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THE NEARFIELD AND FARFIELD RÉGIMES OF ROUGH SURFACE SCATTERING

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INTRODUCTION

The range dependence of the acoustic intensity scattered from a rough surface is sometimes assumed to be a continuation of that of the incident intensity and therefore follows an $(R_o + R_1)^{-2}$ law where R_o and R_1 are the distances of the source and receiver from the scattering surface. Another common assumption is that the scattered intensity reduces as $(R_oR_1)^{-2}$. If the source and receiver are coincident the round trip loss in the former case is $20 \log 2 R_o$ whereas in the latter case it is $40 \log R_o$. There is some validity for both approaches. The total intensity backscattered at normal incidence from a rough surface can be considered as the sum of two components, the coherent and the incoherent. The former is proportional to the square of the pressure, averaged with regards to phase $\langle p \rangle$, the average being over a number of realisations of the surface scattering area, and the latter is proportional to the difference between the average of the pressure squared, $\langle p^2 \rangle$, and $\langle p \rangle^2$. Assuming the incident pressure is a directional, spherically spreading wave and providing the beam pattern is not too narrow the range dependence of the coherently scattered signal is well known, in the first approximation, to be that of the image solution *[1]*. The range variation of the coherently scattered component of the signal is thus simply an extension of that of the source. Now, if the surface height deviations from the mean are small compared with the insonnifying wavelength ($h \lesssim 0.02 \lambda$ where h is the rms surface height and λ the incident wavelength) then the total backscattered intensity is mainly coherent and the range dependence will be $20 \log 2 R_o$, thus giving credence to the use of such a spreading correction factor. Alternatively, if the incoherent component dominates ($h \gtrsim 0.25 \lambda$) then in the farfield régime, the scattered signal intensity reduces as the square of the distance measured from the rough surface and therefore $40 \log R_o$ would be the required spreading factor. An additional consideration for the range dependence of the incoherent signal is the dependence of the scattering patch size on the distance of the transmitter from the rough surface *[2,3]*. The range dependence of the acoustic intensity returned from a rough surface due to the relative proportion of coherent and incoherent scattering together with the effects due to variations in the scattering patch size has been considered by a number of authors *[1-5]*. However, for values of $h \gtrsim 0.25 \lambda$ where the incoherent component dominates, the range dependence in the Fresnel region of the scattering patch is less clearly formulated and it is this region which is the specific concern of this paper.

In the present investigation attention is thus focussed upon the existence of the scattering patch nearfield and the transition from the nearfield to farfield range dependence of the ensemble average backscattered intensity at high frequencies ($h \gtrsim 0.25 \lambda$). Although some authors *[6-12]* have adopted a Fresnel phase approximation in their theoretical developments of rough surface acoustic scattering problems, few of the treatments address themselves to explicit discussion of the range dependence of the scattered intensity in what may be termed the nearfield of the scattering patch. It is this aspect of the range dependence of the backscattered intensity and its importance in the practical measurements of scattering coefficients which is of concern here. Specifically this paper considers the effect on the scattering coefficient of the range dependence of the normal incidence incoherent backscattered intensity in terms of the measurement geometry and rough surface statistics.

The scattering coefficient S is defined by the following equation *[5]*

$$S = \langle I \rangle R_o^2 R_1^2 / I_o A R_{ref}^2 \tag{1}$$

where $\langle I \rangle = \langle pp^* \rangle / 2\rho c$, p is the measured pressure and p^* its complex conjugate, ρc the specific acoustic impedance of water, $\langle \cdot \rangle$ indicates ensemble average, R_o and R_1 are the source and receiver distances respectively from the scattering surface, I_o is the source intensity at the reference distance R_{ref} (= 1 m). A is the insonnified area on the surface arbitrarily defined by the area enclosed on the surface by the intersection of the e^{-1} contour of the incident pressure beam pattern. If the backscattered intensity varies as R_1^{-2}, then this definition provides a scattering coefficient which is independent of both the range of the observation R_1 and the source range R_o, given that the insonnifying field is spherically spreading.

