ARCHIVES OF ACOUSTICS
33, 4, 581–592 (2008)

ULTRASOUNDS IN GAS MEDIA: GENERATION, TRANSMISSION, APPLICATIONS

(review paper)

Tadeusz GUDRA

Wrocław University of Technology
Institute of Telecommunications, Teleinformatics and Acoustics
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
e-mail: tadeusz.gudra@pwr.wroc.pl

(*received June 15; accepted October 21, 2008*)

The focus of this work is on some fundamental issues concerning ultrasonic wave propagation in gas media. First, a short characterization of the gas medium and matters related to transmission of ultrasonic waves in stationary and non-stationary media were presented. Additionally, the study presents an aeroacoustic range equation which is a basis of the development of a computer model of an ultrasonic link. Next, attention turns to matters related to generation of ultrasonic waves in gas media and problems regarding matching high acoustic impedance of transducers and low acoustic impedance of gases. Finally, examples of industrial use of ultrasounds were given and possible future applications in non-contact measurement systems were suggested.

Keywords: ultrasounds, gas medium.

1. Introduction

The subject of generation, transmission and reception of ultrasonic waves in gas media has rarely been covered in professional literature. The main reason for this is that gas is not a convenient medium for ultrasounds. Despite the obvious limitations, using ultrasonic waves in such media may be very tempting because in such cases it is not necessary to use troublesome coupling media, without which it is impossible to perform most ultrasonic measurements. Acquiring highly efficient ultrasound sources intended for use in gases is a major problem. The main difficulties here are poor matching between high acoustic impedance of a transducer and low acoustic impedance of a gas medium and significant attenuation of ultrasonic waves in this medium. (The matters related to the construction and characteristics of ultrasonic transducers intended for use in gas media have been presented in author's monograph [1]).

2. Short characterization of the gas medium

The basic physical parameters of gases are: density, viscosity, specific heat, thermal conductivity coefficient, coefficient κ and diffusion coefficient. All the above parameters can be presented as functions of pressure and temperature, and additionally, in case of mixtures, as a function of molar masses of individual gas components. The parameters allow determination of the two of the most important values in terms of ultrasonic wave propagation: wave propagation velocity and wave attenuation.

2.1. Ultrasonic wave propagation velocity

The problem of ultrasonic wave propagation velocity in gases can be examined by means of classical theory and relaxation theory. For low density gases and steams, when frequency range is below dispersion, sound velocity can be determined by means of the following formula:

$$c = \sqrt{\frac{\kappa(T) p_0 T}{\rho_0 T_0}}, \qquad (1)$$

where $\kappa(T) = c_p/c_v$, p_0 – gas pressure in normal conditions, ρ_0 – gas density in normal conditions, $T_0 = 293$ K. Coefficient $\kappa(T)$ in pressure range of $p = 0.8$–1.2 atm in gas is virtually constant. The only change is in temperature T. Therefore, it can be assumed, according to formula (1), that sound velocity is not pressure dependent in pressure variation range of 0.5 atm. Measurements prove that for pressures close to atmospheric one, increasing pressure by 1 atm results in sound velocity rising by about 0.1–0.12 m/s [2]. On the basis of equation (1) and experimental data included in mathematical and physical tables sound velocity in any gas or mixture can be calculated. Gas containing water steam can be treated as a mixture; sound velocity in such gas will depend on humidity ν [% of total vol.] (it is particularly important for air).

Velocity of ultrasonic waves in gases ranges from about 200 m/s (chlorine) to about 1300 m/s (hydrogen).

2.2. Ultrasonic wave attenuation

Attenuation of elastic wave in a gas medium (understood as weakening of the wave) is caused by absorption and diffusion. Viscosity, thermal conductivity and radiation and relaxation processes are the factors affecting absorption. Diffusion occurs where a medium is heterogeneous. The impact of absorption and diffusion on total attenuation may vary. Additionally, it is often difficult to experimentally separate the effect of the two factors.

