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Considerations regarding the design of a power ultrasonic transducer with flat rectangular plate

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Abstract: There are several industrial applications, like food dehydration [1], atomization and textile washing [2] among others, that are enhanced by the use of power ultrasonic transducers with flat rectangular plate radiator.

These transducers are composed by three main parts, the piezoelectric sandwich transducer, the mechanical amplifier, and the extensive plate radiator. Apart from the general considerations [3-5] to take into account when designing a power ultrasonic transducer, there are other important aspects to analyze like the application of a prestress in the sandwich and the determination of the dimensions of the rectangular plate radiator to excite the operational mode at the desired frequency.

The aim of this work is to provide information about how to simulate the prestress in the piezoelectric stack and its effects using COMSOL Multiphysics® and to assess the vibrational behavior of rectangular plates, comparing theoretical and numerical methods.

Keywords: power ultrasonic transducers, piezoelectric transduction, mechanical prestress, vibration of plates.

1. Introduction

Industrial processes assisted by high-power ultrasound (HPU) have become a new, green and efficient technology with a great potential in its implementation. Previous researches [6, 7] showed that these HPU technologies provide a good performance in processes like particle agglomeration, defoaming of food dehydration.

In order to provoke the desired effects, it is necessary to generate a stable high level ultrasonic field, covering a wide volume in gas media. Previous works indicated that the right devices to produce this ultrasonic field are the high-power ultrasonic transducers with extensive radiators [8, 9].

The design of these ultrasonic systems can be done using finite element methods, considering that this is a multiphysics simulation that comprises electrical, mechanical and acoustical aspects [4, 5].

There are some important aspects regarding the analysis of the behavior of the transducer that is important to take into account.

First of all, a theoretical analysis has to be done in order to know the approximate dimensions of each component, the transducer [10], the mechanical amplifier and the flat rectangular radiator [11].

On the other side, it is necessary to highlight the importance of a mechanical prestress in the ceramic stack in order to avoid fractures in the ceramics when applying high voltage under resonance [12].

The main objective of this work is to provide several tips regarding the theoretical and numerical design of an airborne power ultrasonic transducer with flat rectangular plate, using COMSOL Multiphysics®, taking into account the initial dimensions of every component and the crucial application of a mechanical prestress to the ceramic stack.

2. Simulation of the mechanical prestress

2.1 Determination of the pretension.

The mathematical model corresponds to a Piezoelectric Device, that includes Electrostatics and Structural Mechanics physics, and the multiphysics analysis of COMSOL Multiphysics 5.2a®.

The transducer is composed by two stacks of two piezoelectric ceramics separated by a brass flange, two attached steel masses and a mechanical amplifier (or horn). When the transducer is excited with an electric voltage, the ceramics experience a piezoelectric effect and change its size according to the electric excitation. An alternate current provokes a mechanical vibration of the ceramics, which is transmitted to the rest of the components of the transducer.

The piezoelectric ceramics used in power transducers for industrial applications are exposed to high voltages, which may lead to high strains. These strains can provoke breakages in the ceramics. A mechanical prestress caused by the a central bolt compresses the ceramics and allows strains without higher amplitudes minimizing the risk of fractures [12]. The application of this prestress, depending on its magnitude, may cause changes in the behavior of the transducer [13]. The numerical analysis of the prestress done in this work corresponds to an ultrasonic transducer working at around 21 kHz. The magnitude of the simulated prestress is 25 MPa in the ceramics [4]. In this case, a slight frequency shift is expected compared to the system without this prestress [13].

The 3D model of the transducer is shown in Figure 1, where it can be observed the two piezoceramic stacks separated by a brass flange, the back and front masses, the horn and the central bolt, in charge of applying the required prestress. This model corresponds to a symmetric model, with the simulations carried out only in half of the system:

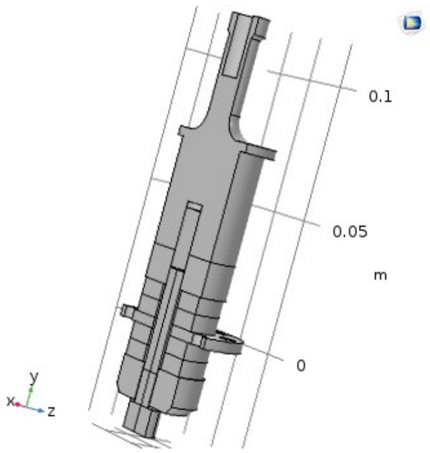
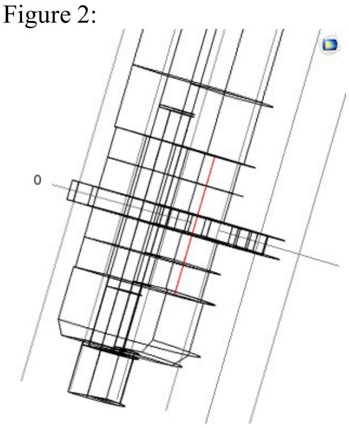


