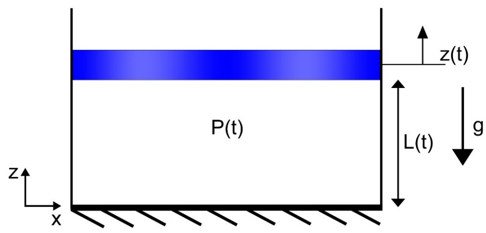


Figure 2. Model with static / non-functional exciter

Given the need for two analyzes, the hypotheses listed here are common to both:

- Compressible fluid so that the specific mass of the gas contained inside is variable
- No mass flow, ie. without adding or removing matter
- Instant homogenization
- Confined gas is ideal
- Friction on the cylinder walls is neglected
- Inertial reference at the base of the cylinder
- Unidirectional outflow
- Linear speed profile with $z$, ie. $w(t, z) = a(t).\ z + b(t)$
- Airtight and adiabatic system
- No turbulent effects or considering instabilities

A final consideration of extreme importance is that: from Ilssar *et al.* (2017) considers the viscosity of the gas itself as a damping force. In contrast, in this work, in order to simplify the mathematical model, we tried to translate the viscous damping force while the viscous dissipation force of a tiny oil gap between the walls of the cylinder and the receiver disc.

### 2.1 Formulation of mathematical model

Table 1. Nomenclature Table

| Variable | Meaning | Variable | Meaning |
|---|---|---|---|
| $\rho$ | Specific mass | $T$ | Fluid Temperature |
| $V$ | Fluid velocity | $R$ | Gas constant |
| $L$ | Length | $\nu$ | Oil viscosity |
| $PF$ | Compression force | $Ad$ | Transverse area |
| $W$ | Weight force | $Al$ | Lateral area |
| $VF$ | Viscous force | $Vr$ | Disc velocity |
| $P$ | Gauge pressure | $\phi$ | Viscous dissipation function |
| $cp$ | Specific heat | $Se$ | Exciter position |
| $e$ | Oil gap | $h$ | Thickness |

Using the variables placed in the Tab. 1, in order to describe the system, ordinary differential equations (ODEs) are required, starting with the Navier-Stokes Equation for Mass conservation (a.k.a Continuity). Obtained from the Reynolds Transport Theorem applied to an infinitesimal volume is given by:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{V}) = 0 \tag{1}$$

Where, from the scalar product between the divergent and the term $(\rho\vec{V})$ can be opened to the sum of the partials applied to the product between the specific mass and each of the components of the fluid velocity $(u, v, w)$. In addition, given the initial hypotheses in which the flow is unidirectional (with $u = v = 0$) and there is instant homogenization (where $\rho(t, z) = \rho(t)$), easily in ODE now with ordinary derivatives as it is described in only one direction:

$$\frac{d\rho}{dt} + \rho\frac{dw}{dz} = 0 \tag{2}$$

The term $\rho\frac{dw}{dz}$ is initially unknown. However, starting from the hypothesis described above, in which the flow velocity profile will be linear with the z coordinate (and with its constants as a function of time), assuming the boundary conditions of Tab. 2, we have:

$$w(t, z) = a(t) \cdot z + b(t) \tag{3}$$

Table 2. Boundary conditions at any time to determine the coefficients of the linear speed profile

| Boundary Conditions | Application in Function | Coefficient Values |
|---|---|---|
| $w(0, t) = 0$ | $0 = a(t) \cdot 0 + b(t)$ | $b(t) = 0$ |
| $w(L(t), t) = V(t)$ | $V(t) = a(t) \cdot L(t) + b(t)$ | $a(t) = V(t)/L(t)$ |

That being done, manipulating Eq. (2) and knowing that $\frac{dw}{dz} = a(t)$ comes to the final form of Eq. (1) for this case, thus having a slight sense of gas behavior due to variations in disc speed and compression film length

$$\frac{d\rho}{dt} = -\rho\frac{V(t)}{L(t)} \tag{4}$$

The length of the compression film can be defined whether the distance between the disc and the surface on the exciter is functional or not:

$$\frac{dL}{dt} = V(t) \tag{5}$$

It remains to find the relationship of velocity considering that both Eq. (4) and Eq. (5) are dependent on this quantity. To do this, one must start from the free-body diagram on the disc as shown in Fig. 3. The acting forces are the disc weight force, force resulting from the variation of the compression film and as also proposed by Ilssar *et al.* (2017) the damping force (dissipative) due to the viscosity of the gas translated into the viscosity of the oil's gap on the cylinder wall. From the sum of forces and verifying that they are all in the same direction we also have:

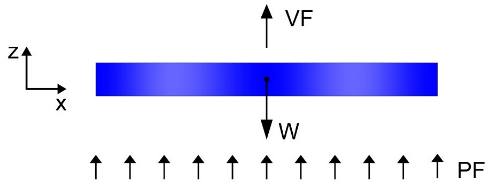


Figure 3. Disc free body diagram

$$\sum F = PF - W - VF \tag{6}$$

Therefore, the resulting force will be, according to the order proposed in Eq. (6), equal to the force that the compression film exerts on the disc walls less the weight of the disc and less the viscous dissipation of the oil's gap. It is important to say that viscous dissipation is always a component of attenuation of movement and, for this reason, it is given by the negative sign. In the equation above, each of the terms requires a more detailed analysis of each of its parameters, thus we have:

$$PF = (\rho(t) \cdot R \cdot T(t) - Patm) \cdot Ad \tag{7}$$

Where the term in parentheses sets the manometric pressure contained between the disc and the exciter and $Ad$ is the transverse area of the disc.

$$VF = \tau \cdot Al \tag{8}$$

$$VF = \mu \frac{dw}{dx} \cdot 2\pi r \cdot h \tag{9}$$

$$VF = \mu \frac{Vr}{e} \cdot 2\pi r \cdot h \tag{10}$$

Where $Al$ is the lateral area of the disc while $\tau$ is the shear stress of the disc over the oil fluid. $Vr$ is the speed of the receiver, $h$ is the thickness of the disc, $e$ and $\mu$ are the gap size and oil viscosity respectively.

In this way, Eq. (6) can be better rewritten and dividing everything by the mass of the disc:

$$m\frac{dVr}{dt} = (\rho(t) \cdot R \cdot T(t) - Patm) \cdot Ad - mg - \mu \frac{Vr}{e} \cdot 2\pi r \cdot h \tag{11}$$

$$\frac{dVr}{dt} = \frac{(\rho(t) \cdot R \cdot T(t) - Patm) \cdot Ad}{m} - g - \mu \frac{Vr}{e \cdot m} \cdot 2\pi r \cdot h \tag{12}$$

An unknown parameter appears again, in this case the internal temperature of the confined gas. To calculate it, the Differential Energy Equation is used, according to White (1991) given by:

$$\rho \cdot cp \frac{DT}{Dt} + P(\nabla V) = k \cdot \nabla^2 T + \phi \tag{13}$$

Where:

- $P$ is the gauge pressure and $P(\nabla V) = -\frac{d\rho}{dt} \cdot \frac{P}{\rho}$

- The total derivative of the temperature and is given by $\frac{DT}{Dt} = \frac{\partial T}{\partial t} + \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z}$

Assuming that the temperature does not vary with space - it is the same for any region of the fluid at a given time, that is $T(t,x,y,z) = T(t) \rightharpoonup \nabla^2 T = 0$ - and dividing the terms by $\rho \cdot cp$ the Eq. (13) is better represented by:

$$\frac{dT}{dt} = \frac{d\rho}{\rho dt} \cdot \frac{P}{\rho \cdot cp} + \frac{\phi}{\rho \cdot cp} \tag{14}$$

The variable $\phi$ is called a viscous dissipation function and is given by:

$$\phi = \mu[2(\frac{\partial u}{\partial x})^2 + 2(\frac{\partial v}{\partial y})^2 + 2(\frac{\partial w}{\partial z})^2 + (\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y})^2 + (\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z})^2 + (\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x})^2] + \\ + \lambda \cdot (\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z})^2 \tag{15}$$

From where a reasonable hypothesis, we have:

$$\lambda = -\frac{2\mu}{3} \tag{16}$$

Since the partials in $u$ and $v$ are null as well as the $w$ partials in the components $x$ and $y$. The $\phi$ function is reduced to

$$\phi = 2\mu(\frac{\partial w}{\partial z})^2 - \frac{2}{3}\mu(\frac{\partial w}{\partial z})^2 \tag{17}$$

