Overview of Sivian's 1937 paper on Sound Propagation in Ducts Lined with Absorbing Materials

Kara Hardy
Michigan Technological University

Leon John Sivian

Born in Russia, immigrated to the United States as a child

Earned a degree in Electrical Engineering from Cornell University

Worked at Bell Labs for 30 years

Briefly interrupted by stints at Missouri State College

And the Navy Radio and Sound Laboratory at the University of California

[1-3]

Leon John Sivian

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One of the founding members of the Acoustical Society of America

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HISTORY OF ACOUSTICAL SOCIETY OF AMERICA

By Wallace Waterfall

(As read at the beginning of the business meeting on May 10th)

At that meeting the following men were in attendance.
F. K. Richtmeyer, Cornell University, Ithaca, N. Y.
L. J. Sivian, Bell Telephone Laboratories, N. Y. C.
R. L. Wegel, Bell Telephone Laboratories, N. Y. C.

[4]

Paper Outline

OCTOBER, 1937 J. A. S. A. VOLUME 9

Sound Propagation in Ducts Lined with Absorbing Materials*

L. J. SIVIAN
Bell Telephone Laboratories, New York, N. Y.
(Received June 28, 1937)

In ventilator and exhaust systems it is desirable to provide a high degree of attenuation for audiofrequency waves while offering low resistance to continuous or slowly pulsating air flow. For that purpose ducts lined with absorbing materials are sometimes used. This paper deals with sound propagation, particularly with its attenuation constant, in such ducts. Two types of lining are considered: (*a*) nonvibratile, i.e., a lining in which there is no wave motion propagated in the direction of the duct axis; (*b*) vibratile, i.e., a lining admitting of such motion. Methods for computing the propagation constants in terms of the acoustic constants of the lining, are given. Some experimental data are presented. Comparison of observed and computed values indicates that the computational procedure is substantially valid up to a frequency at which the sound wave-length is about twice the internal duct diameter.

[5]

Paper Outline

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Sound Propagation in Ducts Lined with Absorbing Materials*

L. J. SIVIAN
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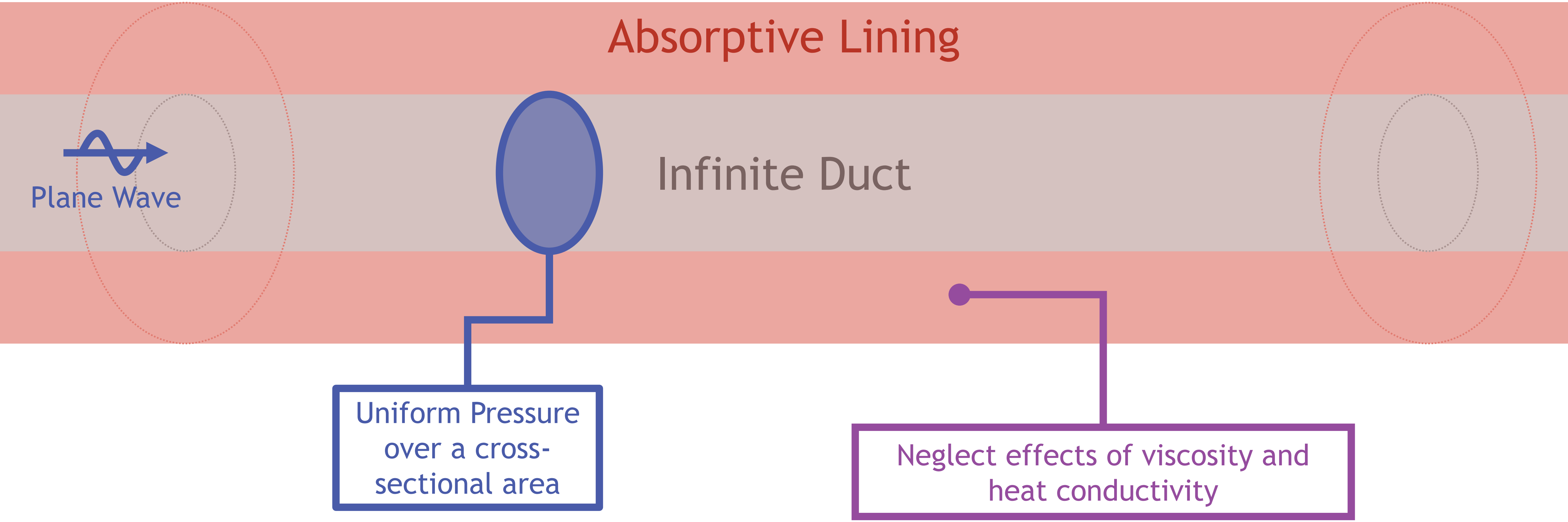
Part A: Non-Vibratile Linings

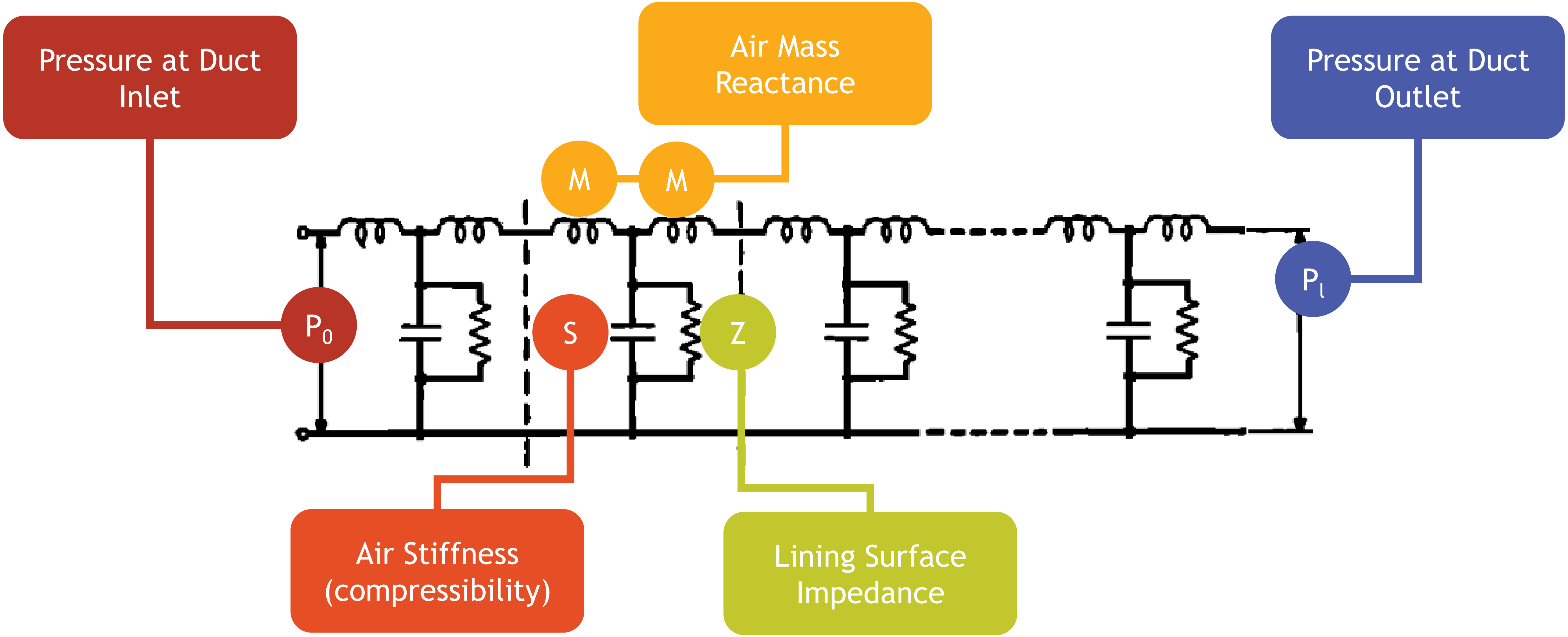
- Three cases of linings
- Transmission through duct of finite length
- Measured and computed values of the attenuation constant
- Effect of superimposed DC air flow

