Muffler Acoustics - Application to Automotive Exhaust Noise Control

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Lecture - 59
Dissipative Mufflers (Lined Circular duct) - A Brief Discussion

Welcome to lecture 59, the final lecture where the almost the final technical lecture of this course on Muffler Acoustics, NPTEL course on Muffler Acoustic. So, we have covered most of the topics that we intended to do.

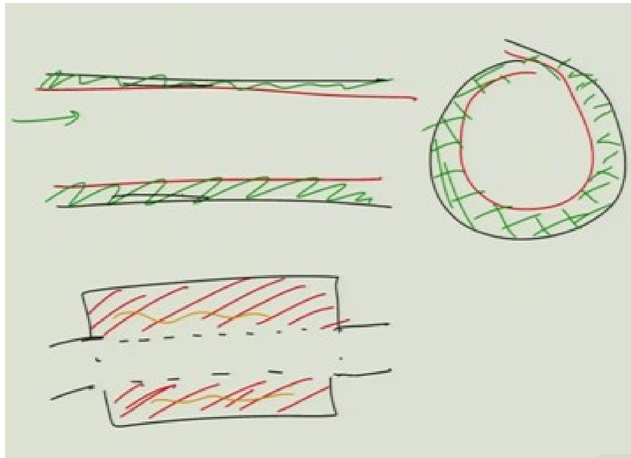
Obviously, muffler acoustics is a huge area, I will be talking about topics to be covered in an advanced course later on in lecture 60 and I will be summarizing all that we have done in the next lecture, final lecture, but the purpose of this lecture is to give you a very brief introduction on the dissipative or the lined muffler concept that is that will be covered later.

Right now, we will just give a, what I will present is just a small introduction so for that I will kind of refer to the book on acoustic reduction mufflers by Munjal and here, what basically you know the different models to you, to analyze a lined muffler or a dissipative muffler. This is the first time we are just you know discussing about these thing.

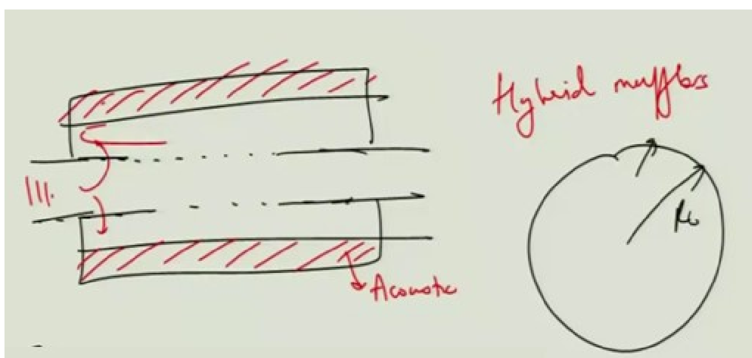
So, basically what happens is that you know if you go to your duct like this the different kind of mufflers lined muffler so, suppose you line the boundary of this thing by something like material. So, when you have such a thing then you realize that you know the waves as the as it traverse across this thing, across the duct you know they are attenuated as they propagate along the duct.

So, what happens is that their amplitude decays and significant amount of acoustic power is dissipated in this duct. So, here you know the main action of this dissipative material is to absorb basically, absorb the energy acoustic energy where basically converted into heat as the waves propagate.

So, that this is a simple line duct, but you can typically have sort of muffler configuration, lined muffler configuration something like this. You have perforated duct and the inside of this is filled with your rock wool, glass wool, mineral wool or some kind of a, acoustic absorbent material.



So, you have this kind of a thing or else another kind of muffler that dissipative muffler that usually is encountered is this sort of a thing which is called hybrid muffler really. So, you do not allow flow to completely expand feel like I have been sort of mentioning. So, you have this you have this kind of a configuration.



So, this is you know what happens here this is a sudden, but the wave as it the wave front as it enters here, it see the sudden expansion here, at the same time the waves at propagate in the annular region they are also absorbed, they are also interacted upon by the by the lining here this is acoustic lining. So, this is called hybrid muffler, because it basically employees the principle of sudden expansion or contraction and you can also have extensions like I was talking about.

So, similar, but this is called a purely dissipative muffler and these are like lined ducts, other than that you also have parallel baffle mufflers something like you know we will we will soon see the figure.

So, the main thing is that we just going to discuss different the different ways to calculate the transmission loss or develop mathematical models, but we can just give you a small introduction just about 10-15 minutes to you know to get your feel of this.

