

FINITE ELEMENT MODELING AND EXPERIMENTS REGARDING ULTRASONIC TRANSDUCERS USED IN AIR FILTERS

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ABSTRACT: The paper presents the studies, research and results obtained using ultrasounds in the field of industrial air filtration. In this regard, there are two types of air filter that have been designed for use in the air filtration system in the paint booths. The first type of filter uses vibrations from a classic system consisting of transducer, amplifier, and activated element. The second filter is based on the ultrasonic cavitation phenomenon. For both types of filtering systems, finite element analysis is useful, and it is very useful in selecting vibration modes and vibration frequencies to be used. Besides these are presented elements of the practical realization of the filters as well as some of the experimental results obtained. The main phenomena that occur in the propagation of ultrasounds through a gaseous medium: propagation velocity; compressing and scaling the environment according to the nature of ultrasonic waves; reflection and refraction of ultrasonic waves at the solid-gas interface; the creation of stationary waves and the emergence of pressure knots and antinodes; diffraction and diffusion of ultrasonic waves; attenuation of ultra-acoustic energy; ultra-acoustic absorption; ultrasonic cavitation, etc. it is proposed to use the effects of their propagation in the filtration and purification process and the construction of ultrasonic filters operating on the principle of "ultrasonic agglomeration" on the principle of "ultrasonic shaking" or combined.

KEY WORDS: ultrasonic, vibration, air, filtering, FEM

1. INTRODUCTION

The finite elements method is an important research method used in multiple scientific areas. This finds a great applicability in certain areas of work where other experimental methods are very difficult to apply or costly. In this case, the method is extremely useful because the determination of vibration frequencies and vibration modes of the whole system or vibrating disk is absolutely necessary in order to assign the system only in the area of useful vibration frequencies. The useful part of the ultrasonic system, which actually performs air filtration, consists of the vibrating disk provided with holes through which the air to be filtered passes. The ultrasonic air filter is presented in the figure 1.

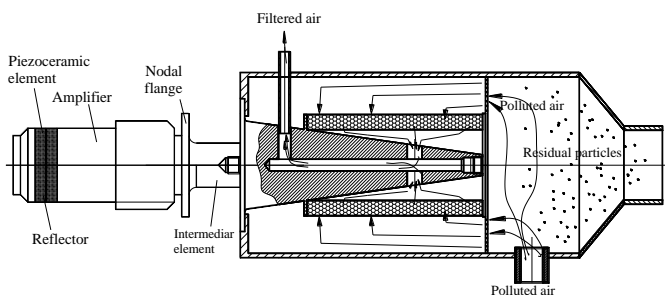


Figure 1. Ultrasonic filtering system

This system will replace the actual classic air filtration system based on glass fiber and carbon used in painting shops as presented in figure 2 [7].

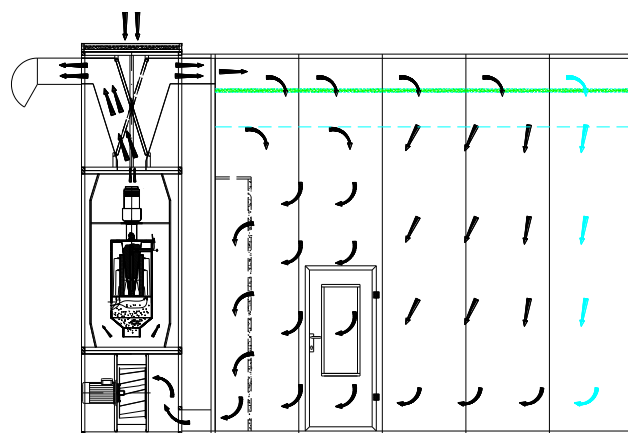


Figure 2. Painting shop using ultrasonic air filtration filter based on ultrasonic vibrations

2. FINITE ELEMENT MODELING OF THE ACTIVE ELEMENT

The active element that provides ultrasonic vibrations it is represented by a disk with very small holes presented in the figure 3.



Figure 3. Ultrasonic vibrating disk

For this disk the finite element model is presented in the figure 4.

