Loudspeaker line array educational demonstration

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This paper presents a physical demonstration of an audio-range line array used to teach interference of multiple sources in a classroom or laboratory exercise setting. Software has been developed that permits real-time control and steering of the array. The graphical interface permits a user to vary the frequency, the angular response by phase shading, and reduce sidelobes through amplitude shading. An inexpensive, eight-element loudspeaker array has been constructed to test the control program. Directivity measurements of this array in an anechoic chamber and in a large classroom are presented. These measurements have good agreement with theoretical directivity predictions, thereby allowing its use as a quantitative learning tool for advanced students as well as a qualitative demonstration of arrays in other settings. Portions of this paper are directed toward educators who may wish to implement a similar demonstration for their advanced undergraduate or graduate level course in acoustics. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3676723]

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I. INTRODUCTION

In student learning of acoustical principles, physical demonstrations can be a key element. Learning at any level may be reinforced and enhanced if the demonstration is made interactive or quantitative in nature (e.g., Interactive Lecture Demonstrations[1] in physics courses), which allows the student the opportunity to explore the application of concept, mathematics, and physical reality. Although a larger body of acoustics demonstration literature exists in the physics education community, some demonstration-related articles have been published previously in this journal. They include an apparatus designed to study the response curve of a tuning fork,[2] a cochlear analog,[3] visualization techniques to illustrate scattering from spheres,[4] and outreach activities appropriate for elementary school kids.[5] Recently, Genis and Zagorski[6] described their development of ultrasonics-related laboratory exercises and Gardner *et al.*[7] reported on a mathematical model and experiments related to the Rubens flame tube demonstration.

When teaching the concepts and mathematics of multiple source interference (i.e., a line array), a physical demonstration is especially helpful. Because the highly directional sound that results from line arrays is not part of the everyday experience for the average student, a demonstration that incorporates both audible and visual elements is particularly useful. With the demonstration, the myriad applications of phased arrays can be better discussed as a class. As examples, sound navigation and ranging (SONAR) related uses include the tracking of enemy submarines, location of mines, profiling the ocean floor, or tracking aquatic animals. Biomedical applications include prenatal ultrasonic imaging, acoustic lithotripsy to destroy kidney stones, or for ultrasonic therapeutic applications. Audio-band line arrays are also commonly employed at the local arena or auditorium for directional sound reinforcement. A classroom demonstration of a line array should enhance students' understanding of both the theory and practical uses of arrays in these applications.

Some array demonstrations have been described previously. Meiners[8] reported the idea of manually rotating a pair of in-phase or out-of-phase loudspeakers in a classroom setting to demonstrate the interference effects as regions of constructive and destructive interference pass by a listener's ears. (We have demonstrated this interference phenomenon for students using two loudspeakers by sweeping through frequency for a fixed loudspeaker separation and then varying separation distance for a fixed frequency.) Tucholski[9] recently presented an inexpensive ultrasonic array alternative that would allow a small group of students to measure the directivity patterns in a classroom laboratory exercise. The angular response of the array was controlled by manual rotation, although phase shading was mentioned as a possibility. Ultrasonic frequencies were used to eliminate the annoyance of the pure tone signals.

This paper discusses the development of an audio-range line array demonstration with real-time control capability for classroom or laboratory-exercise use. In it, we review source interference and coupling phenomena as taught in advanced undergraduate or graduate settings and discuss the demonstration and some of its possible uses.

II. REVIEW OF LINE ARRAY THEORY

Line array theory is widely developed and taught.[10–14] A brief overview of line array theory will now be given.

We first assume a line array made up of sources that are very small with all portions of each source vibrating in phase. We consider a source to be small when the radius of the source (or a characteristic/average radius of an object that is not spherical), a, is much smaller than an acoustic wavelength, λ, mathematically written as $a \ll \lambda$, or more

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often written as $ka \ll 1$, where $k = 2\pi/\lambda$ (we consider the added 2π factor to not change this relationship). Sources that fit into this category are referred to as simple sources. One property of a simple source is that its radiation is independent of angle, termed omnidirectional.