So, basically they are two models local reaction and the bulk reaction. So, in the slide that I have presented here, what we do is that you know the acoustic all this while if the duct was rigid normal thing was that

$$\frac{p}{U_r} = Z \uparrow^{\infty}$$

that can happen Z is tending to infinity, this can happen only when u were the radial velocity is going to 0. So, that is what we do.

We basically put this condition the derivative, the radial derivative of the acoustic pressure or the derivative of the Bessel function is 0 at the boundary at the radius of the in a radius of the chamber at R_0 to get the rigid wall mode, but if this is not the case if you have

$$\left.\frac{dJ_m k_r l}{dl}\right|_{l=R_0} = 0$$

where Z can be complex quantity then you have a lined reaction ok. So, this is what a local reaction is. So, you evaluate this $\frac{p}{U} = Z$ the get you know evaluate get a dispersion relation solve for that and get back the analytical solution which will soon browse through that and you know develop a way, develop a transfer matrix which relates stuff from here to here far from here to here taking into account local reaction of p / u kind of a, compliance kind of a thing here or otherwise you can also consider you know wave propagation.

You can also consider wave propagation within this area, within this region and that is called bulk reaction. So, there are two models local reaction, bulk reaction. Bulk reaction is sort of more accurate, because it considers wave propagation here, but local reaction is also used quite a lot, because of its simplicity. So, what we will do is that we will just go through that in the next 10 minutes.

1.7.1 Rectangular Duct with Locally Reacting Lining

So, rectangular duct you know you have this momentum equation Euler, you know, anyway the particle velocities along the x and y direction and now, when you have this p so we employ this you know impedance condition

$$\rho_0 \frac{\partial u_x}{\partial t} + \frac{\partial p}{\partial x} = 0 \qquad (1.122)$$

or

$$u_x = -\frac{\partial p/\partial x}{j\omega\rho_0} \qquad (1.123)$$

Similarly

$$u_y = -\frac{\partial p/\partial y}{j\omega\rho_0} \qquad (1.124)$$

Thus, the boundary conditions for a duct with uniform normal wall impedance Z_w would be

$$\frac{p(0,y,z,t)}{-u_x\,(0,y,z,t)} = \frac{p(b,y,z,t)}{-u_x\,(b,y,z,t)} = Z_{wx}, \qquad (1.125)$$

$$\frac{p(x,y,z,t)}{-u_y\,(x,y,z,t)} = \frac{p(x,y,z,t)}{-u_y\,(x,y,z,t)} = Z_{wy}, \qquad (1.126)$$

Substituting solution (1.25) and Equations 1.123 and 1.124 in the four boundary conditions (1.125) and (1.126) yields

$$\frac{\omega\rho_0(1+C_3)}{-k_x(1+C_3)} = Z_{wx} \qquad (1.127)$$

$$\frac{\omega\rho_0 e^{-jk_x b} + C_3\, e^{jk_x b}}{k_x\, e^{-jk_x b} + C_3\, e^{+jk_x b}} = Z_{wx} \qquad (1.128)$$

$$\frac{\omega\rho_0(1+C_4)}{-k_y(1+C_4)} = Z_{wx} \qquad (1.129)$$

$$\frac{\omega\rho_0 e^{-jk_y b} + C_3\, e^{jk_y h}}{k_x\, e^{-jk_y b} + C_3\, e^{+jk_y h}} = Z_{wy} \qquad (1.130)$$

And now this impedance like I said it is not infinity, if it is infinity then u x has to be 0, u y has to be 0. Similarly, for the circular duct, you know for a circular duct we do not have, where is it; I guess bit down.

$$\left[\frac{\partial^2}{\partial t^2} - C_0\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}\right)\right] p = 0 \qquad (1.142)$$

$$p(r,\theta,z,t) = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} J_m\left(k_{r,n} r\right) e^{jm\theta}\, e^{j\omega t} \times \left\{C_{1,m,n}\, e^{-jk_{z,m,n}z} + C_{2,m,n}\, e^{+jk_{z,m,n}z}\right\} \qquad (1.143)$$

So, this is the model solution and this is the Euler equation that we get and if u_r a 0 then of course, your Z_w tends to infinity, but that; that is not the case for lined duct or a complain duct.

