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RESEARCH REGARDING THE CONVERSION OF THE ACOUSTIC WAVES INTO ELECTRICAL ENERGY WITH ELECTROMAGNETIC TRANSDUCERS

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Abstract: *This paper presents research results of laboratory test carried out in order to obtain energy from acoustic waves using electromagnetic transducers. A laboratory stand was made to measure input parameters: voltage oscillations at the acoustic signal generator and output parameters: the received acoustic signal of transducer, voltage and current harvested. Maintaining a constant SPL level was generated acoustic signal in the frequency range 25-103 Hz and was analyzed changes in the power and efficiency caused by construction characteristics of the transducer. Based on the results obtained were also analyzed aspects of signal changes due to structural characteristics of the electromagnetic transducer depending on the frequency sound generated. Have been detailed analyzes of efficiency for acoustic to electrical conversion, electrical to acoustic conversion and overall efficiency conversion for two configurations (AC and DC), where acoustic power is maintain constant. Processing of experimental results have shown that electromagnetic transducers can be used to convert low-frequency acoustic signals with a efficiency up to 15% in the specific test conditions of the designed laboratory system.*

Key words: *Sound, wave, acoustic-electrical conversion, electromagnetic transducer, energy harvesting, Power, transformation efficiency.*

1. INTRODUCTION

A constant concern is to develop techniques for obtaining alternative energy. In this context the EU countries have proposed as objective until 2020 energy consumption from renewable energy sources with a weighting depending on each Member State potential [14]. In addition to trends of exploiting these renewable sources by building hydropower plant, wind turbines, solar panels, geothermal plant, etc., there are also trends of saving energy resources such as oil or trends of waste energy recovery heat, vibration, acoustic, etc. Converting acoustic energy into electricity was developing through three techniques using systems based on electromagnetic, electrostatic or piezoelectric transducers [2, 7, 8, 10, 11, 12, 13, 15].

In the context of waste energy recovery stands out, as noise sources commonly encountered, the internal combustion engines. An energy waste of acoustic nature is

represented by functioning of internal combustion engines, conversion potential was identified for acoustic wave that propagate through ducts and cavity of the intake and exhaust system. The purpose of this paper is to test the possibility of converting the acoustic energy using a usually electromagnetic transducer for different frequency of converted sound, we intend in the future to build a noise converter system applicable to the two acoustic residual source mentioned up. Has been created a laboratory stand to measure the characteristic parameters (voltage, current) to determine the electric power generated. Since the noise source used for the conversion laboratory stand is also a speaker of the same type, is additional intended to measure and calculate the power absorbed by the this, electro-acoustic conversion efficiency and overall conversion efficiency of the system for both systems (AC and DC).

The stand and laboratory test has as objective the study of the acoustic plane wave.

2. METHOD OF RESEARCH

2.1 The energy conversion characteristics in the case of electromagnetic transducers

Converting acoustic energy into electrical energy using electromagnetic speaker has as intermediate conversion energy, mechanical energy. Variation of acoustic pressure at the speaker membrane creates a variation of force F on the membrane so moving the membrane with speed v . Speed variation v depends on sound pressure variation at membrane and mechanical characteristic of the speaker. The membrane is fixed to a coil that will oscillate in the magnetic field B of the transducer thus generating a voltage V in accordance with Faraday's law:

$$V = B \cdot l \cdot v \tag{1}$$

where B is the magnetic field, l is the length of coil wire and v is the speed of the coil that oscillates in magnetic field.

If the transducer is connected to a consumer (a lamp or a resistance) coil will oppose the movement with a force F_L (Lorentz force) given by:

$$F_L = B \cdot l \cdot I \tag{2}$$

where I is the current drawn by the consumer. In Figure 1 a) shows acoustic-mechanic-electric transformation chain that can be found in obtaining electrical energy with electromagnetic transducers.