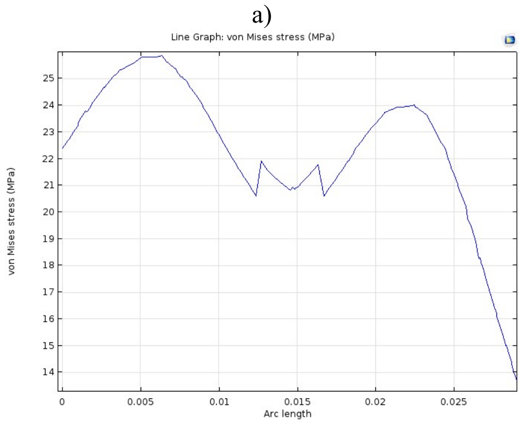
Figure 1. Model of the transducer

When working in a 3D model, the application of a prestress does not imply a high difficulty. After defining the bolt using the parts library in the geometry node, we can use the "Bolt-Pretension" node in the Solid Mechanics physic, and there we can define the magnitude of this prestress.

In order to define and apply the prestress to the transducer, a two steps simulation has to be done in an Eigenfrequencies or Frequency Domain study. The first step is a stationary simulation, under an open-circuit electrical condition (only the negative poles of the ceramics are connected to ground and positive poles are left free). The magnitude of the pretension should guarantee a mechanical prestress of 25 MPa in the piezoceramics [4], as shown in Figure 2:



a)



b)

Figure 2. Pretension obtained in the piezoceramic stack. a) Definition of the line where the prestress is defined. b) Magnitude of the Von Mises stress along the defined line

The second step is a dynamic analysis, in which the results obtained in the previous step have to be considered as input data. The way to do this is considering the geometric nonlinearity on the second step and defining a linear perturbation in the stationary solver, using the previous stored solution in the new one. The configuration of the stationary solver is shown in Figure 3:

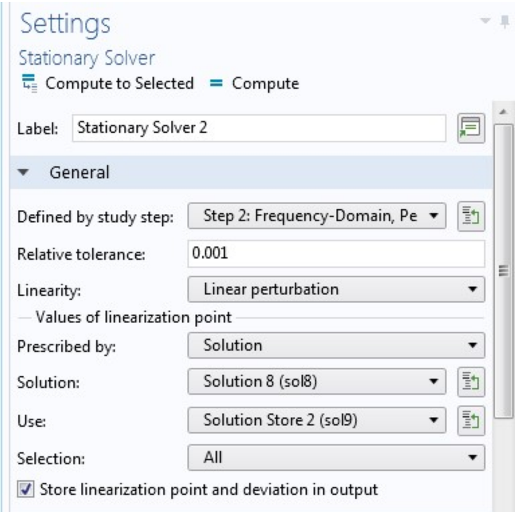


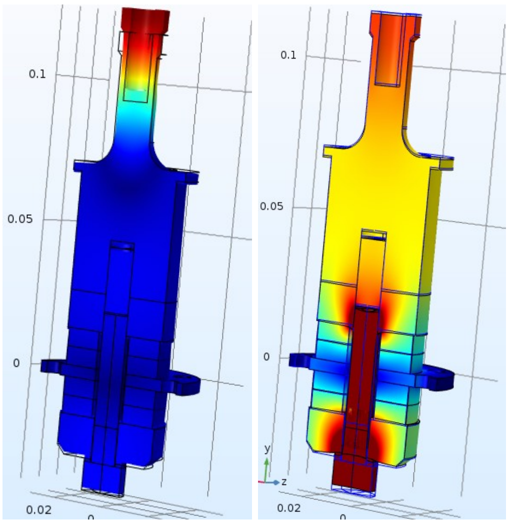
Figure 3. Configuration of the stationary solver to use the static solution to the Frequency Domain study

2.2 Eigenfrequencies study.

The operational mode of this transducer is a thickness mode of the ceramics and an extensional mode in the horn, where displacement amplification takes place.

