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EFFECT OF ACOUSTIC-BARRIER DISPLACEMENT ON THE ENERGY-FOCUSING EFFICIENCY OF AN ACOUSTIC PARABOLIC REFLECTOR

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Abstract
This paper investigates the effect of acoustic-barrier displacement on the energy-focusing efficiency of a acoustic parabolic reflector. A geometrical model is developed to determine the active and effective reflector surface areas as a function of the acoustic-barrier displacement, d. The analysis distinguishes between the effects of the front and back sides of the acoustic barrier on the acoustic energy reaching the reflector and its focus. An experimental investigation is performed using two acoustically coupled parabolic reflectors, with acoustic impulse responses h measured at the focus while the acoustic barrier is progressively displaced. The results show two distinct displacement regions. For small displacements, both the front, S_{Front}^{AB}, and back, S_{Back}^{AB}, sides of the acoustic barrier affect the focusing process, with the back side significantly limiting the energy reaching the focus, E_F . As the displacement increases, this effect rapidly decreases and vanishes due to the geometrical relationship between the acoustic barrier and the reflector. In the second region, the front side remains the dominant limiting factor, while the effective reflector surface increases continuously. The surface efficiency, η_S, increases from 0.0011 at zero displacement to 1 when the reflector aperture becomes fully active. The agreement between the geometrically predicted surface variations and the experimentally determined energy trends confirms the proposed approach for describing the influence of acoustic-barrier displacement on acoustic energy focusing.

Keywords: Acoustic parabolic reflector, acoustic focusing, acoustic impulse response.

INTRODUCTION

Paraboloidal reflecting surfaces focus an incident plane acoustic wave propagating parallel to the axis of symmetry into a single focal point [1], [2]. Owing to their ability to concentrate acoustic energy, parabolic acoustic reflectors can be regarded as acoustic energy concentrators, with their focusing performance depending on the reflector geometry and the wavelength of the incident sound field [3], [4]. Analytical expressions relating the reflector gain to its geometric parameters, including the aperture radius, reflector depth, and focal length, as well as to the acoustic frequency, have been reported in [5]. The focusing characteristics of acoustic parabolic reflectors have also been investigated experimentally, including measurements of acoustic impulse responses and spatial directivity patterns [6] - [8].

In this paper, the effect of an acoustic barrier on the energy-focusing efficiency, η_S, of an acoustically coupled pair of parabolic reflectors is investigated. First, a geometrical model of the reflector system with a movable acoustic barrier is described, and the active aperture surface $S_{\mathrm{in}}(d)$, effective aperture surface $S_{\mathrm{eff}}(d)$, and their dependence on the acoustic-barrier displacement d are defined. Subsequently, an experimental investigation is conducted using an acoustically coupled pair of parabolic reflectors installed in the courtyard of the Academy of Technical and

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Educational Vocational Studies in Niš, Serbia. The experimental setup and measurement conditions are described, and the acoustic impulse responses h are measured for different positions of the acoustic barrier. The obtained results are then presented and analyzed in terms of the dependence of the effective aperture surface $S_{\text{eff}}(d)$, the energy $E(d)$ reaching the reflector, and the energy E_F measured at the focal point on the acoustic-barrier displacement d. Particular attention is paid to the energy blocked by the front surface of the acoustic barrier, $E_{\text{Front}}^{\text{AB}}$, and, especially, to the energy intercepted by its back surface, $E_{\text{Back}}^{\text{AB}}$, after reflection from the reflector. The contributions of these two surfaces to the energy distribution are separately analyzed in order to clarify their respective effects on the energy reaching the focal point and, consequently, on the energy-focusing efficiency of the reflector system. The experimental results are presented graphically and analyzed to identify the main trends associated with the displacement of the acoustic barrier.

The paper is organized as follows. Section II presents the reflector model with a movable acoustic barrier. Section III presents the experimental results and their analysis, while Section IV concludes the paper.

REFLECTOR MODEL WITH A MOVABLE ACOUSTIC BARRIER

The parabolic acoustic reflector consists of an acoustic reflecting surface [5], which is described in the Cartesian x, y, z coordinate system by:

$$z(x,y) = \frac{x^2+y^2}{4z_F}, \qquad (1)$$

where the vertex is located at $O(0,0,0)$, and the focus is at $F(0,0,z_F)$. The circular aperture plane is located at $z = H$, where H is the reflector depth. The aperture radius R is given by $R = 2\sqrt{z_F H}$.

