On the measurement of airborne, angular-dependent sound transmission through supercritical bars

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Abstract: The coincidence effect is manifested by maximal sound transmission at angles at which trace wave number matching occurs. Coincidence effect theory is well-defined for unbounded thin plates using plane-wave excitation. However, experimental results for finite bars are known to diverge from theory near grazing angles. Prior experimental work has focused on pulse excitation. An experimental setup has been developed to observe coincidence using continuous-wave excitation and phased-array methods. Experimental results with an aluminum bar exhibit maxima at the predicted angles, showing that coincidence is observable using continuous waves. Transmission near grazing angles is seen to diverge from infinite plate theory.

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1. Introduction

Above the critical frequency for a given plate there exists an angle, called the coincidence angle, at which the component of an incident acoustic wave number traveling parallel to the plate matches the bending wave number in the plate. (This occurs at both positive and negative angles, mirrored about normal incidence.) Maximum sound transmission exists at the coincidence angle (compared to angles below and above the coincidence angle). Since the bending wave speed is dispersive for thin plates, this angle shifts towards normal incidence as frequency increases. Additionally, if an acoustic wave is incident upon the plate at an angle other than the coincidence angle, then a traveling wave is still excited in the plate but the transmission of the sound through the plate is reduced. The angular dependence of sound transmission at a specific frequency can be useful in various applications, including using supercritical plates as angular filters for sound transmission.[1]

Bhattacharya *et al.*[2] asserted that for a finite plate, it was impossible to observe the coincidence effect in steady state without backing the plate with a cavity. This conclusion was based on previous work by Bhattacharya and Crocker[3] where they found that for a plate backed by a cavity, the coincidence effect could be observed through matching of flexural, standing waves in the plate and standing waves in the acoustic cavity. This resulted in a coincidence effect that was independent of angle, and it could only be observed at a critical frequency and subsequent discrete coincidence frequencies that corresponded with cavity modes. They made the assertion that coincidence could not be observed in finite plates in the same manner that it can be as Cremer had proposed for infinite plates. In their measurement setup, they essentially measured better transmission when the cavity or the plate was excited at a

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resonance. One of the shortcomings of their experimental setup was the use of a single microphone inside the cavity which prevented them from directly sensing angular dependent sound transmission.

Davies and Gibbs[4] suggested that the conclusions of Bhattacharya *et al.* were valid only for steady state conditions and proposed exciting the finite plate using short-duration pulse signals. Their work was based on the approach used by Raes[5] and Louden,[6] in which an impulse was measured before and after transmitting through an impedance change and the comparison of the amplitudes of the two spectra yielded the transmission properties.

Anderson *et al.*[7] used the pulse approach for finite length bars submerged in water. (A bar, in this case, has only one dimension much longer than a wavelength.) For their experiment, several transducers in a line array were mounted to an alumina bar, and the combination was rotated to various angles as sound energy impinged on the bar. Their work allowed measurement of the angular dependence of sound transmission through a bar at a specific frequency.

The literature shows a lack of experimental data that exhibit the coincidence effect using continuous waves. One purpose of using continuous waves is to obtain a better SNR at a chosen frequency. The literature also shows a lack of experimental validation of the divergence of theory from experiment at grazing angles. Better experimental results confirming this discrepancy could increase understanding of the physical phenomena, and understanding the degree of departure between theory and experiment could potentially lead to developing more appropriate theoretical equations for finite plates and bars.

The purpose of this paper is to show that coincidence is observable in a finite bar or plate using continuous waves using a measurement system similar to that of Anderson *et al.*[7] This paper will show that it is possible to observe the coincidence effect using continuous waves without backing the bar with a cavity. It also provides further evidence of the departure of theory from experiment for finite plates near grazing angles.

2. Experimental setup

The angular dependent transmission measurements described below were taken inside an anechoic chamber.[8] A turntable capable of rotating at 2.5° increments was controlled using LabVIEW. With the same LabVIEW program, data were streamed at 204 800 samples per second per channel through National Instruments PXI-4461 and 4462 cards from eight 6.35 mm (0.25 in.) GRAS type-I pre-polarized microphones. These microphones were placed in a line array mounted on the turntable with center-to-center spacing of 6.35 mm between array elements, such that the midpoint of the array at the microphone diaphragms lies on the axis of rotation.