The classical attenuation of ultrasounds in gases depending on viscosity η and thermal conductivity σ is expressed using attenuation coefficient α_{cl}, determined by Stokes–Kirchhoff formula.

In case of minor pressure variations ranging around atmospheric pressure (0.8–1.2 atm) c_p values for gases are nearly constant. Measurements show that at pressure variation of approximately 1–1.2 atm in relation to atmospheric pressure, attenuation coefficient can change by more than 80% [2].

On the grounds of experimental data and model calculations EVANS, BASS, SUTHERLAND and ZUCKERWAR [3, 4] derived formulas rendering it possible to accurately determine attenuation coefficient in air for a wide range of frequencies, with relaxation processes taken into consideration. Ultrasonic wave attenuation in gas media is heavily dependant on frequency; e.g. in case of air it changes from 0.5 dB/m (for $f = 20$ kHz) to about 80 000 dB/m (for $f = 20$ MHz) [5].

2.3. Acoustic impedance of gas media

Medium's acoustic impedance is a value, which has an essential influence on the load of ultrasonic transducers. Since this value depends only on medium properties, it is often defined as specific acoustic resistance of a medium R_w. Specific resistance of gas media changes in a rather wide range, however its value is a number of times (10^4–10^7) lower than acoustic resistance of solid media. This constitutes a fundamental problem in the area of generating ultrasonic waves in gas media by means of electromechanical transducers. Acoustic impedance for a plane wave ranges from about 100 kg/(m^2·s) (hydrogen) to about 600 kg/(m^2·s) (chlorine).

3. Transmission of ultrasonic waves in stationary and non-stationary media

Propagation of ultrasonic wave in a gas medium which is stationary, homogeneous and does not absorb energy occurs according in accordance with well known (classical theories) phenomena related to acoustic waves – wave theory and geometrical theory. The path of a sound ray is a straight line and the amplitude and shape of a signal depend solely on medium parameters. For a heterogeneous medium i.e. one in which heterogeneity of constitution (e.g. differences in density), heterogeneity of physical state (e.g. differences in temperature), foreign matter (e.g. water drops in air), medium motion (e.g. flow, turbulence) occur the path of a sound ray is a curve, the signal shape is very complex [6, 7] and, in case of turbulences, renders it impossible to define it using mathematical expressions [8].

When examining effects in a gas medium on a macroscopic scale the medium is treated as a continuous medium. Mathematical description of gas in motion is based on deriving functions which determine the structure of gas flow velocities $v(x, y, z, t)$, gas pressure $p(x, y, z, t)$ and density $\rho(x, y, z, t)$. In case of stationary (determined) gas flow the velocity is constant in time in every point of the gas filled space, i.e. $\delta v/\delta t = 0$. Stream lines (i.e. lines the tangents of which indicate the direction of velocity vector) do not change and do not overlap with paths of gas particles. In case of non-stationary gas flow the tangents of stream lines indicate the directions of movement of various gas particles in consecutive points in a space determined in an instant. Tangents of the path of gas particles indicate the directions of velocity of these particles in consecutive instants. In terms of transmission of ultrasonic signals in a non-stationary medium this problem is very significant because the type of flow may affect the nature and shape of ultrasonic pulses propagating in such a medium. This, in turn, can considerably affect e.g. the type of ultrasonic transducers which can be used e.g. to measure gas flow.

4. Aeroacoustic range equation

Nearly all applications of ultrasonic waves in gas media require correct assessment of the possibilities of both their generation and reception. By means of analysis of chemical constitution of a gas, its temperature, pressure, humidity and the effect of acoustic molecular processes occurring in gases, as well as physical parameters of gases (density, viscosity, specific heat, thermal conductivity coefficient, coefficient κ, diffusion coefficient) it is possible to determine relations for two of the most important acoustic parameters of a gas medium: ultrasonic wave velocity and attenuation, and at the same time specify the effect they have on the range of systems working in gas media. On these grounds a range equation of an aeroacoustic link, which is a modification of the range equation for hydroacoustic link [9]:

$$\frac{P_T}{P_R} = \frac{4\pi\, d^2 e^{2\alpha d}}{\Omega\, S_R}, \tag{2}$$

where P_T – power emitted by the sending transducer, P_R – power received by the receiving transducer, d – distance between transducers in aeroacoustic link, α – amplitude attenuation coefficient in air, S_R – receiving transducer surface, Ω – directivity factor of the sending transducer (for $\pi f D_T/c >> 1$, $\Omega = \pi^2 f^2 D_T^2/2c^2$, where f – ultrasonic wave frequency, D_T – sending transducer's diameter). With some simplifications in the process of determining individual power values, the relation P_T/P_R can be shown in equation (2) in two ways:

$$\frac{P_T}{P_{R\min}} = \left(\frac{S_n S_o \widetilde{U}_T k_u}{\widetilde{U}_{sz} 10^{\frac{L_\Gamma}{20}}} \frac{D_T}{D_R} \right)^2, \tag{3}$$

where $P_{R\min}$ – threshold signal power, specified by the required level difference signal-noise L_Γ, U_{sz} – total noise voltage on the electric part, U_T – voltage powering the sending transducer, k_u – amplification in the receiving set-up, S_o – sensitivity of the receiving transducer, S_n – effectiveness of the sending transducer on the assumption that the medium is lossless,

$$\frac{P_T}{P_{R\min}} = \frac{\widetilde{U}_T^2}{|Z_T|} \frac{R_p R_0}{(R_v + R_p)\,(R_0 + R_v + R_p)} \frac{4\rho c S_o^2 k_u^2}{\pi D_R^2 \widetilde{U}_{sz}^2 10^{\frac{L_\Gamma}{10}}}, \tag{4}$$

where R_0 – resistance of electric losses of the sending transducer, R_v – resistance of mechanical losses of the sending transducer, R_p – resistance of the radiation of the sending transducer, Z_T – impedance of the sending transducer in resonance.

This treatment of power relation results distance d in Eq. (2) being the link's range $d_{\max}$. Equation (2) allows designing an aeroacoustic link [10] by setting a specific range and calculating the required power relation P_T/P_R with all factors affecting ultrasound velocity and attenuation in air taken into consideration. It also renders possible select of the values of this relation by choosing parameters of ultrasonic transducers with accordance to Eqs. (3) or (4) [11]. Assuming the same operating frequency of the sending and receiving transducer, the relation between sound velocity and temperature and air humidity provided among others by J. OBRAZ [12] and allowing for the value of attenuation coefficient in air determined by BASS, SUTHERLAND and ZUCKERWAR, the range equation can also be derived as follows:

$$\frac{P_T}{P_R} = \left(\frac{4\sqrt{2} \cdot 331.82(1 + 1.83 \cdot 10^{-3}t)\ (1 + 2.2 \cdot 10^{-3}\upsilon)}{\pi D_T D_R f} \right)^2 d^2 e^{2\alpha_{rz} d}, \qquad (5)$$

where α_{rz} – attenuation values derived from the graph by BASS *et al.* [3].

5. Generation of ultrasonic waves in gases

Although not the only ones, bats are the most known animals generating ultrasonic waves in air. In 1941, after radar was invented, it was discovered that those mammals rely on echolocation for their spatial orientation. This discovery led to a increased scientific interest in these animals. Bats generate sound and ultrasound pulses (squeaks) ranging from 4 kHz to 150 kHz (depending on the species). Due to strong directivity the level of acoustic pressure can reach the value of 145 dB (similar level of noise is produced by a taking off jet plane!). Signals generated by bats are very complex. Figure 1 presents an example of the structure of a signal generated by noctule bat (*Nyctalus noctula*), which is native to Lower Silesia region of Poland.