The pressure, p_0, at a distance r, from a simple source located at the origin can then be described by

$$p_0(r,t) = \frac{A}{r} e^{j(\omega t - kr)}, \tag{1}$$

where a time-harmonic, or steady-state, dependence has been assumed, and where $A = P_0 R_0$ is point source amplitude (the pressure amplitude, P_0, is a calibration pressure measured at a calibration distance, R_0), j is the complex number $\sqrt{-1}$, ω is the angular frequency, and k is the acoustic wave number. A discrete line array is then a line segment of these equally spaced simple sources. Figure 1 gives an illustration of the array and its geometry, where the slanted arrows point off in the direction of the field point where the pressure is evaluated. The total angular dependent pressure field, p_{total}, of the array (in the plane of the array depicted by Fig. 1) is determined by summing the pressure fields due to each individual array element, i, that is

$$p_{\text{total}}(r,t) = e^{j\omega t} \sum_{i=-N/2}^{N/2} \frac{A_i}{r_i} e^{-jkr_i}, \tag{2}$$

where N is the total number of array elements.

The far-field assumption for arrays, $r \gg d$, where d is the distance between adjacent elements, allows the approximation to be made that the distances between each array element and the field point, r_i, are equal to each other for the amplitude dependence, $1/r_i = 1/r, \forall r_i$. The slight differences in these distances cannot be ignored in determining the overall phase at the field point. Here, $kr_i \approx k\{r + [i - (1/2)\text{sign}(i)]d \sin\theta\}$, where $\text{sign}(i)$ gives -1, 0, or 1 depending on whether i is negative, zero, or positive, respectively. It may thus be assumed that the phase of the wave front produced by each element at the field point, ϕ, differs by a constant amount for adjacent elements

$$\phi = kd \sin\theta, \tag{3}$$

where θ is the angle of the field point with respect to the line running perpendicular to the array axis. The assumption leading to Eq. (3) requires that the field point is far enough away so that the lines connecting the field point with each of two adjacent elements can be considered parallel to one other.

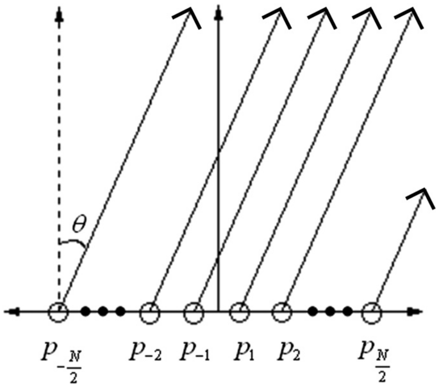

FIG. 1. Illustration of the geometrical layout of the array geometry used in Sec. II. Open arrows represent directions of acoustic rays from simple sources. The length of the shorter arrow does not physically mean anything, it is cut short to make a square picture.

The total pressure from each source is the sum of the contribution from each of the N simple sources, assuming N is even, is [with p_0 given by Eq. (1)]

$$\begin{aligned} p_{\text{total}} = p_0 \Big(& e^{-j[(N-1)/2]\phi} + \cdots + e^{-j(3/2)\phi} + e^{-j(1/2)\phi} \\ & + e^{j(1/2)\phi} + e^{j(3/2)\phi} + \cdots + e^{j[(N-1)/2]\phi} \Big). \end{aligned} \tag{4}$$

The term $e^{j[(N-1)/2]\phi}$ is then factored out of Eq. (4), yielding

$$p_{\text{total}} = p_0 e^{j[(N-1)/2]\phi} \left[\sum_{q=0}^{N-1} x^q \right], \tag{5}$$

where $x = e^{-j\phi}$. With the use of the geometric progression $1 + x + x^2 + \cdots + x^{N-1} = (1 - x^N)/(1 - x)$,[13] Eq. (5) reduces to