It presents an equivalent system of the electromagnetic transducers in Figure 1 b), where M is the transformation factor of acoustic energy into mechanical energy and N ($B \cdot l$) is the transformation factor of mechanical energy into electrical energy. Equivalent circuit in Figure 1 b) is based on the proposal of Jens Blauert and Ning Xiang [6] and show features that highlight:

- acoustic quantities: variation of the pressure p in front of membrane transducer, volumetric velocity q , acoustic mass m_a and acoustic resistance r_a ,
- mechanical quantities: variation of force F on the membrane transducer, speed variation v of the membrane, elasticity n of the membrane, moving mass of the transducer (diaphragm and coil mass) and mechanical resistance m_r of the transducer, and
- electrical quantities: voltage variation V , variation of current I , inductance L of the transducer and resistance R of the transducer, that are particular conversion analyzed, and were acoustic quantities p and q are input parameters, mechanical quantities F and v are intermediate parameters of transformation and V and I are output parameters of the system.

For the noise source, the equivalent electrical system match with that in the Figure 2 b) but saw in the mirror and input parameters will be those electric and output parameters will be those acoustic. Characteristic to plane wave is their limitation in controlled environments

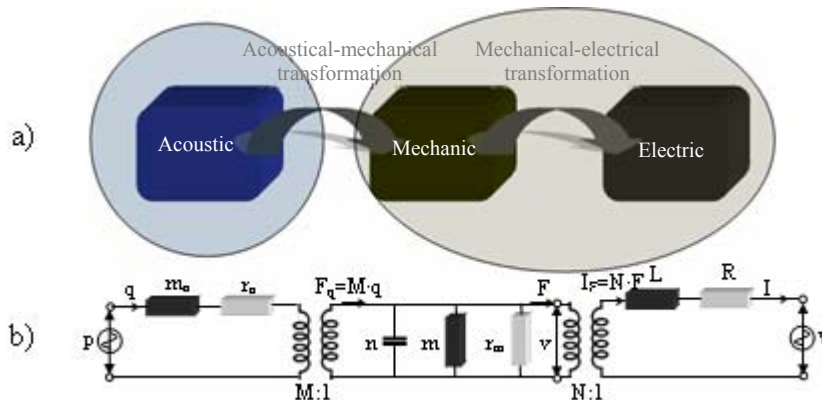


Fig. 1. Conversion of acoustic energy into electrical energy with electromagnetic transducer: a) Schematic representation, b) equivalent circuit of the system.

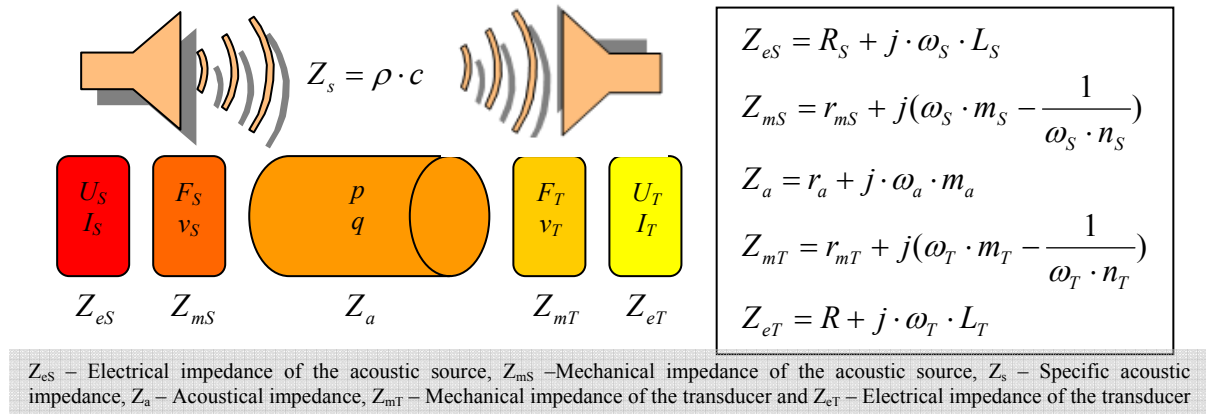


Fig. 2. Cumulation of impedance in AC system and their related formulations

with constant cross-section that provides direction of propagation. The source, the medium and the transducer (with load R) are elements of the system show schematically in Figure 2, where input energy passing through several successive transformations. Characteristic equations for each type of electricity, mechanics and acoustic energy have the form [6, 9]:

$$\begin{cases} p = m_a \frac{dq}{dt} + r_a \cdot q \\ F = m \frac{dv}{dt} + r_m \cdot v + \frac{1}{n} \int v \cdot dt \\ V = L \frac{dI}{dt} + R \cdot I \end{cases} \quad (3)$$