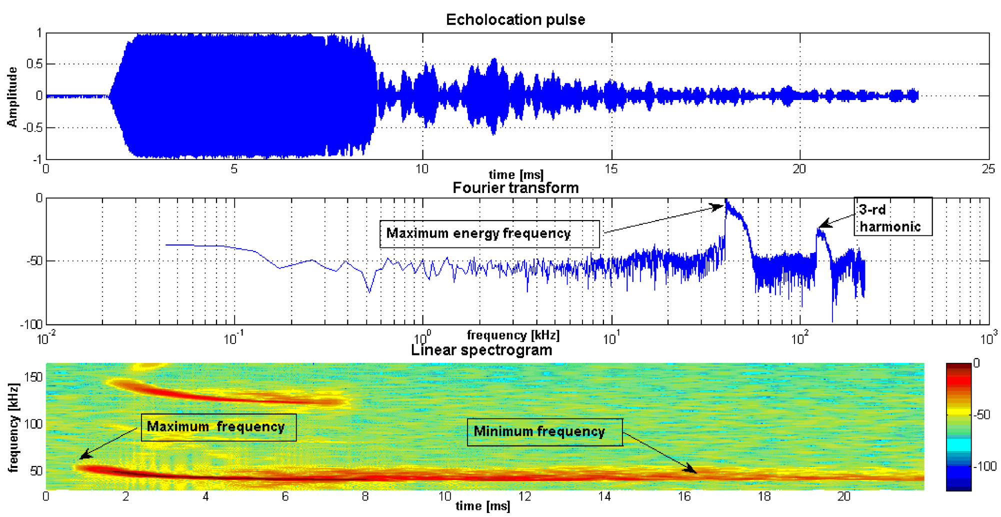


Fig. 1. Echolocation pulse of noctule bat.

In technical applications vibrating elements or systems, activated by alternating electric or magnetic field or by transducers made of electromechanically active materials are usually the source of ultrasonic waves in a gas medium. Although less common, so called flow sources are also used, which are characterized by constant flow of gas, filling the space in which sound propagates.

The main problem faced when emitting ultrasonic energy in a gas medium is considerable difference in acoustic impedance of transducers and a gas medium. Acoustic impedance of a vibrating element is usually a number of times higher than acoustic impedance of a gas medium. For example acoustic impedance of air is 5 orders lower than acoustic impedance of nearly all piezoelectric ceramics, which can be calculated using a formula for energy transmission coefficient.

Better matching between acoustic impedance of a ultrasonic transducer and a gas medium can be obtained as a result of increasing the emitting surface of the transducer or using matching layers between the transducer and the gas medium.

There are some limitations in both the above methods, resulting from the range of frequencies used. The method of increasing the emitting surface, usually by equipping the transducer with a suitably vibrated emitting plate, can be applied to transducers operating at lower ultrasonic frequencies (up to 100 kHz). The use of matching layers is possible predominantly in case of transducers operating at higher ultrasonic frequencies.

A number of novel transducer systems operating at frequencies ranging from 20 kHz to 2 MHz and suitable for use in various gas media were developed in Ultrasonic Technology Laboratory of Institute of Telecommunications, Teleinformatics and Acoustics of Wrocław University of Technology. These are mostly resonance transducers, which provide a suitable level of acoustic pressure; many of them are used in various areas of science and technology. Principles of operation and properties of these transducers are provided in detail in monograph [1].

6. Examples of applications of ultrasounds in gas media

The use of ultrasonic waves in gas media requires suitable knowledge of the conditions of their propagation. In order to assess the measurement possibilities of various types of equipment and ultrasonic systems it is fundamental to correctly solve the range equation for ultrasonic link (which can be used for both transmission systems and systems based on reflection). There are numerous areas of application of ultrasounds propagated in gas media: from the study of physical phenomena occurring in these media to industrial uses. The most noticeable solutions for industry include: measurement of levels of output on belt conveyors, measurement of discontinuity of stream on belt conveyors, measurement of the level of filling of containers, measurement of the cross-section of pipes, measurement of gas flow velocity.

Descriptions of some of the most innovative solutions chosen from among other potential applications of ultrasounds in gas media have been provided below.