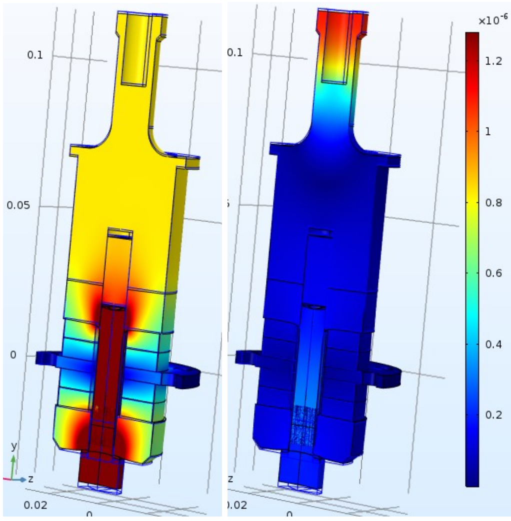
An eigenfrequency study has been done in order to find the frequency where this operational mode takes place. This study has been carried out for the two situations, without and with prestress, obtaining a frequency displacement of around 600 Hz (27731 Hz in the case of a transducer without prestress, and 27138 Hz for the simulation with prestress) when applying the prestress. The displacement obtained in both situations can be observed in Figure 4.

All these simulations are composed by a static and a dynamic component. The final solution comprises both of them and the contribution of the static and dynamic parts can be observed in every simulation. These contributions to the eigenfrequency determination can be seen in Figure 5, where it is easy to appreciate how the bolt pretension provokes a displacement in the whole transducer, and how the extensional mode achieves maximum values of displacement in the tip of the horn.



a) b)

Figure 4. Extensional mode of the transducer. a) Without prestress. b) With prestress

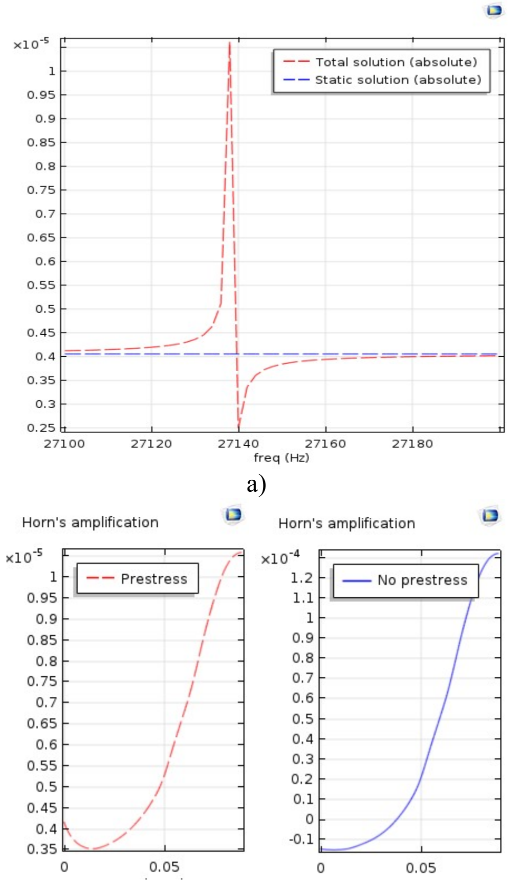


a) b)

Figure 5. a) Static contribution to the total displacement. b) Dynamic contribution

2.3 Frequency domain study.

A frequency domain analysis around resonance has been done, applying a voltage of 10V to the ceramics, in order to determine the maximum displacement at the tip of the mechanical amplifier (Figure 6.a) and the amplification achieved in the horn (Figure 6.b):



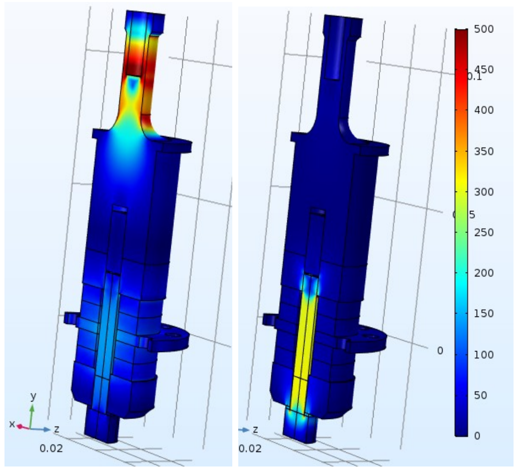
a) b)

Figure 6. Frequency domain analysis. a) Maximum displacement at the tip. b) Displacement amplification in the horn

As it can be observed in Figure 6.a, the stationary step, the prestress, applies a fixed displacement in the whole frequency range that reduces the maximum displacement at the tip, as can be observed in Figure 6.b, where the system without prestress achieves a displacement of 120 µm and the system with prestress has a maximum of about 11 µm.