$$\begin{aligned} p_{\text{total}} &= p_0 \frac{e^{j(N/2)\phi}}{e^{j(1/2)\phi}} \frac{1 - e^{-jN\phi}}{1 - e^{-j\phi}} = p_0 \frac{e^{j(N/2)\phi} - e^{-j(N/2)\phi}}{e^{j(1/2)\phi} - e^{-j(1/2)\phi}} \\ &= p_0 \frac{\sin\left(\frac{N}{2}\phi\right)}{\sin\left(\frac{1}{2}\phi\right)}, \end{aligned} \tag{6}$$

$$p_{\text{total}}(r,\theta,t) = \frac{A}{r} e^{j(\omega t - kr)} \frac{\sin\left(\frac{N}{2} kd \sin\theta\right)}{\sin\left(\frac{1}{2} kd \sin\theta\right)}. \tag{7}$$

The ratio of the normalized angular dependence of the total pressure due to the array to the pressure on the beam axis at $\theta = 0$, defined as the directivity function, $H(\theta)$, is

$$H(\phi) \frac{p_{\text{total}}(\theta)}{p_{\text{total}}(\theta = 0)} = \frac{1}{N} \frac{\sin\left(\frac{N}{2} kd \sin\theta\right)}{\sin\left(\frac{1}{2} kd \sin\theta\right)}. \tag{8}$$

In array applications it is desirable to electronically steer the array through the use of phase shading rather than physically turning the array. The phase shading is performed through introducing a time delay, τ_0, difference between adjacent channels,

$$\tau_0 = \frac{d \sin\theta_0}{c}, \tag{9}$$

where c is the speed of sound, d is the distance between sources, and θ_0 is the desired steer angle. (Note that τ_0 is independent of frequency and therefore multiple frequencies may be steered in the same direction simultaneously with a single τ_0.) Steering a beam of sound into a certain direction is accomplished by creating a traveling wave along the line array of transducers. The faster this traveling wave moves along the array, the further the steering angle is tilted away from normal incidence. The radiated sound beam propagates at c in a direction θ_0 and the speed of the traveling wave, c_T, corresponds to the Cartesian component of the acoustic wave speed in the plane of the array, $c_T = c/\sin\theta_0$. The discrete array of transducers creates a stepwise version of this traveling wave. This successive time delay can then be applied to Eq. (4), to successively delay the sinusoidal frequency that is driving each transducer, and the adjusted directivity function then becomes

$$H(\theta) = \frac{1}{N}\frac{\sin\left[\frac{N}{2}kd(\sin\theta - \sin\theta_0)\right]}{\sin\left[\frac{1}{2}kd(\sin\theta - \sin\theta_0)\right]}. \tag{10}$$

It should be noted here that Eq. (10) gives the directivity pattern for an array of simple sources. If the actual sources cannot be considered simple sources, and are instead of a finite size, then one may use the so-called First Product Theorem to better estimate the directivity pattern.[10–14] The First Product Theorem allows one to estimate the directivity function of a line array of identical sized sources where $ka \ll 1$ no longer holds. The total directivity function then is determined by multiplying the directivity pattern of a single source by the directivity function of a line array of point sources (where the point sources are located at the positions of the finite sized sources).

III. DEMONSTRATION

A. Physical array apparatus

An eight loudspeaker array is constructed to provide example results for this demonstration. Each loudspeaker has a radius of $a = 7.3$ cm. The backside of each loudspeaker is acoustically isolated (individually enclosed) using 3/4 in. medium-density fiberboard. Four loudspeakers each are housed in two separate boxes, such that when the two boxes are placed adjacent to each other, the total length of the array is 137.2 cm, with a consistent center to center spacing of $d = 17.14$ cm. The array is designed to operate at 1 kHz (1 kHz nominally corresponds to a wavelength of $2d$).[10]

B. Software interface

For our demonstration, software with a graphical interface for the instructor is developed in LABVIEW®. The program allows a sine wave of user-specified specified frequency, amplitude, and phase shading angle to be generated and updated in real time. A theoretical directivity pattern based on the current phase shading angle selected, Eq. (10), and single element directivity via the First Product Theorem[10–14] may be projected in the classroom for the students to view. As the user sweeps through the phase shading angle, the plot is updated. The program also allows for turning on and off individual loudspeakers, and arbitrary phase and amplitude adjustment for individual loudspeakers.