For acoustic signals with a wavelength λ smaller than the reflector dimensions, the reflector gain depends on the reflector geometry (H, R, z_F) and is given as a function of wavelength by [8]:

$$F_z \approx 4\pi \cdot \frac{z_F}{\lambda} \cdot \ln\left(\frac{R^2}{4z_F^2}\right). \qquad (2)$$

The reflector gain expressed in decibels is given by $G = 20 \cdot \log_{10}(F_z)$.

If an acoustic barrier with dimensions $W \times V$, made of an acoustically insulating material, is placed in front of the reflector aperture in the plane $z_p = z_F - h$, symmetrically with respect to the x- and y-axes, a portion of the incident acoustic energy cannot reach the reflecting surface (Fig. 1, rays 4 – 6). Consequently, this portion of the acoustic energy does not contribute to the focused field at the focus. In addition, a portion of the reflected acoustic energy is prevented by the barrier from reaching the focus (Fig. 1, rays 2, 3, 7, and 8). The acoustic barrier is displaced in the z_p plane along the horizontal x-axis by a distance d, where $d \geq 0$. Fig. 2 shows the position of the acoustic barrier for $d = 0.4$ m.

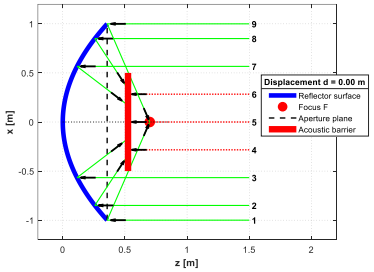


Fig. 1. *Reflector with a symmetrically positioned acoustic barrier of dimensions* $W \times V$.

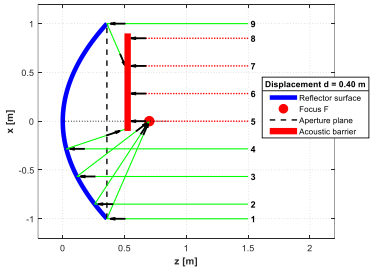


Fig. 2. *Reflector with the acoustic barrier displaced along the x-axis* ($d = 0.4\,m$).

The geometric region occupied by the acoustic barrier is defined by the set of coordinates:

$$P(d)=\begin{cases}(x,y)\in\square^{2}\mid\\ \quad -\dfrac{W}{2}+d\le x\le\dfrac{W}{2}+d\\ \quad -\dfrac{V}{2}\le y\le\dfrac{V}{2}\end{cases}. \qquad (3)$$

For an acoustic ray, representing a part of the acoustic wave whose wavefront is normal to the symmetry axis z, to reach the aperture plane and the reflecting surface of the reflector, it must belong to the set $\Omega_{\text{in}}(d)=K\setminus P(d)$. The reflector aperture is bounded by the set of points $K=\{(x,y)\in\mathbb{R}^2\mid x^2+y^2\le R^2\}$, and the corresponding incident area is defined as $S_{\text{in}}(d)=\iint_{\Omega_{\text{in}}(d)}d\,x_0\,dy_0$. If the barrier height satisfies $V\ge 2R$, the shadowed reflector area can be obtained by evaluating the integral over the limits $x_1=-W/2+d$ and $x_2=W/2+d$. The resulting expressions are given for the following two cases.

a) When the barrier is entirely within the reflector aperture, $0\le d<R-\frac{W}{2}$:

$$S_{\text{sa}}(d)=\left[\begin{matrix}x\sqrt{R^2-x^2}\\ +R^2\arcsin\left(\dfrac{x}{R}\right)\end{matrix}\right]_{-\frac{W}{2}+d}^{\frac{W}{2}+d}, \qquad (4)$$

b) When the right edge of the barrier extends beyond the reflector aperture, $R-\frac{W}{2}\le d<R+\frac{W}{2}$:

$$S_{\text{sa}}(d)=\frac{\pi R^2}{2}-\left[\begin{matrix}\left(-\dfrac{W}{2}+d\right)\sqrt{R^2-\left(-\dfrac{W}{2}+d\right)^2}\\ +R^2\arcsin\left(\dfrac{-\frac{W}{2}+d}{R}\right)\end{matrix}\right]. \qquad (5)$$

The active surface in the reflector aperture plane is therefore given by:

$$S_{\text{in}}(d)=\pi R^2-S_{\text{sa}}(d), \qquad (6)$$

The rays passing through S_{in}impinge on the paraboloid surface at the point $M(x_0,y_0,z_M)$, where $z_M=(x_0^2+y_0^2)/4z_F$. After reflection, the rays propagate toward the focus $F(0,0,z_F)$ along a straight line whose parametric form is:

$$x(z)=x_0\cdot\frac{z_F-z}{z_F-z_M},\ y(z)=y_0\cdot\frac{z_F-z}{z_F-z_M}. \qquad (7)$$

The reflected ray passes through the acoustic barrier plane $z_p=z_F-h$ at the point (x_p,y_p), where:

$$\begin{aligned}x_p&=x_0\cdot\frac{4z_Fh}{4z_F^2-\left(x_0^2+y_0^2\right)},\\ y_p&=y_0\cdot\frac{4z_Fh}{4z_F^2-\left(x_0^2+y_0^2\right)}\end{aligned}. \qquad (8)$$

After reflection from the paraboloid surface at point M, the acoustic ray can either reach the focus F or hit the rear surface of the acoustic barrier and, consequently, be blocked from reaching the focus.