It can be seen in Figure 6.b that the displacement provoked by the pretension also implies a smaller displacement at the tip and amplification in the horn.

Finally, one of the main objectives of applying this pretension is to avoid high values of mechanical stress when applying power. In Figure 7 the differences in terms of stress can be observed. The transducer without prestress suffers values of mechanical stress higher than 500 MPa in the horn, while the prestressed system has maximum values of 300 Pa in the bolt and less than 100 Pa in the horn:



a) b)

Figure 7. Mechanical stress in the transducer. a) System without prestress. b) System with prestress

3. Vibration of rectangular plates

3.1 Theoretical studies.

Vibration of plates has been widely studied in the past. In the case of rectangular flat plates vibrating freely, works of Warburton [14] or Leissa [15], among others, ended with the determination of an equation (Eq.1) for vibration of rectangular plates, published by W.G. Caldersmith [11]:

$$f_{m,n}{}^2 = \frac{h^2}{4.86\rho}\left[\frac{D_x}{L_x{}^4}\left(\frac{2m-1}{2}\right)^4 + \frac{D_y}{L_y{}^4}\left(\frac{2n-1}{2}\right)^4\right] + \\ + m^2 n^2 f_{1,1} \qquad (1)$$

Where:

- $f_{m,n}$ is the frequency where the desired mode happens.
- m and n are the number of nodal lines perpendicular to x and y side, respectively.
- L_x, L_y y h are the length of x and y sides, and the thickness, respectively.
- ρ is the density of the plate.

- D_x and D_y are the corrected Young Modulus for dimensions x and y.
- $f_{1,1}$ is the first shear mode.
- c_l is the sound speed in the plate.

The previous expression has been proved to have a good matching in rectangular thin plates, but the theoretical calculations differ from the real behavior of thick rectangular plates.

There are different configurations of airborne power ultrasonic transducers with rectangular plates depending on the specific industrial application of each transducer. The rectangular radiator is attached to the mechanical amplifier in its center and is the place where the mechanical excitation takes place to obtain a free vibration of the plate.

The typologies of the rectangular plates are diverse, with different dimensions. It is not easy to assure that a plate is or not a thin plate, so a FEM analysis is useful.

A theoretical and numerical analysis of the vibration of plates has been done for three different rectangular radiators that have operational modes with a number of nodal lines in only one direction:

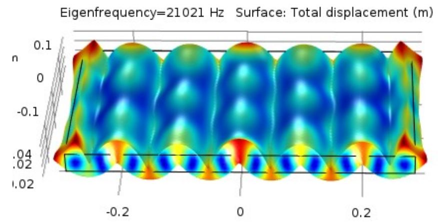
- **Plate A**: Plate with dimensions 570x308x34 mm and an operational mode of 12 nodal lines (NL) in the transversal direction for food dehydration purposes. According to the Eq.1, this mode happens at 33799 Hz.
- **Plate B**: Plate with dimensions 220x50x10 mm and an operational mode of 2 NL in the longitudinal direction for ultrasonic cleaning. According to the Eq.1, this mode happens at 21979 Hz.
- **Plate C:** Plate with dimensions 580x220x15,4 mm and an operational mode of 16 NL in the transversal direction for atomization. According to the Eq.1, this mode happens at 33799 Hz. According to the Eq.1, this mode happens at 26860 Hz.

In order to check the suitability of this method, a numerical study has been done for the three plates, trying to find this operational mode and other near modes.

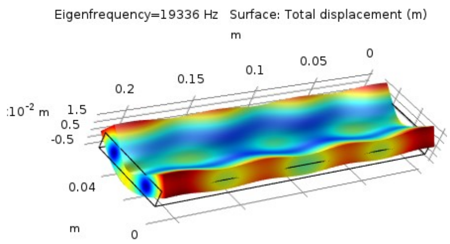
3.2 Numerical study.

The numerical study of vibration of plates has been done with the Structural Mechanics Module of COMSOL Multiphysics 5.2a®. Only an Eigenfrequency study is necessary for this task. This analysis is necessary to assess the accuracy of the Caldersmith equation (Eq.1) depending on the dimensions and the order of the desired mode.