Part B: Vibratile Linings

The Problem and Sivian’s Assumptions



1D Propagation: Transmission Line Model



1D Propagation: Transmission Line Model

Lining Surface Impedance

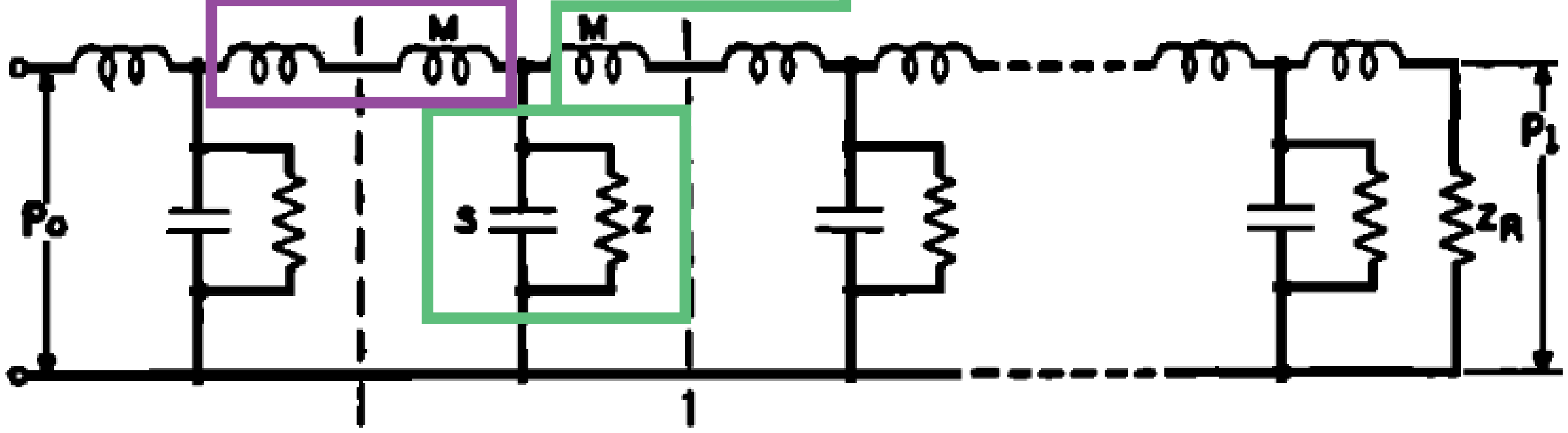
$$z = r + i\omega m \; - is/\omega$$

- **r**
  resistance
- **m**
  mass reactance
- **s**
  stiffness

Propagation Constant and Impedance of the System

Series Impedance, z_1

Shunt Admittance, z_2

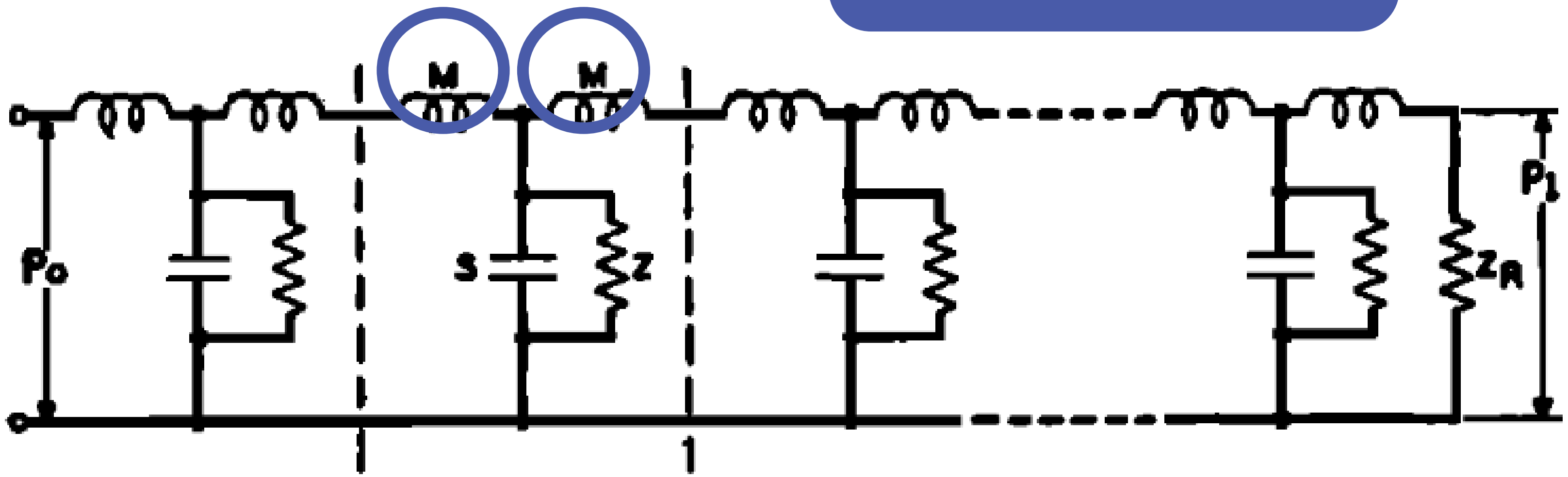


$Propagation\ Constant\!: \Gamma = \sqrt{\frac{z_1}{z_2}} = ikM = \alpha + i\beta$

$Characteristic\ Impedance\!: z_c = \sqrt{z_1 z_2} = \frac{\rho c}{AM}$

Propagation Constant and Impedance of the System

Not the same M!
(it's frustrating, I know!)