The software-generated signals are then sent to two National Instruments (Austin, TX) 9263 Analog Output Modules (4 channels/module, ± 10 V, 16 bit/channel, 100 kS/s). Prior to being sent to the loudspeakers, the signals are each amplified by relatively inexpensive Pyle Pro (Brooklyn, NY) PCA3 75 W power amplifiers.

The software interface capability extends beyond that demonstrated in this paper. It allows the educator to control the frequency, θ_0, N, c, d, a, and overall voltage output level on one panel, as shown in Fig. 2(a). The second panel interface, shown in Fig. 2(b), allows the individual amplitudes and phases to be modified for an array with $N \leq 8$. Phase and amplitude mismatch adjustments for loudspeakers whose responses are not identical can be applied on a separate panel (not shown). With all of the available controls just described, the educator is able to demonstrate many different simple source configurations and common array configurations as described in Sec. VI.

IV. EXPERIMENT

A. Anechoic chamber measurements

One standard method of measuring the directivity function of a sound source is to have a fixed receiver and rotate the source, measuring the amplitude versus angle as the array is physically rotated. Measurements of this type were made in a large anechoic chamber (working dimensions $8.71 \times 5.74 \times 5.66$ m^3) on the campus of Brigham Young University (see Fig. 3). Unless otherwise stated, the frequency at which the array is operated is 1 kHz (thus $ka = 1.34$, assuming $c = 343$ m/s). Precautions were taken to reduce reflections from equipment using additional foam wedges (not pictured in Fig. 3).

The array is mounted to a computer-controlled, single-axis turntable so that the normal incidence, or broadside direction would correspond to 0°. The turntable is rotated in 2.5° increments with a microphone recording made at each angular increment. This setup is displayed in Fig. 3. Type-1 Larson Davis (Provo, UT) 2551 12.7 mm (1/2 in) free-field microphones with PRM426 preamplifiers are used in the experiments for both the anechoic chamber and the classroom. A microphone is placed a distance of approximately 3.3 m ($kr = 60.5$) from the center of the array. The array is rotated from the $-90°$ position (negative end fire direction) to the 90° position (positive end fire direction), resulting in a total of 73 angular measurements. A normalized plot of the relative decibel magnitude of each of the measurements at the 73 angular rotations constitutes the directivity pattern.

Figure 4 contains the measured directivity patterns with the array steered to 0° and 30° for Figs. 4(a) and 4(b), respectively, recorded from the rotation measurements made in the anechoic chamber plotted along with corresponding theoretical patterns. Both patterns are normalized to their respective peaks on their main lobes. The main lobes in both theoretical and experimental data are extremely similar in lobe width and angular location. The sidelobes are similar,

