Stripping one-dimensional acoustic pressure response into propagating- and standing-wave components

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Most realistic boundary conditions are partially absorptive, with the rest of the incident acoustic power being reflected. This results in a response that can be viewed as a summation of propagating- and standing-wave effects. A one-dimensional, measurement-based, two-microphone spectral analysis technique is developed which separates the total acoustic response into propagating and standing (STRIPS) wave components. STRIPS uses measurements that contain implicit information about the boundary condition to extract the propagating- and standing-wave components. These sum to be the total system response without requiring explicit knowledge of the particular boundary condition. An exact decomposition example for a one-dimensional acoustic pressure model with a known mixed boundary condition is used to validate the STRIPS method. The utility of the STRIPS method is demonstrated using experimental measurements from a tube as input to STRIPS to obtain the propagating- and standing-wave pressure components. Changes in experimental boundary absorptivity are seen in the STRIPS results when a flared end is attached to the tube.

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INTRODUCTION

Traditional analytical modeling of the acoustic pressure response in an enclosed volume requires an explicit specification of boundary conditions. Many enclosed volumes have numerous surfaces with complicated acoustic boundary impedances that may be difficult, or impossible, to obtain. Specifying the boundary condition inaccurately can lead to significant errors in the predicted response compared to that measured in the real system. Consider the complicated response of auditoriums, factories, and ducts, for example. Boundary conditions are very often assumed to be either reflective or absorptive for convenience.

More precise characterizations of the boundary materials are possible through empirical measurement. The standard standing-wave tube technique requires measurements at discrete frequencies and is a tedious and time-consuming process. If a boundary consists of several different materials, testing for each material is required.

Finite element methods have been used to predict the acoustic response of enclosed volumes primarily exhibiting a low-frequency standing-wave response. This is an especially useful method when a complicated boundary is involved, however, the problem of specifying the boundary impedance remains. Limited success has been attained at higher frequencies where the propagating-wave response begins to interact.

Experimental modal analysis techniques have been used to extract a standing-wave response in acoustic systems. Systems selected for experimental comparison are usually hard surfaced, with a reflective boundary condition. This is not typical in many important real acoustic systems encountered. All of these analytical and experimental modeling techniques are difficult to implement accurately for a general system because the boundary condition must be estimated.

Completely absorptive boundary conditions are found in only a few enclosed volumes, such as an anechoic room. Fully reflective boundary conditions are also unusual in real systems of interest. Each ideal extreme has a well-known response associated with it. An absorptive boundary condition is associated with a propagating-wave response. A reflective boundary condition is associated with a standing-wave response.

Most realistic boundary conditions are partially absorptive, with the rest of the acoustic power being reflected. These mixed boundary conditions have an associated mixed response. van Zyl et al. have described a similar superposition of ideal effects in three dimensions by comparing the mean-square pressures of the sound intensity and total energy density in rooms with varying amounts of boundary absorptivity. Nicolais et al. also show an interest in the effects of a partially progressive field as it affects the errors introduced into acoustic intensity measurements.

This article develops a measurement-based two-microphone spectral analysis technique which separates the total acoustic response into propagating- and standing-wave (STRIPS) wave components. STRIPS uses measurements that contain implicit information about the boundary condition to extract the propagating- and standing-wave components. These sum to be the total system response without requiring knowledge of the particular boundary condition. An exact analytical decomposition of a one-dimensional acoustic pressure response resulting from a known mixed
boundary condition is used to prove the validity of the STRIPS model. Analyzing the components separately is advantageous because each is associated with an ideal boundary condition. The propagating-wave pressure component is absorbed at the boundary. The standing-wave pressure component, due to a reflective boundary condition, contains information about the natural frequencies and mode shapes. STRIPS is derived here for a simple one-dimensional acoustic system to focus on the technique rather than the complexity of the system. A harmonic excitation is placed at one end of a tube and a mixed boundary condition at the other. The required inputs to the STRIPS model are the measured autospectra and cross spectrum of the pressure response at two locations. Closed-form STRIPS solutions for the propagating- and standing-wave components are presented. Experimental inputs are also used to obtain results for comparison.