The equivalent system from Figure 2 shows the energies of transformation and the characteristic impedance of each phase. Thus details the electrical impedance Z_{eS} of the source, mechanical impedance Z_{mS} of the source, acoustic impedance Z_a of the medium in which sound wave propagates, determined by the tube dimensions and distance between source and transducer, mechanical impedance Z_{mT} of the transducer and electrical impedance Z_{eT} of the transducer. The load R of the transducer is considered measurable parameter and acoustic mass and resistance is determined by relations (4) and (5).

$$m_a = \rho \cdot d / S \quad (4)$$

where ρ is the density of the acoustic medium where wave propagates, d is the length between source and transducer and S is the section of the cavity.

$$r_a = \Theta \frac{d}{S} \quad (5)$$

where Θ is the flow resistivity.

2.2 Laboratory stand

For identification and quantitative evaluation of the electrical energy produced from acoustic signals was set up an experimental stand (Figure 3). The stand unit contains the following features:

- Physical unit intended for propagation of plane wave (the acoustic tube 4 mounted on rigid media). Tube length covers a wavelength corresponding too the lower domain. A the tube and are attached two

Characteristics of the source and the transducer (speaker SAL SBX 1320)

Acoustic power	Weight of magnet	Mass in motion of the speaker
Pz=60 [W]	567 [g]	Mms=13.18 [g]
Rated power	Membrane surface	Mechanical resistance
Pn=40 [W]	Sd=95 [cm ²]	Rms=1.23 [kg/s]
Impedance	Equivalent volume	The elasticity of the membrane
Z=8 [Ω]	VAS=8.28 [l]	Cms=0.65 [mm/N]
Resonance frequency	Mechanical quality factor	The transform. factor (BxI)
fr=54 [Hz]	Qms=3.96	T=6.56 [Tm]
Frequency domain	Electrical quality factor	Inductance
f=50-7000 [Hz]	Qes=0.72	L=1.75 [mH]
Sensitivity	Total quality factor	
Spl=85 [dB]	Qts=0.61	

speakers (SAL SBX 1320), one as a transmitter of acoustic signal other having the function transducer the acoustic signal into electrical signal.

- Unit of measurement systems consisting of the oscilloscope 8, the microphone 3 and the Solo Pro phonometer 5, the data acquisition system 10 and the multimeters 11.

Table 1

- Software unit that contains: software for signal generation, signal analysis software for acoustical signal (dBFA Suit 4.8.1) [5], software for analysing electrical signals (SP107E) [4], software for measuring and visualizing electrical parameters in DC system.

As sound source and transducer is used the same type of speaker, its characteristics are presented in table 1.

The experiment research consisted in generating low frequency acoustic waves between 25 and 103 Hz. For each measurement was set the amplification of the acoustic signal from the amplifier 9 so that it maintain a constant noise level of 120 dB at the microphone 3 placed in front of transducer 2. Signal received from microphone is transmitted to the Solo Pro sound level meter 5 that send it forward to the laptop 6, where this can be processed and viewed in real time and saved with the dBFA Suite program. In order to quantify electrical energy harvested was used acquisition board 10 and N11 software in the