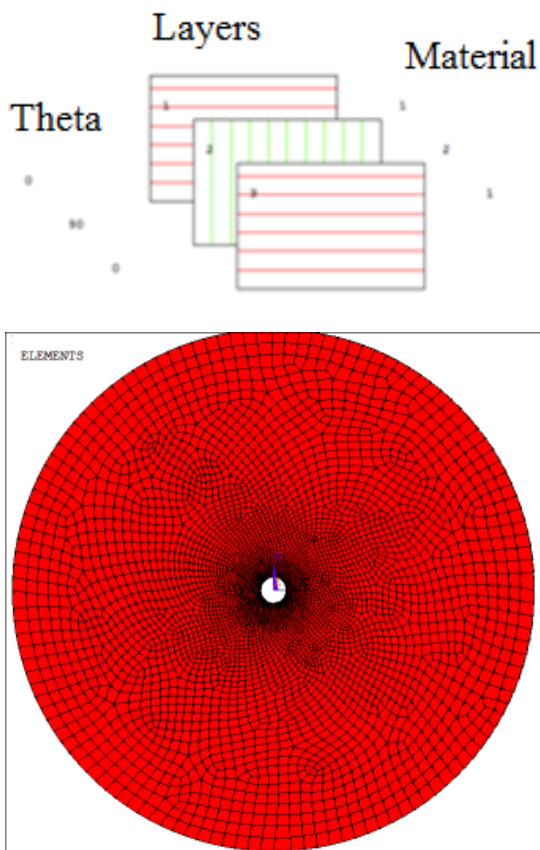
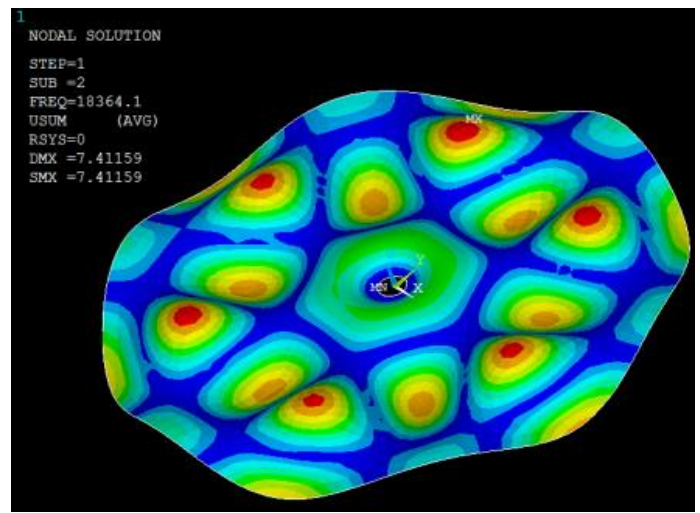


Figure 4. Finite element model for the vibrating disk

To determine the vibration modes and their frequency a modal analysis was performed. During experiments only one type of vibration was found to be useful. The useful vibration mode, used in experiments, performed at frequency $f = 18358$ Hz. In figure 5a it is presented this vibration mode. Another close frequency at $f = 18364$ Hz has relatively the same result in experiments. The geometric shape of this vibration mode is showed in figure 5b.



b.

Figure 5. Ultrasonic vibration modes; a - at frequency $f = 18358$ Hz; b - at frequency $f = 18364$ Hz

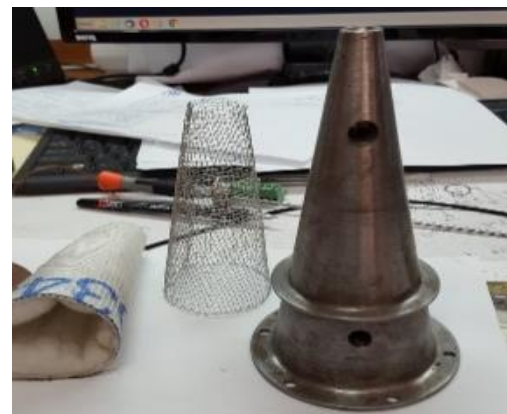
3. PRACTICAL REALIZATION OF THE ULTRASONIC AIR FILTERING SYSTEM

The constructive elements of the air filter are the following:

- ultrasonic transducer (Figure 6a);
- ultrasonic concentrator (Figure 6b)

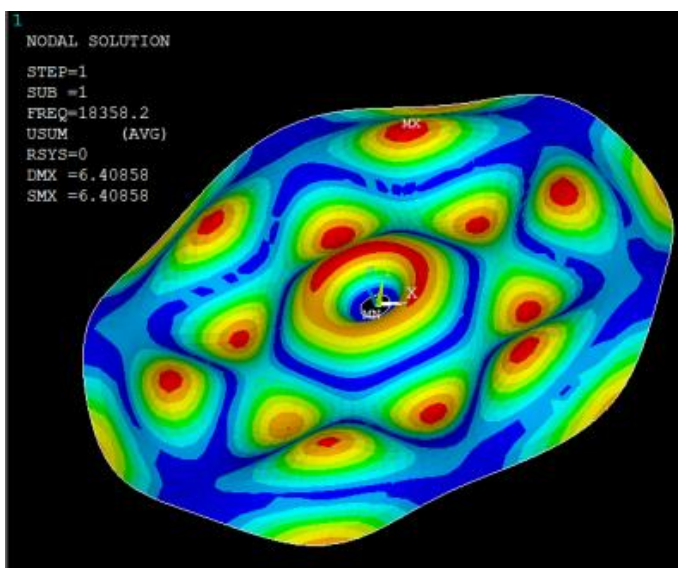


a.



b.

Figure 6. Ultrasonic transducer and ultrasonic concentrator; a - ultrasonic transducer; b - ultrasonic concentrator



a.

The ultrasonic transducer is fixed in the air column using a nodal flange that is presented in the figure 7a. The air column that is used to pass the air to be filtered is presented in the figure 7b.



a.



b.

Figure 7. Ultrasonic flange used to fix the filter in the air pipe; a - nodal flange; b - mounting in the exhaust column

4. EXPERIMENTAL RESULTS

To demonstrate the performances of the ultrasonic air filtration system, measurements were made

within three days of introducing the new filtration system into operation. The measurements were made in the painting shop 1 m from the painted piece. In the cabin, not only the painting and welding operation, grinding and grooving operation are performed also, operations that are not carried out continuously but randomly, but the polluting substances that appear are still in the working environment. In table 1 there are presents the measured values for the specified chemical substances concentration compared with the limit values (LV) according to Romanian standard.

Table 1. Experimental results on the NO_x, SO₂, CO, acetone, powders and butyl acetate values measured at the outlet of the exhaust

Day	Medium concentration measures						
	NO ₂ ppm	SO ₂ ppm	CO ppm	NO _x ppm	Acetone mg/m ³	Powders mg/mc	Butyle acetate mg/mc
1	0.28	0.72	4.8	2.5	15	2	1.8
2	0.37	0.49	5.3	2.6	14	2	1.8
3	0.42	0.32	5.7	1.7	14	2	2.7
LV	10	151 5	30	50 cumulative	1210	10	150
Medium Conc.	0.25 7	0.37 3	3.8 3	1.97	13.4	0.235	1.75
	98 %	98 %	96 %	98%	96%	99%	99%

It is noted that there are no exceedances of the LV for any polluting substance in the case of using the ultrasonic vibration filtering system (Table 1.), the degree of retention being in the range of 96 ... 99%, in some cases (powders in suspension) even 100% on some days;

5. INDUSTRIAL AIR FILTERING SYSTEM BASED ON CAVITATION PHENOMENON

5.1 Generalities

Ultrasonic cavitation is the phenomenon of breaking and immediate reconstruction of a fluid under the action of sufficiently high stress or rapid and sudden pressure variations.

Under the action of pressure changes, the mean distance between the liquid particles varies until the

liquid breakdown value is reached. Breaking occurs when the ultrasonic pressure is negative and cancels the pressure corresponding to the cohesive forces between the liquid particles. Breaking is followed by genesis in those places of microscopic cavities. It does not occur simultaneously in the whole mass of the liquid, but only in weak points of resistance, generated by inhomogeneities called germs or cavitation nuclei. With the help of ultra-fast shooting, it was able to track and study the behaviour of cavitation bubbles. Thus, it has been found that under the action of ultrasonic waves the cavitation bubble increases its volume by filling it with evaporative air or vapors that were present at the time of their formation. The cavity bubble develops to a certain size, which at a certain pressure depends on the duration of development and the frequency of ultrasounds. In the immediate next phase, after the relatively slow expansion of the cavitation bubble, sudden compression and sudden destruction occur.