I. IDEAL RESPONSE COMPONENTS

A generalized model for a one-dimensional, steady-state, acoustic pressure propagating-wave response \( P_p \) is normalized by the excitation magnitude \( P_0 \), and shown below:

\[
\frac{P_p}{P_0} = A e^{i\omega x} e^{i\theta} \tag{1}
\]

Here, \( A \) is the normalized unknown wave magnitude, \( \omega \) is the frequency, \( t \) is the time, \( x \) is the spatial coordinate in a tube of length \( L \), \( c \) is the wave velocity, and \( \theta \) is the unknown initial phase angle with respect to the excitation. The magnitude is constant and independent of the spatial location. Transport delay causes the phase of \( P_p \) to decrease linearly with \( x \), and to be equal to \( \theta \) at \( x = 0 \) to zero. The absolute maximum that an excitation normalized propagating response \( P_p \), and therefore \( A \), can attain is unity.

A generalized model for a one-dimensional, steady-state, acoustic pressure standing-wave response \( P_s \), when normalized by the excitation magnitude, results in the expression

\[
\frac{P_s}{P_0} = R(x) e^{i\omega t + \theta - \pi/2} \tag{2}
\]

The standing-wave amplitude distribution \( R(x) \) is not known prior to measurement. It is only assumed to be a function of the spatial coordinate \( x \). These "mode shapes" are easily obtained for a specified boundary condition for the one-dimensional case and will be useful for comparison. The unknown initial phase angle with respect to the excitation is given by \( \theta \). The \( \pi/2 \) appears because standing waves are a resonant phenomena lagging the propagating waves generated at the excitation. A standing wave has an amplitude that changes spatially, but with all points in the standing-wave response in-phase with one another.

II. TOTAL ACOUSTIC RESPONSE

The total acoustic response \( P \) is shown at an arbitrary spatial location \( x \) to be

\[
P(x,t) = P_p + P_s = A e^{i\omega t - i\omega/c x + \theta} + R(x) e^{i\omega t + \theta - \pi/2} \tag{3}
\]

It is equal to the linear summation of the propagating- and standing-wave response components associated with purely absorptive and reflective boundary conditions, as in Eqs. (1) and (2). This decomposition of a total mixed response with a known mixed boundary condition was shown in Ref. 15 to be analytically possible for the one-dimensional wave equation case.

For two arbitrary locations, \( 0 < x_1 < x_2 < L \), the total responses will be \( P_{1t} \) and \( P_{2t} \), respectively,

\[
P_{1t} = P_p + P_s = A e^{i\omega t - i\omega/c (x_1 + \theta)} + R(x_1) e^{i\omega t + \theta - \pi/2} \tag{4}
\]

\[
P_{2t} = P_p + P_s = A e^{i\omega t - i\omega/c (x_2 + \theta)} + R(x_2) e^{i\omega t + \theta - \pi/2} \tag{5}
\]

A propagating-wave response measured at two points is characterized by a constant amplitude, but a changing phase with respect to the excitation. A standing-wave response is characterized by a changing amplitude, but a constant phase with respect to the excitation. These characteristics are superimposed in a mixed response. The differences in the measured magnitudes and phases characterizing the propagating- and standing-wave components at the two points will aid in their extraction.

III. STRIPS SPECTRAL EQUATIONS

The total response at the two measurement points is used to form two autospectra and a cross spectrum between the two total pressures. These spectral quantities can be easily measured with any of several relatively inexpensive digital fast Fourier transform analyzers. They can also be formed from the total response resulting from an analytical one-dimensional acoustic pressure response model with a specified mixed boundary condition.

The autospectrum \( G_{11} \) of the total response at \( x_1 \) is

\[
G_{11} = E\left\{ P_{1t}^* P_{1t} \right\} \tag{6}
\]

where \( E \) represents the expected value of the \( ^* \) represents the complex conjugate of the quantity. The total response term at \( x_2 \) is substituted from Eq. (4) to give an equivalent expanded form. Multiplying the terms out and then gathering similar terms gives Eq. (9):

\[
G_{11} = E \left\{ \left( A e^{i\omega \left[ \cos \left( \frac{\pi}{2} - \frac{\omega x}{c} \right) + \theta \right]} + R e^{i\omega t + \theta - \pi/2} \right) \right. \\
\left. \times \left( A e^{i\omega \left[ \cos \left( \frac{\pi}{2} - \frac{\omega x}{c} \right) + \theta \right]} + R e^{i\omega t + \theta - \pi/2} \right) \right\} \tag{7}
\]

\[
= E \left\{ A^2 + A R e^{i\omega t + \theta} + \frac{\pi}{2} \left( \cos \left( \frac{\pi}{2} - \frac{\omega x}{c} \theta \right) \right) + R^2 \right\} \tag{8}
\]

\[
= E \left\{ A^2 + R^2 + 2 A R \sin \left( \frac{\pi}{2} - \frac{\omega x}{c} \theta \right) \right\} \tag{9}
\]