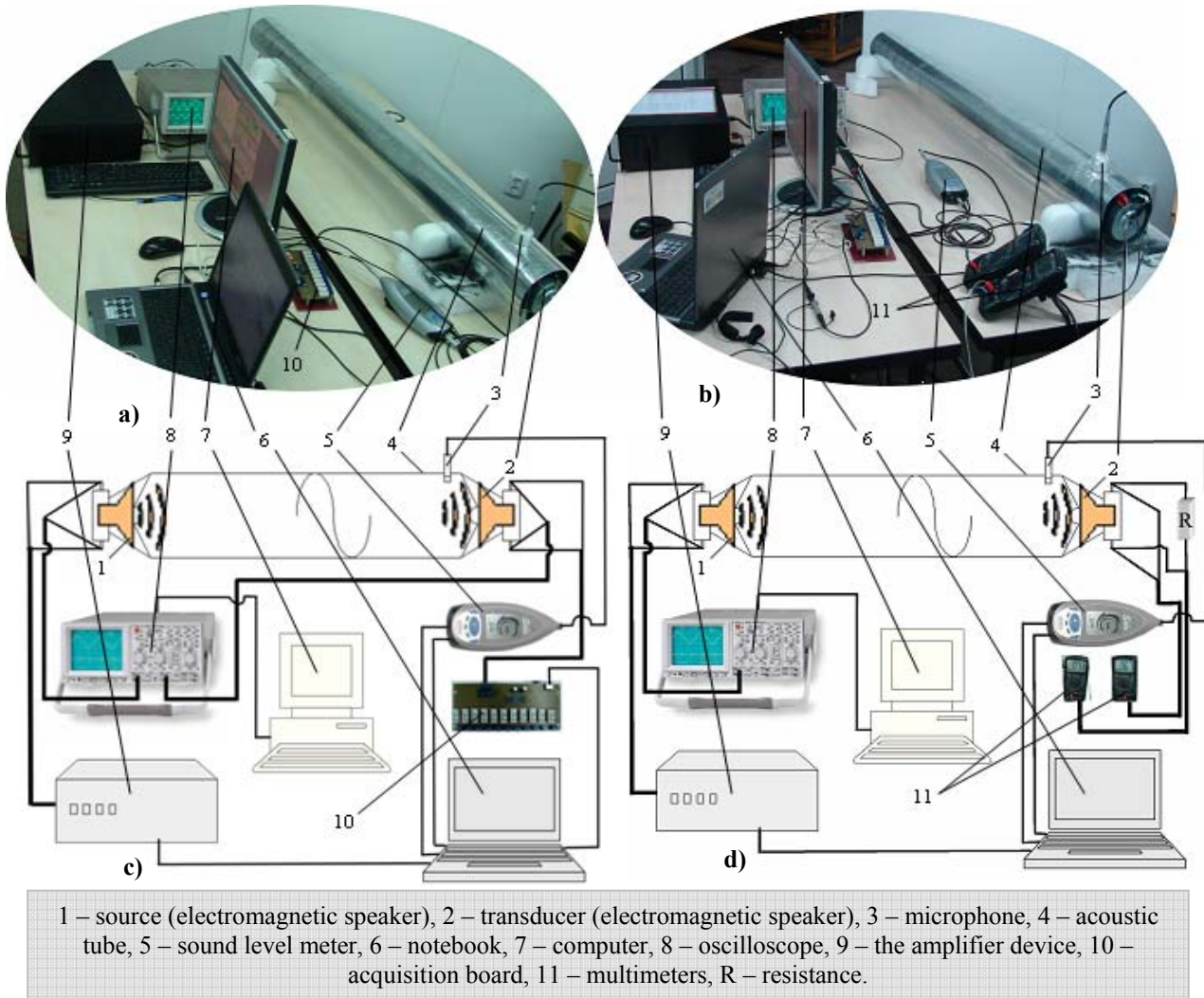


Fig. 3. Experimental variants: a) laboratory stand configuration for direct current system, b) laboratory stand configuration for alternating current system, c) Schematic representation of the laboratory stand for direct current and d) Schematic representation of the laboratory stand for alternating current.

direct current system (DC) and resistance R (7.8Ω) and the multimeters 11 in the alternating current system (AC).

Harvesting of continuous electrical power is important because this can be store in storage elements such as batteries.

Following parameters were measured: sound level L_p , peak to peak voltage U_{Spp} at acoustic source 1, rms voltage U_{Tef} and rms intensity I_{Tef} at the transducer 2 measured with multimeters 11 for experiment configuration in alternating current (AC) and rms voltage U_{Tef} and rms intensity I_{Tef} at the transducer 2 measured with acquisition board 10 and N11 software for the experiment configuration in the direct current.