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Propagation Constant Breakdown

$$Propagation\ Constant\!: \Gamma = \sqrt{\frac{z_1}{z_2}} = i\mathrm{kM} = \alpha + i\beta$$

α

Attenuation per unit length of an infinite duct or duct terminated in its characteristic impedance

β

Wavenumber

$$\beta = \frac{\omega}{c_1} = \frac{2\pi f}{sound\ velocity\ in\ the\ duct}$$

Dimensionless Constants

$$\sigma = \frac{s}{s_a}$$

Ratio of lining stiffness to air stiffness

$$q = \frac{\omega r}{s_a}$$

Relates lining resistance to frequency and air stiffness
Used as a non-dimensional proxy for frequency in plots

$$\mu = \frac{m s_a}{r^2}$$

Relates lining mass reactance to air stiffness and resistance

$$h = \frac{q}{k}$$

Relates q to the wavenumber (k)

Part A: Non-Vibratile Linings

The Problem and Sivian's Assumptions

Plane Wave

Infinite Duct

Non-Vibratile Lining (Local Reaction)

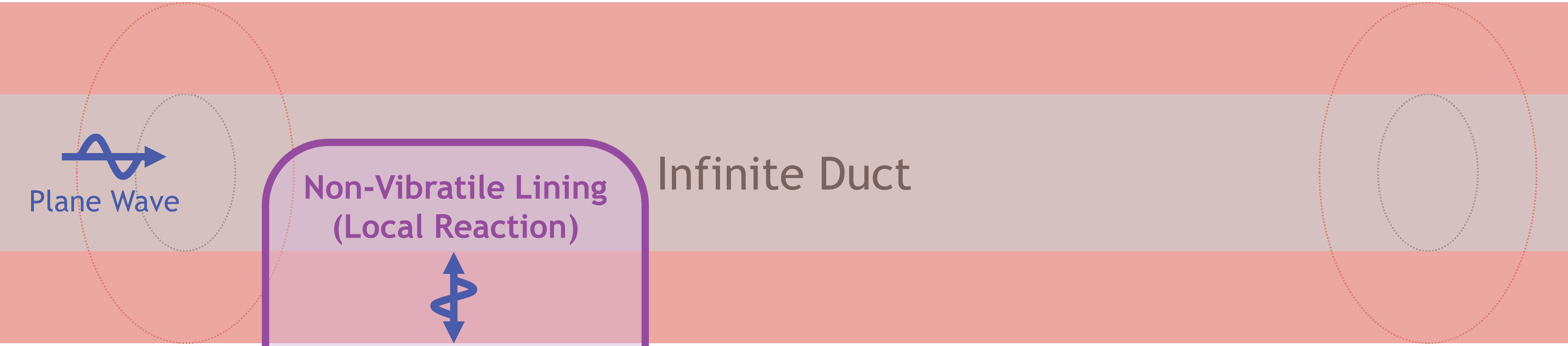
Sound only propagates normally to the liner surface

Any axial propagation is negligible

Vibratile Lining (Extended Reaction)

Sound can propagate axially through the liner (along the duct axis)

The Problem and Sivian's Assumptions



Non-Vibratile Lining (Local Reaction)

Sound only propagates normally to the liner surface
Any axial propagation is negligible