For the reflected acoustic ray to avoid hitting the rear surface of the acoustic barrier and reach the focus, the coordinates (x_p,y_p) must satisfy the condition for missing the rectangular region $P(d)$. The acoustic ray passes freely if at least one of the following logical conditions is satisfied: a) $x_p(x_0,y_0)<-W/2+d$, b) $x_p(x_0,y_0)>W/2+d$, or c) $|y_p(x_0,y_0)|>V/2$. The set of all rays with entrance coordinates (x_0,y_0) that satisfy both conditions: a) free passage through the aperture and b) missing the acoustic barrier after reflection, forms the effective region ($\Omega_{\text{eff}}(d)$) in the aperture plane. The effective area in the aperture plane from which the rays reach the microphone after reflection is defined as:

$$S_{\text{eff}}(d)=\iint_{\Omega_{\text{eff}}(d)}d\,x_0\,dy_0. \qquad (9)$$

The reflector surface from which the acoustic wave reaches the focus is given by:

$$S_{\text{r}}(d)=\iint_{\Omega_{\text{eff}}(d)}\sqrt{1+\frac{x_0^2+y_0^2}{4z_F^2}}\,dy_0\,dx_0. \qquad (10)$$

The effect of the translational displacement of the $W\times V$ acoustic barrier

by (d) along the x-axis on the incident area is:

$$S_{\text{in}}(d) = \begin{cases} \pi R^2 - \left[F\left(\frac{W}{2}+d\right) - F\left(-\frac{W}{2}+d\right)\right], \\ \qquad\qquad 0 \le d < R - \frac{W}{2} \\ \frac{\pi R^2}{2} + F\left(-\frac{W}{2}+d\right), \\ \qquad\qquad R - \frac{W}{2} \le d < R + \frac{W}{2} \\ \pi R^2, \\ \qquad\qquad d \ge R + \frac{W}{2} \end{cases} . \quad (11)$$

The reflector surface from which the acoustic energy is focused is:

$$S_{\text{eff}}(d) = S_{\text{in}}(d) - S_{\text{sa}}(d), \quad (12)$$

The efficiency of the reflector in the presence of the acoustic barrier is defined as the ratio of the effective area in the aperture plane to the total aperture area. It is therefore given by:

$$\eta_S(d) = \frac{S_{\text{eff}}(d)}{\pi R^2}. \quad (13)$$

Thus, $\eta_S(d)$ represents the fraction of the total aperture area that contributes to the acoustic energy reaching the focus after accounting for the blocking effect of the acoustic barrier.

EXPERIMENTAL RESULTS AND ANALYSIS

For the practical verification of the effect of a movable acoustic barrier on the efficiency of a parabolic acoustic reflector, an experiment was conducted. The experiment was performed using the acoustic reflectors located in the courtyard of the Academy of Technical and Educational Studies in Niš, Serbia (Fig. 3).



Fig. 3. *Acoustic reflectors (Refl. 1 and Refl. 2) in the courtyard of the Academy of Technical and Educational Studies in Niš, Serbia*

The acoustic reflectors Refl. 1, shown as the left reflector in Fig. 3, and Refl. 2, shown as the right reflector in Fig. 3, are acoustically coupled, as they are positioned on the same z-axis. The effect of the movable acoustic barrier was analyzed using Refl. 2. The reflectors have identical dimensions: a) depth $H = 0.3571$ m, b) aperture radius $R = 1$ m, and c) focal length $z_F = 0.7$ m. The distance between the reflector vertices is $l = 23$ m.

Experiment

The experiment was conducted according to the following procedure.

a) A sweep signal was emitted from the focus of Refl. 1, and the acoustic impulse responses were measured at the focus of Refl. 2.

b) The acoustic barrier was displaced by a distance d along the x-axis, and the acoustic impulse response was measured for each position of the acoustic barrier.