3. RESULTS AND DISCUSSIONS

In accordance with identified parameters in figure 2 measurements were made that have been necessary to calculation of the powers and efficiencies of the corresponding test conditions. On development of the calculations was considered that waves propagate as plane wave and thus pressure variation will be directly proportional to particle velocity of air. Because periodic pressure variations remain constant particle velocity variations remain constant and a tube sections is constant

volumetric speed will be constant. This sound power which is the product of pressure and volumetric speed remains constant and is determined with relations below (6-10) [6, 9, 3, and 1]:

$$p_{ef} = 2 \cdot 10^{-5} \cdot 10^{\frac{L_p}{20}} = 20 \text{ [Pa]} \quad (6)$$

$$u_{ef} = \frac{p_{ef}}{\rho \cdot c} = 0.048 \text{ [m/s]} \quad (7)$$

$$A = \pi \cdot r^2 = 0.018 \text{ [m}^2\text{]} \quad (8)$$

$$q_{ef} = u \cdot A = 8.744 \times 10^{-4} \text{ [m}^3\text{/s]} \quad (9)$$

$$Pa_{ef} = p_{ef} \cdot q_{ef} = 0.01749 \text{ [W]} \quad (10)$$

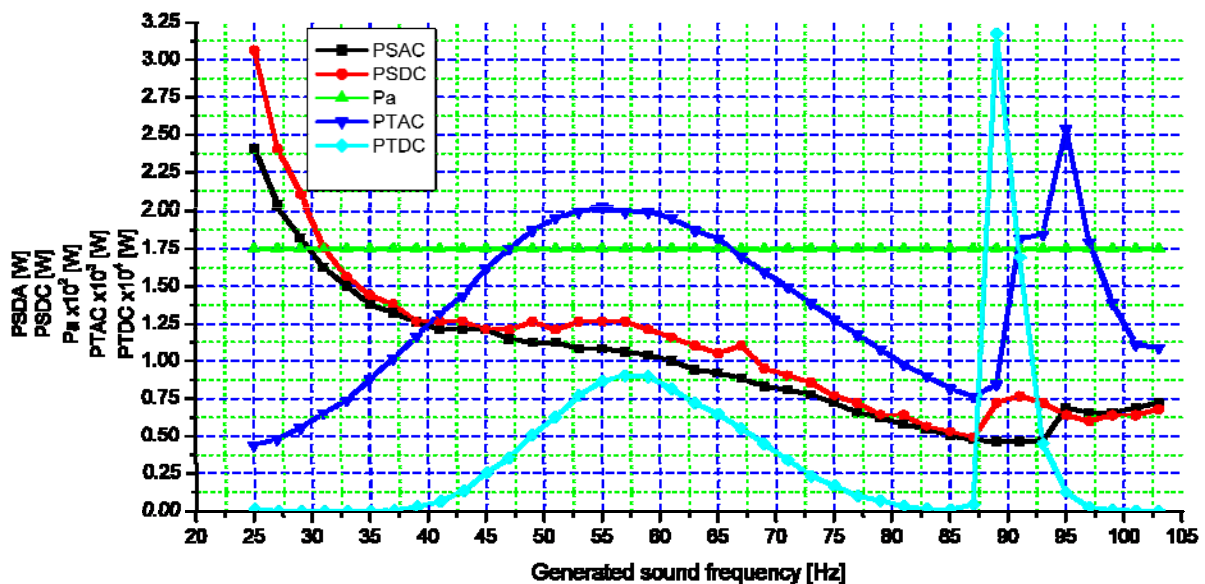
where $L_p=120$ dB is the noise level, $c=343$ m/s is the speed of sound (at 20°C), $\rho=1.21$ kg/m³ and $r=0.076$ is the radius of the tube in meters.