Coming back to Eq. (14)

$$\frac{dT}{dt} = \frac{d\rho}{\rho dt} \cdot \frac{P}{\rho \cdot cp} + \frac{4}{3 \cdot \rho \cdot cp}\mu(\frac{\partial w}{\partial z})^2 \tag{18}$$

According to the Tab. 1 and the boundary conditions of the model thus we have:

$$\frac{dT}{dt} = \frac{d\rho}{\rho dt} \cdot \frac{P}{\rho \cdot cp} + \frac{4}{3 \cdot \rho \cdot cp}\mu(\frac{V(t)}{L(t)})^2 \tag{19}$$

With the internal temperature now set, all the equations that govern the model are covered. It is important to deal with the beta parameter, as it is possible to compare responses for the disc's equilibrium height, given a dissipative force, obtained analytically and using numerical methods. To do so, assuming that the speed is zero at equilibrium, we have at that moment the absence of dissipative force. Thus, there is a balance of pressure forces and the weight of the disc.

Once again, starting with the mass conservation in the cylinder and given by:

$$M_i = M_o \tag{20}$$

$$\rho_i v_i = \rho_i v_i \tag{21}$$

$$A \cdot H_i \cdot \frac{P_i}{R \cdot T_i} = A \cdot H_o \cdot \frac{P_o}{R \cdot T_o} \tag{22}$$

Where sub-indices $i$ and $o$ indicate the initial and final conditions, H is the height of the disc, R is the ideal gas constant. The A is the surface area of the disc. Being $P_i$ equal to atmospheric pressure we have $P_o$ equal to the final absolute pressure (defined as the sum of atmospheric pressure plus the system manometric pressure) of the system when equilibrium is reached, then:

$$H_i \cdot \frac{P_{atm}}{T_i} = H_o \cdot \frac{P_{atm} + P_{man}}{T_o} \tag{23}$$

$$H_o = H_i \cdot \frac{T_o}{T_i} \cdot \frac{P_{atm}}{P_{atm} + P_{man}} \tag{24}$$

$$H_o = H_i \cdot \frac{T_o}{T_i} \cdot \frac{P_{atm}}{P_{atm} + \frac{m \cdot g}{A}} \tag{25}$$

A simplification is to assume that the process is isothermal, so both the final and initial temperatures are the same. This consideration is made only in order to obtain proof that the numerical model is consistent, that is, whether the height of equilibrium will be close to that suggested via the $\beta$ parameter. Thus,

$$H_o = H_i \cdot \frac{P_{atm}}{P_{atm} + \frac{m \cdot g}{A}} \tag{26}$$

And the $\beta$ parameter is:

$$\beta = \frac{P_{atm}}{P_{atm} + \frac{m \cdot g}{A}} \tag{27}$$

$$0 < \beta < 1$$

It is easy to see that the parameter is contained in a range from zero to one excluding these, that is, being close to zero, it occurs that the final height is particularly null and being close to one indicates that the disc has practically not moved. For it to tend to zero it is necessary that either the mass of the disc approaches infinity or that the area is close to zero.

So two manly conclusions are drawn: the first is that the smaller the mass of the receiving disc, the greater the balance position, in turn the second indicates that the smaller the surface area of the disc, the lower the height of the equilibrium condition.

Now it remains to analyze the whole set, disc and exciter with all the present forces. The differential mathematical model changes a little. Basically what differs from the previous model is that, the term that was previously given by the speed of the disc, will now be explained by the difference in speeds between the receiver and the exciter. The only equation of the ODE's system that does not change is the Eq. (28), since it is relative to the free body diagram of the receiver only.

Thus the equations that govern the model are:

$$\frac{dVr}{dt} = \frac{(\rho(t) \cdot R \cdot T(t) - Patm) \cdot Ad}{m} - g - \mu \frac{Vr}{e \cdot m} \cdot 2\pi r \cdot h \tag{28}$$

$$\frac{d\rho}{dt} = -\rho \frac{Vr(t) - Ve(t)}{L(t)} \tag{29}$$

$$\frac{dL}{dt} = Vr(t) - Ve(t) \tag{30}$$

$$\frac{dT}{dt} = \frac{d\rho}{\rho dt} \cdot \frac{P}{\rho \cdot cp} + \frac{4}{3 \cdot \rho \cdot cp} \mu (\frac{Vr(t) - Ve(t)}{L(t)})^2 \tag{31}$$

Also, it is important to determine the behaviour of the exciter. The position of the exciter over time is known and is governed by a sine wave given by:

$$S_e = S_{max} \cdot sin(2\pi f \cdot t) \tag{32}$$

Thus, the exciter speed term is given through the derivative of the Eq. (32):

$$V_e = S_{max} \cdot 2\pi f \cdot sin(2\pi f \cdot t) \tag{33}$$

Where $S_{max}$ is maximum amplitude of the surface and $f$ is the exciter frequency.