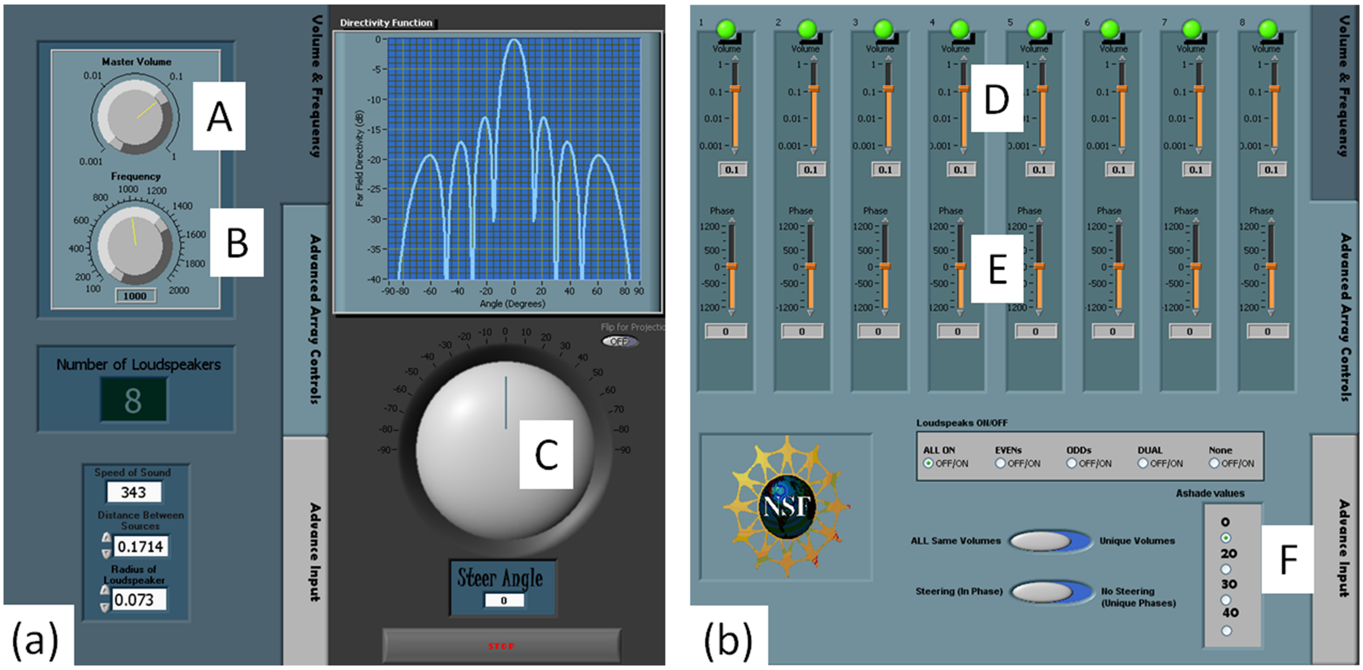

FIG. 2. (Color online) (a) Pane 1 of the user interface for the line array demonstration software controls. This pane allows adjustment of the overall amplitude (depicted by A), frequency (depicted by B), and steer angle (depicted by C). (b) Pane 2 of the user interface for the line array demonstration software controls. This pane allows individual adjustment of amplitude (depicted by D) and phase (depicted by E) in arbitrary configurations and also allows amplitude shading (depicted by F) to be applied to the elements.

but there are differences in sidelobe levels (the largest sidelobes are 1–2 dB higher than theory), differences near ±90°, and in the case of the steered pattern, one sidelobe is missing. An ideal eight-element line array's largest sidelobe is normally 13 dB down from the main lobe, where the measurement shows a difference of 11–12 dB. These kinds of differences can arise from slightly different element magnitude and phase responses (element mismatching) and other effects that are outside the scope of this paper, such as baffle edge effects, and element positioning inaccuracies.[15] In this paper we do not account for any element mismatching that may exist in our array for ease of presentation. However, the software that has been developed to control our array does have the ability to make adjustments to individual transducers to account for any phase or amplitude mismatching.

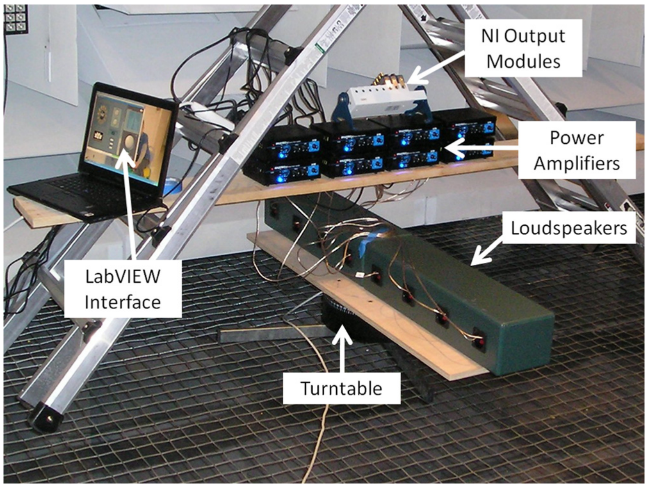

FIG. 3. (Color online) Photograph of the line array mounted to the turntable. The hardware described in Sec. III is identified in the photograph.

