The Parametric Formation of Acoustic Waves in the Air by Using Ultrasonic Transducers

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Gudra, Tadeusz ; Opieliñski, Krzysztof J.
Institute of Telecommunications and Acoustics, Wroclaw University of Technology
Wybrzeze Wyspianskiego 27
Wroclaw
Poland
Tel: +48 71 320-30-16
Fax: +48 71 320-31-89
E-mail: gudra@zakus.ita.pwr.wroc.pl

ABSTRACT

The paper presents the results of experiments in obtaining audible acoustic waves using ultrasonic sources working in air within frequency bands of 40 kHz and 160 kHz. Using the Westervelt's and Burger's equations parametric wave pressure levels were indicated for two primary frequencies. For primary waves with frequencies within the 160 kHz band, the low-to-high level transition time of the parametric wave is much shorter and the maximum pressure level is lower in relation to the results obtained for the 40 kHz frequency band. This effect is mainly caused by the higher attenuation of high frequency waves in air. The paper also present the results of measurements of the differential wave obtained for an exampled configuration of ultrasonic transducers working in the transducer matrix.

The experiments were done in an anechoic chamber, using separate groups of sources for two primary waves. The obtained rates of acoustic pressure and directivity patterns correspond to the theoretical model of the parametric source for which the directional characteristic depends on the primary source characteristic and the primary waves interactions.

INTRODUCTION

The parametric formation of acoustic waves consists in using the non-linearity of the medium, thanks to which two acoustic waves with high frequency produce, as the result of their mutual influence, not only additional waves with harmonic frequencies, but also the sum and the difference of the primary waves' frequencies. Because the subsequent harmonics and the sum component are beyond the acoustic band, the only audible result of this change is the differential component.

The first experiments in this field were done already in the 1970s [2] – unfortunately further experiments in the air were given up, mainly due to the low efficiency and instability of obtained results, and the focus was on the water medium. In this medium parametric sources are used in echo ranging, because their narrow directional characteristic and the small dimensions of the transducer are ideal for this type of usages [5].

The issue of parametric sources working in the air was revived among other things thanks to papers [3,7] and information on a parametric source working in the air and producing a phonic signal whose quality matched dynamic loudspeakers [6]. It seems that the direct cause enabling the creation of such a source is the development in ultrasonic transducers working in the air.

THEORETICAL BASES OF PARAMETRIC WAVE FORMATION

A monochromatic wave produced by a surface source with a high volume is subject to non-linear distortion. The result of the influence of two monochromatic waves with different frequencies propagating in the same area is, among others, the formation of a wave with a frequency that equals the difference between the primary waves' frequencies. The efficiency of energy transmission from the propagated waves through particular transducers to the waves formed in the medium depends on the non-linear properties of the medium. The non-linearity of the medium is the cause of shortening the wave front, up to the point where discontinuity occurs (i.e. the shock wave). The wave front shortening effect may be considerably weakened because of losses and the wave dispersion phenomenon. The losses of the non-linear wave (for the flat wave) are defined by the Burgers equation:

$$\frac{\partial p}{\partial x} - \frac{\varepsilon}{c^3 \rho_0} p \frac{\partial p}{\partial \tau} = \frac{b}{2\rho_0 c^3} \frac{\partial^2 p}{\partial \tau^2}, \tag{1}$$

where: p – wave pressure,
ε – non-linear parameter,
b – dissipativeness coefficient (bound up with the medium viscosity),
c – sound velocity,
ρ_0 - density,
$\tau = t - \frac{x}{c}$.

The dissipativeness coefficient for air is defined as:

$$b = \frac{4}{3}\mu + \xi, \tag{2}$$

where: μ – dynamic viscosity coefficient,
ξ – volumetric viscosity coefficient.

This coefficient is related to acoustic wave attenuation through the following dependence:

$$\alpha = \frac{\omega^2}{2\rho_0 c_0^3} b. \tag{3}$$

Table 1 compares the values of particular parameters describing the properties of water and air.

