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Farid G Mitri, Zine El Abiddine E.A. Fellah, Jean-Yves Chapelon. Acoustic backscattering form-function of absorbing cylinder targets. Journal of the Acoustical Society of America, 2004, 115 (4), pp.1411-1413. 10.1121/1.1649332 . hal-00105757

HAL Id: hal-00105757

<https://hal.science/hal-00105757>

Submitted on 20 Jun 2022

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Acoustic backscattering form function of absorbing cylinder targets (L)

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A new expression of the backscattering form function $|f_\infty(k_0 a, \theta)|$ for cylindrical targets, suspended in an inviscid fluid in a plane incident sound field, is presented. The theory is modified to include the effects of absorption of shear and compressional waves in viscoelastic materials. The numerical results presented show how damping effect due to ultrasound absorption influences the cylinder's material properties.

I. INTRODUCTION

Echo reflected from spherical and cylindrical targets has been the subject of many theoretical (Faran, 1951; Hickling, 1962) and experimental (Hampton *et al.*, 1961; Neubauer *et al.*, 1974; Dragonette *et al.*, 1974) investigations. Dardy *et al.* (1977) computed the normalized steady-state reflected pressure or form function $|f_\infty(k_0 a, \theta)|$ for aluminum cylinder that is quite in agreement with his experimental measurements.

However, the theory as it stands may not be applicable to absorbing materials such as lead, rubber, and polymeric materials, since it does not include induced loss effects due to shear and compressional waves' absorption in the solid cylinder.

In this work, a new expression of the scattered far-field form function is proposed and the theory is modified in order to calculate sound reflection from absorbing cylinders at normal incidence. This study follows the work done by Schuetz and Neubauer (1977), who calculated in a different way the far-field form function for aluminum and lucite cylinders. Here, a wide frequency range is explored and a systematic comparison with the backscattering form functions' curves for three viscoelastic materials (lucite, phenolic polymer, and polyethylene) is given with emphasis on the effect of absorption. The case of a lucite cylinder immersed in a high-density fluid is also discussed. It is difficult to include all types of absorption in solids since all the mechanisms involved are frequency dependent. In this analysis, the absorption of sound was considered of constant amplitude in function of frequency. This assumption accurately describes the behavior of many polymeric materials.

II. BACKSCATTERING FROM CYLINDRICAL TARGETS

The scattered pressure produced when an infinite elastic cylinder is placed in an incident plane acoustic field is given in the far field $r \gg a$ by (Faran, 1951)

$$P_s = P_0 \sqrt{\frac{2}{\pi k_0 r}} \sum_{n=0}^{\infty} \varepsilon_n \sin(\eta_n) \exp(i \eta_n) \cos(n \theta), \quad (1)$$

where P_s is the scattered wave measured at the field point, P_0 is the incident pressure amplitude at the position of the cylinder center in the absence of the cylinder, r and θ are the polar coordinates, k_0 is the wave number in the fluid medium, and η_n is the phase-shift angle of the n th partial wave defined below. The backscattering form function evaluated at $\theta = \pi$ is given by (Dardy *et al.*, 1977)

$$|f_\infty(x_0, \pi)| = \sqrt{\left(\frac{2r}{a}\right)} \frac{P_s}{P_0}, \quad (2)$$

where a is cylinder radius and $x_0 = k_0 a$.

The amplitude of the backscattered form function is then, from Eq. (1) and Eq. (2)

$$|f_\infty(x_0, \pi)| = \left| \frac{2}{\sqrt{\pi x_0}} \sum_{n=0}^{\infty} (-1)^n \varepsilon_n \sin(\eta_n) \exp(i \eta_n) \right|. \quad (3)$$

Absorption is included by the standard method of introducing complex wave numbers into the theory (Hasegawa *et al.*, 1977).