In this paper the discussions draw on expressions for rough surface acoustic scattering based on the Helmholtz-Kirchoff integral for the scattered pressure with the Kirchoff boundary conditions. A second order phase approximation is used and Fresnel scattering coefficient is developed which predicts the range dependence even at distances very close to the surface.

Ensemble averaged backscattered intensity measurements were taken in a laboratory water tank with the transmitting transducer at a fixed distance from a rough surface whilst an on-axis hydrophone was placed at a number of ranges from the scattering surface. Results were obtained at two frequencies using two rough boundaries. One was a pressure release surface constructed to have Gaussian statistics and the other surface consisted of the surface of graded gravel. The experimental results obtained are compared with the theoretical developments of the following section.

THEORY

To be able to predict ensemble average intensities of sound scattered from a rough surface for a range of distances from the surface, a development which uses a higher than first order phase approximation in the scattering integral is required. Such an approach has been presented by Clay and Medwin *[13]* and is based on the Helmholtz-Kirchoff integral. Recently this has been applied *[12]* successfully to the analysis of broadband normal incidence backscattering from a rough surface. In the present paper this work is drawn upon and specifically the range dependence of the scattered intensity comes under closer examination.

In reference 14 it is shown that the ensemble average intensity scattered from a rough surface, assumed to have Gaussian height statistics with an rms height h and a Gaussian autocorrelation function C, may be expressed as

$$\langle I \rangle = \frac{R^2 G^2 D^2 e^{-g}}{2\rho c (R_o + R_1)^2} + \frac{R^2 G^2 F^2 XY}{16 \rho c R_o^2 R_1^2} \frac{T_1 T_2}{\gamma^2 h^2} m(g)$$

where

$$m(g) = g e^{-g} \sum_{n=1}^{\infty} \frac{g^n}{n!} \frac{e^{-\frac{T_1^2 k^2 \alpha^2}{4(S_1 T_1^2 + n)}} \, e^{-\frac{T_2^2 k^2 \beta}{4(S_2 T_2^2 + n)}}}{(S_1 T_1^2 + n)^{\frac{1}{2}} (S_2 T_2^2 + n)^{\frac{1}{2}}} \tag{2}$$

where $G^2 = 2\rho c\, I_O R^2_{ref}$, R is the pressure reflection coefficient of the surface, D is the directivity function of the incident pressure field, k is the scalar wave number, T_1 and T_2 are orthogonal surface autocorrelation lengths and g is the roughness parameter.

$$g = (h k \gamma)^2$$
$$D = \exp\left(-\left((x^2/X^2) + (y^2/Y^2)\right)\right)$$
$$C = \exp\left(-\left((\varepsilon^2/T_1{}^2) + (\eta^2/T_2{}^2)\right)\right)$$

The geometry is shown in Figure 1 and the following geometry dependent quantities are defined

$$\alpha = \sin\theta_1 - \sin\theta_2\cos\theta_3$$
$$\beta = -\sin\theta_2\sin\theta_3$$
$$\gamma = -(\cos\theta_1 + \cos\theta_2)$$
$$F = \frac{1 + \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2\cos\theta_3}{\cos\theta_1 + \cos\theta_2}$$

The second order phase approximation is manifest in equation (2) entirely through the parameters *[14]* S_1 and S_2 where for the present case of normal incidence backscatter ($\alpha = \beta = 0$, $\gamma = 4$, $F = 1$) may be approximated by

$$S_1 = \frac{X^2k^2}{8}\left[\frac{1}{R_O} + \frac{1}{R_1}\right]^2 \qquad (3a)$$

$$S_2 = \frac{Y^2k^2}{8}\left[\frac{1}{R_O} + \frac{1}{R_1}\right]^2 \qquad (3b)$$