## 2.2 Numerical Discretization

As it is a system of linked ordinary differential equations (ODEs), it is impossible to solve it analytically. For this reason, numerical techniques for the resolution of ODEs are used. In this case, the Progressive Finite Differences Method was chosen. UFRGS (2020) postulates that the method consists of the discretization of the function domain in finite sub-intervals of the same size.

After discretizing the domain, one finds the approximate expressions of the derivatives in each of the ordinary equations. As an example, taking a function $u(x)$, the value of $u(x + k)$ can be expanded around $x$ via Taylor series as shown in Eq. (34)

$$u(x + k) = u(x) + \frac{ku'(x)}{1!} + \frac{k^2u''(x)}{2!} + \frac{k^3u'''(x)}{3!} + ... \tag{34}$$

Where $O(k)$ is

$$O(k) = \frac{ku'(x)}{1!} + \frac{k^2u''(x)}{2!} + \frac{k^3u'''(x)}{3!} + ... \tag{35}$$

So

$$u'(x) = \frac{u(x + k) - u(x)}{k} + O(k) \tag{36}$$

$$u'(x) \approx \frac{u(x + k) - u(x)}{k} \tag{37}$$

Consequently, for each point in the now discrete domain, the value of $u'(x)$ is obtained by varying the $h$ spacing according to

$$u'(i) = \frac{u(i + 1) - u(i)}{k} \tag{38}$$

On what:
$u'(i) = u'(x)$
$u(i+1) = u(x+k)$
$u(i) = u(x)$
$i = 1, 2, 3, ..., n$
Applying this concept to Eq. (28) until Eq. (31), we have:

$$Vr_{i+1} = Vr_i + k \cdot (\frac{(\rho_i \cdot R \cdot T_i - Patm) \cdot Ad}{m} - g - \mu \frac{Vr_i}{e \cdot m} \cdot 2\pi r \cdot h) \tag{39}$$

$$\rho_{i+1} = \rho_i - k \cdot \rho_i \frac{Vr_{i+1} - Ve_i}{L_i} \tag{40}$$

$$L_{i+1} = L_i + k \cdot (Vr_{i+1} - Ve_i) \tag{41}$$

$$T_{i+1} = T_i + k \cdot (\frac{\rho_{i+1} - \rho_i}{\rho_{i+1} \cdot k} \cdot \frac{\rho_{i+1} \cdot R \cdot T_i - Patm}{\rho_{i+1} \cdot cp} + \frac{4}{3 \cdot \rho_{i+1} \cdot cp} \mu (\frac{Vr_{i+1} - Ve_i}{L_{i+1}})^2) \tag{42}$$

## 3. RESULTS

Making the numerical formalization on MATLAB, the constant properties and initial conditions are given in the Tab. 3

Table 3. Constant Properties and Initial Conditions used in the numerical approach

| Constant Properties | | Initial Conditions | |
|---|---|---|---|
| Disc mass (kg) | 9 | disc initial height (m) | 0,1 |
| Disc diameter (m) | 2 e-02 | Initial specific mass (kg/m$^3$) | 1,22 |
| Disc thickness (m) | 2 e-03 | Initial Temperature (K) | 288 |
| Oil dynamic viscosity (N.s/m$^2$) | 2,9 e-01 | Initial Speed (m/s) | 0 |
| Oil gap (m) | 0,8 e-06 | | |
| Gas constant (J/kg.K)$^{(1)}$ | 287 | | |
| Specific heat (J/kg.K)$^{(1)}$ | 1004,8 | | |
| Dynamic viscosity (N.s/m$^2$)$^{(1)}$ | 17,76 e-06 | | |

$^{(1)}$ measured at 15$^o$C using ISA - International Standard Atmosphere

Figure 4 shows that the numerical model approach has a good quality when compared to analytical analyzes using the parameter $\beta$. Using the properties provided on the Tab. 3 and also using Eq. (26) we reach that the final positions are actually 0.0264 m and differ from the value found numerically by 0.43%