As given by Faran (1951), the phase-shift angle is expressed by

$$\eta_n = \tan^{-1} \left[\frac{\Delta_n(x_0)(F_n + \Lambda_n(x_0))}{F_n + \Gamma_n(x_0)} \right], \quad (4)$$

where $\Delta_n(x_0) = -[J_n(x_0)]/[Y_n(x_0)]$, with $J_n(x_0)$ and $Y_n(x_0)$ the Bessel function of the first and second kind, respectively, with order n and argument x_0 .

$$F_n = \frac{\rho_0}{\rho^*} \frac{\tilde{x}_2^2}{2} \left[\frac{A_n(\tilde{x}_1) - B_n(\tilde{x}_2)}{C_n(\tilde{x}_1) - D_n(\tilde{x}_2)} \right],$$

with ρ_0 and ρ^* the mass densities of the fluid medium and cylinder material, respectively, $\tilde{x}_1 = x_1(1 - i\gamma_1)$, $\tilde{x}_2 = x_2(1 - i\gamma_2)$, $x_1 = (\omega/c_1)a$, $x_2 = (\omega/c_2)a$, with c_1 and c_2 the velocities of longitudinal and shear waves in the cylindrical material, and γ_1 and γ_2 the normalized longitudinal and shear absorptions, respectively (Schuetz and Neubauer, 1977).

$$A_n(\tilde{x}_1) = \frac{\Lambda_n(\tilde{x}_1)}{\Lambda_n(\tilde{x}_1) + 1}; \quad B_n(\tilde{x}_2) = \frac{n^2}{\Lambda_n(\tilde{x}_2) + n^2 - \frac{1}{2}\tilde{x}_2^2};$$

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TABLE I. Material parameters used in the numerical calculations.

Material	Mass density [10^3 kg/m^3]	Compressional velocity c_1 [m/s]	Shear velocity c_2 [m/s]	Normalized longitudinal absorption γ_1	Normalized shear absorption γ_2
Lucite	1.191	2690	1340	0.0035	0.0053
Phenolic polymer	1.22	2840	1320	0.0119	0.0257
Polyethylene	0.957	2430	950	0.0073	0.022

$$C_n(\tilde{x}_1) = \frac{\Lambda_n(\tilde{x}_1) + n^2 - \frac{1}{2}\tilde{x}_2}{\Lambda_n(\tilde{x}_1) + 1};$$

$$D_n(\tilde{x}_2) = \frac{n^2(\Lambda_n(\tilde{x}_1) + 1)}{\Lambda_n(\tilde{x}_2) + n^2 - \frac{1}{2}\tilde{x}_2}, \quad (5)$$

with $\Lambda_n(\tilde{x}_i) = -[\tilde{x}_i J'_n(\tilde{x}_i)]/[J_n(\tilde{x}_i)]$; $i=0,1,2$, and $\Gamma_n(x_0) = -[x_0 Y'_n(x_0)]/[Y_n(x_0)]$; where $J'_n(x)$ and $Y'_n(x)$ are the first-order derivatives of Bessel function of the first and second kind, respectively, with order n and argument x .

III. NUMERICAL RESULTS AND DISCUSSION

The $|f_\infty(x_0, \pi)|$ relationship was evaluated numerically using Eq. (3). The results obtained by Dardy *et al.* (1977) were recalculated for an aluminum cylinder in the absence of absorption. Excellent agreement was found. The three materials' physical constants (Hartmann and Jarzynski, 1972; Hartmann, 1975) for which graphical results are shown, are listed in Table I. The fluid outside the cylinder was assumed to be water of density $\rho_0 = 1000 \text{ kg/m}^3$ in which the sound velocity is $c_0 = 1500 \text{ m/s}$. The $|f_\infty(x_0, \pi)|$ curves are plotted as function of the parameter $k_0 a$. In addition, for ease of comparison, the same scales on the graphs have been used. A large range in $k_0 a$ was investigated (i.e., $0 \leq k_0 a \leq 40$) with a step of 0.004. Notice the importance of the statement of the $k_0 a$ step used in the numerical calculations, since the resonance phenomena encountered are very sharp.