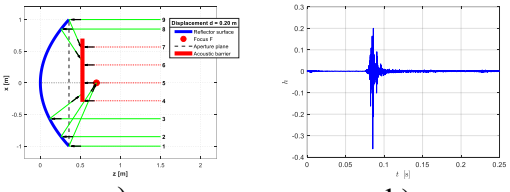
c) For each position of the acoustic barrier, the energy of the measured acoustic impulse response at the focus of Refl. 2 was calculated as:

$$E(d) = \sum_{n=0}^{N_h} h^2[n,d], \quad (14)$$

where $h[n,d]$ is the measured acoustic impulse response for the acoustic-barrier displacement d, and N_h is the number of samples considered in the impulse response. Thus, $E(d)$ represents the energy measured at the focus as a function of the acoustic-barrier displacement.

Results

Fig. 4.a shows the acoustic reflector and the acoustic barrier for $d = 0.2$ m. The corresponding acoustic impulse response h is shown in Fig. 4.b.



a) b)

Fig. 4. *a) Position of the acoustic barrier relative to the acoustic reflector for $d = 0.2$ m; b) corresponding acoustic impulse response.*

The variation of the incident surface area in the reflector aperture plane, $S_{\text{in}}(d)$, defined by (11), the effective reflector surface area, $S_{\text{eff}}(d)$, defined by (12), the reflector surface area from which the reflected acoustic wave reaches the focus, $S_{\text{r}}(d)$, defined by (10), and the acoustic-barrier surface areas associated with the front and back sides, $S_{\text{Front}}^{AB}(d)$ and $S_{\text{Back}}^{AB}(d)$, respectively, is presented in Fig. 5 as a function of the acoustic-barrier displacement d. The efficiency of the parabolic acoustic reflector, η_S, in the presence of the acoustic barrier, as a function of the displacement d, defined by (13), is shown in Fig. 6. The experimentally determined energy at the focus, $E_F(d)$, defined by Eq. (14), is shown in Fig. 7 as a function of the barrier displacement d.

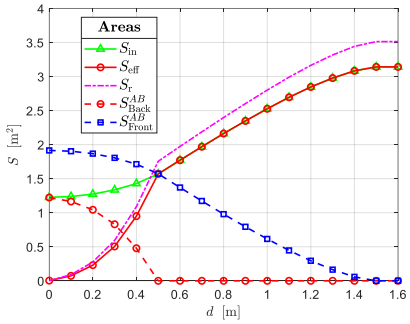


Fig. 5. *Reflector surface areas associated with the focusing process as functions of the acoustic-barrier displacement d.*

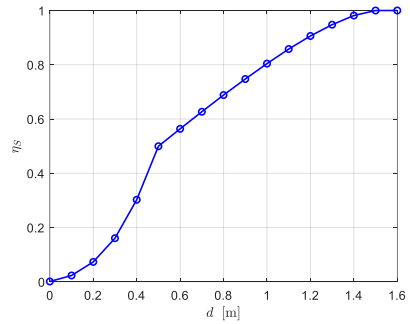


Fig. 6. *Efficiency of the parabolic acoustic reflector in the presence of the acoustic barrier as a function of the acoustic-barrier displacement d.*

The dependence of the energy measures $E_F(d)$ (energy measured at the focus after reflection from the effective reflector surface $S_{\text{eff}}(d)$), $E_{\text{eff}}(d)$ (energy incident on the effective reflector surface $S_{\text{eff}}(d)$), $E_{\text{Front}}^{\text{AB}}(d)$ (energy reflected from the front side of the acoustic barrier), and $E_{\text{Back}}^{\text{AB}}(d)$ (energy reflected from the back side of the acoustic barrier) on the acoustic-barrier displacement d is shown in Fig. 8. The mean values of the energy components over the considered range of acoustic-barrier displacement, $0 \le d \le 1.6$ m, are $E_F(d) = 0.0018$, $E_{\text{eff}}(d) = 0.0020$, $E_{\text{Front}}^{\text{AB}}(d) = 9.0222 \times 10^{-4}$, and $E_{\text{Back}}^{\text{AB}}(d) = 2.0147 \times 10^{-4}$.