Similarly, the auto spectrum \( G_{22} \) of the total response at \( x_2 \) is formed in the same manner:

\[
G_{22} = E \left\{ P_{2t}^* P_{2t} \right\} \tag{10}
\]

\[
= E \left\{ A^2 + R^2 + 2 A R \sin \left( \frac{\pi}{2} - \frac{\omega x_2}{c} \right) \right\} .
\]

The cross spectrum \( G_{12} \) between the total responses measured at \( x_1 \) and \( x_2 \) is also formed:

\[
G_{12} = E \left\{ P_{1t}^* P_{2t} \right\} .
\]

The total responses from Eqs. (4) and (5) are substituted
into the cross spectrum and are multiplied out. This equation is then expanded and similar terms are gathered together to obtain Eq. (14):

\[
G_{12} = E \left\{ (A e^{-i(\omega t + \theta)} x_1 + B e^{+i(\omega t + \theta)} x_2) \times (A e^{i(\omega t + \theta)} x_1 + B e^{-i(\omega t + \theta)} x_2) \right\} \\
= E \left( A^2 e^{i(\omega t + \theta)(x_1 - x_2)} + A R_2 e^{-i(\omega t + \theta)(x_1 + x_2)} + A R_2 e^{i(\omega t + \theta)(x_1 - x_2)} + A R_2 e^{-i(\omega t + \theta)(x_1 + x_2)} \right) \\
= E \left[ A^2 \cos \left( \frac{\omega}{c} (x_1 - x_2) \right) + A R_2 \sin \left( \frac{\omega}{c} x_2 \right) + A R_2 \sin \left( \frac{\omega}{c} x_1 \right) + A R_2 \cos \left( \frac{\omega}{c} x_1 \right) \right]. \tag{14} \]

IV. STRIPS EQUATIONS

The above results, Eqs. (9), (10), and (14), define the STRIPS equations. Autocorrelation is listed as developed, with the expected value reprinted. The cross spectrum is divided into real and imaginary parts, \( \text{Re}(G_{12}) \) and \( \text{Im}(G_{12}) \), yielding four nonlinear equations with three unknowns:

\[
G_{11} = A^2 + R_1 + 2 A R_1 \sin \left( \frac{\omega}{c} x_1 \right), \tag{15} \\
G_{22} = A^2 + R_2 + 2 A R_2 \sin \left( \frac{\omega}{c} x_2 \right), \tag{16} \\
\text{Re}(G_{12}) = A^2 \cos \left( \frac{\omega}{c} (x_1 - x_2) \right) + A R_2 \sin \left( \frac{\omega}{c} x_2 \right) + A R_2 \sin \left( \frac{\omega}{c} x_1 \right) + A R_2 \cos \left( \frac{\omega}{c} x_1 \right), \tag{17} \\
\text{Im}(G_{12}) = A^2 \sin \left( \frac{\omega}{c} (x_1 - x_2) \right) + A R_2 \cos \left( \frac{\omega}{c} x_2 \right) - A R_2 \cos \left( \frac{\omega}{c} x_1 \right). \tag{18} \\
\]

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\text{Im}(G_{12}) = A^2 \sin \left( \frac{\omega}{c} (x_1 - x_2) \right) + A R_2 \cos \left( \frac{\omega}{c} x_2 \right) - A R_2 \cos \left( \frac{\omega}{c} x_1 \right). \tag{18} \\
\]

Simultaneous solution of the STRIPS equations results in the propagating-wave component \( A \) and the standing-wave components \( R_1 \) and \( R_2 \), at locations \( x_1 \) and \( x_2 \), respectively. No boundary condition model need be specified, or assumed, because the results are derived from assumed response components only.