The results are given in Fig. 1, Fig. 2, and Fig. 3 for

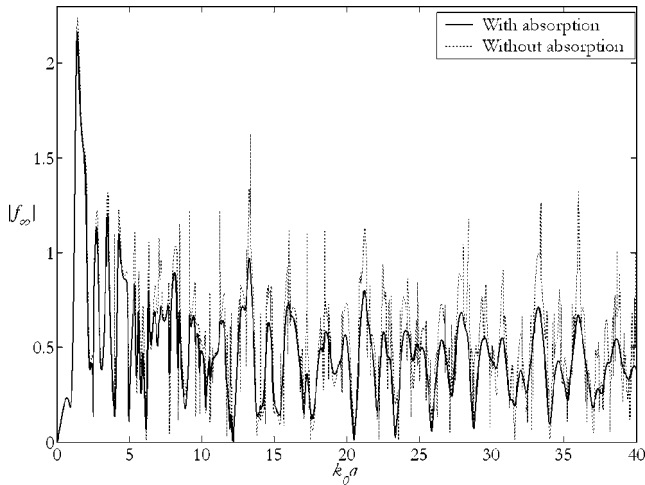


FIG. 1. Backscattering form function for a lucite cylinder immersed in water with and without the effect of absorption, respectively. One should note the damping of resonance peaks for the case of absorption.

lucite, phenolic polymer, and polyethylene cylinders, with and without the inclusion of absorption, respectively. Maxima and minima in $|f_\infty(x_0, \pi)|$ curves for these materials in the case of nonabsorption correspond to resonance frequencies of normal vibrational modes of the cylinder. As expected, the decrease in peak values in the case of absorption should undoubtedly be attributed to the damping due to ultrasound absorption by the cylinder material.

In an ingenious paper, Hefner and Marston (2000) studied the backscattering response of a lucite sphere in water using the ray approximation theory. They concluded that lucite material exhibits a large increase of low-frequency backscattering signals associated with tunneling to a subsonic Rayleigh wave. This can be verified also from the form-function curve of a lucite cylinder (Fig. 1) that elicits high backscattering amplitude at low frequency (low $k_0 a$ values). The presence of this backscattering enhancement may make lucite cylinders a potential candidate for passive sonar targets for cases where the narrow resonances may be used to advantage. Certain other polymers such as phenolic polymer and polyethylene may also be useful for this application (Fig. 2 and Fig. 3). Figure 4 shows an additional calculation of the backscattering form function for lucite cylinder immersed in a low-viscosity and high-density fluid (in this case mercury) with and without the effect of absorption. The fluid density is $\rho_{Hg} = 13\,579.04 \text{ kg/m}^3$ in which the sound velocity is $c_{Hg} = 1407 \text{ m/s}$ (at 20°C) (Wikipedia Encyclopedia, 2004). (Here, the viscosity of the fluid surrounding the cylinder is

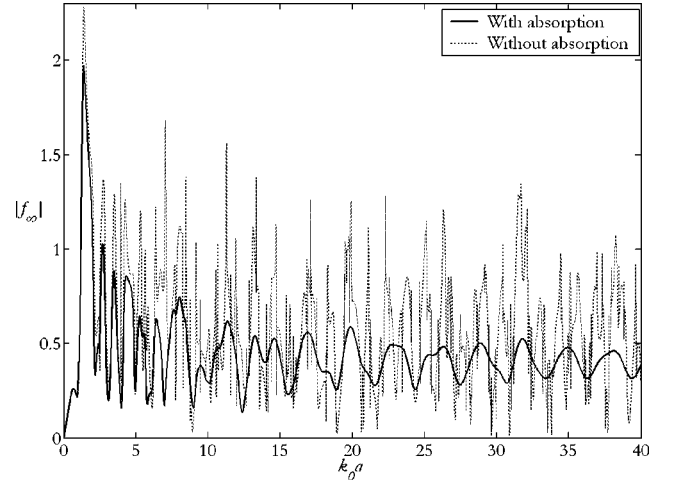


FIG. 2. Backscattering form function for a phenolic polymer cylinder immersed in water with and without the effect of absorption, respectively. The high attenuation of resonance peaks appears more clearly for this material whose absorption coefficients are greater than lucite.