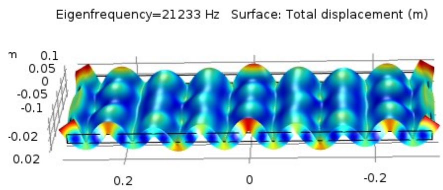
The operational modes of the three plates (made of duralumin) are shown in Figure 8.



a) Plate A



b) Plate B



c) Plate C

Figure 8. Operational modes of the three rectangular plates studied

The frequencies where the operational modes happen are different in the theoretical and in the numerical studies, with errors of almost 13 kHz (38%) in Plate A, of about 2,6 kHz (12%) in Plate B and of 5,6 kHz (21%) in Plate C.

Eq.1 has different errors depending on the dimensions of the plates. In order to determine the nature of these errors, an extended study has been done, trying to identify other modes using both methods. The input parameters have been normalized establishing a relationship between the length, thickness and number of nodal lines in the plate. In this case, the new parameter is h/d, which is the ratio between the thickness (h) and the distance between nodal lines (d). The results obtained after this new study has been summarized in Figure 9:

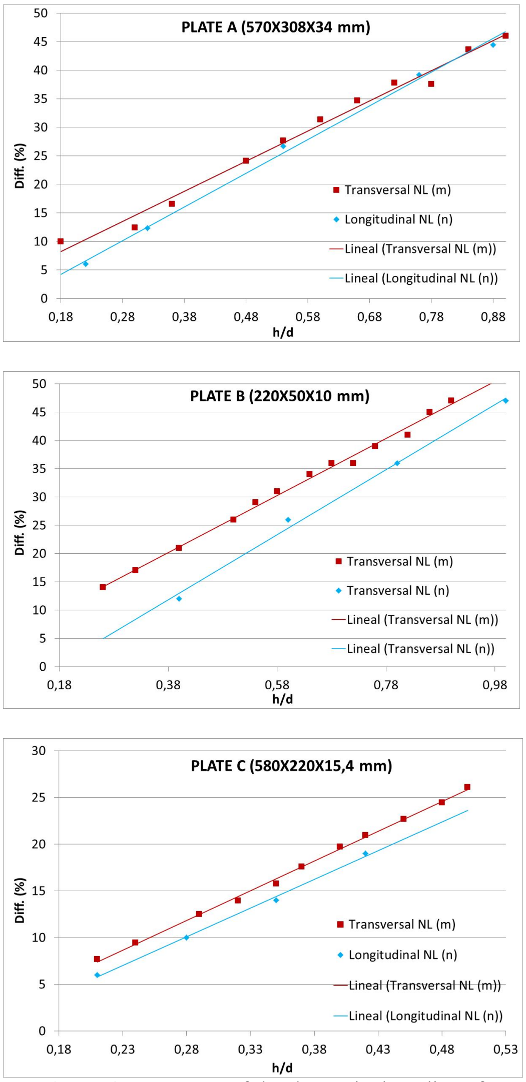


Figure 9. Accuracy of the theoretical studies of vibration of plates depending on the dimensions and vibration mode of the plate

The results obtained after these three studies are very similar. The difference between the theoretical and numerical studies increases with the parameter h/d, meaning that this error is higher in higher modes or when the distance between nodal lines is smaller.

Furthermore, this error not only increases with the parameter h/d, but it is also similar in the three plates.

Considering an error of 15% between the theoretical and the numerical studies as acceptable, the parameter h/d should not be higher than 0.35. This means that the theoretical study is accurate when the distance between nodal lines is, at least three times the thickness of the plate.

4. Conclusions

The design and analysis of the behavior of an airborne power ultrasonic transducer with flat rectangular radiator has been done using COMSOL Multiphysics®.

Nevertheless, there are some aspects that should be considered in order to improve the global study. Among others, the study of the bolt pretension and the vibration of the rectangular plate are of special interest.

The simulation of the prestress can be done with a two-step simulation: a stationary analysis in which the application of the prestress is set; and a second step that includes the results of the previous one as an input.

In the case of the study of vibration of plates, the theoretical equations have been checked for three different configurations using the Structural Module of COMSOL Multiphysics®. It has been proved numerically that the theoretical method has an error of around 15% when the distance between nodal lines in the vibrational mode is three times, or more, the thickness of the plate.

5. References

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