Case 1.1: Constant Resistance

Example Liner

Wire mesh over hard wall, no air cavity

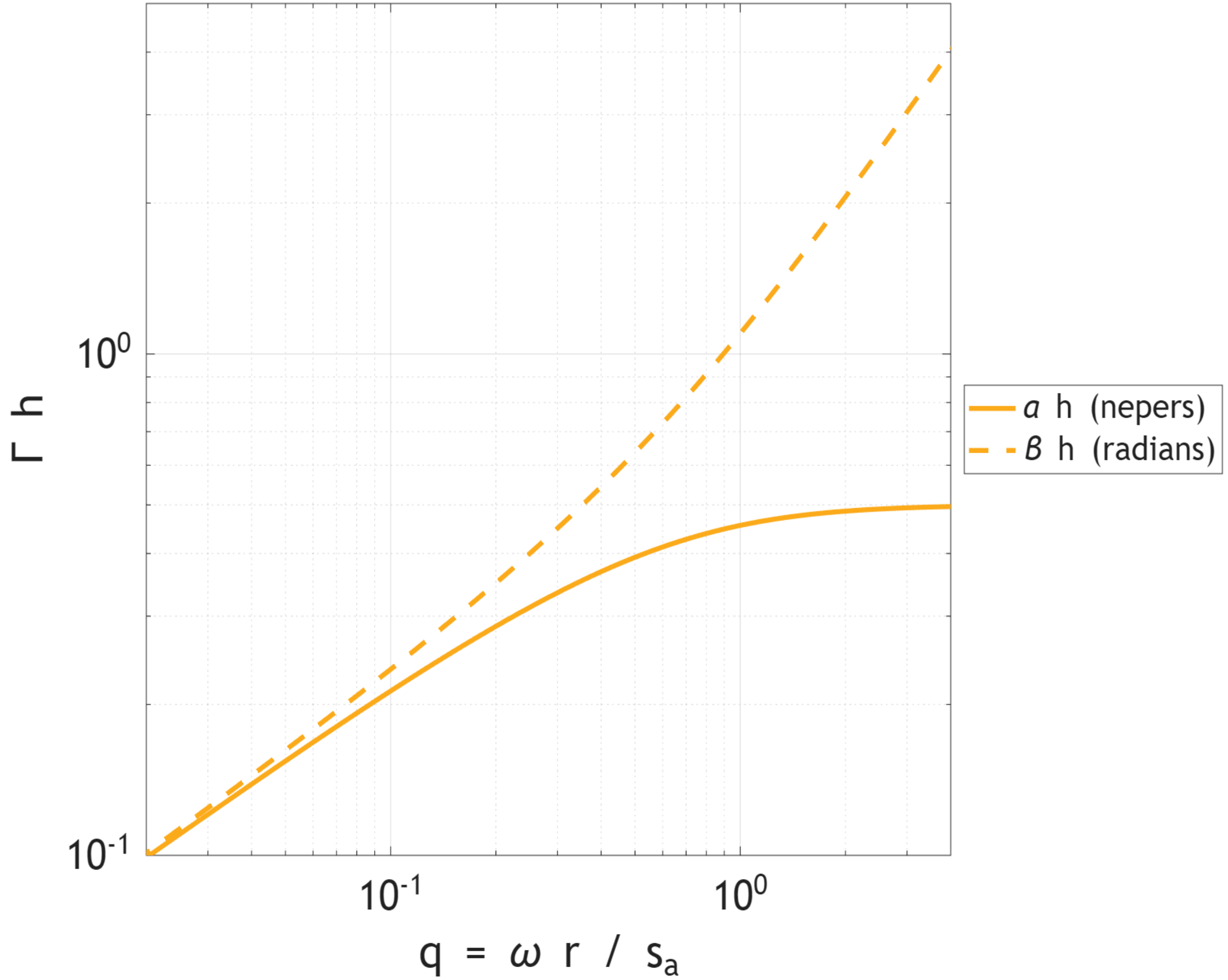
Surface Impedance

$$z = r$$

Auxiliary Impedance Function

$$M^2 = 1 - \frac{i}{q}$$

Fig. 2 -- Case 1.1: z = r



Case 1.2: Constant Resistance and Stiffness

Example Liner

Wire mesh over air cavity

Surface Impedance

$$z = r - \frac{is}{\omega}$$

Auxiliary Impedance Function

$$M^2 = 1 + \frac{1}{\sigma + iq}$$

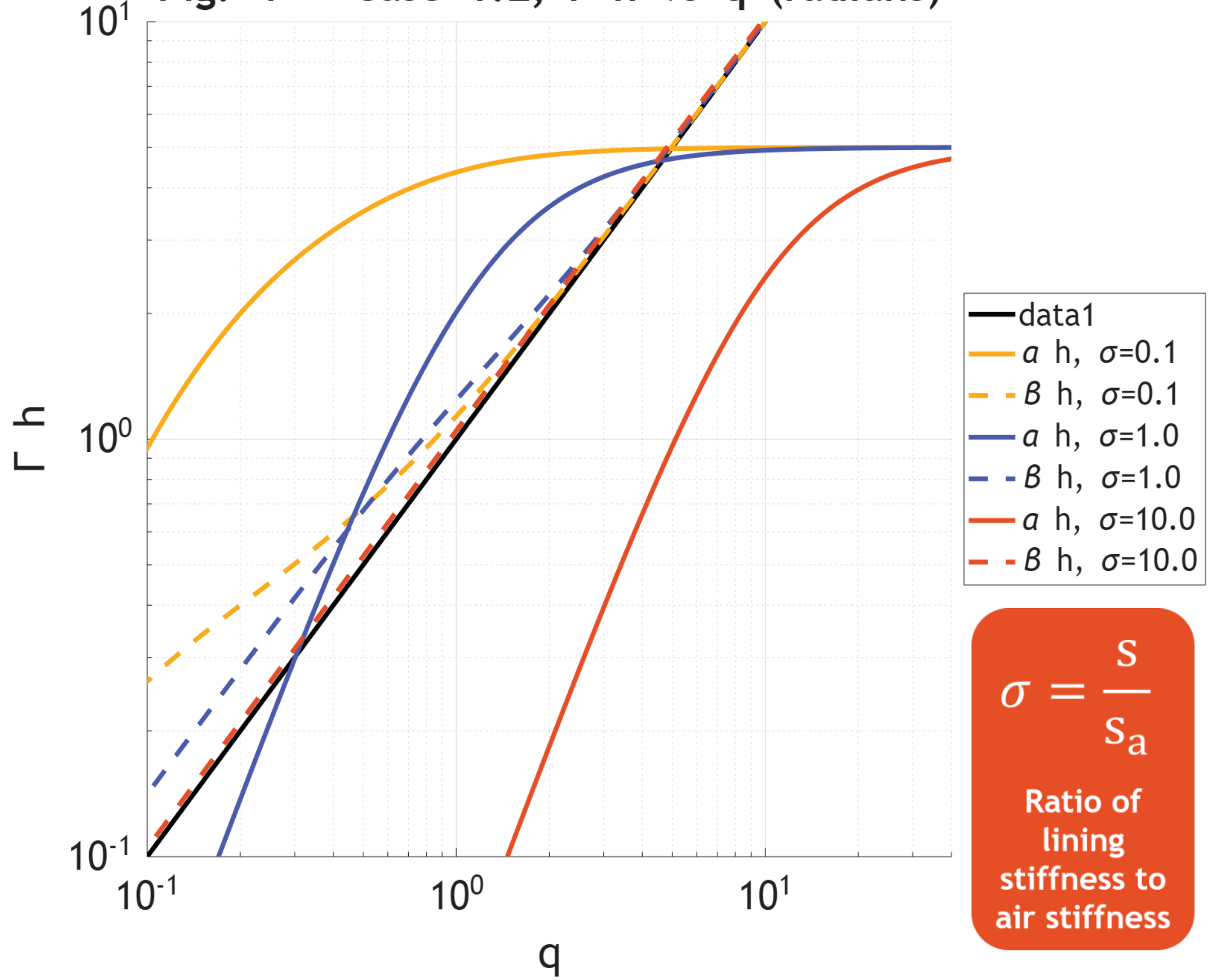


Fig. 4 -- Case 1.2, Γ h vs q (radians)