So, you have this condition:

$$\rho_0\frac{\partial u_r}{\partial t} + \frac{\partial p}{\partial r} = 0 \qquad (1.144)$$

yields

$$u_r = -\frac{\partial p/\partial r}{j\omega\rho_0} \qquad (1.145)$$

Therefore,

$$Z_w \equiv \left(\frac{p}{u_r}\right)_{r=r_i} = \frac{-j\omega\rho_0 p}{\frac{\partial p}{\partial r}} \qquad (1.146)$$

$$= \frac{-j\omega\rho_0\, J_m\left(k_{r,m,n} r_i\right)}{k_{r,m,n}\, J'_m\left(k_{r,m,n} r_i\right)} \qquad (1.147)$$

where

$$J'_m(k_{r,m,n}r_i) = \left[\frac{dJ_m\left(k_{r,m,n}r\right)}{d\left(k_{r,m,n}r\right)}\right]_{r=r_i} \qquad (1.148)$$

Thus, $k_{r,m,n,}$ $n = 0, 1, 2 \ldots$ are the infinite roots of the transcendental eigen equation

$$\frac{J_m(k_{r,}r_i)}{(k_{r,}r_i)J_1(k_{r,}r_i)} = j\frac{Z_w}{\rho_0 C_0}\frac{1}{k_0 r_i} \qquad (1.149)$$

Where, m this m n is the mnth mode and Z_w can be a complex quantity in general which depends on the properties of the absorbent material.

So, you have a regular model solution which is solution of the Helmholtz equation from the moment[um] from the momentum equation derive the expression of the particle velocity, radial particle velocity and get the expression for impedance where this is the derivative and technically as usual it will give you infinite roots, just like we had infinite roots for the for the rigid wall case, you know for a given order m there the set of ordered roots you know ah, because it belongs to the properties of Sturm Liouville problem.

But similarly here also, you have forgiven m we have a set of ordered roots and once you get Z_w expression you can find out the these roots and substitute back in the expression for the particle velocity as well as the pressure to get the field acoustic pressure field in a line duct and once we and, this is the dispersion relation that is usually considered.

$$p(r,\theta,z,t) = \sum_{n=0}^{\infty} J_0\left(k_{r,n}r\right)e^{j\omega t} \times \left\{C_{1,m,n}\, e^{-jk_{z,m,n}z} + C_{2,m,n}\, e^{-jk_{z,m,n}z}\right\} \qquad (1.151)$$

where $k_{r,n}$ is the (n + 1)th of the root of the eigen equation

$$\frac{J_0(k_{r,n}r_i)}{(k_{r,n}r_i)J_1(k_{r,n}r_i)} = j\frac{Z_w}{\rho_0 C_0}\frac{1}{k_0 r_i} \qquad (1.152)$$

And one thing that is there is that you know for a line duct or a dissipative duct the plane wave mode does not really exist, because dissipative duct means that a pressure even for the lowest order mode, we talk about the least attenuated mode or the lowest order mode the pressure variation will be there across the cross section. So, the plane wave mode does not exist.

So, next to happens is the duct is heavily damped. If there is a significant damping even the first few modes you can help us get a good you know estimation the transmission loss in the low frequencies at least and then there bulk reaction, rectangular duct with the bulk reaction model where you consider wave propagation within this thing also.

$$p(z,r,t) = C_1 J_0 \left(k_{r,0} r\right) e^{-jk_z z} e^{j\omega t} \tag{1.170}$$

$$u_{z,0}(z,r,t) = \frac{k_z}{\omega \rho_0} C_1 J_0 \left(k_{r,0} r\right) e^{-jk_z z} e^{j\omega t} \tag{1.171}$$

$$u_{z,0}(z,r,t) = j \frac{k_{r,0}}{\omega \rho_0} C_1 J_1 \left(k_{r,0} r\right) e^{-jk_z z} e^{j\omega t} \tag{1.172}$$

Inside the wall lining (subscript w):

$$p_w(z,r,t) = C_2 \{J_0 \left(k_{r,w} r\right) + C_3 N_0 \left(k_{r,w} r\right)\} e^{-jk_z z} e^{j\omega t} \tag{1.173}$$

$$u_{z,w}(z,r,t) = \frac{k_z}{\omega \rho_0} C_2 \{J_0 \left(k_{r,w} r\right) + C_3 N_0 \left(k_{r,w} r\right)\} e^{-jk_z z} e^{j\omega t} \tag{1.174}$$

$$u_{z,w}(z,r,t) = \frac{-jk_{r,w}}{\omega \rho_0} C_2 \{J_1 \left(k_{r,w} r\right) + C_3 N_1 \left(k_{r,w} r\right)\} e^{-jk_z z} e^{j\omega t} \tag{1.175}$$

Similarly, **bulk reaction** model will also given an for a circular duct, where you have this expressions for the pressure in the airway and that in the in annular cavity and then you get this you get this basically, you are compatibility sort of conditions and once and then we get the dispersion relation for this kind of a thing.