PARAMETER	MEDIUM	
	WATER	AIR
Sound velocity *c [m/s]*	1497	331
Density ρ_0 *[kg/m^3]*	997	1,29
Proper acoustic resistance R_w *[MPa/m]*	1490	4,26
Total attenuation coefficient α/f^2 *[10^{-11} s^2/m]*	0,0025	2,4 (for 160 kHz)
Dissipativeness coefficient *b [kg/(m·s)]*	0,004	0,00005
Non-linearity parameter ε	3,5	1,2

Tab.1. The values of particular parameters describing the properties of water and air.

Because the acoustic resistance of water is by far higher than that of the air, then in the case of identical deflections of the transducer's surface in the water and in the air the wave propagated in the water will have much more power, and so it is much easier to be found in the non-linear range. Additionally, water has more non-linear properties than the air, so the parametric formation of acoustic wave in the air is much more difficult.

The numeric results of the Burgers equation show that whereas the original wave amplitude falls as the distance from the source grows, the differential wave amplitude rises as the distance grows [1]. The frequency difference wave pressure on the acoustic beam axis can be obtained by solving the Burgers equations. The obtained dependences allow us to indicate the acoustic pressure on the beam axis, however they do not take into account the phenomena of non-linear diffraction and non-linear attenuation. Using the model proposed by Westervelt [8] the parametric transducer can be presented as the area of the environment limited by the cylinder surface. The expression describing the distribution of the frequency difference wave is as follows [4]:

$$\underline{A} = -\frac{\boldsymbol{e}\Omega^2}{c^4\,\boldsymbol{r}_0}\,\frac{e^{-iKR_0}}{4\boldsymbol{p}R_0}\,D_t D_l\,, \tag{4}$$

where: D_t – the directivity indicator defining the influence of the pressure distribution in the horizontal cross-section of the beam upon the shape of the directional characteristic,

D_l – directivity indicator defining the influence of the distribution of primary waves' amplitudes in the propagation direction upon the shape of directional characteristic of the frequency difference wave.

Calculations included in the paper [4] lead to the following conclusions:

- the directional characteristic for the frequency difference wave is approximately equal to the width of the major lobe of primary waves' characteristics,
- pressure distribution on the surface of the transducer generating the primary wave has no influence on the shape of the directional characteristic of the parametric transducer,
- parametric transducers have a fixed width of the directional characteristic within a broad frequency range and do not have any side lobes,
- the shape of the directional characteristic, unlike in traditional transducers, is not influenced by pressure distribution in the horizontal cross-section of the acoustic beam, but by the distribution of amplitudes of primary waves along the radiation axis.

Figures 1a and 1b show differential waves' levels calculated according to the Burgers equation for the frequencies of 40 kHz and 39 kHz as well as of 160 kHz and 159 kHz, whereas Fig.1c and 1d present parametric waves' levels calculated from the Westervelt equation for the same primary waves' frequencies.

