Finite element modelling of the ultrasonic system used in ultrasonic gas filters

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Abstract. The paper presents the general scheme of the ultrasonic filter proposed and the finite element modeling of this system. The method can be used in air purification system from the highly polluting processing technology of an industrial shop (paint shops, foundries, welding constructions, forging, etc.). The advantages of using ultrasounds in the pollutant air filtration and purification process and an ultrasonic filter designed are presented. Paper insists in the design of the main part of the ultrasonic system represented by ultrasonic transducer. In this case, the transducer that is used consist in two asymmetrical passive elements (reflector and radiant element). For the ultrasonic system design there are presented the principal theoretical elements and in the final the finite element analyze of the whole ultrasonic system. The FEA provides the optimal frequency used in system during its operation time. The considered theoretical elements: the mechanical resonance condition; the electromechanical resonance condition; the acoustic power emitted by the resonance; acoustic power emitted at low frequencies; the acoustic power frequency characteristic; the electrical impedance of the transducer; electro-acoustical, acoustical-mechanic and electromechanical efficiency; the sensitivity of the low frequency transducer; the transducer sensitivity frequency characteristic and the resonance sensitivity of the transducer.

1. Introduction
In most machine-building companies, there are highly polluting sections due to their specificity (material preparation, casting, welding, thermal treatments, painting, etc.). In order to maintain the health of operators and to minimize the pollution of the working environment and the natural environment, it is necessary to keep the pollutants as large and efficient as possible. The analysis of the classic filtration methods and the equipment used for air filtration and purification resulted in a number of limitations of the methods used and a number of disadvantages, among which the most important are the following:
- the degree of particle retention is variable during operation, there being a danger of incomplete separation of particulates with a diameter of less than 5 μm;
- in most cases, step-by-step filtration, which involves more filtration devices, is becoming more and more complicated;
- pressure loss is variable, in many cases reaching the limit value allowed after a short period of operation, mainly due to the phenomenon of clogging of the filter elements;
- the necessity of periodic cleaning of the filter elements and consequently the decrease of the efficiency of the process of their use;
- the impossibility of retaining all solid and liquid particles;
- high energy consumption and high maintenance cost in some cases;
In order to reduce some of these disadvantages and to substantially improve the air filtration process, the research included in this paper proposes the use of ultrasonic waves in the filtration and purification process, following the analysis of the main phenomena that occur in the propagation of ultrasonic waves through a gaseous medium.

2. Design of ultrasonic filters that makes improvement of air filtering processes
Analyzing the main phenomena and effects that occur in the propagation of ultrasounds through gaseous media and taking into account the kinetics of the gas filtration process, a series of filters were designed and tested to perform the filtration and design operation with increased efficiency and efficiency, thus achieving higher economic performance [1, 2, 3]. In choosing the filtering method and the appropriate filter, the following were considered:
- do not require changes in the positioning and fastening elements when replacing the classic filter with an ultrasonic filter;
- do not require dismantling to clean the filter element, cleaning periodically when the pressure drop reaches a limit value by commanding the operation of the ultrasonic transducer;
- allow restraint of the finest particles leading to the final consumer (in some technological processes) pure air;
- have a much longer operating life than conventional filters, in the sense that the ultrasonic activated filter elements have a higher reliability;
- to achieve a pressure drop in a range of restricted values, practically to be kept constant or with very small variations;
- creating stationary waves to allow not only very fine particle retention but also air drying;
- allow easy maintenance, the operating costs of which do not exceed the costs of the classic ones.

In these conditions, an ultrasonic filter model is further proposed, which by the shape and dimensions of the final element creates the ultrasonic field corresponding to the desired filtering process (figure 1). The figure presents the ultrasonic system designed for air filtration for industrial application. This type of filter is designed in such a way that the body of the filter excites stationary ultrasonic waves and resonates from time to time.

3. Theoretical elements used in ultrasonic system design
Also, ultrasounds during their propagation by making successive pressure and depression zones will also lead to the continuous extraction of the liquid or vapour present in the stream. The most important part of any ultrasonic filter is the ultrasound system to be calculated, designed and executed in such a way that to produce a stationary wave field or to operate in resonance mode, and the most important part of an ultrasonic system is the ultrasonic transducer [4-7]. In the construction of this type of ultrasonic filter, a mechanically polarized compound transducer was used. In the figure 1, the designed ultrasonic system (with vertical working position) is presented, with the corresponding dimensions

For the calculation and design of this type of transducer, the following elements were used [8,9]:
- mechanical resonance condition, resulting from equality:
\[ \rho \nu' A' \tan(\omega_0 l' / \nu') = \rho \nu E A \cot(\omega_0 l / (2\nu)^E) \]  
(1)

where: \( \rho \nu' A' \) and \( \rho \nu E A \) are the characteristic acoustic impedances of the passive element and the active element respectively; \( l' \) and \( l \) their lengths; \( q \) the characteristic impedance ratio;
- the electromechanical resonance condition results from equality:
\[ \rho' \nu' A' \sec (\omega_0' / \nu') = \rho \nu^D A \sec \left( \omega_0 / (2 \nu^D) \right) \]  
(2)

- the acoustic power \( P_0^a \) emitted at the resonance is:
\[ P_0^a = \frac{4n^2 U^2 \cos^2 (\omega_0 l' / \nu')}{4 \left( \nu^D \right)^2} \]  
(3)

where: \( n \) is the electromechanical transform coefficient;

- the acoustic power at low frequencies \( P_{aj}^0 \) is calculated with the relation:
\[ P_{aj}^0 = \frac{\alpha_j^2 U^2 \rho_m v_m A' \omega^2}{4 \left( \nu^D \right)^2} \]  
(4)