The overriding compatibility conditions:

$$k_{z,0} = k_{z,w} = k_z \ (say) \tag{1.176}$$

$$k_z^2 + k_{r,0}^2 = k_0^2 \implies k_{r,0} = \{k_0^2 - k_z^2\}^{1/2} \tag{1.177}$$

$$k_z^2 + k_{r,w}^2 = k_w^2 \implies k_{r,w} = \{k_w^2 - k_z^2\}^{1/2} \tag{1.178}$$

Which, yield the impedance relationship

$$Z_{r,0}(r_i,\omega) = Z_{r,w}(r_i,\omega), \qquad Z_r = \frac{p}{u_r} \tag{1.182}$$

$$J\ \frac{\omega\rho_0 J_0(k_{r0}r_i)}{k_{r,0}J_1\left(k_{r,0}r_i\right)} = j\,\frac{\omega\rho_w J_0\left(k_{r,w}r_i\right) + C_3 N_0\left(k_{r,w}r_i\right)}{k_{r,0}J_1\left(k_{r,w}r_i\right) + C_3 N_1\left(k_{r,w}r_i\right)} \tag{1.183}$$

And finally, you know the whole idea of doing a bulk reaction is to simultaneously, consider you know wave propagation in this domain as well as this domain are coupled kind of analysis. So, that is naturally expected to be more accurate and one can find out the transfer matrix.

Let me go to the chapter 6, I reckon or the muffler acoustics book duct and muffler duct acoustics of ducts and mufflers by Munjal, where a practical expressions are sort of presented for measuring the transmission or obtaining the transmission loss.

So, where I will go for the case of a circular duct only for the lack of time you know.

$$\left[\frac{D^2}{Dt^2} - C_0^2\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2} + \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}\right)\right]p = 0 \tag{6.28}$$

$$\begin{aligned} p(r,\theta,z,t) = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\ &\{C_{1,m,n}J_m\left(k_{r,m,n}^{+}r\right)e^{-jk_{z,m,n}^{+}z} \\ &+ C_{2,m,n}J_m\left(k_{r,m,n}^{-}r\right)\left(k_{r,m,n}^{-+}r\right)e^{+jk_{z,m,n}^{+}z}\}e^{im\theta}e^{i\omega t} \end{aligned} \tag{6.29}$$

So, I will and that to with the moving medium. So, in moving medium you have k z plus k z minus like we have been discussing and you have this model.

$$\frac{J_m\left(k_{r,m,n}^{+}r_0\right)}{\left(k_{r,m,n}^{+}r_0\right)J'_m\left(k_{r,m,n}^{+}r_0\right)}\left(1\frac{Mk_{z,m,n}^{+}}{k_0}\right) = j\frac{Z_w(M)}{\rho_0 C_0}\frac{1}{k_0 r_0} \tag{6.36}$$

So, we get this constants and then from the dispersion relation we can find out k z m n plus minus for a given k_r can be found out using solving the dispersion relation as we obtained previously also for given

$$k_{r,m,n}^{+} = \frac{\mp Mk_0 + \left[k_0^2 - (1-M)k_{r,m,n}^{\pm 2}\right]^{1/2}}{1-M} \tag{6.37}$$

For a perforate impedance expression has to be known as of now sorry, the impedance expression for a line duct which is backed by a perforated sheet has to be obtained which when we will soon see the expressions for that and once you obtain p and u we can find out the transfer matrix for a dissipated duct.

$$u_z\,(r,\theta,z,t) = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{1}{\rho_0 C_0}\left[\frac{k_{z,m,n}^{+}}{k_0 - Mk_{z,m,n}^{+}}\,C_{1,m,n}J_m\left(k_{r,m,n}^{+}r\right)\,e^{-jk_{z,m,n}^{+}z}\right.$$

$$\left.-\frac{k_{z,m,n}^{-}}{k_0 + Mk_{z,m,n}^{-}}\,C_{2,m,n}J_m\left(k_{r,m,n}^{+}r\right)\,e^{+jk_{z,m,n}^{-}z}\right]e^{im\theta}e^{i\omega t} \qquad (6.39)$$