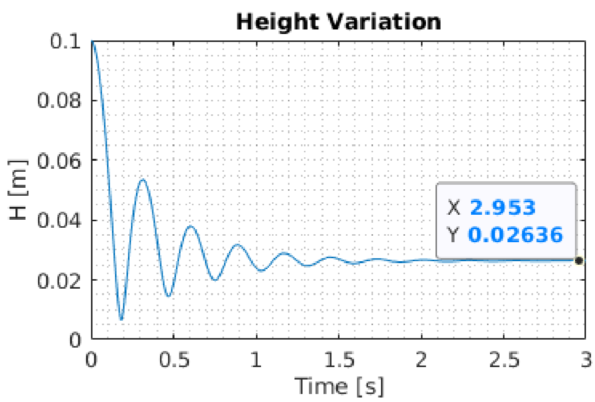


Figure 4. Equilibrium position of the disc via numerical discretization for comparison with the beta parameter Constant temperature and no exciter

In relation to the complete model, the graphics of the position of the disc over time, the variation of the specific mass and the internal temperature were derived from the data acquired in the numerical approach. The Fig. 5 show the results for the exciter frequency of 15 Hz and maximum amplitude of 0.0052 m. The Fig. 6 illustrates the position of the disc over time, and also shows the interesting behaviour of both frequencies and amplitudes been almost the same.

At the same time, Fig. 7 shows what happens if the frequency and amplitude are changed. We can see that these properties increase their values for both parameters. Last, but not least, in Fig. 8 it is possible to notice that due to the higher frequency, now 32 Hz, and greater amplitude of 0.0092 m, the amplitude of oscillation of the disk is also recognized to be greater.

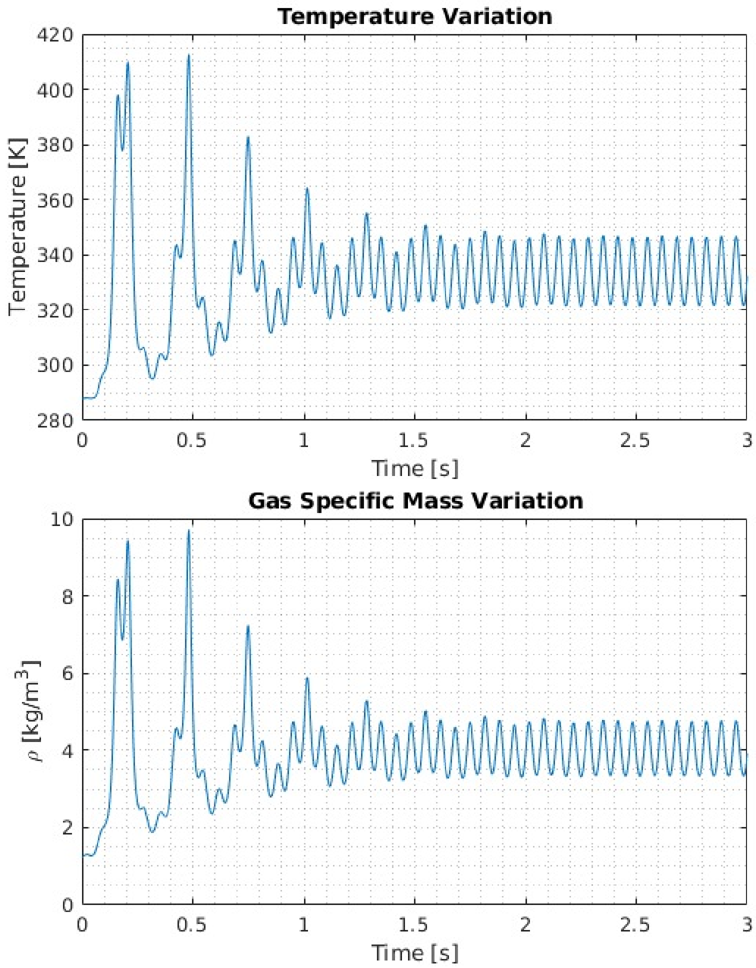


Figure 5. Temperature and Specific Mass of the gas.
Exciter frequency = 15 Hz and Maximum Amplitude of the surface = 0,0052 m