$$\sigma = \frac{s}{s_a}$$

Ratio of lining stiffness to air stiffness

Case 1.2: Constant Resistance and Stiffness

Example Liner

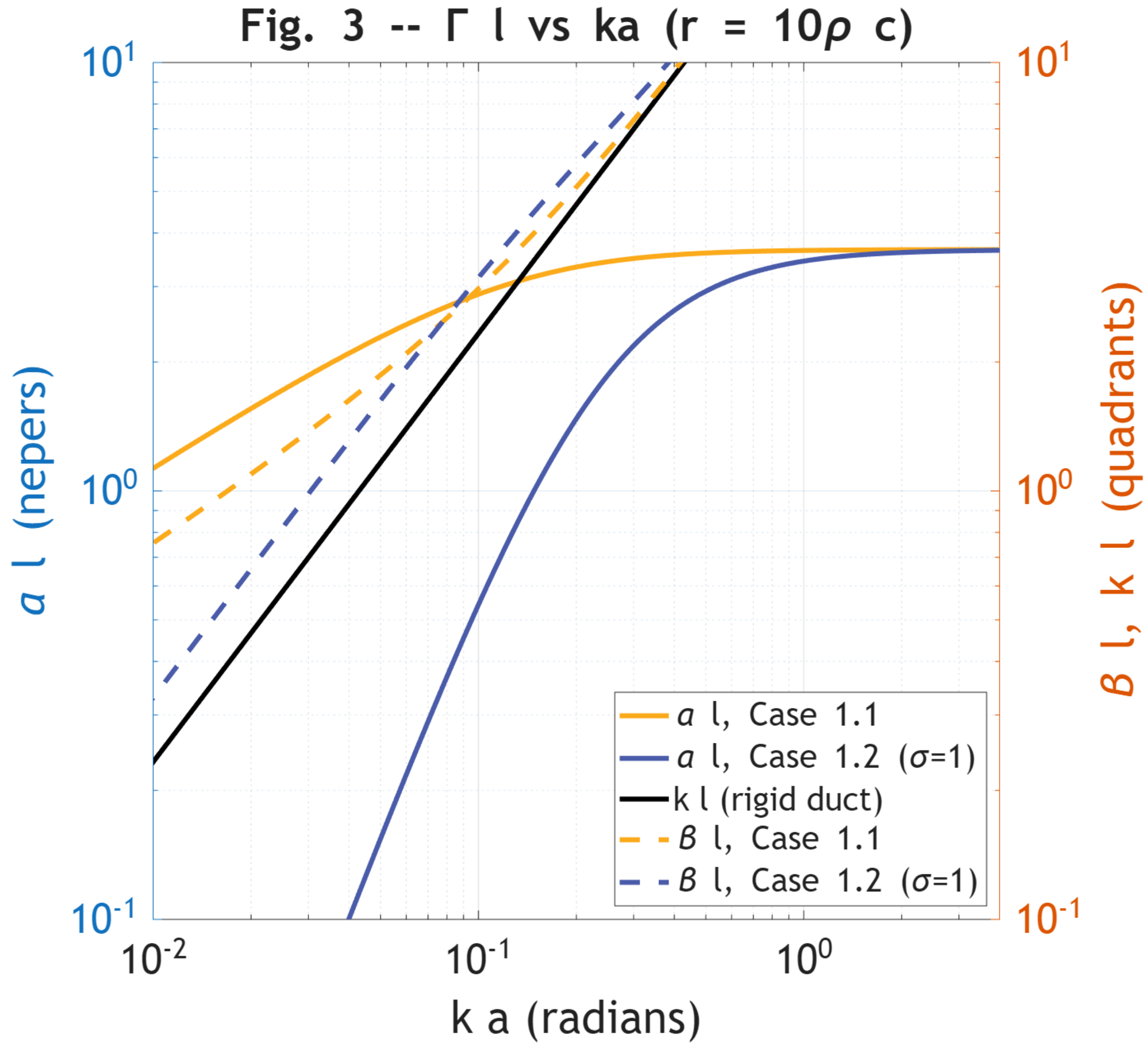
Wire mesh over air cavity

Surface Impedance

$$z = r - \frac{is}{\omega}$$

Auxiliary Impedance Function

$$M^2 = 1 + \frac{1}{\sigma + iq}$$



Case 1.3: Constant Resistance and Mass Reactance

Example Liner

Perforate plate over hard wall, no air cavity

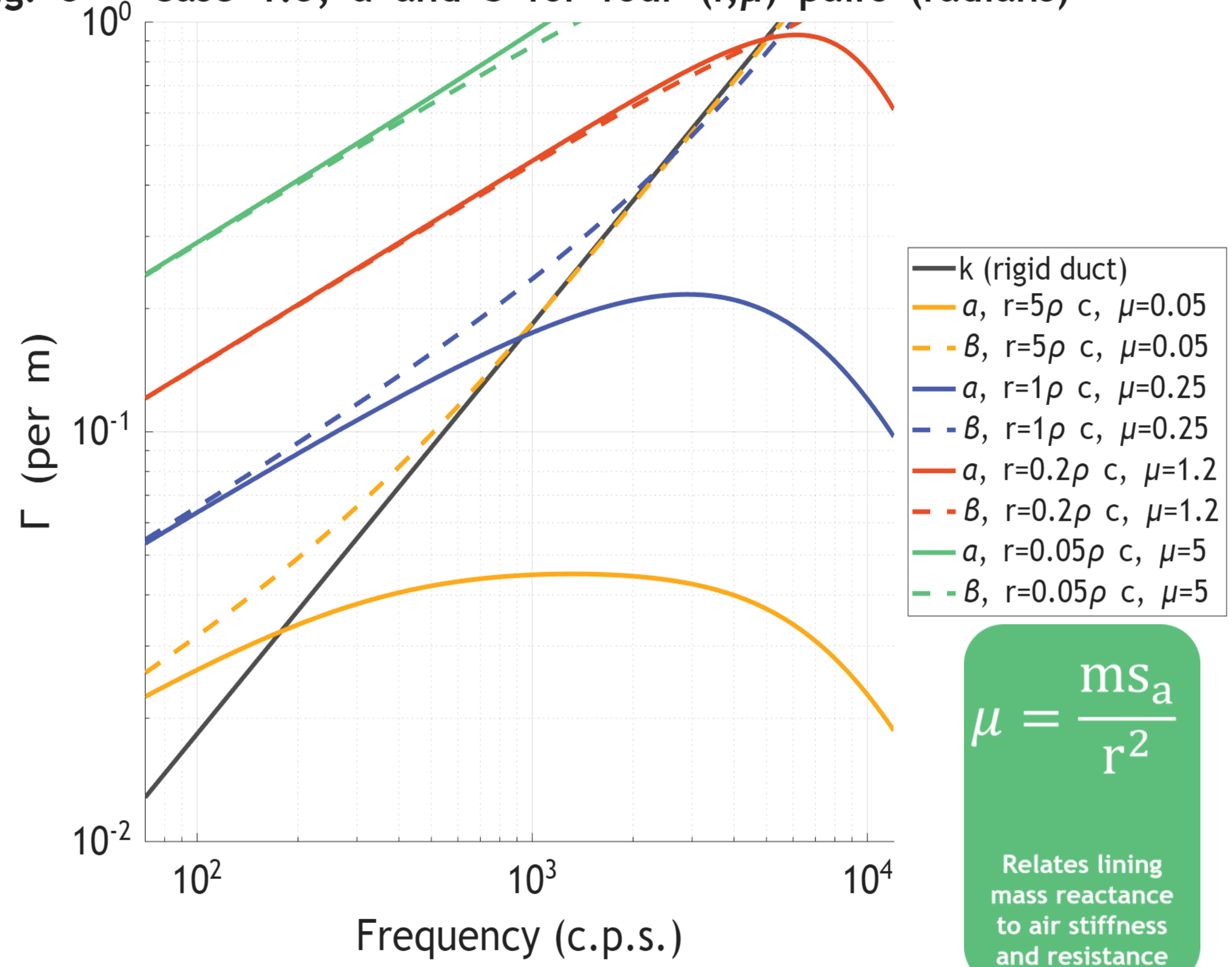
Surface Impedance

$$z = r + i\omega m$$

Auxiliary Impedance Function

$$M^2 = 1 + \frac{1}{q + iq^2}$$

Fig. 8 -- Case 1.3, *α* and *β* for four (r,*μ*) pairs (radians)



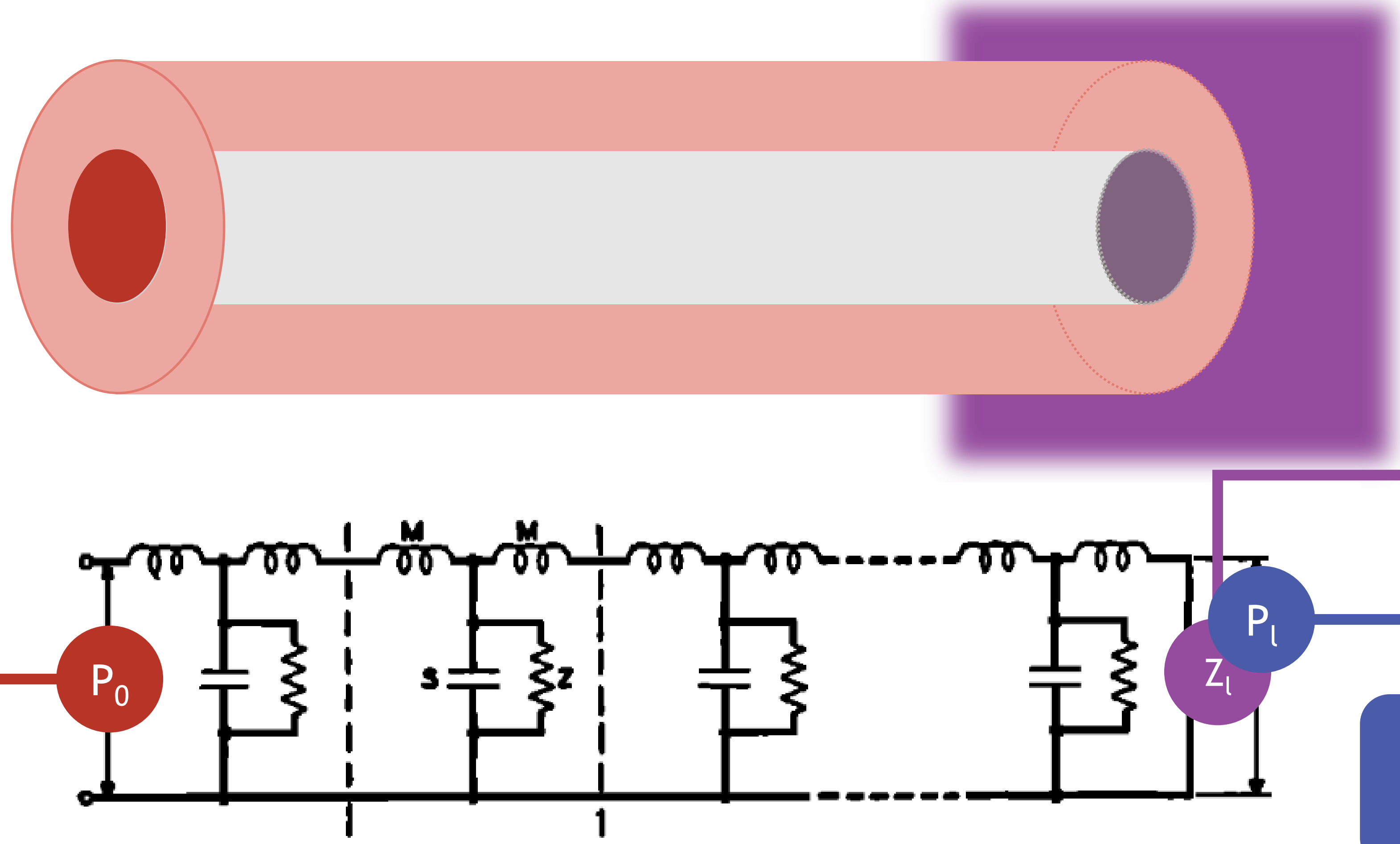
$$\mu = \frac{\mathrm{ms_a}}{\mathrm{r}^2}$$