Having voltage variations from speaker 1 measured with oscilloscope 8 and its impedance (8Ω) was calculate the power absorbed by the noise source depending on the frequency of sound generated for the AC and DC systems, with relationship:

$$P_{Sef} = \left(\frac{U_{Spp}}{2\sqrt{2}} \right)^2 / R_s \quad (11)$$

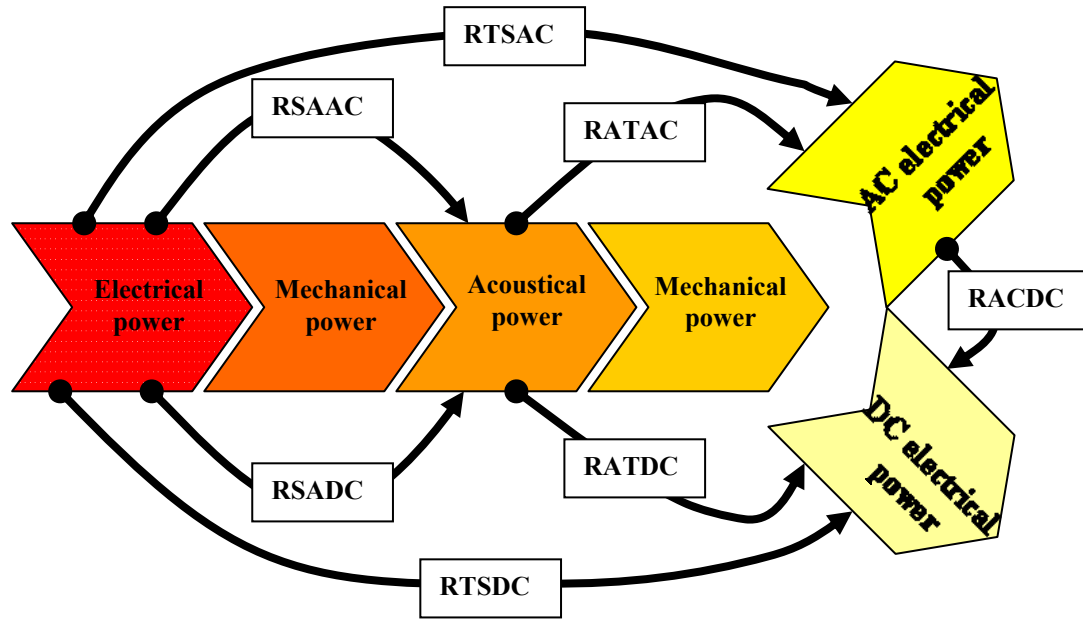
where U_{Spp} is peak to peak voltage amplitude and R_s is resistance of the speaker.

For the calculation of the power generated by the transducer in AC system were used rms



PSAC – Power absorbed of source in AC system, PSDC – Power absorbed of source in DC system, Pa – Acoustic power, PTAC – Power generated by transducer in AC system and PTDC – Power generated by transducer in DC system.

Fig. 4. Variations of power at source and transducer in AC and DC systems depending on the generated sound frequency when acoustic power remains constant at 1.75×10^{-2} [W]



RSAAC – efficiency conversion of electric power absorbed by the source into acoustic power in AC system, RSADC – efficiency conversion of electric power absorbed by the source into acoustic power in DC system, RATAAC – efficiency conversion of acoustic power into electrical power in AC system, RATDC – efficiency conversion of acoustic power into electrical power in DC system, RTSAC – overall efficiency in AC system, RTSDC – overall efficiency in DC system and RACDC – efficiency conversion between electrical powers generated into AC and DC systems.

Fig. 5. Schematic representation of the power efficiency that we want to present

value of the voltage and current measured with multimeters 11, and N11 software for DC system that saves DC voltage and current at certain intervals (for example 0.0041 seconds with a data acquisition frequency of 243 values per seconds).