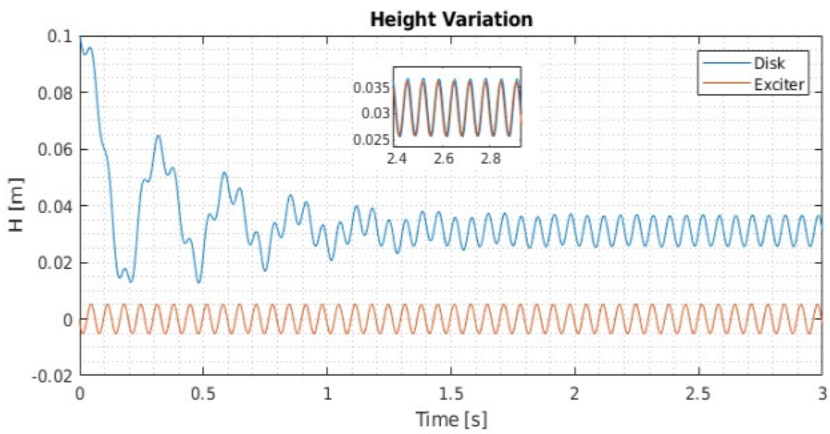


Figure 6. Position of the disc over time
Exciter frequency = 15 Hz and Maximum Amplitude of the surface = 0,0052 m

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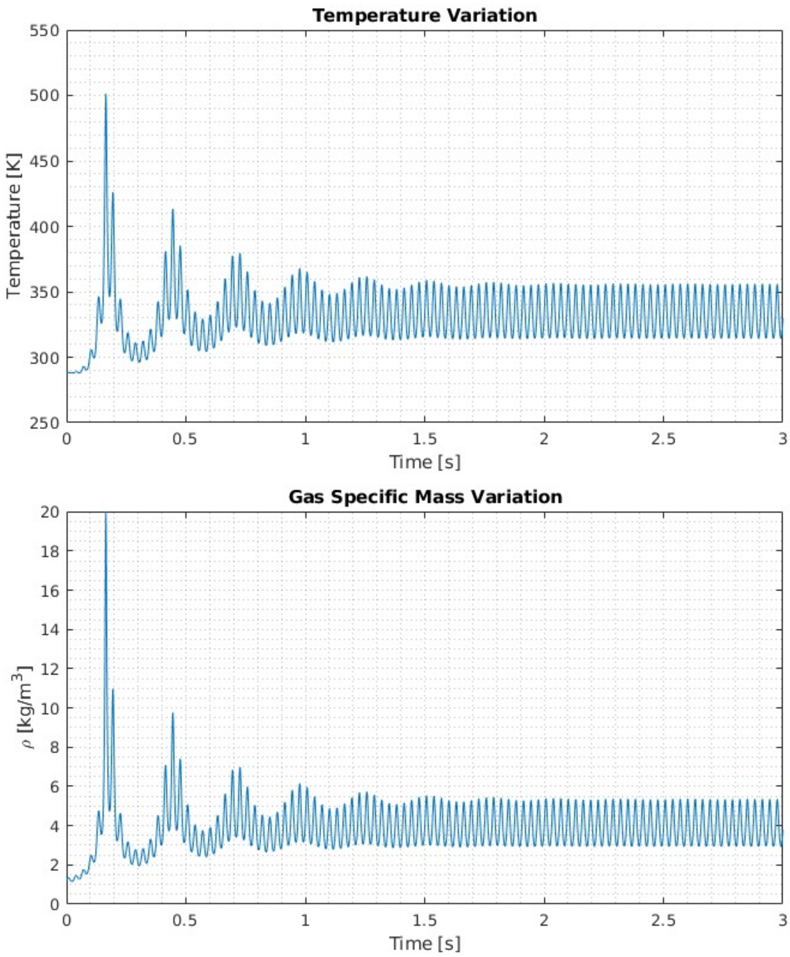


Figure 7. Teperature and Specific Mass of the gas.
Exciter frequency = 32 Hz and Maximum Amplitude of the surface = 0,0092 m