V. STRIPS SOLUTIONS

The solution of the STRIPS equations is a set of \( A, R_1, \) and \( R_2 \), which satisfy all STRIPS equations exactly. Other sets of \( A, R_1, \) and \( R_2 \) result in a residual error \( E \), for each equation:

\[
E_1 = A^2 + R_1 + 2 A R_1 \sin \left[ \frac{\omega}{c} x_1 \right] - G_{11}, \tag{19} \\
E_2 = A^2 + R_2 + 2 A R_2 \sin \left[ \frac{\omega}{c} x_2 \right] - G_{22}, \tag{20} \\
E_3 = A^2 \cos \left( \frac{\omega}{c} (x_1 - x_2) \right) + A R_1 \sin \left( \frac{\omega}{c} x_2 \right) + A R_2 \sin \left( \frac{\omega}{c} x_1 \right) \tag{21} \\
E_4 = A^2 \sin \left( \frac{\omega}{c} (x_1 - x_2) \right) + A R_1 \cos \left( \frac{\omega}{c} x_1 \right), \tag{22} \\
\]

The residual errors serve another useful purpose. So far, all other quantities are assumed to be independent of the system that exactly follows the stated model. Systems different from this one will have different measures of the accuracy, including \( G_{11}, G_{22}, \) \( \text{Re}(G_{12}), \) \( \text{Im}(G_{12}), x_1, x_2, A, \) and \( \omega \). The sum of the squares of the residual errors is then useful to display because it identifies a mismatch between the model and the system being measured.

The residual errors are set equal to zero and Eqs. (19)–(22) are solved simultaneously to obtain the STRIPS solutions:

\[
A = \text{Im}[G_{12}] \left[ G_{11} \cos^2 \left( \frac{\omega}{c} x_1 \right) + G_{22} \cos^2 \left( \frac{\omega}{c} x_2 \right) \right]^{0.5}, \tag{23} \\
R_1 = -A \sin \left( \frac{\omega}{c} x_1 \right) \pm \left[ -A^2 \cos^2 \left( \frac{\omega}{c} x_1 \right) + G_{11} \right]^{0.5}, \tag{24} \\
R_2 = -A \sin \left( \frac{\omega}{c} x_2 \right) \pm \left[ -A^2 \cos^2 \left( \frac{\omega}{c} x_2 \right) + G_{22} \right]^{0.5}. \tag{25} \\
\]

The propagating-wave response component \( A \) is directly proportional to the imaginary part of the cross spectrum, \( \text{Im}(G_{12}) \), and is a function of frequency. The denominator contains information on the difference in magnitude and phase between the two measurement points. There are four combinations of plus–minus signs to select when calculating \( R_1 \) and \( R_2 \). These solutions are substituted back into the residual error equations [Eqs. (19)–(22)], which immediately yields the residual errors \( E_1 \) and \( E_2 \) equal to zero. The same substitution into the third and fourth residual errors, \( E_3 \) and \( E_4 \), will also yield zero residual errors if the following property of cross and auto spectra is used:

\[
G_{11} G_{22} = \text{Im}^2(\text{G}_{12}) + \text{Re}^2(\text{G}_{12}). \tag{26} \\
\]

The final two residual error equations define the conditions that determine the selection of the plus or minus sign in \( R_1 \) Eq. (24), and \( R_2 \) Eq. (25).
STRIPS condition
\[
G_{11} \cos\left(\frac{(a/c)x_1}\right) < \Re(G_{12}\cos\left(\frac{(a/c)x_1}\right)) \\
G_{21} \cos\left(\frac{(a/c)x_1}\right) > \Re(G_{22}\cos\left(\frac{(a/c)x_1}\right))
\]
\[
G_{11} \cos\left(\frac{(a/c)x_2}\right) < \Re(G_{12}\cos\left(\frac{(a/c)x_2}\right)) \\
G_{21} \cos\left(\frac{(a/c)x_2}\right) > \Re(G_{22}\cos\left(\frac{(a/c)x_2}\right))
\]
\[
G_{11} \cos\left(\frac{(a/c)x_3}\right) > \Re(G_{12}\cos\left(\frac{(a/c)x_3}\right)) \\
G_{21} \cos\left(\frac{(a/c)x_3}\right) > \Re(G_{22}\cos\left(\frac{(a/c)x_3}\right))
\]
The individual terms are the same in each of the above four sets of inequalities. A determination of which of the inequalities is present is all that is needed to select the signs in Eqs. (24) and (25). Exact solutions have been defined because the residual errors are zero. The above results involve spectral calculations that can be easily implemented on a small microcomputer system.