$$P_{Tef} = U_{Tef} \cdot I_{Tef} \quad (12)$$

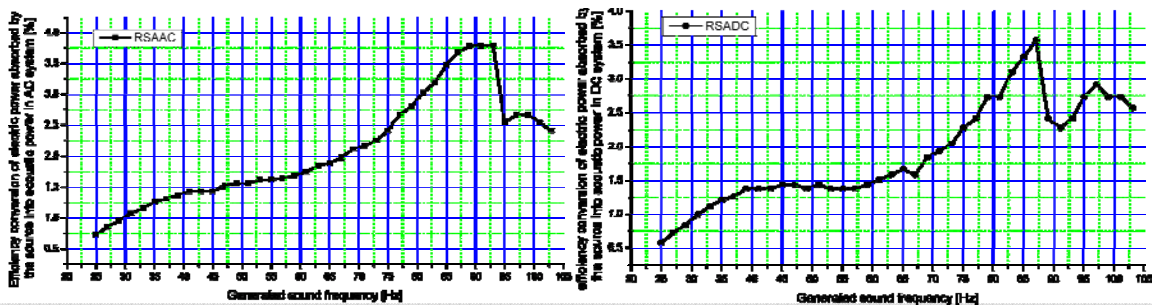
It show the results obtained of power depending on the generated sound frequency in figure 4, when in the tube is maintains a noise level of 120 dB.

For detailed evaluation of transformation efficiency, based on the obtained experimental results was propose a diagram to allow detailed analysis. Figure 5 schematically represents the

range of calculated efficiencies and the itinerary of calculation:

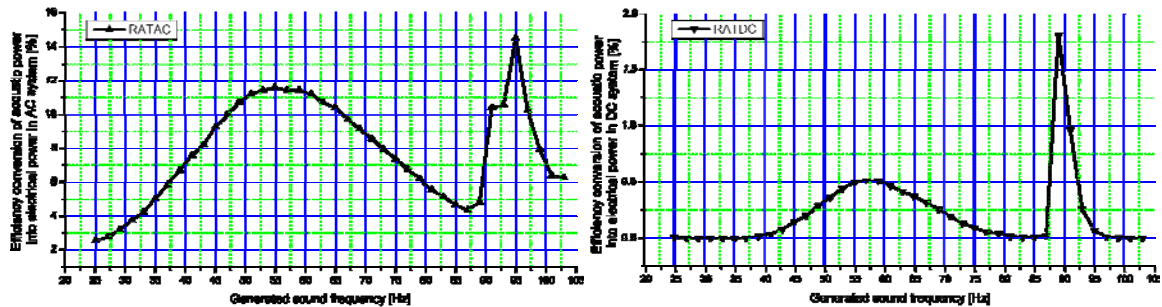
$$\eta = \frac{P_{out}}{P_{in}} \cdot 100 [\%] \quad (13)$$

Was calculated RSA efficiency with that the source converts electrical energy into acoustic energy (electro-acoustic transformation), RAT efficiency with which the transducer converts the acoustic energy (acoustic-electric transformation), and RTS overall efficiency (electro-acoustic-electrical transformation) in both AC and DC configuration. He also calculated the energy conversion efficiency of alternative electrical energy into direct



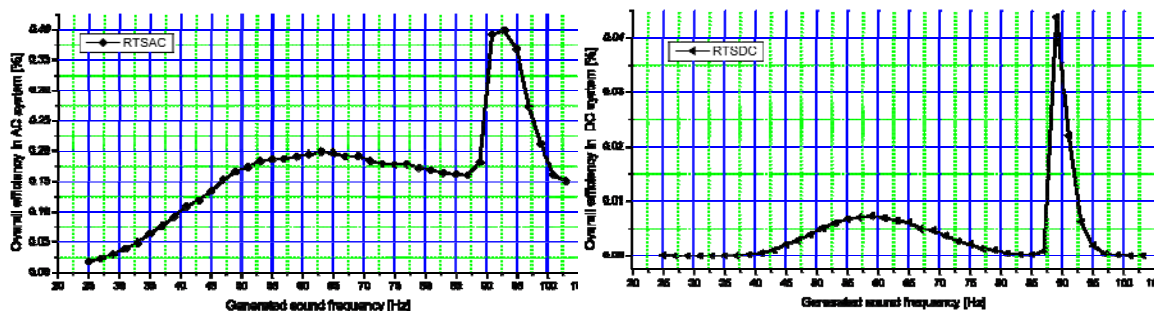
RSAAC – efficiency conversion of electric power absorbed by the source into acoustic power in AC system and RSADC – efficiency conversion of electric power absorbed by the source into acoustic power in DC system