So, we will talk about only the least attenuated mode m is equal to 0, n is equal to 0 and drop the high order modes and let us worry about the circular duct only.

$$v(Z) = \frac{A}{Y^{+}}\,e^{-jk_z^{+}z} - \frac{B}{Y^{-}}\,e^{-jk_z^{-}z} \qquad (6.45)$$

So, over a circular duct, it will it will be like this. Z_w is related to the least attenuated mode is given by is obtained or the roots are obtained k r is obtained by solving this equation numerically, say using some Newton Raphson scheme or things like that.

$$p(0) = A + B \qquad (6.48)$$

$$v_z(0) = \frac{A}{Y^{+}} - \frac{B}{Y^{-}} \qquad (6.49)$$

$$A = \frac{p(0)/Y^{-} + v_z(0)}{1/Y^{-} + 1/Y^{+}} = \frac{Y^{+}\{p(0) + Y^{-}v_z(0)\}}{Y^{-} + Y^{+}} \qquad (6.50)$$

And

$$B = \frac{p(0)/Y^{+} - v_z(0)}{1/Y^{-} + 1/Y^{+}} = \frac{Y^{-}\{p(0) - Y^{-}v_z(0)\}}{Y^{-} + Y^{+}} \qquad (6.51)$$

Particle velocity is obtained and then the mass volume, mass velocity is obtained and from these relation 6.45 you know velocity and actually 6.48 and 6.49 once we get that we can obtain the transfer we can obtain the transfer matrix parameters, where we relate the upstream variable to the downstream variable and cooperating only the and cooperating only the least order mode.

So, the effect of all the information pertaining to the dissipative or the line duct is stored already in k z's which is you know k z is related to k r using the you know the dispersion relation k k z square plus k r square is equal to k naught square ok.

$$k_z^{\pm} = \frac{\mp M k_0 + [k_0^2 - (1-M)(k_r^{\pm})^2]^{1/2}}{1-M^2} \qquad (6.42b)$$

So, and k r itself is found out using your this equation ok.

$$\frac{Z_{w,x} k_x^{\pm}}{\rho_0 C_0 k_0} = jcot\left(\frac{k_x^{\pm} b}{2}\right)\left(1 \mp \frac{M k_z^{\pm}}{k_0}\right)^2 \qquad (6.43a)$$

$$\frac{Z_{w,y} k_y^{\pm}}{\rho_0 C_0 k_0} = jcot\left(\frac{k_y^{\pm} h}{2}\right)\left(1 \mp \frac{M k_z^{\pm}}{k_0}\right)^2 \qquad (6.43a)$$

and

$$\frac{Z_{w,}}{\rho_0 C_0} \frac{1}{k_0 r_0} = -j \frac{j_0 k_r^{\pm} r_0}{(k_r^{\pm} r_0) j_0 (k_r^{\pm} r_0)} \left(1 \mp \frac{M k_z^{\pm}}{k_0}\right)^2 \qquad (6.43c)$$

$$u_z(Z) = \frac{1}{\rho_0 C_0}\left\{\frac{k_z^{+}}{k_0 - M k_z^{+}} \; A e^{-jk_z^{+} z} - \frac{k_z^{-}}{k_0 + M k_z^{-}} \; A e^{+jk_z^{-} z}\right\} \qquad (6.44)$$

So, you can just M is equal to 0 and find out things you can solve for k r and then you can find out k z is root over k naught square minus k r square to get the transfer matrix for infinite length duct or not assuming any reflections.

$$\begin{aligned} &= [1/(Y^+ + Y^-)] \left[\left\{Y^+ e^{-jk_z^{+} l} + Y^- e^{+jk_z^{-} l}\right\} p(0) \right. \\ &\qquad \left. + \; Y^+ Y^- \left(e^{-jk_z^{+} l} - e^{+jk_z^{-} l}\right) V_z(0)\right] \quad (6.53) \end{aligned}$$