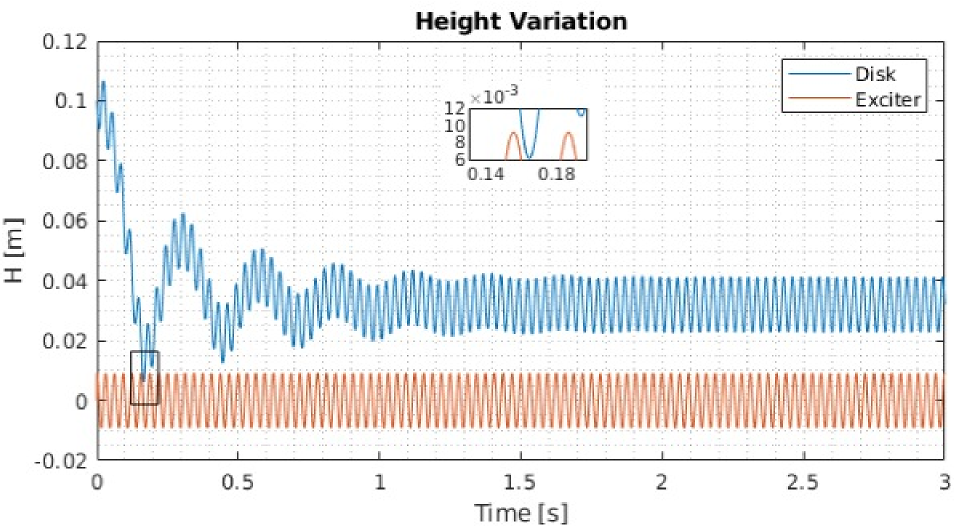


Figure 8. Position of the disc over time
Exciter frequency = 32 Hz and Maximum Amplitude of the surface = 0,0092 m

## 4. CONCLUSIONS

An fludic acoustic levitation model was proposed, numerical discretization was used to solve the problem and it was found that: regarding the temperature and specific mass of the gas, as expected, peak values are reached when there is the shortest length between the exciter surface and the disc. This fact occurs in the two amplitudes and frequencies analyzed. In addition, it is possible to conclude that, although they are governed by different mathematical expressions, both present a similar behavior in terms of plot shape.

With regard to the position of the disc, it must first be accompanied by a shape similar to that in which the exciter has zero frequency, with the difference that, now there is a second frequency, which attenuates the first, as time passes. It turns out that in regime, both resonate, because the frequency of the disc is practically identical to that of the exciter and the same goes for the amplitude of the wave.

## 5. REFERENCES

Ilssar, D. and Bucher, I., 2015. "On the slow dynamics of near-field acoustically levitated objects under high excitation frequencies". *Journal of Sound and Vibration*, Vol. 354, pp. 154–166.

Ilssar, D., Bucher, I. and Flashner, H., 2017. "Modeling and closed loop control of near-field acoustically levitated objects". *Mechanical Systems and Signal Processing*, Vol. 85, pp. 367–381.

Andrade, M.A.B., 2010. *ESTUDO DA FORÇA DE RADIAÇÃO ACÚSTICA EM PARTÍCULAS PRODUZIDA POR ONDAS PROGRESSIVAS E ESTACIONÁRIAS*. Ph.D. thesis, Universidade de São Paulo - USP, São Paulo, Brasil.

Castro, A., 2013. *Manipulation of biomimetic objects in acoustic levitation*. Ph.D. thesis, Uiversité Pierre et Marie Curie, Paris VI, France.

Ferreira Júnior, F.M., 2018. "InvestigaÇÃo numÉrica de levitaÇÃo acÚstica de campo prÓximo". In *Bachelor's Thesis - Universidade Federal de Uberlândia*. Uberlândia, Brazil.

Li, W., Liu, Y. and Feng, K., 2017. "Non-contact handling in microassembly: Acoustical levitation". *Tribology International*, Vol. 116, pp. 138–146.

Ueha, S., Hashimoto, Y. and Koike, Y., 2000. "Non-contact transportation using near-field acoustic levitation". *Ultrasonics*, Vol. 38, pp. 26–32.

UFRGS, 2020. "Numerical calculus a collaborative book (in portuguese)". Universidade Federal do Rio Grande do Sul. 09 Jan. 2020 <https://www.ufrgs.br/reamat/CalculoNumerico/livro-py/main.html>.

Vandaele, V., Lambert, P. and Delchambre, A., 2005. "Non-contact handling in microassembly: Acoustical levitation". *Precision Engineering*, Vol. 29, pp. 491–505.

White, F.M., 1991. *VISCOUS FLUID FLOW*. McGraw-Hill,Inc, Pennsylvania, 2nd edition.

## 6. RESPONSIBILITY NOTICE

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