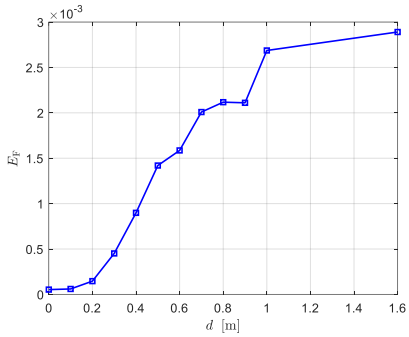


Fig. 7. *Dependence of the acoustic impulse response energy measure at the focus, $E_F(d)$, on the acoustic-barrier displacement d.*

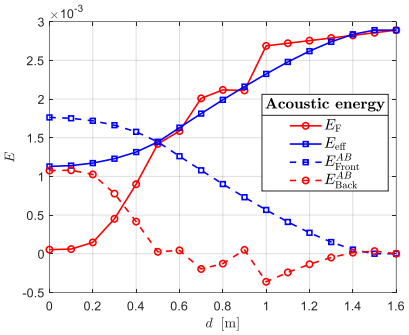


Fig. 8. *Dependence of the energy measures $E_F(d)$, $E_{eff}(d)$, $E_{Front}^{AB}(d)$, and $E_{Back}^{AB}(d)$ on the acoustic-barrier displacement d.*

Analysis of the Results

Based on the results presented in Figs. 5–8, the effect of the acoustic barrier displacement d on the energy-focusing efficiency of the parabolic acoustic reflector can be analyzed, depending on the displacement, in two distinct regions:

a) $0 \le d \le 0.5$ m – The efficiency is affected by both the front absorbing surface $S_{\text{Front}}^{\text{AB}}(d)$ and the back absorbing surface $S_{\text{Back}}^{\text{AB}}(d)$ of the acoustic barrier. At small

displacement values, $d \leq 0.2$ m, both surfaces have a significant effect on the energy loss ($S_{\mathrm{Back}}^{AB} \leq 1.0434$ m^2, $E_{\mathrm{Back}}^{\mathrm{AB}} \leq 0.001$, $S_{\mathrm{Front}}^{AB} \leq 1.8679$ m^2, $E_{\mathrm{Front}}^{\mathrm{AB}} \leq 0.0017$, $E_F \leq 0.0001$), resulting in a very low reflector efficiency, $\eta_S \leq 0.0733$. At the end of this range, $d = 0.5$ m, the effect of the back surface decreases sharply, while the front surface of the acoustic barrier becomes dominant ($S_{\mathrm{Back}}^{AB} = 0$ m^2, $E_{\mathrm{Back}}^{\mathrm{AB}} = 0$, $S_{\mathrm{Front}}^{AB} = 1.5718$ m^2, $E_{\mathrm{Front}}^{\mathrm{AB}} = 0.0014$, $E_F = 0.0014$, $\eta_S = 0.4997$). Within this displacement range, the theoretical values and experimental measurements are in very good agreement, as shown in Figs. 5 and 8.

b) $0.5 \leq d \leq 1.6$ m – In this range, the reflector efficiency is no longer affected by the back surface of the acoustic barrier, but exclusively by its front surface, which prevents acoustic energy from reaching the reflecting surface. As d increases, the reflector efficiency also increases, reaching $\eta_S = 1$ at the upper limit of the range, $d = 1.6$ m, for which $S_{\mathrm{Back}}^{\mathrm{AB}} = 0$ m^2, $E_{\mathrm{Back}}^{\mathrm{AB}} = 0$, $S_{\mathrm{Front}}^{\mathrm{AB}} = 0$ m^2, $E_{\mathrm{Front}}^{\mathrm{AB}} = 0$, and $E_F = 0.0029$, $\eta_{\mathrm{S}} = 1$. In this range, a discrepancy occurs between the theoretical values and those obtained from measurements of the acoustic impulse response. In particular, $E_{\mathrm{Back}}^{\mathrm{AB}} \neq 0$, which can be attributed to the ambient acoustic conditions. The courtyard of the Academy is surrounded by buildings, which contributes to increased sound reflections, as well as to measurement uncertainties.

The presented experimental results and their analysis indicate that, when assessing the effect of a movable acoustic barrier on the efficiency of parabolic acoustic reflectors, both the effect of the front surface of the acoustic barrier, which prevents the acoustic wave from reaching the reflecting surface, and the effect of the back surface, which prevents the reflected wave from reaching the focus, should be considered.

CONCLUSION

The experimental results demonstrate that the displacement of an acoustic barrier has a significant effect on the energy-focusing efficiency of a parabolic acoustic reflector. Two displacement regions were identified. For small displacements, both the front and back surfaces of the acoustic barrier contribute to energy losses and consequently reduce the reflector efficiency. With increasing displacement, the effect of the back surface decreases, while the front surface becomes the dominant factor limiting the energy reaching the reflecting surface. For sufficiently large displacements, the acoustic barrier no longer affects the reflector efficiency, and the theoretical and experimental results converge toward the unobstructed-reflector condition.

The results also show that, in addition to the effect of the front surface of the acoustic barrier, its back surface should be considered when analyzing the influence of a movable acoustic barrier on the energy-focusing efficiency of parabolic acoustic reflectors.

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