Relates lining mass reactance to air stiffness and resistance

Duct Transmission and Experimental Comparisons

Duct of Finite Length and Open Termination

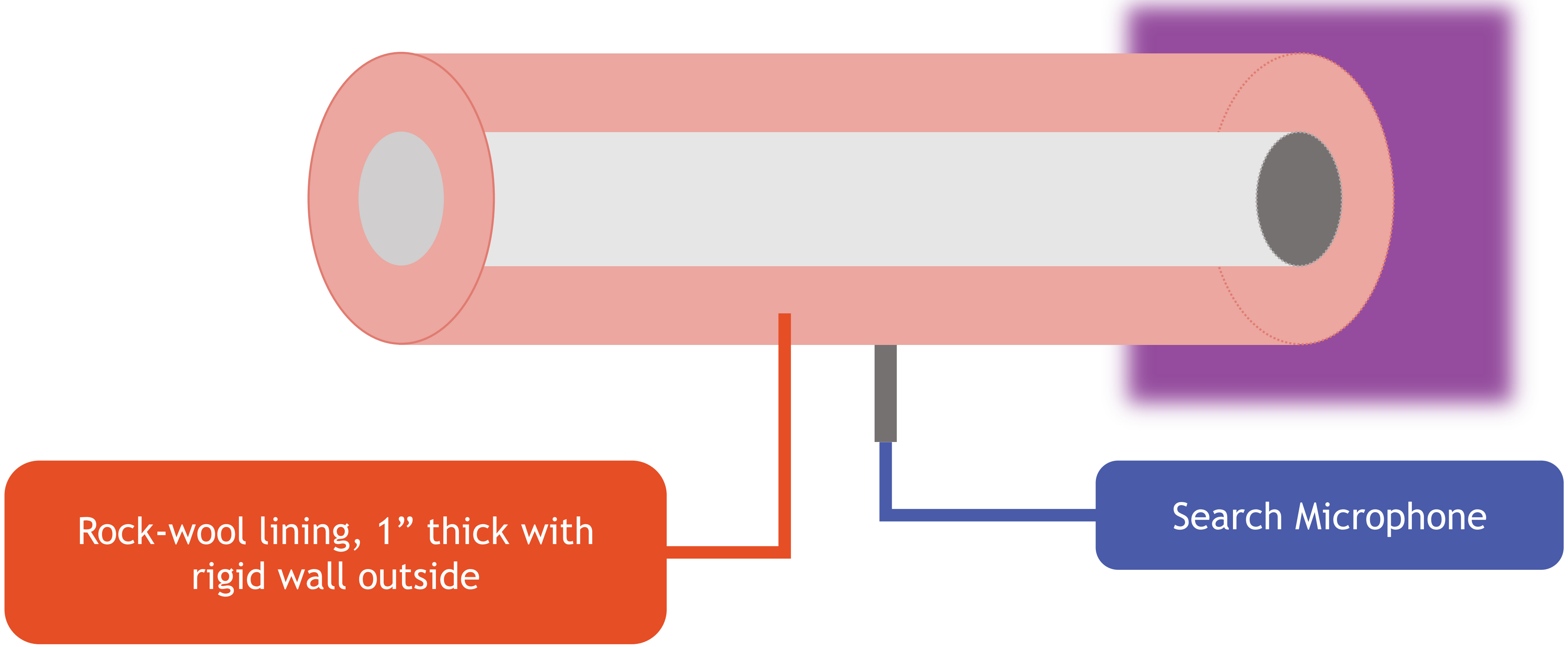
Sound Source



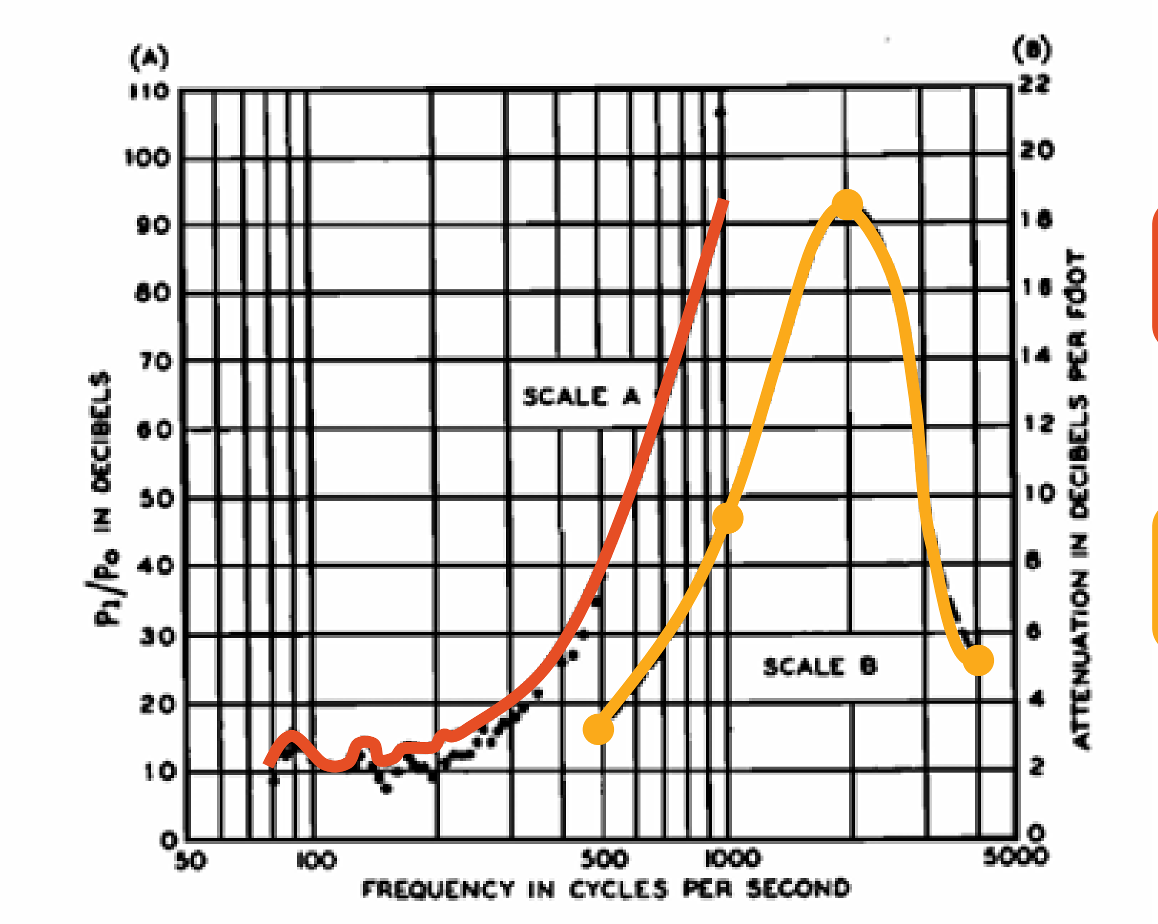
Open to air, with infinite baffle, z_l

Pressure at Duct Outlet

Duct of Finite Length and Open Termination



Calculations vs. Experimental Results



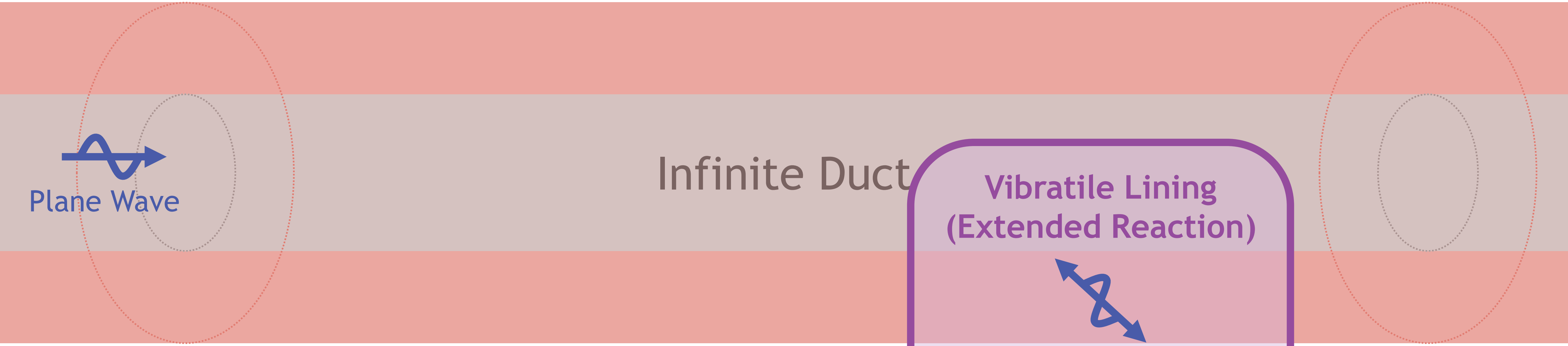
Calculated P_1/P_0

Attenuation (dB/ft)

With D.C flow speeds up to 2,100 ft/min, the acoustic attenuation was found to be within 5% of the no-flow cases at 500 and 1000 Hz