As the present interest is confined to cases of $g \geq 10$, the coherent term is not significant and the approximation

$$m(g) = \left(\frac{ST^2}{g} + 1\right)^{-1}; \qquad g \geq 10 \qquad (4)$$

is possible, where for simplicity the surface autocorrelation function has been assumed to be circulary symmetrical with an autocorrelation length T. For a circular transmitting transducer with an e^{-1} half-beam width of $\theta_O = W/R_O$, $W = X = Y$, the backscattering coefficient becomes

$$S = \frac{R^2}{32\pi}\,\frac{T^2}{h^2}\left[1 + \frac{T^2\theta_O^2}{32h^2}\left[1 + \frac{R_O}{R_1}\right]^2\right]^{-1} \qquad (5)$$

The scattering coefficient described by equation (5) is dependent upon the surface statistics, the reflection coefficient, the transmitter and receiver ranges from the surface and the insonnified area through θ_O.

If $(R_O/R_1) \ll (4\sqrt{2h}/T\theta_O) - 1$, the second order term reduces to unity so that the inequality may be seen as the condition for the farfield or Fraunhofer region of the insonnified area. Thus the farfield scattering coefficient is

$$S_{FF} = \frac{R^2}{32\pi}\,\frac{T^2}{h^2} \qquad (6)$$

This simple expression is a function only of the surface statistics. On moving towards the surface the scattering coefficient reduces relative to its farfield value and becomes a function of both the surface statistics and the range. When the extreme of $(R_o/R_1) \gg (4\sqrt{2h}/T\theta_o) - 1$ is true

$$S = S_{NF} = \frac{R^2}{A}\left(\frac{R_1 R_o}{R_1 + R_o}\right)^2 \qquad (7)$$

with $A = \pi\theta_o{}^2 R_o{}^2$, and may be termed the nearfield scattering coefficient. Thus in the surface nearfield, the average backscattered intensity is interestingly that expected from a plane surface, of reflection coefficient R.

In summary, discussion of the scattering coefficient as predicted by equation (5) may be divided into three range zones. Zone I is defined as the region in which the scattering coefficient is always within 1 db of S_{NF}. Similarly Zone III is defined as the region in which the scattering coefficient is always within 1 db of S_{FF}. Zone II is the region where the full expression, equation (5), for S must be used. Table 1 gives the range limits for the three zones.

The remainder of this paper describes an experimental investigation of the scattering coefficient and compares the results with theory.

SURFACES USED FOR THE ACOUSTIC BACKSCATTER MEASUREMENTS

Two rough surfaces were used in the study. Surface A was constructed with great care out of a low density polyeurethane foam to have Gaussian height statistics and a Gaussian autocorrelation function. Surface B consisted of the surface of naturally occurring gravel, sieved to restrict the particle size range. A full account of the construction and of the statistical tests on these surfaces may be found in reference 14. Table 2 summarises the parameters of the surfaces.

EXPERIMENTAL MEASUREMENTS OF THE BACKSCATTERING COEFFICIENT

A series of experiments to measure the range dependence of the scattering coefficient were conducted. Two circular transducers were employed which operated at frequencies of 250 kHz and 1 MHz. The directivity patterns of both transducers compared *[14]* well with a Gaussian form over the angular range of interest. These two transducers were used to insonnify the rough surfaces at normal incidence, from a fixed range of 150 cm.

A small cylindrical hydrophone, the Celesco LC5-2 was used to measure the backscattered signal. This was chosen because of its small dimensions, having an element of radius 0.12 cm and length 0.1 cm. A small hydrophone was required to minimise the effect the on-axis hydrophone had on the transmitted signal. Measurements were conducted with the hydrophone distance from the surface ranging from 2 cm to 144 cm. This span covered the three zones discussed in the theory section. A diagram showing the experimental arrangement is given in Figure 2.