VI. DISCUSSION OF STRIPS SOLUTIONS

A model of a one-dimensional system with a known mixed boundary condition was developed in Ref. 15 and is used now to create analytical input to STRIPS for test purposes. The propagating- and standing-wave components of this mixed response were also found in Ref. 15 and will be compared to those found here. A modeled mixed response in a 1.524-m (5-ft) tube is calculated 150 mm (0.492 ft) apart at 0.46 m (1.52 ft) and at 0.61 m (2.01 ft). A boundary absorbivity of 20\% is chosen where the other 80\% of the incident acoustic power is reflected at the boundary and results in a standing wave. The auto spectra and cross spectra are formed using the mixed responses at the two specified locations. These spectra are input to the STRIPS solutions, Eq. (23)–(25), and the propagating- and standing-wave components are calculated. Two of the resulting STRIPS propagating- and standing-wave components, \( A \) and \( R_\mu \), are shown in Fig. 1.

The sum of the squared residual errors (SRE) is zero at all frequencies, as expected, because exact modeled mixed responses are used that conform to the assumed response components. The standing-wave response component \( R_\mu \) has first and second modes at 112.8 and 225.6 Hz. This location, at 0.46 m, is approximately at a node for the third mode, 338.4 Hz, and has nearly zero response there. The fourth mode at 451.2 Hz is just beginning to appear. It is out-of-phase with the first two, as expected. The propagating-wave response component \( A_2 \) is maximized at natural frequencies and midway between natural frequencies. It is minimized at one-quarter and three-quarter between natural frequencies.

These STRIPS method components are compared in Fig. 2 to the analytical method components from Ref. 15. Both have the same mixed response input. There is no discernible difference in the curves. The same comparison is made in Fig. 3 for a boundary absorbivity of 60\%. Again, the comparison is exact. STRIPS has found propagating- and standing-wave components using the total mixed response without requiring knowledge of the boundary condition.

FIG. 1. STRIPS method propagating-wave (solid line), \( A \), and standing-wave (dotted line), \( R_\mu \), components using modeled acoustic pressure spectra as input. Twenty percent of incident acoustic power is absorbed at the boundary in the model. Spectra calculated at 0.46 m (1.52 ft) and 0.61 m (2.01 ft) in a 1.524-m (5-ft) tube. Squared residual error (SRE) is zero.

![FIG. 1](image1)

FIG. 2. Comparison of STRIPS (solid line) propagating-wave, \( A \), and standing-wave, \( R_\mu \), components using modeled acoustic pressure spectra and analytical components obtained from an analytical decomposition (dotted line) of same input spectra. An exact comparison is seen. Twenty percent of incident acoustic power is absorbed at the boundary in model. Spectra calculated at 0.46 m (1.52 ft) and 0.61 m (2.01 ft) in a 1.524-m (5-ft) tube.

![FIG. 2](image2)
VI. EXPERIMENT

The auto spectra and cross spectrum of the total acoustic response at two points in a tube (Fig. 4) are also input to the STRIPS method. The tube is excited at one end with random noise. Two boundary conditions are tested at the other end, an open end and a megaphone-shaped flare.

A 1.524-m (5-ft)-long, 76.2-mm (3-in.) i.d. PVC pipe was used to simulate the one-dimensional plane-wave acoustic response models described previously (Fig. 5). Holes were drilled through one surface of the pipe at a spacing of 150 mm (0.492 ft). The microphone spacing must be wide enough to avoid any correlation between the standing wave and the phase change of the propagating wave, and it is measurable. A two-microphone probe assembly was inserted into two holes to measure two total acoustic pressure responses. The remaining holes were plugged during the measurement.

Each of the 1-in. microphones (Bruel & Kjaer 4166 random incidence condenser) were calibrated with a sound level calibrator (Bruel & Kjaer 4230). The calibrated pressure signals were connected through a microphone preamplifier (Bruel & Kjaer 2619) to a spectral analyzer (Hewlett-Packard 5423A). The analyzer also provided the band limited (50-450 Hz) random noise signal to drive the speaker exciting the pipe entrance.