5.2 Geometrical design of ultrasonic transducer used in air filtering using cavitation process

In accordance with the proposed purpose and the functional role of the transducers, the required geometric shape and their dimensions were designed [1,2].

The radiation field area of the active element must be correlated with the input power (P_{in}) and the required acoustic intensity (I_a) and is [5]:

$$A_p = \frac{P_{in}}{I_a \cdot \eta_{ea}} = 6.92 \text{ cm}^2 \quad (1)$$

- Active element radius (for circular section):

$$r_p = \sqrt{\frac{A_p}{\pi}} = 20 \text{ mm} \quad (2)$$

Elements of calculation for the ultrasonic energy concentrator:

- the length of the concentrator is calculated with the relation:

$$L = \frac{n \cdot c}{2 \cdot f_0} \sqrt{1 + \left[\frac{\ln(n)}{\pi} \right]} = 75.2 \text{ mm}$$

$$\text{in which: } f_0 = 2.8 \cdot 10^4 \text{ Hz ; } n = 1; N = 3.5; \quad (3)$$

- nodal points, x_{nod} , are calculated with the following:

$$x_{nod} = \frac{L}{n\pi} \arctg\left(\frac{\ln N}{n\pi} + n'\pi\right) \quad (4)$$

wherein: $n = 1$; $n' = 1, 2, 3$; L - ultrasonic concentrator length

-the first nodal point is $x_{nod1} = 38.3 \text{ mm}$

As a result of the presented calculations, in figure 8 it is presented the schematic of the ultrasonic transducer used in air filtration system.

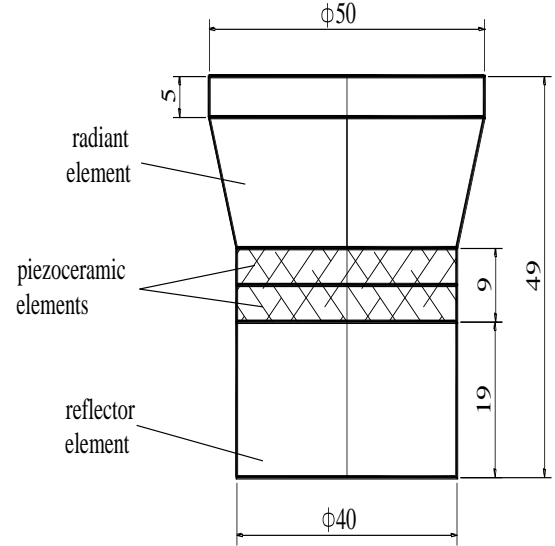


Figure 8. Schematic of the piezoceramic transducer components used in ultrasonic air filtering system

5.2 FEM for the ultrasonic transducer

The design of the ultrasonic active elements that are used to produce the ultrasonic cavitation phenomenon involves two important steps. The first is represented by the analytical calculation, after which, on the basis of the obtained data, the second step is the modeling and simulation of the ultrasonic system vibration modes [4,6]. This second step is very useful because it offers a very complete and near-reality picture of how the ultrasonic transducer vibrates. From here it goes further and from the modes of vibration calculated and offered by the program will be chosen those that are useful for the proposed purpose. Characteristic of the useful vibration mode is the frequency at which it occurs so that using this frequency the ultrasonic generator can be tuned to provide optimal energy transfer and achieve the desired effect with minimal energy consumption.