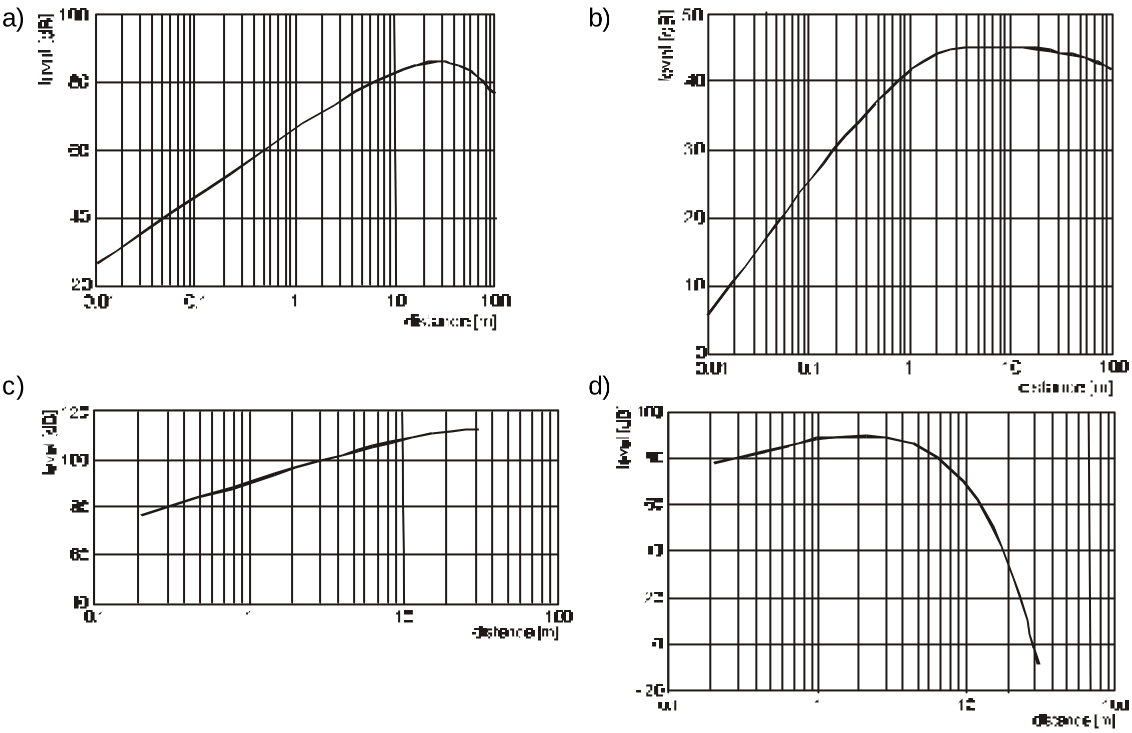

Fig.1. Differential waves' pressure level calculated: a) acc. to the Burgers equation for the frequencies of 40 and 39 kHz, b) acc. to the Burgers equation for the frequencies of 160 and 159 kHz, c) acc. to the Westervelts equation for the frequencies of 40 and 39 kHz, d) acc. to the Westervelts equation for the frequencies of 160 and 159 kHz.

THE CHOICE OF ULTRASONIC TRANSDUCERS FOR THE EXPERIMENT

Ultrasonic transducers used for the parametric formation of acoustic wave in the air should meet the following criteria:

- operating with a continuous wave,
- producing an appropriately high volume of acoustic pressure (above 100 dB),

- the working frequency of the transducers should match the calculated primary waves' frequencies,
- the dimensions of the transducers should enable their connecting in order to create a transmitting matrix.

These conditions are fulfilled by transducers manufactured by the Japanese firm MURATA, with the working frequency of 40 kHz, allowing us to generate the pressure volume L = 106 dB at the distance of 30 cm. This frequency was chosen because of the relatively small, within this frequency range, attenuation of ultrasonic waves: 1,22 dB/cm.

To obtain a differential frequency of about 1 kHz, the primary waves' frequencies were 39 kHz and 40 kHz. 16 pairs of transducers were selected, enabling the formation of the acoustic pressure level L = 100 dB at the distance of 1 m from the source. The selected transducers differed only slightly in their resonance frequencies and the quality factor, and particular transducers had one resonance and the input impedance Z = 650 Ω. The transducers were fixed in the matrix (Fig.2a) and joined in parallel, and the resultant impedance was ca 50 Ω.

The other groups of transducers used in this research were transducers designed to operate in the air, manufactured by the Polish firm CERAD and working at the frequency of 160 kHz. These transducers were built into a matrix consisting of 18 transducers altogether (Fig.2b). In order to obtain the differential frequency equaling 1 kHZ, the frequencies of primary waves were 160 kHz and 159 kHz.