The auto spectra of each pressure response and the cross spectrum between the two pressure responses were measured by the analyzer and stored on cassette tape. The excitation was measured separately because only a two-channel analyzer was available. The excitation auto-spectrum magnitude was used to normalize the total acoustic pressure spectra, so that the STRIPS results are independent of the excitation used. An ICS Electronics Corporation model 4885 A RS-232 to IEEE 488 controller interfaced the HP analyzer to a Prime 750 minicomputer in the A. H. Case Center for Computer-Aided Design at Michigan State University. The spectra were transferred to the Prime 750 for the STRIPS analysis and graphics display.

VIII. BOUNDARY CONDITIONS

The open-ended configuration, simulates a nearly reflective boundary condition. The very large impedance change at the pipe end acts as an acoustic barrier. Because some acoustic energy does escape from the end of the pipe, a small absorptivity is expected.

The other boundary condition employed a flare-ended configuration that had a linear flare from 9.525-mm (3.75-in.) diameter to 35.56-mm (14-in.) diameter over a 16.5-mm (6.5-in.) axial distance in an attempt to match the impedance at the pipe end with the room impedance. Impedance is inversely proportional to the cross-sectional area. A linearly increasing flare helps to match the large impedance inside the tube to the essentially zero impedance in the room exterior to the pipe. The boundary absorptivity increases with the flared end attached because of the cross-sectional area change. The impedance is also inversely proportional to the frequency. Higher frequencies have a smaller impedance. Therefore, higher frequencies will escape more readily with a flared boundary condition.

IX. EXPERIMENTAL RESULTS

The STRIPS method components at $x = 0.46$ m, without the flared boundary condition are shown in Fig. 6. The
These experimental STRIPS components are compared in Fig. 7 to the analytical method components when 3% of the acoustic power at the pipe end is absorbed. The heights of the propagating wave troughs compare very well near 300 Hz. It is obvious that low frequencies have less absorption and higher frequencies have more absorption than the constant absorptivity shown. The standing wave amplitudes also compare well, considering the lack of frequency resolution and that no internal damping was assumed.

The experimental natural frequencies become increasingly lower than the modeled natural frequencies at higher frequencies. The effective pipe length for the experimental system becomes longer for higher frequencies because the response waves are beginning to escape further out of the end of the pipe before being reflected back. The pipe natural frequencies should occur at integer multiples of the fundamental frequency and the change in the effective length of the pipe can again be seen by the decreasing difference in the frequencies at which the peaks occur.

The STRIPS components found from experimental spectra input when the flared end was attached are shown in Fig. 8. The propagating component is virtually unchanged at lower frequencies. There is more propagation at higher frequencies, however. This is expected since higher frequencies are affected more by the change in impedance at the tube end than the lower frequencies are.

**X. CONCLUSIONS**

A STRIPS method to separate total acoustic response into propagating and standing wave response was developed. STRIPS is a one-dimensional two-point spectral analysis model, which includes measurements of the total mixed response that contain implicit information about the boundary condition. The results are the propagating- and standing-wave response components, $A$, $R_p$, and $R_s$. They were found to compare very well with an analytical decomposition in both the simulation and laboratory tests.

A STRIPS squared residual error function also results from the STRIPS method. It is zero if the system from which
the measured responses are taken from fit the derived model. System deviations from this model will result in a STRIPS squared residual error. A person using the STRIPS method on a microcomputer could use the STRIPS error as an indicator of whether good results were obtained. Knowledge of the details of the analysis would not be needed. In laboratory tests, an error was seen when one of the microphones was at a standing-wave node of the tube tested. The STRIPS error was zero at other frequencies, showing that the real system matched the modeled response well for the tube test.

This technique is intended for implementation on a microcomputer for experimental measurements of acoustic pressure response. The analytically ideal propagating- and standing-wave components are found directly from measurements of the mixed response without knowledge of the actual boundary condition. It may therefore be possible to develop a method to determine the impedance of an unknown termination. The two components measured by the STRIPS method give valuable insight to the acoustic response behavior of one-dimensional systems.


"M. Richardson and J. Knisley, "Identifying Modes of Large Structures from Multiple Input and Response Measurements," SAE 760375 (1976).