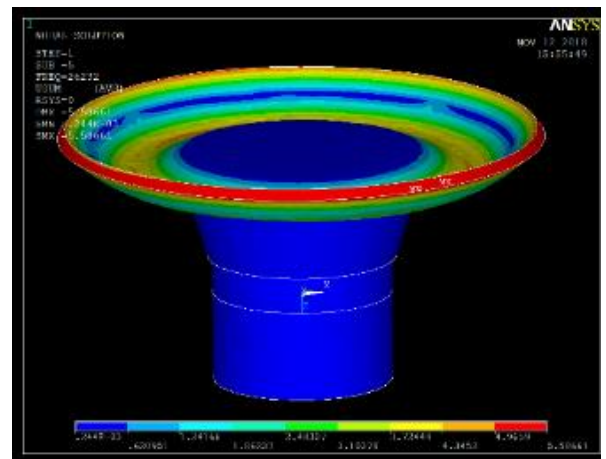


Figure 9. Vibration mode at frequency $f = 26232 \text{ Hz}$.

In the modal analysis different vibration modes were found. One of them, the fifth mode of vibration occurs at the frequency $f = 26232$ Hz and consists only in oscillations in the direction of the OZ.

The oscillations are useful, and has also the advantage consisting in the absence of undesirable vibrations in the piezoceramic plates which do not deform by bending to the longitudinal axis. All vibrational energy is concentrated at the liquid level (Figure 8).

5.3 Practical realization of the ultrasonic air filter using cavitation phenomenon

In the field of ultrasonic air filtration there is relatively little research and the present paper aims to awaken the practical experiments done for this purpose. Because the main phenomenon used in the ultrasonic filtration process is ultraacoustic cavitation, a phenomenon that occurs at the propagation of ultrasonic waves through a liquid medium, the team has carried out a series of researches on ultra-acoustic cavitation bath design [6,7].

Taking into account the air flow, these dimensions were considered useful for the operation of a small working water tank. The depth of the tray in which the liquid is located is 350 mm. As a result of the research on acoustic cavitation, the design of water tank in which the industrial air filtration is produced reflects the geometric dimensions presented in figure 10.

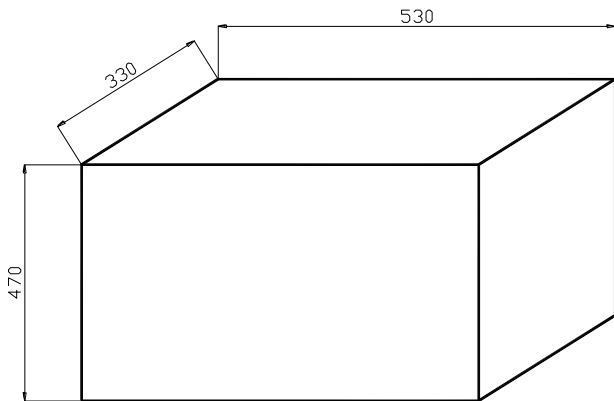


Figure 10. Geometrical dimensions of ultrasonic bath

A ten-element ultrasonic transducer network was placed on the bottom of the water tank as shown in figure 11. Depending on the number of transducers available, the useful volume of the liquid was establish. As can be seen from the figure, the distances between the ultrasonic transducers have been designed so as to achieve an optimal transfer of ultrasonic energy to the liquid medium in which industrial air filtration will occur through ultra-acoustic cavitation [4]. Finite element analysis has

helped in establishing the distance between the transducers so that there is no overlap of the oscillations produced by each of them.

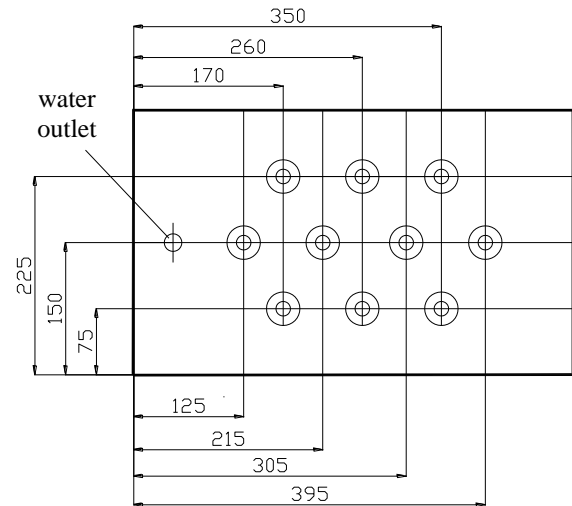


Figure 11. Positioning the ultrasonic transducers on the bottom surface of the ultrasonic bath

The design of the ultrasonic transducer element, as shown in figure 7, has led to the realization of such a transducer, whose construction is shown in figure 11.