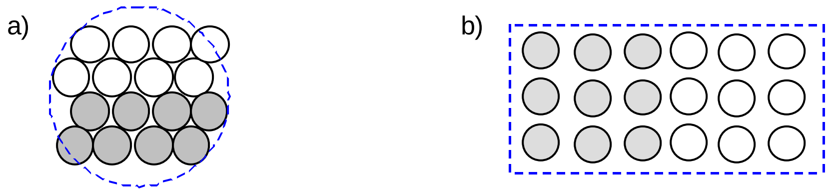

Fig.2. Distribution of transducers in the matrix in the band of: a) 40 kHz, b) 160 kHz.

MEASUREMENT RESULTS

The measurements' purpose was to examine to what extent the theoretical assumptions related to the phenomenon of parametric formation of acoustic wave would be verified in practice. The research was done in anechoic chamber, in the measurement set up shown in Fig.3.

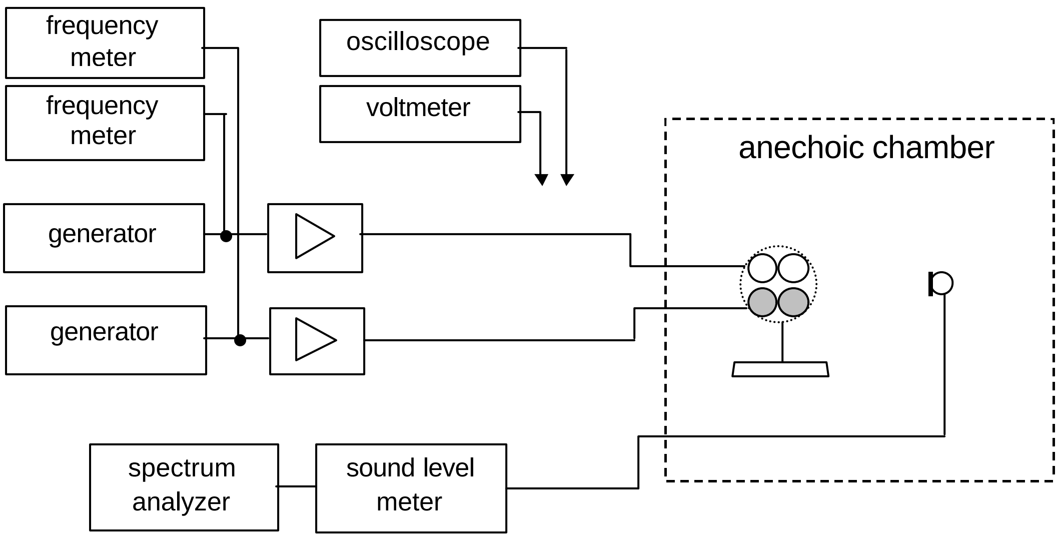

Fig.3. Measurement set-up for the examination of parametric sources.

Only the ultrasonic transducers and a microphone were placed in the echo-free chamber, with remaining appliances outside the chamber. The transducers were fixed on a revolving table. An RFT condenser microphone received the produced signals of the differential wave. A STANFORD RESEARCH SYSTEM SR 760 FFT spectrum analyzer was used to examine the signal specter.

Figure 4 shows the obtained dependence of the acoustic pressure level of the primary waves 40 kHz and 39 kHz and the differential wave on the distance from the source. Fig.5 shows the directional characteristics of the primary waves' sources and of the parametric source for the frequency of 1 kHz.