B. Classroom measurements

In order to determine the effectiveness of the array in an actual classroom (non-anechoic conditions), the array demonstration is set up in a large classroom measuring approximately $3.28 \times 11.99 \times 14.35\ \mathrm{m}^3$, with a seating capacity of 177. Figure 5(a) shows a photograph of the classroom from an audience member's point of view, taken at the position where the normal incidence array measurement is made.

Since the array demonstration is intended to be experienced by a stationary listener in the audience of an actual classroom, the array's directivity is measured by steering the array in 2.5° steps from −90° to 90° and measuring the pressure response with microphones at two field locations. Two microphones are configured so that they are at head level at seating locations corresponding to normal incidence and 30° off of normal incidence. Figure 5(b) shows a photograph of the classroom from the educator's point of view with the microphone locations identified. The microphones are connected to a HP 35670 two-channel dynamic signal analyzer. An averaged frequency spectrum of the microphone voltage signals is computed by the analyzer. For each rotation angle, levels are recorded at 1 kHz frequency with ten averages.

The classroom measurements were designed to test the degradation of ideal array performance in a somewhat reverberant environment. In a typical (non-anechoic) room there exists a distance, called the critical distance,[16] at which the level of sound directly from a source in that room equals the level of the cumulative, diffuse reflected energy in the room. Within this critical distance from a source, the direct sound

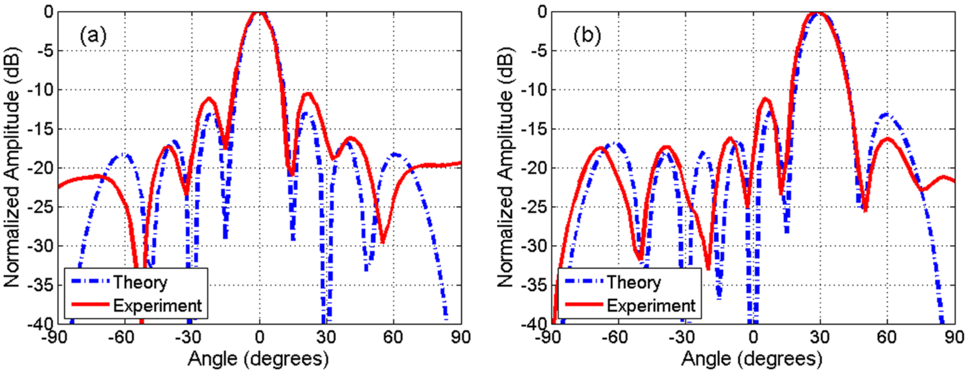

FIG. 4. (Color online) Theoretical and experimental directivity patterns from the line array using eight sources. Experimental patterns are measured in an anechoic chamber. (a) Unsteered array. (b) Array steered to 30°.

energy arriving at a listener is greater than the reflected energy. Outside, in the so-called reverberant field, the reflected energy begins to dominate. To gauge the array performance in a non-ideal environment relative to free-field line array theory, the microphone locations were chosen to be beyond the critical distance and in the reverberant field. Although further education of the reader on the subject of room acoustics is beyond the scope of this paper, Ref. 16 and other literature provide exhaustive discussion on this topic.

Although room acoustics is not described in detail, we do feel it helpful to provide some discussion of the process used to obtain the critical distance in our room for the benefit of educators who may wish to demonstrate arrays in their classrooms. The average reverberation time in our unoccupied classroom is $T_{60} = 0.71$s, from an average of four different impulse response measurements made at random seat locations. With an eight-element line array, one may theoretically obtain a directivity factor (a measure of how directional a source is) of 6.08 using Eq. (10) in this paper and Eq. 2.19 given by Albers.[10] The critical distance may then be calculated using the directivity factor in Eqs. (6-2.13) and (6-2.15) given by Pierce.[16] The average absorption coefficient for the surfaces in the room may be obtained by solving the Norris–Eyring reverberation time equation,[17,18] which relates the reverberation time to the average absorption coefficient. We then obtain the value for the critical distance, $r_c = 4.2$ m. Thus the microphones are placed just outside the critical distance in the reverberant field at a distance of 5.0 m from the center of the array so as to test the capabilities of the array demonstration in a classroom.