6.1. Identifying shape, size and location of objects in a gas medium by means of ultrasonic transmission tomography method

The idea of using ultrasonic transmission tomography to identify shape, size and location of an object in a gas medium is similar to the idea of using UTT in order to acquire images of internal structure of objects. In this case, however, due to the characteristics of the measurement environment, ultrasonic wave is completely reflected from the surface of the studied object [13, 14].

6.2. Determining the distribution pattern of gas temperature and composition of binary gas mixtures by means of ultrasonic transmission tomography method

Ultrasonic transmission tomography can also be used to determine spatial distribution pattern of temperature in a studied area, in cases where a heterogeneous field of this parameter exists [15]. This method can also be used to determine the distribution pattern of concentration of components of selected binary gas mixtures. Its non-invasive nature and short measurement time are great advantages. Figure 2 presents the measurement set-up (Fig. 2a) and the results of reconstruction of image obtained as a result of a measurement of local values of sound velocity on a path between individual transducers on the whole surface of the measuring channel (Fig. 2b and Fig. 2c).

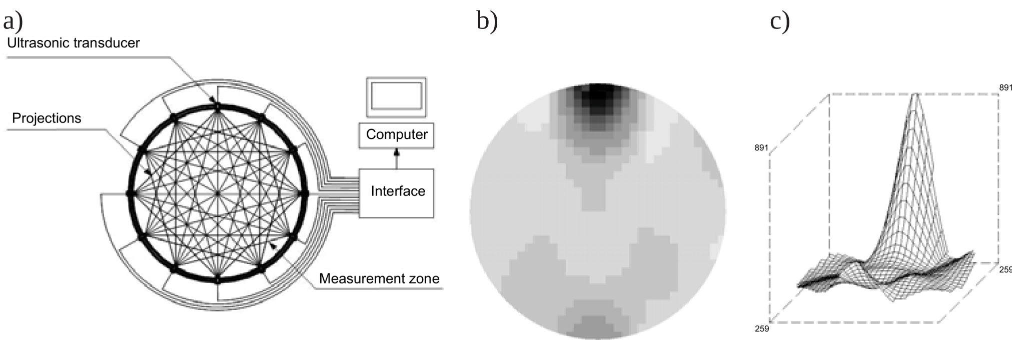


Fig. 2. Measurement set-up of ultrasonic tomograph: a) configuration of ultrasonic transducers, b), c) reconstruction of an image of helium flow in a channel on 2D and pseudo-3D image.

The dark area on the 2D image and the highest point on the pseudo-3D image (Fig. 2c) correspond to the measured maximum sound value $c_{\max} = 891$ m/s; this velocity reflects the volume fraction of helium in air, which is about 95% [15]. The study of the amount of helium content in air (or identification of its presence in air) were performed with the view of checking the possibilities of using ultrasonic transmission tomography method in CERN laboratory in Switzerland, where liquid helium is used as a coolant in the accelerator.

Helium leak from a cryogenic system (e.g. accelerator tunnel) is very dangerous for the personnel (due to significant lack of oxygen in the region of the leak). Ultrasonic measurement of the amount of helium content in air is an alternative for the commonly used methods of measuring oxygen content by means of electrochemical cells: it is convenient, non-invasive and takes very little time. Initial testing in CERN confirmed high effectiveness of the ultrasonic method and its sufficient accuracy. Fifteen percent concentration of helium in air results in increase of sound velocity by 28 m/s (i.e. about 8%). This makes the method very attractive, taking into consideration the accuracy of sound measurement in air: 0.1 m/s.

6.3. Scanning acoustic microscopy with a gas coupling medium

Scanning acoustic microscopy (SAM) is a known study method, which allows visualization of the internal structure of various objects (visualization type B and C), detection of minor changes in distance (also below 0.1 nm) and determination of various physical parameters, such as elastic constants in individual crystals and other mechanical parameters of solid or liquid bodies. The use of ultrasonic microscopy in biology and medicine is becoming increasingly notable.