- the frequency characteristic of the acoustic power near the resonance \( P_a \) is given by the relation:
\[ P_a = \frac{\alpha \rho_m v_m A' n^2 U^2}{\left| Z \right|^2 \cos^2 (\omega_0 l' / \nu')} \]  
(5)

where:
\[ \left| Z \right| = \tau^2 + \chi^2 \]  
(6)
\[ \tau = \tau_0 \left[ 1 + \left( \frac{\alpha}{\alpha_0} - 1 \right) n_{am} \right] \]  
(7)

and
\[ \tau_0 = \frac{\alpha \rho_m v_m A'}{4 n_{am} \cos^2 (\omega_0 l' / \nu')} \]  
(8)

The coefficient \( \chi \), from the impedance expression, is given by the relation:
The approximate formula of power frequency dependence, near resonance, is given by the expression:

$$\frac{P_0}{P_n} = \frac{1}{1 + Q_m^2 (f / f_0 - f_0 / f)^2}$$  \hspace{1cm} (10)$$

where: $Q_m$ is the mechanical quality factor obtained from the relation:

$$Q_m = \frac{4\pi f_0 \eta_m m'}{\alpha \rho_v A' v} \left[ 1 + \left( m / 2m' \right) \left( \cos^2 (\omega l' / v') + q^2 \sin^2 (\omega l' / v') \right) \right]$$  \hspace{1cm} (11)$$

In relation (11) $m$ is the mass of the active element; $m'$ - the mass of the passive element; the characteristic impedance ratio.

4. Finite element analyze of the ultrasonic system used in air purification filter

Finite element method is a research tool that can be successfully applied for this study. For the first, two important elements are calculated:

- ultrasonic concentrator length:

$$L = \frac{n \cdot c}{2 \cdot f_0} \sqrt{1 + \left[ \frac{\ln(n)}{nm} \right]} = 162.3 \text{ mm}$$  \hspace{1cm} (12)$$

where: $f_0 = 2.5 \cdot 10^4$ Hz ; $n = 1$; $N = 5$;

- location of nodal points $x_{nod}$, where amplitude vibration is equal to zero, are calculated as:

$$x_{nod} = \frac{L}{n\pi} \arctg \left( \frac{\ln N}{n\pi} + n' \pi \right)$$  \hspace{1cm} (13)$$

where $n = 1$; $n' = 1,2,3$

Coordinate of first nodal point, for the presented ultrasonic filter, $x_{nod 1}$ is: $x_{nod 1} = 40.4 \text{ mm}$

As a result of the previously calculated values, in figure 2 is presented the resultant transducer, which has the function of transforming the electric energy of the piezoceramic elements into mechanical oscillations which are reflected by the reflective element, amplified and then transmitted to the intermediate element. Between the amplifier and the intermediate element is the nodal flange representing the transducer mounting area. In this area, the oscillation amplitude is zero, being optimal for system fixation.

The transducer system presented in figure 2 will be the active element of the presented ultrasonic filter shown in figure 1. As can be seen, the ultrasonic concentrator within which the air intake channel to be cleaned due to the ultrasonic vibrations which have maximum amplitude in the area of the drilled disc. Residues resulting from air filtration will be captured at the bottom of the filter and then stored in safe or chemically treated areas so that the air filtration process is totally ecological.

As a result of a modal analysis, the vibration modes of the ultrasound system and the corresponding frequencies were determined. Figure 3a shows the vibration mode at frequency $f = 18410$ Hz, which is a very useful vibration mode for the proposed purpose. Oscillations with maximum amplitude occur exactly in the area of the disc with holes through which the air to be purified.
At frequency $f = 18923$ Hz (figure 3b), oscillations also occur in the area of the disc with holes, but the oscillations amplitude are much smaller.

Figure 3. Possible oscillations for ultrasonic filter working:

a. $f_1 = 18410$ Hz; b. $f_2 = 18923$ Hz.

5. Conclusion
The characteristics of ultrasonic wave propagation in the gaseous medium that drives the solid and liquid particles depend on the phenomena and effects that arise due to the creation of the ultrasonic field, namely the 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;

The design of an ultrasonic filter in such a way that there is stationary waves in it allows to retain the finest particles of dust because in the pressure antinodes there is a phenomenon of coalescence involving the addition of fine particles to a larger particle ($> 10 \mu m$) it is also a retention problem, so that an ultrasonic filter has a retention depth of nearly 100%;
During the propagation of the ultrasonic waves in the gaseous environment compressions and thinners are produced and the temperature in the compassion zone becomes higher than in the scarifying zone and therefore in the depression zone the extraction of the water from the environment takes place and in the compression zone it occurs vaporization.

By “ultrasonic agglomeration” of fine particles, their initial mass increases by coalescence of 2500 to 3500 times compared to the mass of the primary particles, being easily captured by the filter element;

"Ultrasonic shaking" avoids the phenomenon of clogging the filter cartridge or clogging it, making it clean during operation without requiring the filter to be interrupted and dismantled.

An ultrasonic filter automatically switches on when the pressure drop has reached a certain limit (previously adjusted) by setting up the ultrasonic generator or the ultrasonic system that produces the ultrasonic shaking of the filter element until the pressure drop is the initial.

An ultrasonic filter does not require periodic disassembly and cleaning, its operating life being given by the lifetime of the filter element that is subjected to the "ultrasonic shaking" phenomenon whenever needed.

The finite element method real helps in practical working investigation because it gives the frequency of work, that means proper, optimal, working conditions and less time during experimentation.

Acknowledgements

This work has been funded by University POLITEHNICA of Bucharest, through the “ PNCDI III, SP 2.1, Transfer of knowledge to the economic agent „Bridge Grant” Identifier: NR. 90BG/2016 – “Installation for air preparation using ultrasonic filter system”

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