A stationary ultrasonic source was pointed towards the center of the microphone array and synchronized to the microphone input channels. For measurements at 45 kHz, a Parasonics Corp. 4012 A ultrasonic transducer (center frequency of 40 kHz) was used. For measurements at 65 kHz, a Parasonics Corp. PAR58T ultrasonic transducer (center frequency of 58 kHz) was used. The corresponding single-frequency sine wave was created in LabVIEW with an amplitude of 5 V and sent through the PXI to control the source. The signal was also routed back into an input and recorded in order to compute transfer functions between the source signal and the microphone recordings in post processing.

To begin a measurement the turntable was rotated to −90° away from normal incidence to the array, and five 16 384-point data blocks were recorded. For each block, the source signal was a single-frequency sine wave that started and stopped in the 16 384 point data set. The turntable was then rotated 2.5° towards normal incidence, and five more blocks were recorded. This same operation was performed at each 2.5° increment, through normal incidence, to +90°. In order to obtain a transmission measurement, the entire process was repeated with an aluminum bar in front of the array, and the without-bar and with-bar measurements were compared.

For each microphone, at each rotation angle, the five recorded blocks of data were analyzed with MATLAB. The beginning of each time signal, including the time of flight and transient portion of the sound from the source, was removed in order to ensure analysis of only the steady state portion of the microphone signals. The resultant blocks were then windowed using a Hanning window. In order to reduce the effect of noise in the signals and to average out variations in magnitude and phase between blocks, the windowed blocks were summed together in the time domain. A fast Fourier transform (FFT) of each summed microphone signal was taken, and the (complex) value at the source frequency was extracted. The transfer function, H_n, between this value and the corresponding value from the source signal was calculated as

$$H_n = \frac{a^* b_n}{a^* a}, \tag{1}$$

where a is the value of the FFT from the source signal, b_n is the value from the nth microphone channel, and * denotes a complex conjugate. The magnitude and phase of H_n were used in the beam forming process for the nth microphone at each angle. Performing these operations for each rotation angle gave the magnitude and phase of each microphone as a function of rotation angle.

The extracted magnitudes and phases were then added together to compute the directivity of the array, $D_{f,\theta_0}(\theta)$, as a function of rotation angle, θ, using the equation

$$D_{f,\theta_0}(\theta) = \sum\nolimits_n A_{f,\theta_0,n}(\theta) e^{j\phi f,\theta_0,n(\theta)} e^{j\omega\delta_n}, \tag{2}$$

where $A_{f,\theta_0,n}$ is the extracted magnitude from the FFT of the nth microphone signal, $\phi_{f,\theta_0,n}$ is the extracted phase, and

$$\delta_n = nd \sin\theta_0 / c \tag{3}$$

is the time delay associated with steering an array of spacing, d, to a steer angle of θ_0. This equation is associated with standard beam forming.[9–13]

During the data processing, θ_0 was set equal to the rotation angle of the turntable so that the main lobe of the array pattern was directed towards the source. This caused the array to be most sensitive to the direct transmission path rather than other paths (to reduce diffraction and grating lobes in the plane of the array). Further, beam forming allowed for separation of the two traveling waves which make up the standing wave in the bar that results from steady-state excitation. The magnitude of the steered pattern was extracted at the steer angle (the main lobe peak of the array) for both the with-bar and without-bar cases, and 20 times the logarithm of the ratio of the two was recorded as the transmission, $T(\theta)$, at that rotation angle. The transmission as a function of angle was compiled by calculating this ratio for each rotation angle.

One experimental difficulty is in creating incident plane waves on the bar. For the experimental setup described here, the ultrasonic sources were placed 90 cm ($kr = 742$ at 45 kHz and $r = 0.9$ m $> a = 0.02$ m, where r is the distance between the source and the center of the array and a is the radius of the source) from the center of the array. This meant that the bar and microphone array were in the acoustic and geometric far field of the source ($kr \gg 1$ and $r \gg a$, respectively), providing a locally planar wave incident on the bar. To further ensure plane waves, the beam forming of the array and smaller bar size limits the range of wave numbers incident upon the bar, as does increasing the distance between the source and the bar.