Part B: Vibratile Linings

The Problem and Sivian's Assumptions



Vibratile Lining (Extended Reaction)

Sound can propagate axially through the liner (along the duct axis)

Propagating Waves

Wall Propagation Constant

$$\Gamma_w = \left(i\omega \cdot \frac{r_e + i\omega m}{s + i\omega r} \right)^{\frac{1}{2}}$$

"Mostly Air-Borne" Wave

$$\Gamma_1^2 = \tfrac{1}{2}(\Gamma_w^2 - k^2 - R)$$

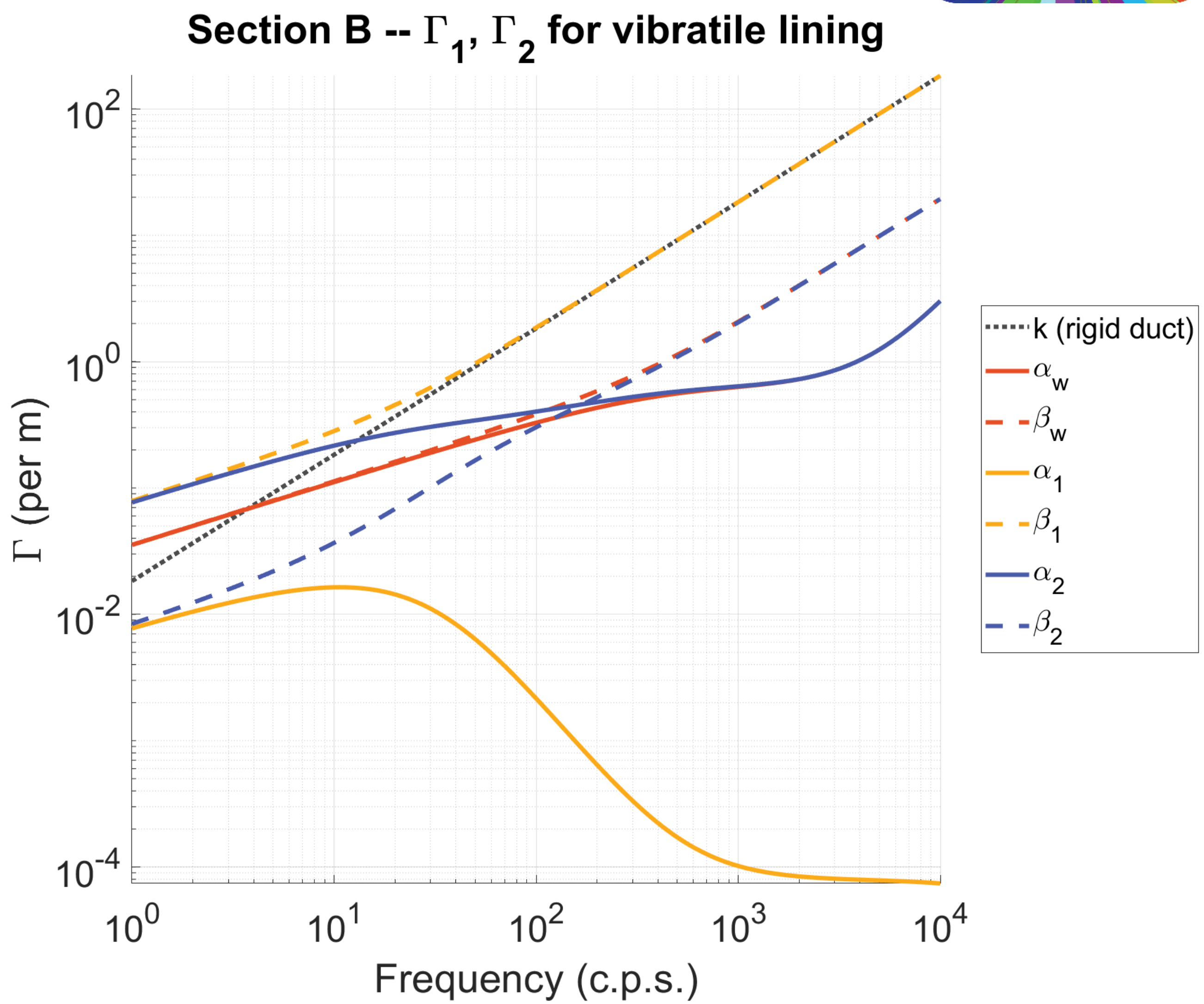
where $R = [(\Gamma_w^2 - k^2)^2 + 4k^2\Gamma_w^2 + 4k^2 s_a/(s + i\omega r)]^{\frac{1}{2}}$