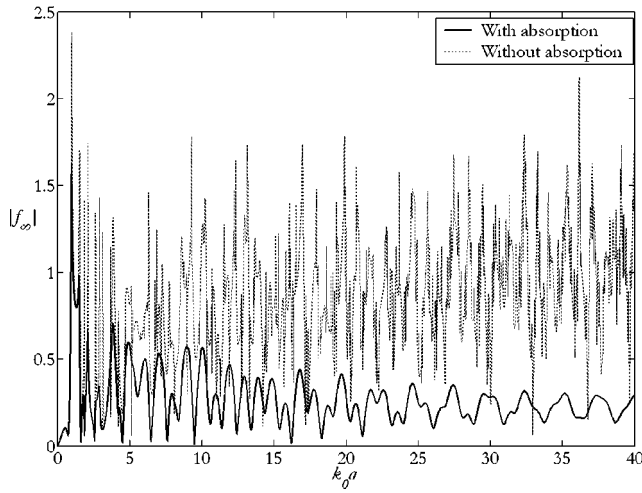


FIG. 3. Same as in Fig. 2 but for a polyethylene cylinder.

neglected.) As it was discussed by Hefner and Marston (2000), the fluid-loading effect produces interactions between various resonance modes that can have a significant effect on the frequency response of the cylinder. This is clearly observed in Fig. 4, where a “giant resonance” peak appears at low $k_0 a$ values and confirms the results of the work done on lucite spheres (Hefner and Marston, 2000).

Absorption effects upon $|f_∞(x_0, \pi)|$ curves appear more clearly in Fig. 2 and Fig. 3 for phenolic polymer and polyethylene materials whose absorption coefficients are much greater than lucite. It is a noteworthy fact that many sharp resonance peaks tends to decrease gradually versus $k_0 a$ in the nonabsorbing case. The reason for this is that the absorption of sound (or ultrasound) by the cylinder material increases at high frequency, as it is well known.

IV. CONCLUSION

A new expression of the backscattering form function of absorbing cylinder is given and its frequency dependence in a large frequency bandwidth is analyzed for polymeric materials. The numerical calculation results are presented indicating how absorption affects the frequency dependence of the scattering properties of the cylinder material. These results are of significant importance in underwater acoustics to compute backscattered sound-field intensity from absorbing cylindrical targets. Additional work must focus on extending these computations to calculate the backscattering form function for tilted absorbent cylinders.

ACKNOWLEDGMENTS

The author gratefully acknowledges the associated editor and anonymous reviewers for their helpful comments.

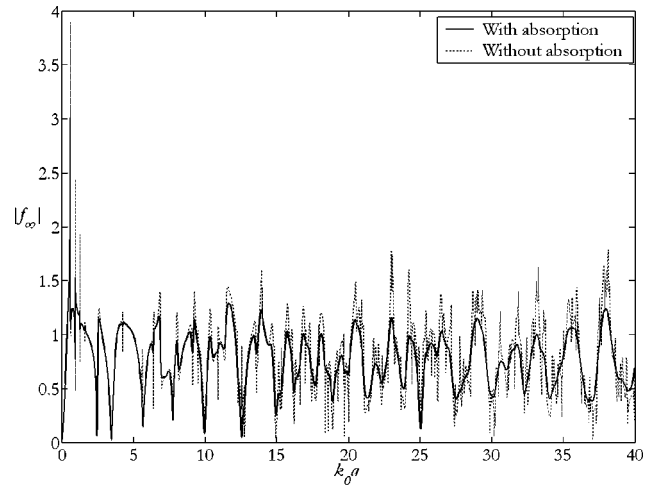


FIG. 4. Backscattering form function for a lucite cylinder immersed in a high-density fluid (mercury) with and without the effect of absorption, respectively. The high-resonance peak appears clearly at $k_0 a = 0.6$ (low frequency).

This work was supported by Grant No. 01-2-93-0314 of an RNTS project from the French Ministry of Economy, Finance and Industry.

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