Another difficulty is diffraction around the bar. While the use of beam forming can help reduce the sensitivity to diffracted waves in the plane of the array, it is still necessary to attenuate them using a baffle or blocker of some kind, especially for diffraction paths not in the plane of the array (over the top, for example). For the case without the bar, the path from the source to the microphones was unimpeded. For the with-bar case, the bar was mounted to a 53 cm by 46 cm by 9 cm foam baffle using duct tape so that the portion exposed to the array was 2 cm by 13 cm. This baffle supported the bar in the desired location and was found to significantly reduce diffraction, while still allowing incident sound energy to transmit through the bar. The effect of the duct tape on the amplitude and reflection of traveling waves in the exposed portion of the bar is unknown, but it likely increases the effective damping loss factor for the bar (thus decreasing the sound transmission at the coincidence angles). Further investigations into other methods of securing the bar and reducing diffraction would be necessary to fully understand the influence of boundary conditions on measuring the transmission through bars.

Anderson *et al.*[7] found that it was possible to steer a beam from an array of transducers through a supercritical bar in the near field. They suggested that the array standoff distance be small. The chosen standoff distance here was 5 mm. Further investigations could also determine the influence of standoff distance on the experimental transmission results.

For the results given in Sec. 3, a 3.8 cm by 40.6 cm aluminum bar with a thickness of 0.5 mm, was used. This bar width was determined through experimentation in order to significantly reduce the waves traveling in the direction perpendicular to the array while still exhibiting coincidence in the parallel direction. Theory suggests that the width of the bar/plate should have no direct effect on the observation of coincidence, assuming a plane wave incident in the direction perpendicular to the bar/plate's width dimension. A larger plate appears to suffer from severe interference fluctuations likely due to traveling waves in the perpendicular direction to the array. A picture of the final experimental setup, without the bar and with the bar, showing the sources, bar, foam baffle, array, and turntable in the anechoic chamber, is given in Fig. 1.

A measurement was taken to determine whether the results were contaminated by the noise floor. The noise floor of the entire system was 9 dB on average, and the main lobe of the without-bar, steered array directivities was above 90 dB for each rotation angle. This suggests that the measurement system is capable of measuring transmission levels down to approximately −81 dB.

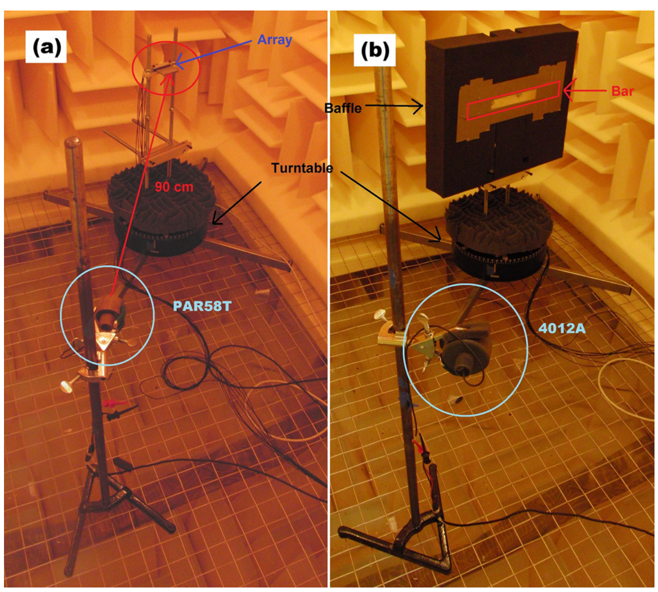

Fig. 1. (Color online) Photographs of the experimental setup (a) without the bar with the 65 kHz source and (b) with the bar, foam baffle, and 45 kHz source.

3. Results and discussion

Figure 2 shows the comparison of theoretical transmission curves and experimental results of the extracted main lobe values as a function of rotation angle. The theoretical equation used for transmission as a function of angle is Eq. (5.38a) in Ref. 14,

$$\tau(\theta) = \frac{(2\rho_0 c \sec\theta)^2}{[2\rho_0 c \sec\theta + (D/\omega)\eta k^4 \sin^4\theta]^2 + [\omega m - (D/\omega)k^4 \sin^4\theta]^2}. \tag{4}$$

The numerator and the first term in the denominator represent the sum of the fluid loading on the transmitted and incident sides, dependent on the density of the fluid, ρ_0, the speed of sound in the fluid, c, and the angle of incidence, θ, measured from the normal to the surface of the plate. The second term in the denominator is governed by the damping in the plate, with dependence on the loss factor, η, of the plate, the bending stiffness of the plate, D, the angular frequency, ω, and the acoustic wave number, k. The third and fourth terms are governed by the mass of the plate and the stiffness of the plate, respectively. The mass per unit area, m, and the bending stiffness are defined as

$$m = \rho h, \tag{5}$$

and

$$D = \frac{Eh^3}{12(1-\sigma^2)}, \tag{6}$$

respectively, where ρ is the density of the plate material, h is the thickness of the plate, E is Young's modulus, and σ is Poisson's ratio. The plots in Fig. 2 are shown on a dB scale.