"Mostly Structure-Borne" Wave

$$\Gamma_2^2 = \tfrac{1}{2}(\Gamma_w^2 - k^2 + R)$$

where $R = [(\Gamma_w^2 - k^2)^2 + 4k^2\Gamma_w^2 + 4k^2 s_a/(s + i\omega r)]^{\frac{1}{2}}$

As the frequency increases, the coupling between the two waves decreases and the waves become almost completely fluid-borne and structure-borne



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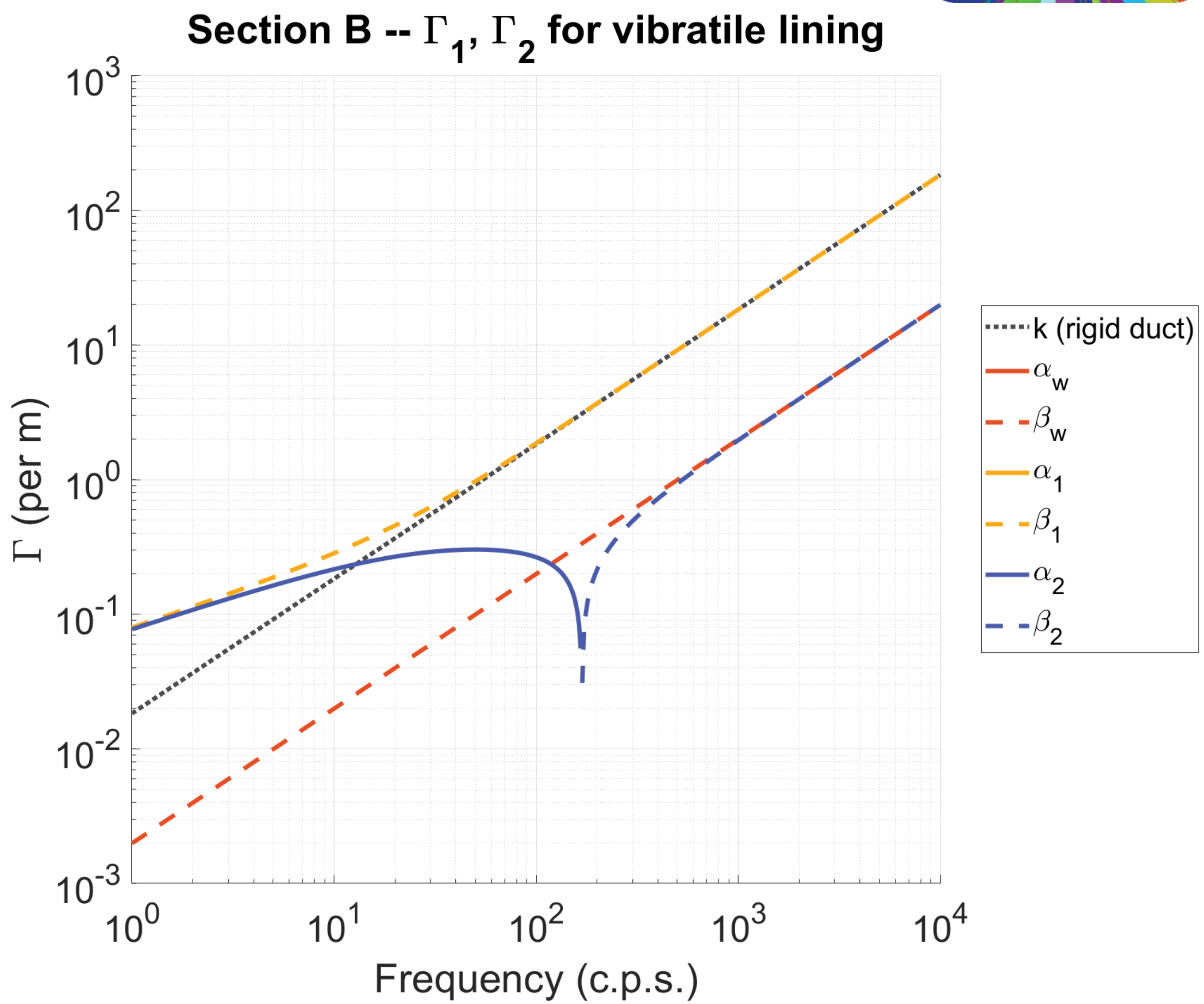
In a no dissipation case, we see that no propagation occurs in the structure-borne wave until the cuton frequency



A Historical Perspective of Liners in Grazing Flow

1937 vs. Present Day Differences and Similarities

What is considered common knowledge?

- Sivian doesn’t explicitly define all variables used
- Lack of citations of other work

Effects of Cut-on Modes

- Limits frequency range to when half the wavelength is greater than the diameter of the tube cross-section ($0.5\lambda > 2a$)
- Discusses what sounds like a (0,1) duct mode

Measurement Similarities

- Plane wave
- Measure pressure along the duct axis to find the propagation constant
- Surface impedance is still the “state of the art”

Vibratile and Non-Vibratile vs. Local and Extended Reaction

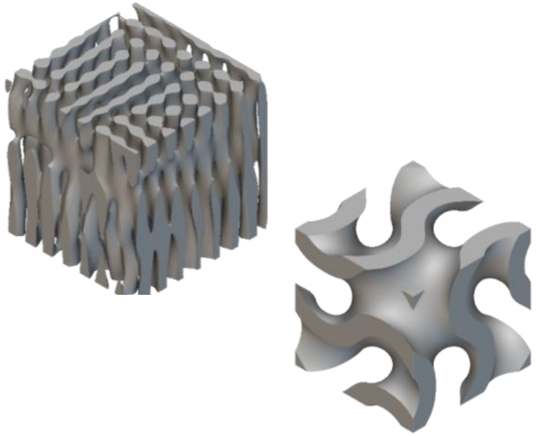
Study Extended Reaction (Vibratile) Linings

Mitigating grazing flow impedance eduction errors in additively manufactured porous liners
presented by Kara Hardy, Friday (tomorrow) 10:40 AM, Melbourne

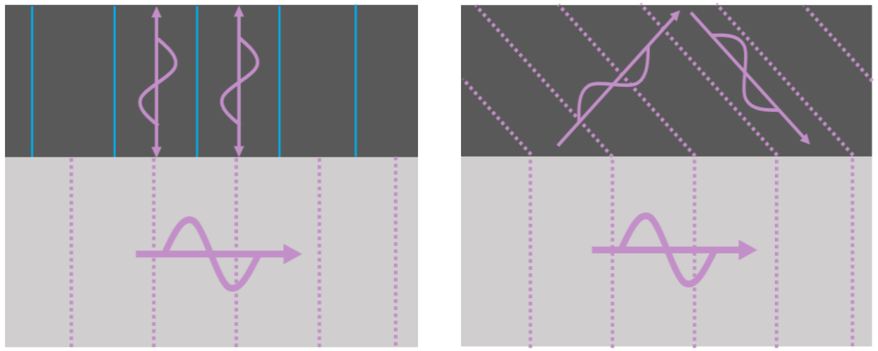
Traditional absorbers behave like quarter-wavelength resonators, attenuating a very small band of frequencies

Bulk absorbers tend to have a more broadband response, better for current aircraft engine acoustic environments

Bulk Absorbers (Extended Reacting) [6]



Extended reacting absorbers violate the locally reacting assumption that grazing flow impedance eduction uses, making them un-engineer-able [7-9]



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Thank You!