Figure 6 displays the classroom-measured directivity patterns for the microphones at 0° [Fig. 6(a)] and at 30° [Fig. 6(b)]. One can clearly see the departure of the measured patterns from the theoretical patterns in terms of larger amplitudes of some of the sidelobes. As stated before from the anechoic chamber measurements, some of the increases in the sidelobes may be due to mismatching of the loudspeakers (amplitudes, phases, or element positioning), and/or baffle edge effects.[15] However, the main departures in this case likely result from non-anechoic room effects. In particular, the peaks at ±60° in both experimental patterns correspond to reflections off of the sidewalls. The nulls of the measured patterns generally match the nulls of the theoretical pattern, suggesting that the interference of the multiple sources is occurring as expected. From the measured patterns, the main lobe is at least 7 dB higher than the highest sidelobe (an increase of 4–5 dB in the side lobe level relative to the anechoic measurements due to the room reverberation), which in our experience is a large enough of a difference for the audience to experience the onset of the main lobe as it is steered toward them.

V. DISCUSSION OF POTENTIAL EDUCATIONAL USES

The level of agreement between the theory and the classroom measurements suggests that an audio-range demonstration can be used in the classroom to engage groups of students in the learning of acoustical principles and the mathematics behind them, whether for outreach education or for classroom demonstrations of theory. Experiencing a highly directional source, especially one whose direction can be changed without physically rotating the source, is not an everyday experience. In addition to classroom use, the demonstration can be used as a laboratory experiment, similar to the suggestions made by Tucholski.[9]

The demonstration can be used for more than real-time beam steering in a classroom. The ability to adjust array element amplitude and phases allows this demonstration to be

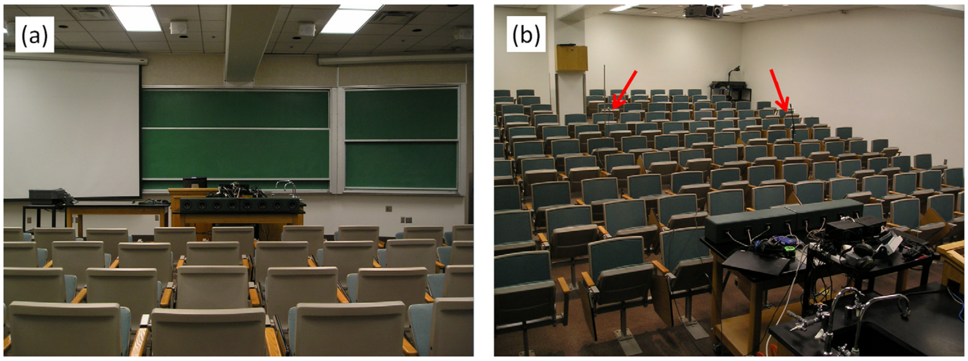

FIG. 5. (Color online) Photographs of the large classroom in which the directivity measurements made in Fig. 6 were taken. (a) View of the loudspeaker array. (b) View of the microphone locations (identified by the arrows).