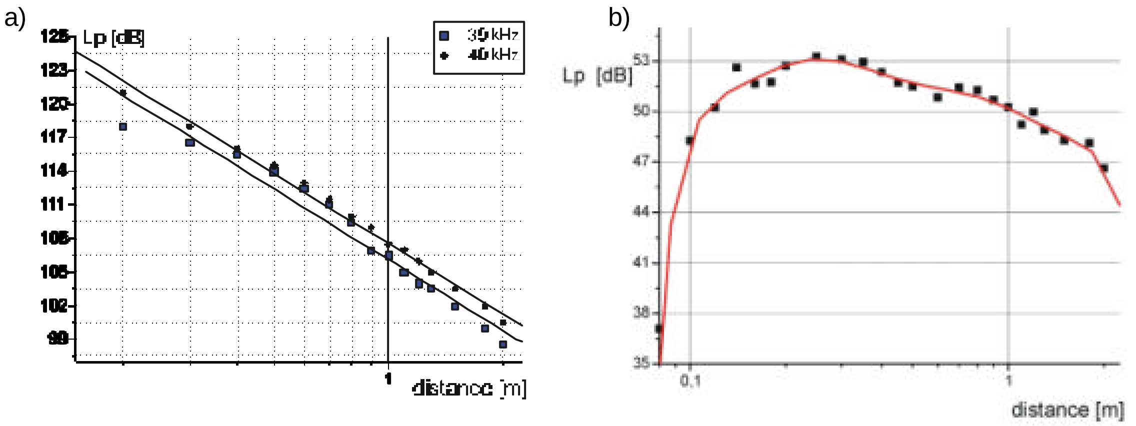

Fig.4. Dependence of the level of acoustic pressure of: a) the primary waves 40 kHz and 39 kHz on the distance from the source, b) the differential wave on the distance from the source.

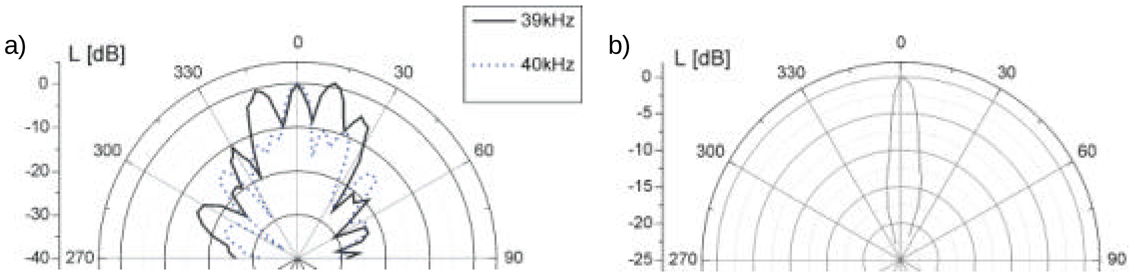

Fig.5. Directional characteristic of: a) the primary waves sources, b) the parametric source for the frequency of 1 kHz.

Frequency characteristics are an important parameter for every source. The operating principle of parametric sources leads to the conclusion that their frequency characteristic depends directly on the characteristic of primary sources, which is confirmed by measurement results. Fig.6a presents the frequency characteristics of the matrix of transducers generating primary waves, whereas Fig.6b shows the frequency characteristic of the parametric transducer. It was obtained at the fixed primary wave frequency of 40 kHz and upon retuning the other primary component. The bandwidth (defined as a decibel decrease in the average level of acoustic pressure) is between 750 Hz and 4750 Hz and is proportional to the resultant transfer band of both sources of primary waves. It can be seen that even at relatively low frequencies of primary waves it is possible to obtain bands sufficient for the transmission of speech.

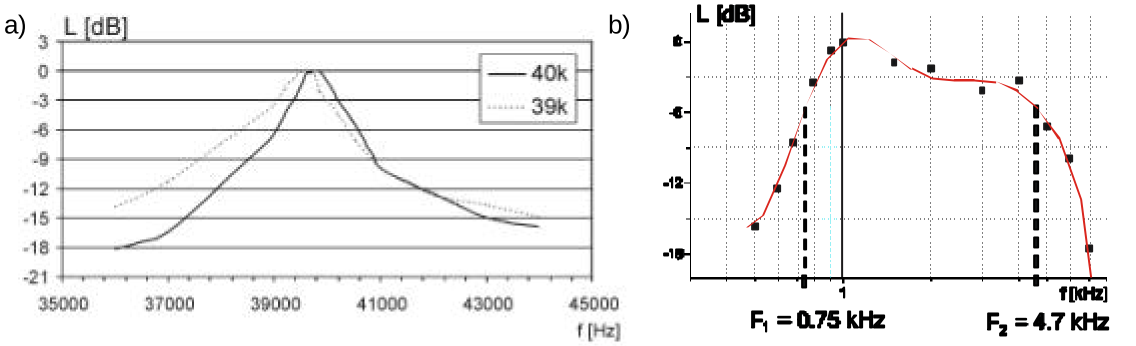

Fig.6. Frequency characteristic of: a) the primary waves sources, b) the parametric source.