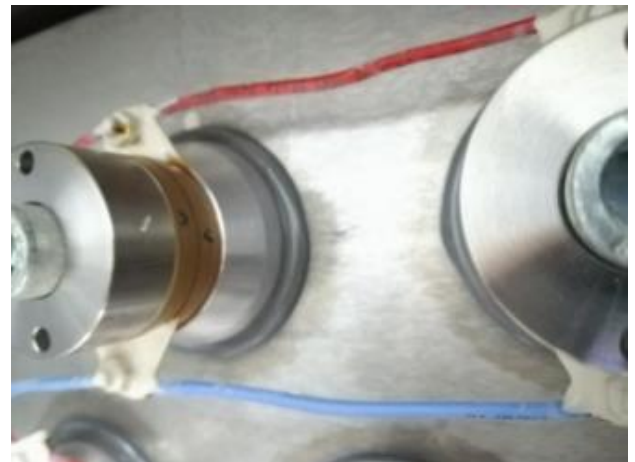


Figure 12. Image of the ultrasonic transducer used in ultrasonic bath for air filtering

The operation of the ultrasonic filter system involves the introduction of the air to be filtered into the liquid tank and the removal of the purified air from the tank.

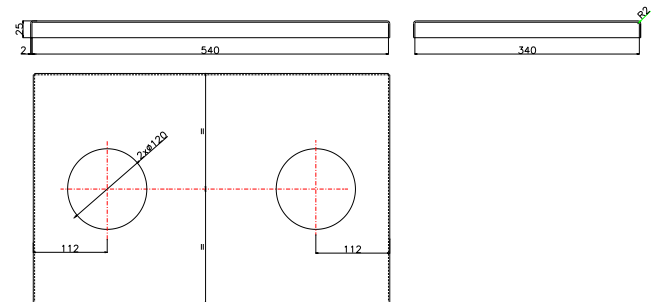


Figure 13. Presentation of the air inlet area (left), and the evacuation of purified air on the right

In order to achieve the inlet and outlet of the air, the upper part of the tank is also presented in figure 13. By the right circular hole, the air to be filtered at the pressure $p = 0.6$ atm (pressure determined experimentally) is introduced, and the left-hand tubing is used to extract the filtered air. The practical water tank realization is presented in figure 14. The two tubes for the inlet and outlet of the air are presented. As can be seen, in the experiments carried out, the air intake is made through the tubing on the right side of the tank, while the left tube realized the evacuation of the filtered air.



Figure 14. Ultrasonic cavitation filtering system

5.4 Experimental results

For the validation of the air filtration system using the cavitation-ultrasonic phenomenon three sets of analyzes for the exhaust air from the painting shop were made. The main subject of the analyses is the measurement of volatile organic compounds. Because the technological process of painting produces powders, the second measurement was done for the total powder. For the expression of these compounds was considered to measure total organic carbon as efficacious. Below are the tables of measurements presented (Table 3) and the conditions in which they were made (Table 2).

Table 2. Environmental data

No.	Component	MU	Measured value
1	average temperature	$^{\circ}\text{C}$	0;1;1

No.	Component	MU	Measured value
2	barometric pressure	hPa	1025;1022;1027
3	average atmospheric humidity	un%	96;100;93

According to presented environmental data, in table 3 there are presented the performed measurements.

Table 3. Average value of pollutant concentrations

No.	Name	MU	Measured value	Limit value	Standard method
1	volatile organic compounds expressed by total organic carbon	mgC/ Nm^3	1.15	150	SR EN 12619:2013
2	total powders	mg/ Nm^3	1.64	50	SR EN 13284-1 2018

6. CONCLUSIONS

Analyzing the results we conclude that the results of the measurements shall be within the limits provided by the legal norms in force under the specified conditions. The estimated measurement uncertainty does not affect the result of the sample and its compliance with the admissible limit values. Under these conditions it can be considered that ultrasonic vibrations expressed in the two air filtering methods are a viable working systems that proves its effectiveness for the intended purpose.

7. REFERENCES

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