The experimental data show coincidence near the angles predicted from the theoretical equation. For 45 kHz, the peak levels are 34 and 28 dB below the theoretical peak values. For 65 kHz, the peaks are reduced by 32 and 27 dB. The main cause of this disagreement is likely poor angular resolution, meaning that the coincidence peaks do not line up exactly with a measurement point.

Another cause of this reduction could result from the duct tape effectively increasing the damping loss factor in the bar. Further, small non-uniformities in the bar could prevent pure bending waves from being excited. The theory in Fig. 2 assumes no damping ($\eta = 0$) whereas a value of $\eta = 0.07$ matches date fairly well.

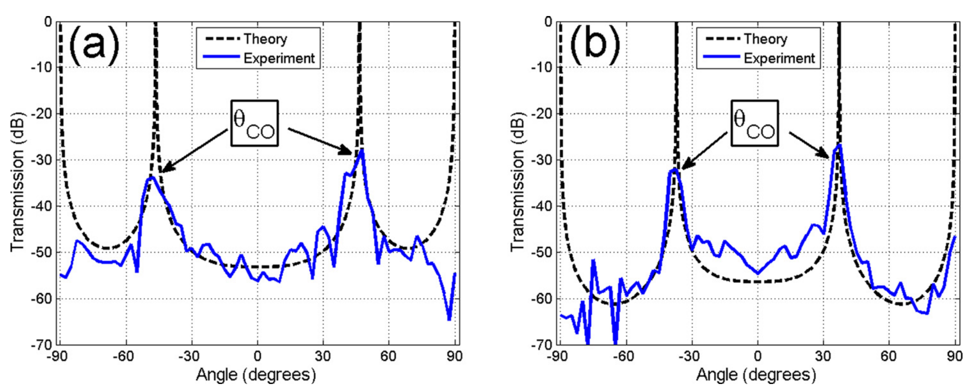

Fig. 2. (Color online) Undamped theory and experimental data for transmission through the 0.5-mm aluminum bar versus angle (a) at 45 kHz and (b) at 65 kHz.

The 45 kHz data also show agreement with a root mean square error of 2.8 dB in the mass law region (between $-30°$ and $+30°$). The transmission at grazing incidence is an average of 54.7 dB less than the perfect transmission predicted by theory. For 65 kHz, the root mean square error in the mass law region is 5.7 dB, and the average reduction at grazing angles is 54 dB.

Through these measurements and ones at other frequencies,[15] we have thus found that coincidence does not occur only at specific frequencies for continuous wave excitation of finite bars not backed by a cavity, contrary to the findings of Bhattacharya *et al.* [5]

The authors acknowledge that the measurement conducted could be considered an insertion loss measurement rather than a transmission measurement. The acoustic interaction of the receivers with the specimen could potentially participate in reducing the quantitative accuracy of the measurements, but the data show close agreement in the mass law region and generally follow the theoretical curve for transmission.

4. Conclusions

An experimental setup has been developed to measure the angular dependence of airborne sound transmission through thin bars. The coincidence effect has been shown to be observable in finite bars with no cavity backing. Coincidence has also been observed using continuous waves, i.e., in steady state, contrary to assertions made by others. Finally, further experimental evidence has been given to suggest that the theory for transmission near grazing angles of incidence does not match experimental findings with departures on the order of 50 dB.

The use of a cavity to observe coincidence in finite plates described by Bhattacharya *et al.*[5] is shown to be unnecessary when using an array of microphones. The matching of propagating flexural wave numbers to propagating acoustic wave numbers is possible in finite bars, even when using continuous wave excitation. This wave number matching is the basis for the standard coincidence effect predicted for infinite plates.

Transmission near grazing angles has also been addressed. Experimental data further verify that theory for infinite plates and experimental results for finite bars diverge at angles near grazing incidence. The implication of this result merits further investigation.

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