Figure 7 shows the pressure level of the parametric wave source in the distance function for the frequency of 1 kHz (the primary waves' frequencies were 160 kHz and 159 kHz), and the directional characteristic measured at the distance of 2 m from the transducers' matrix. The frequency characteristic of such a parametric source is shown in Fig.8. The bandwidth at a 3 dB decrease in the acoustic pressure is from 2 kHz to 9 kHz.

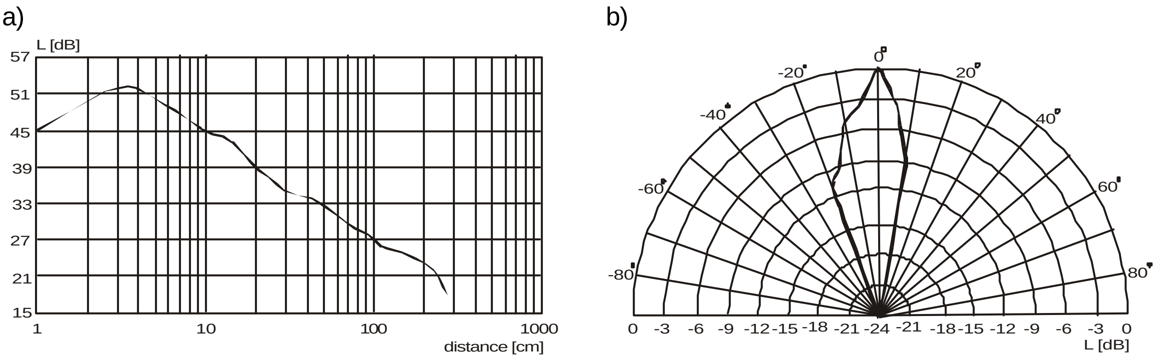

Fig.7. Measurement results of parametric wave from primary waves with frequency 160 and 159 kHz: a) level of the differential wave pressure in the distance function, b) directional characteristic of the parametric source measured at the distance of 3 m from the matrix.

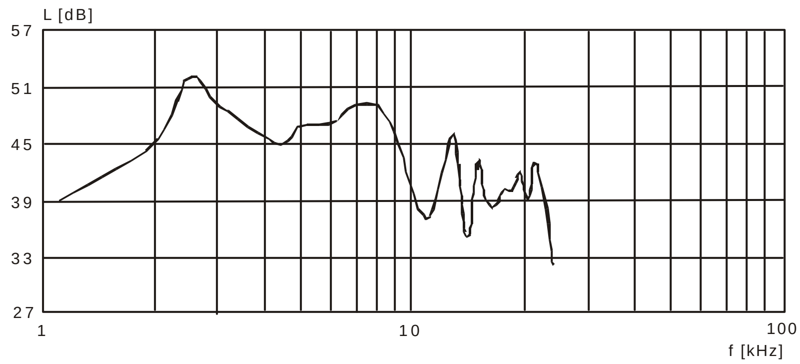

Fig.8. Frequency characteristic of the parametric source from primary waves with frequency 160 and 159 kHz.

CONCLUSIONS

The results of experiments confirmed the theoretical possibility of parametric formation of acoustic waves by means of ultrasonic transducers working in the air. The basic fault of parametric sources working in the air i.e. their limited capacity to produce acoustic pressure levels enabling their practical usage, that is at the level of 70–75 dB, seems to be correctable due to development in the construction of ultrasonic transducers working in the air. However, their relatively low transformation efficiency, determining the manufacturing cost of such sources, is a problem.

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