Fig. 6. Variation of the RSAAC and RSADC efficiencies depending on the generated sound frequency



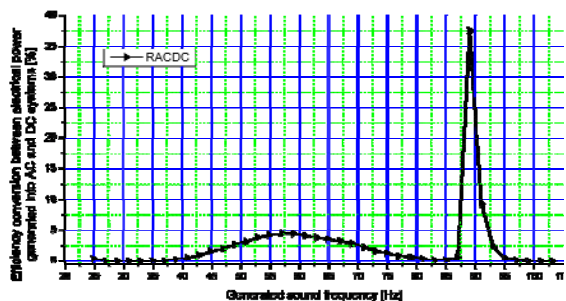
RATAC – efficiency conversion of acoustic power into electrical power in AC system, RATDC – efficiency conversion of acoustic power into electrical power in DC system

Fig. 7. Variation of the RSADC and RSAAC efficiencies depending on the generated sound frequency



RTSAC – overall efficiency in AC system and RTSDC – overall efficiency in DC system

Fig. 8. Variation of the RTSAC and RTSDC depending on the generated sound frequency



RACDC – efficiency conversion between electrical powers generated into AC and DC systems RACDC – randamentul dintre puterea electrică generată în sistem AC și DC

Fig. 9. Variation of the RACDC efficiency depending on the generated sound frequency

electrical energy RACDC that actually represents conversion efficiency of the rectifier bridge from the acquisition board. Calculated efficiency is presented graphically in the Figures 6-9.

4. CONCLUSIONS

Recovery of electrical energy for these two systems (AC and DC) has a higher efficiency in

a wide frequency band for the generation of sounds with frequencies near the mechanical resonance frequency of the transducer and a maximum efficiency for the system resonance frequency.

Although acoustic power remains constant acoustic-electric energy conversion efficiency in both AC and DC system varies depending on the generated sound frequency with a maximum near 15% for AC system and about 1.7% for DC system for system resonant frequency and almost a efficiency of 12% for AC system and 0.5% for DC system around mechanical resonance frequency of the transducer.

In the DC system efficiency is much lower (Figure 9) because at the acoustic-electric energy conversion efficiency is added the rectifier bridge efficiency (double alternation rectifier bridge) that has low efficiency at low voltage.

In order to design and building of noise recovery systems by converting sound wave that are transmitted through pipes and cavities

must take account of the mechanical, electrical and dimensional characteristics of the transducer and of noise level and frequency of the sounds that we want to submit conversion, but also of the acoustic system configuration consisting of pipes and cavities. Also another factor that influence conversion is the propagation medium of the acoustic waves.

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Conversia undelor acustice în energie electrică cu transductoare electromagnetice

Rezumat: În lucrare se prezintă rezultatele cercetărilor de laborator efectuate în scopul obținerii de energie electrică din unde acustice, utilizând transductoare electromagnetice. A fost realizat un stand de laborator pentru măsurarea parametrilor de intrare: oscilațiile de tensiune la generatorul de semnal acustic și parametrii de ieșire: semnalul acustic receptat de traductor, tensiunea și intensitatea recoltată. Păstrând un nivel SPL constant au fost generate semnale acustice de frecvențe în gama 25-103 Hz și au fost analizate modificările de putere și randament datorate caracteristicilor constructive ale traductorului. În baza rezultatelor obținute au fost analizate de asemenea aspecte privind modificările de semnal datorate caracteristicilor constructive ale transductoarelor electromagnetice funcție de frecvența sunetului generat. Au fost detaliate analize privind randamentele de conversie acustico-electrice, electro-acustice și randamentele totale al sistemelor pentru două configurații (AC și DC), când se păstrează o putere acustică constantă. Prelucrarea rezultatele experimentale au arătat că traductorii electromagnetici pot fi utilizați la conversia semnalelor acustice de joasă frecvență cu un randament de până la 15% în condiții de încercare specifice sistemului de laborator conceput.

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