The scattering coefficient given in equation (1) can be written as

$$S = \frac{\langle V^2\rangle R_o^2 R_1^2}{V_{ref}^2\, A\, R_{ref}^2} , \qquad (8)$$

where V is the hydrophone output due to the backscattered acoustic signal. At least thirty realisations of the backscattered signal were recorded over the surfaces to obtain $\langle V^2\rangle$. The insonnified area A is given by πW^2. $V_{ref}^2 R_{ref}^2$ is simply a constant and $V_{ref} R_{ref} = V_a R$ where V_a is proportional to the axial outgoing signal level at range R. The value for $V_{ref} R_{ref}$ was obtained experimentally by measuring the outgoing signal at increasing ranges from the transducer and calculating $\overline{(V_a R)^2}$ to obtain $V_{ref}^2 R_{ref}^2$. Specific precautions *[14]* were taken to allow for the effect of the presence of the hydrophone on the values of the incident field.

The results of the experiments are shown in the form of scattering coefficients as a function of range in Figure 3. Theoretical curves calculated using equation (5) with its farfield and nearfield approximations respectively equations (6) and (7) are compared with the measured data sets in Figure 3. The curve has been split into the three zones, I (nearfield), II (intermediate) and III (farfield) introduced in the theory section. In all three zones the experimental and theoretical values are very similar. It is interesting to note that as the surface is approached then as predicted by equation (7) the surface appears plane. As confirmation of this consider the solid circles. These are effectively measurements from a plane surface. They were obtained by removing the rough surface and taking axial pressure measurements beyond the surface position. These values were reduced by the reflection coefficient of the rough surface and thereby results were obtained as if a plane surface had replaced the rough surface. These measured values follow the nearfield curve and close to the surface are the same magnitude as those due to the backscattered signals from the rough surface. This gives credence to the concept that the rough surface appears plane in the nearfield zone. In the farfield, although there are not many measurements the scattering coefficient does appear to become constant.

The series of measurements presented here are some of the very few on range dependence which have been reported in the literature. They were taken under well controlled conditions on surfaces of known statistical paramaters. The computed curves calculated from equations developed using a Fresnel phase approximation when solving the Helmholtz-Kirchoff integral are in good agreement with the measured data over the three régimes described.

CONCLUSIONS

In summary a theoretical expression for the normal incidence backscattering coefficient as a function of range from a rough surface with Gaussian statistics has been presented and its correctness substantiated with a series of experimental measurements. The particular situation of the backscattering of a directional, spherical spreading normally incident pressure field observed with an axially placed point receiver has been discussed.

Ideally the backscattering coefficient of a rough surface should be dependent only on properties of the surface. This is shown to be true only in the farfield of the surface scattering patch. In the nearfield of the surface, the scattering coefficient becomes independent of all properties of the surface except its reflection coefficient. In a range interval between the nearfield and farfield the scattering coefficient depends on both the surface statistics and the measurement geometry. This paper has attempted to provide the necessary understanding of the range dependence of rough surface backscattering so that experimentally determined scattering coefficients may be used with confidence in calculations involving other geometries.

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ZONE	SCATTERING COEFFICIENT	RANGE LIMITS
I Near-field	$S_{NF} = \frac{R^2}{A}\left(\frac{R_1 R_o}{R_1 + R_o}\right)^2$	$R_1 \leq R_o\left[\frac{8\sigma}{\theta_o} - 1\right]^{-1}$
II Intermediate	$S = \frac{R^2}{16\pi\sigma^2}\left[1 + \frac{\theta_o^2}{16\sigma^2}\left(1 + \frac{R_o}{R_1}\right)^2\right]^{-1}$	$R_o\left[\frac{8\sigma}{\theta_o} - 1\right]^{-1} \leq R_1 \leq R_o\left[\frac{2\sigma}{\theta_o} - 1\right]^{-1}$
III Far-field	$S_{FF} = \frac{R^2}{16\pi\sigma^2}$	$R_1 \geq R_o\left[\frac{2\sigma}{\theta_o} - 1\right]^{-1}$

TABLE 1

Expressions for the normal incidence scattering coefficient which apply in the three range zones indicated.
where $\sigma^2 = 2h^2/T^2$

Surface	Reflection Coefficient R	rms Height h/cm	Correlation Length T/cm	Frequency of Measurement kHz	g	$\frac{T^2}{h^2}$
A } see ref. 12	0.93	0.22	1.9	250	21.8	74.6
A	0.93	0.22	1.9	1000	348	74.6
B	0.6	0.18	0.33	250	14.6	3.4
B	0.6	0.18	0.33	1000	233	3.4

TABLE 2

Parameters of the rough surfaces.