Due to relatively low ultrasonic waves attenuation in liquids, the most common medium coupling an ultrasonic transducer with the studied object is water. Since ultrasonic waves attenuation increases with frequency which in turn is a decisive factor as far as resolution is concerned, trying to increase resolution always results in reducing distance between ultrasonic transducer (usually in a shape of a lens) and the examined object. For a microscope operating at the frequency of 1.2 GHz in water, the typical distance between the ultrasonic lens and the studied object is about 50 μm. It is not a major disadvantage in case of this microscope, but in certain situations much longer distance is necessary (e.g. in robotics applications). Using air as transmission medium resolves this problem to a large extend, as ultrasonic wave velocity (and wave length) is about 5 times lower in air than in water. This partially compensates for the use of higher frequencies, which can be used in a microscope with a liquid coupling medium (it is possible to obtain identical resolution at 5 times lower frequency).

Figure 3 shows an example of the possibilities of visualisation of surface structures with no liquid as the coupling medium. The figure represents an image of a profile of papillary lines on a wax finger imprint. The visible contour lines correspond to the measured phase changes shifts, which can be used e.g. to improve personal identification.

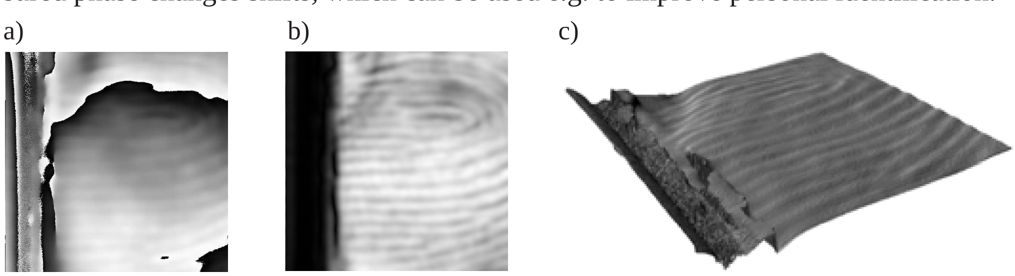


Fig. 3. Image of a paraffin finger imprint: a) phase distribution, b) amplitude distribution, c) pseudo 3D presentation.

6.4. Non-contact object relocation system using the phenomenon of ultrasonic levitation

Ultrasonic levitation can be used for both horizontal and vertical non-contact relocation of objects. There are two types of levitation: levitation in standing wave nodes and near field acoustic levitation (NFAL). Ultrasonic levitation in standing wave nodes can be observed in both liquid and gas media. Ultrasonic levitation in standing wave nodes and near field acoustic levitation result from the existence of radiation pressure, which counterbalances gravitation. Despite having common source, both the mentioned types of levitation are of a slightly different nature. It is possible to use an axial-symmetrical plate transverse vibrated in its symmetry axis for vertical relocation of objects. Object relocation takes place in leaps between the pressure nodes of a standing wave. This kind of relocation requires the use of a flat reflector located in parallel with the surface of the ultrasonic wave source.

Object that can levitate in pressure nodes of a standing wave between the source and the reflector must be smaller than the length of waves. The distance between the transducer generating ultrasonic wave and the reflector is equal to the total multiple of half of the wave length. In microgravitational conditions levitation occurs precisely in the points corresponding to acoustic pressure nodes. In Earth conditions the levitating objects are situated slightly above the nodes, where their position is stabilised by a force, the source of which is believed to be in the asymmetrical part of radiation pressure [16].

Figure 4 shows the results of an experiment proving the possibility of vertical relocation (movement) of two sphere shaped objects with different mass. By changing the value of intensity of sound generated by radiating plate it is possible to locate objects with different mass on a given height.