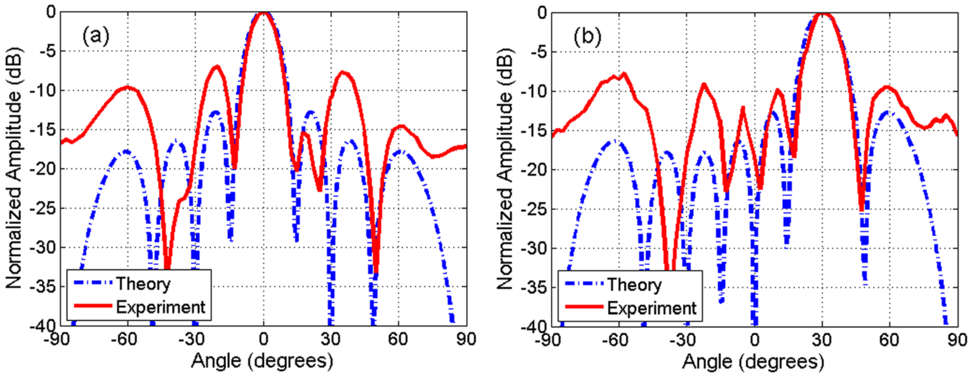

FIG. 6. (Color online) Theoretical and experimental directivity patterns from the line array using eight sources. Experimental patterns are measured in the large classroom pictured in Fig. 5. (a) Unsteered array. (b) Array steered to 30°.

used in a variety of pedagogical contexts. Although full descriptions/explanations of additional possible uses are not within the scope of this paper, a list of ideas shows to educators "value-added" benefits of developing their own array hardware. The control software can be obtained from the authors for educational purposes.[19]

The demonstration may be used in a classroom setting to illustrate various multiple-source coupling configurations. The same software and hardware can be used to explore properties of, e.g., bipoles (two in-phase simple sources where $kd \ll 1$), diploes (two out-of-phase simple sources where $kd \ll 1$), and longitudinal quadrupoles (four simple sources of positive–negative–negative–positive phase extrema where $kd \ll 1$). The frequency may be then varied to show how these source combinations vary with frequency (particularly interesting when kd is no longer much less than one). Alternatively, the frequency may be held constant while varying the distance, d, between the sources by selecting a pair of loudspeakers with a greater separation distance in the array. In general, the radiation of any arbitrary combination of $N \leq 8$ simple sources with selectable magnitudes and phases may be demonstrated.

The array can also be used to demonstrate a spatial aliasing phenomenon in arrays, referred to as "grating lobes." These spurious lobes occur when the elements in the array are not positioned with a sufficient linear density to properly sample the traveling wave necessary to create a single steered main lobe, as discussed after Eq. (9) in Sec. II. Grating lobes may be identical to the main lobe in amplitude but will point in different directions. For the case where $d < \lambda < 2d$, grating lobes may only be present if the array is steered with phase shading. However, when $\lambda < d$, the lobes are present regardless of any imposed steering. An educator could explain that if this array were instead a set of receiving transducers then one would not be able to tell the angle of incidence for sounds that impinge upon the array, and that this behavior is the spatial analog to analyzing a sine wave whose frequency is above the Nyquist frequency in temporal analog to digital conversion.

One further demonstration could be to illustrate to students a psychoacoustic principle related to our perception, or lack thereof, of phase. The radiation of the line array is that the symmetric sidelobe patterns are equal in amplitude but opposite in phase. This can be used to demonstrate that the phase of a lobe is not detectable by the human hearing mechanism.

VI. CONCLUSIONS

An educational demonstration of line arrays, i.e., the interference of multiple sources, has been proposed as a valuable educational tool for outreach or for a classroom environment.[19] Software has been developed to allow an educator to steer an array around a room in real time while simultaneously displaying theoretical directivities. This allows students to hear the interference effects in arrays and to correlate it to the expected theory. This demonstration is accomplished through the use of relatively inexpensive multiple channel output plug and play devices, amplifiers, and an array of loudspeakers.

The similarities between the unsteered and steered theoretical patterns and experimentally measured patterns in both the anechoic chamber and a large classroom show good agreement. The largest sidelobes were measured to be 1–2 dB higher than theory when the array is operated in an anechoic chamber. When operated in a classroom the highest sidelobes are found to be 6 dB higher on average than theory for the two classroom locations chosen, but with a difference of 7 dB between the main lobe and the highest sidelobe the classroom demonstration should still be reasonably convincing. The demonstration can also serve as a laboratory exercise where students are asked to experimentally measure directivity functions for various multiple source combinations and compare them to theory.

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[19] The current LABVIEW software will be made available to others for educational purposes by sending an electronic mail request to the corresponding author.