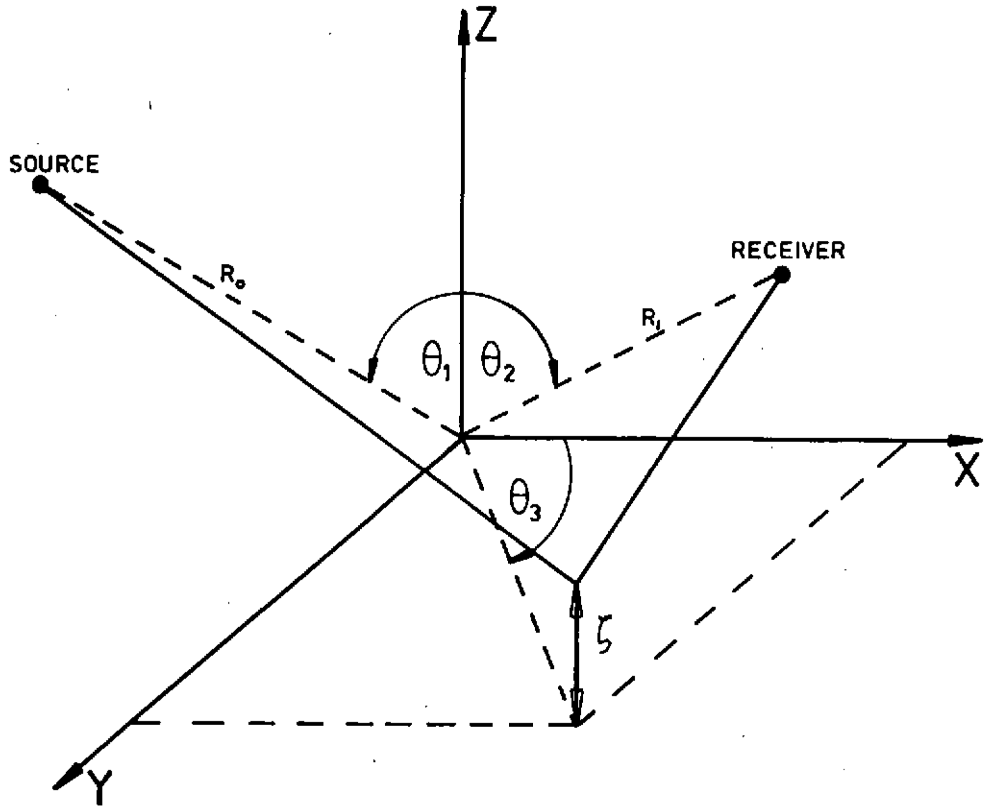

Figure 1 Geometry

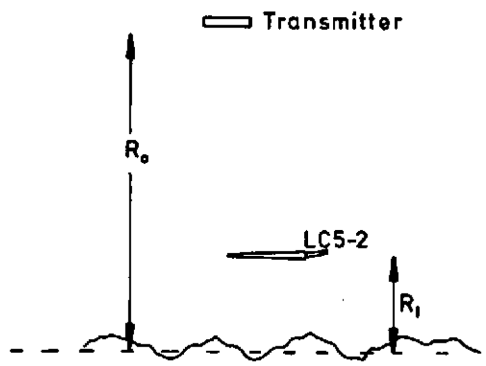

Figure 2 Experimental arrangement

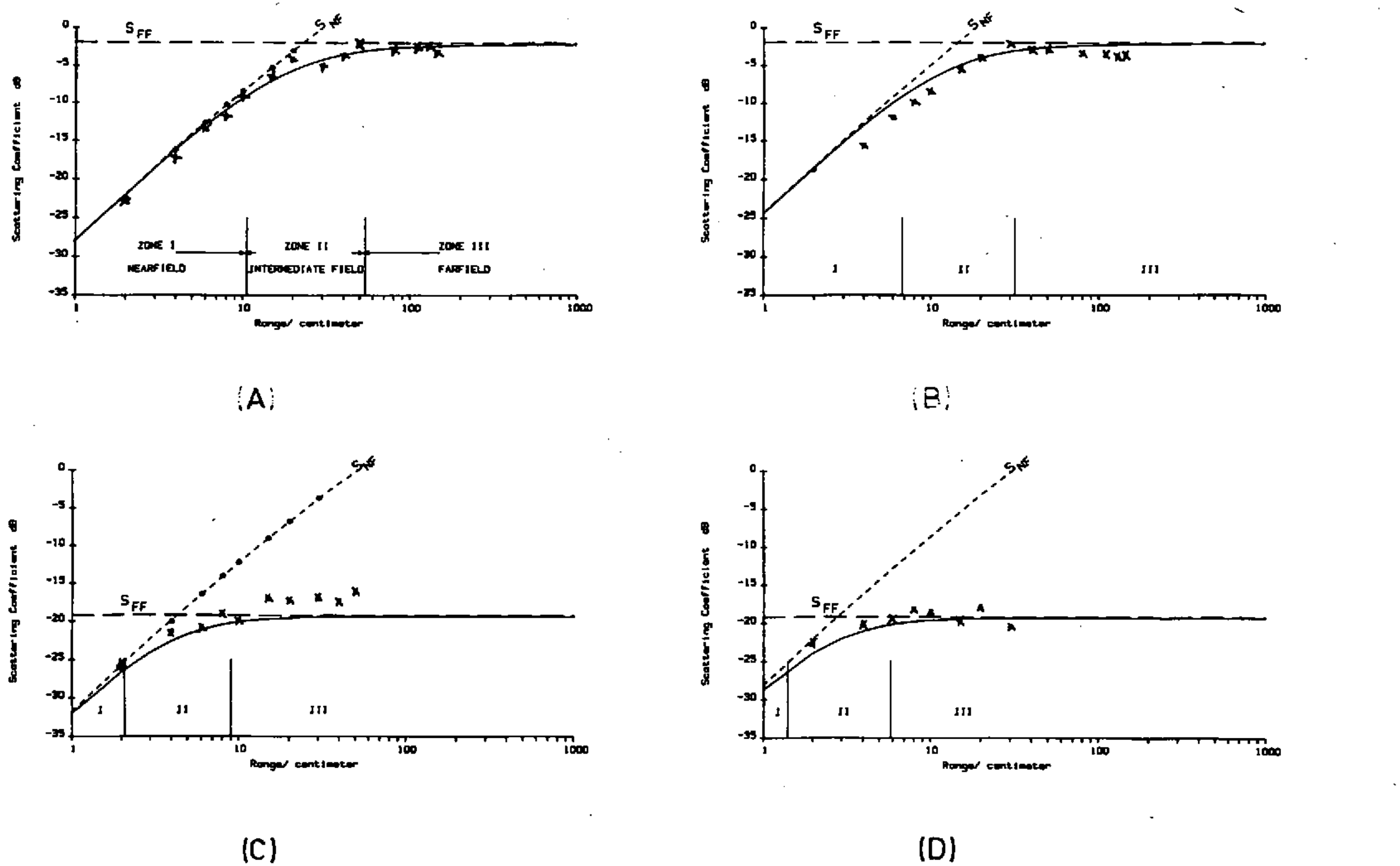

Figure 3. Scattering coefficient versus range. (A) Surface A, f = 250 kHz, w = 13 cm. (B) Surface A, f = 1 MHz, w = 8.6 cm. (C) Surface B, f = 250 kHz, w = 13 cm. (D) Surface B, f = 1 MHz, w = 8.6 cm (X) Experimental values, (●) experimental values from a plane surface (see text), (—) Equation 5, (- -) S_{NF} Equation 7, (--) S_{FF} Equation 6.