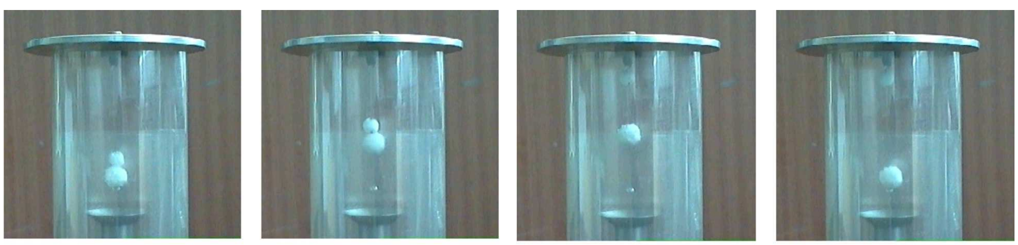


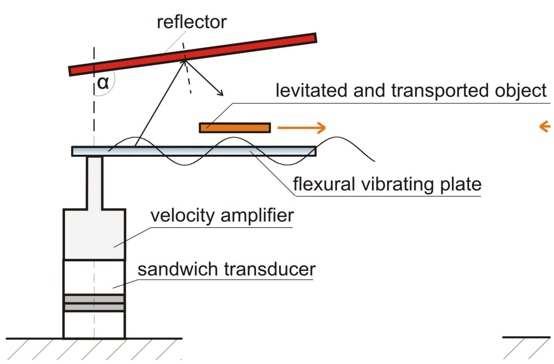
Fig. 4. Demonstration of the phenomenon of ultrasonic levitation used to vertically relocate two objects with different mass.

In order to perform non-contact horizontal relocation of objects using levitation phenomenon it is most effective to use a striped mode vibrating rectangle plate. A few solutions using near field ultrasonic levitation can be enumerated [17, 18].

In case of levitation in a standing wave it is necessary to use a reflector. In case of near field levitation a reflector is not required – ultrasonic wave is reflected directly from the moved object.

The first works on NFAL date from the 1990s. Y. HASHIMOTO, Y. KOINE, S. UEHA in the paper [17] inform that they observed a phenomenon which allows flat objects with considerable masses (even up to single kilograms) to float over a vibrating surface of a source of ultrasonic wave, achieving heights of a few tens of micrometers. Despite very small distance between the vibrating surface and the levitating object – it is possible to move object much bigger and heavier than in case of levitation in a standing wave. The effect of moving plates can be obtained in various ways: by slightly inclining the transverse vibrating plate and using gravitation force, by using a stream of air directed at the levitating plate, by changing the frequency of the plate's vibration and by using a reflector situated at a certain angle in relation to the transverse vibrating plate and the surface of the relocated object. The latter method is especially interesting due to the ease with which it is possible to control movement speed of the object. This is achieved by changing the angle at which the reflector is situated in relation to the plate's surface. Figure 5 shows force distribution pattern at various angles at which the reflector is situated in relation to the vibrating plate. By changing the value of α angle it is possible to move the object in any direction with any speed or make the levitating object motionless (when the reflector is parallel to the vibrating plate).

a)



b)

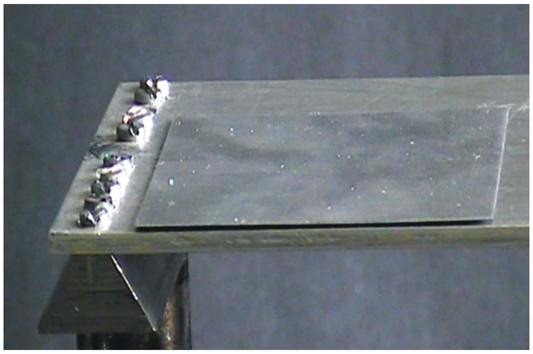


Fig. 5. Force distribution pattern at various angles at which the reflector is situated in relation to the plate (a) and aluminium plate levitating above the surface of a transverse vibrating plate (b).

7. Conclusions

Despite the unfavourable physical conditions of gases, propagation of ultrasonic waves in such media can have many interesting practical applications. The main advantage of such waves realizes in the possibility of use in the above presented non-contact measurement systems, but also in their active impact on the gas medium, in which cases physical phenomena such as dispersion, coagulation, radiation pressure are used. Using these phenomena in practice requires application of high power ultrasonic transducers.

References

[1] GUDRA T., *Properties and application of ultrasonic transducers working in gaseous media* [in Polish]: *Właściwości i zastosowanie przetworników ultradźwiękowych do pracy w ośrodkach gazowych*, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2005.

[2] GUMANIUK M.N., *Ultrasound in mining automatics* [in Russian]: *Ultrazvuk w gornoj avtomatike*, Technika, Kiev 1970.

[3] BASS H.E., SUTHERLAND L.C., ZUCKERWAR A.J., *Atmospheric absorption of sound: Update*, JASA, **88**, 4, 2019–2021 (1990).

[4] EVANS L.B., BASS H.E., SUTHERLAND L.C., *Atmospheric Asorption of Sound: Theoretical Predictions*, JASA, **51**, 5, 2, 1565–1575 (1972).

[5] BOND L.J., CHIANG C.H., FORTUNKO C.M., *Absorption of ultrasonic waves in air at high frequencies (10–20 MHz)*, JASA, 94, 2006–2015 (1992).

[6] BLANC–BENON PH., HUGON–JEANNIN Y., JUVE D., *Reconstructuin de fronts d'onde distordus par la turbulence*, Journal de Physique IV, 2, 545–548 (1992).

[7] ISHIMARU A., *Wave Propagation and scatering in random media*, Academic Press, New York, London 1978.

[8] TATARSKIJ W.J., *Wave propagation in turbulent atmosphere*, [in Russian]: *Rasprostranienie wołn w turbulentnoj atmosferie*, Nauka, Moskwa 1994.

[9] JAGODZIŃSKI Z., *Transmission of underwater signals using utrasonic waves* [in Polish]: *Przenoszenie sygnałów podwodnych na falach ultradźwiękowych*, Archiwum Akustyki, **3**, 4, 373–378 (1968).

[10] GUDRA T., OPIELIŃSKI K.J., *Computer model of acoustic link in the air* [in Polish]: *Komputerowy model łącza aeroakustycznego*, XLII Open Seminar on Acoustics, pp. 149–154, Prace IPPT PAN, Warszawa 1995.

[11] BEDNAREK J., GUDRA T., OPIELIŃSKI K., *Analysis of some parameters of range equation for acoustic link in the air* [in Polish]: *Analiza wybranych parametrów równania zasięgu dla łącza aeroakustycznego*, XXXIX Open Seminar on Acoustics, pp. 113–116, Kraków 1992.

[12] OBRAZ J., *Ultrasonics in measuring technique* [in Polish]: *Ultradźwięki w technice pomiarowej*, WNT, Warszawa 1983.

[13] BROWN G.J., REILLY D., *Ultrasonic Tomographic Imaging of solid objects in air using an array of fan-shaped-beam electrostatic transducer*, Ultrasonics, **34**, 111–115 (1996).

[14] MENZ B., *Application of Simultaneous Multiplex Techniques to Ultrasonic Reflection Tomography and Model Based Object Recognition*, Proc. of the World Congress on Ultrasonics, pp. 464–465, Yokohama 1997.

[15] CHOROWSKI M., GIZICKI W., WACH J., *Possibility of applying of acoustic methods for temperature and gas composition measurenent* [in Polish]: *Możliwości wykorzystania ultradźwięków do wyznaczania temperatury i składu binarnych mieszanin gazów*, Mat. Konferencji Naukowo-Technicznej „Energetyka 2002", pp. 157–163, Wrocław 2002.

[16] VANDEALE V., LAMBERT P., DELCHAMBRE A., *Noncontact handling in microassembly*, Precision Engineering, **29**, 491–505 (2005).

[17] KOIKE Y., UEHA S., HASHIMOTO Y., *A theoretical study of near-field acoustic levitation of planar objects*, Proc. of 1995 World Congress on Ultrasonics, pp. 832–842, Berlin 1995.

[18] HASHIMOTO Y., KOIKE Y., UEHA S., *Near-field acoustic levitation of planar specimens using flexural vibrations*, JASA, **100**, 4, 2057–2064 (1996).