Similarly,

$$\begin{aligned} V(l) &= [1/(Y^+ + Y^-)] \left[\left\{e^{-jk_z^{+} l} - e^{+jk_z^{-} l}\right\} p(0) \right. \\ &\qquad \left. + \; \left\{Y^- e^{-jk_z^{+} l} + Y^+ e^{+jk_z^{-} l}\right\} V_z(0)\right] \quad (6.54) \end{aligned}$$

$$\begin{bmatrix} p(l) \\ V_z(l) \end{bmatrix} = \begin{bmatrix} \dfrac{Y^+ e^{-jk_z^+ l} + Y^- e^{-jk_z^- l}}{Y^+ + Y^-} & \dfrac{Y^+ Y^- (e^{-jk_z^+ l} - e^{+jk_z^- l})}{Y^+ + Y^-} \\ \dfrac{e^{-jk_z^- l} - e^{-jk_z^+ l}}{Y^+ + Y^-} & \dfrac{Y^- e^{-jk_z^+ l} + Y^+ e^{-jk_z^- l}}{Y^+ + Y^-} \end{bmatrix} \begin{bmatrix} p(0) \\ V_z(0) \end{bmatrix} \quad (6.55)$$

which can be inverted to yield the desired transfer matrix relation

$$\begin{bmatrix} p(0) \\ V_z(0) \end{bmatrix} = \frac{e^{j(k_z^+ - k_z^-)}}{Y^+ + Y^-} \begin{bmatrix} Y^- e^{-jk_z^+ l} + Y^+ e^{-jk_z^- l} & Y^+ + Y^- \left(e^{-jk_z^- l} - e^{-jk_z^+ l}\right) \\ e^{-jk_z^- l} - e^{-jk_z^+ l} & Y^+ e^{-jk_z^+ l} + Y^- e^{-jk_z^- l} \end{bmatrix} \begin{bmatrix} p(l) \\ V_z(l) \end{bmatrix}$$

(6.56)

Normal Impedance of the Lining

For the idealized case of plane wave incident on a locally reacting lining of uniform thickness d backed by a rigid wall, the impedance encountered by the plane wave, Zw, is given by Equation 2.26 that is

So, this can be related to that and the their expressions for the Z Z omega which is basically you know given by Y in terms of $Z_w = -jY_w \cot(k_w d)$ that is a characteristic impedance of the material and the wave number and they are well established formulas for obtaining that and they given in Ver's paper, Berenice and Ver.

$$k_0 = \omega/C_0 \ \ and \ Y_0 \rho_0 C_0$$

$$\frac{Y_w}{\rho_0 C_0} = \begin{bmatrix} 1 + 0.00485(A)^{0.754} - J0.087(A)^{0.73} & for\ A < 60 \\ \dfrac{0.5A/\pi + J1.4}{\{-1.466 - J0.212A\}^{1/2}} & for\ A > 60 \end{bmatrix} \quad (6.76)$$

$$\frac{Y_w}{\rho_0 C_0} = \begin{bmatrix} -j0.189(A)^{0.6185} + 1 + 0.0978(A)^{0.6929} & for\ A < 60 \\ \{1.466 - J0.212A\}^{1/2} & for\ A > 60 \end{bmatrix} \quad (6.77)$$

So, it is given in the these non dimensional expressions which are obtained experimentally or through lot of simulations then they are two expressions given in Selamet's paper also. So, once we know it for a given material we can find out the Z w value and solve for that.

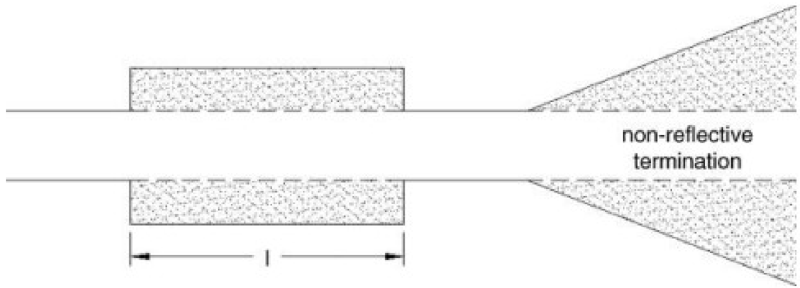


Figure 6.6 Measurement of the transmission loss of an acoustically absorptive duct

So, transmission loss for such a thing for a for a you know this kind of a muffler is basically you know it can be it can be thought or something like 8.68 that is simple algebraic simplification time alpha naught where alpha naught is the pressure attenuation constant for a low least order mode and for the muffler that I showed here this one the transmission loss would actually sort of you know look like it is given here.

TL_{ent} is TL due to the area change at the entrance,

Tl_l is TL due to the absorptive section of length l, and

TL_{ex} is TL due to the area change at the exit of the absorptive section.

$$TL \simeq TL_l \qquad (6.82)$$

$$TL_l = 20\log\left|\frac{p(0)}{p(l)}\right| \simeq 20\log\,(e^{\alpha 0 l}) = 8.68\alpha 0 l \qquad (6.83)$$

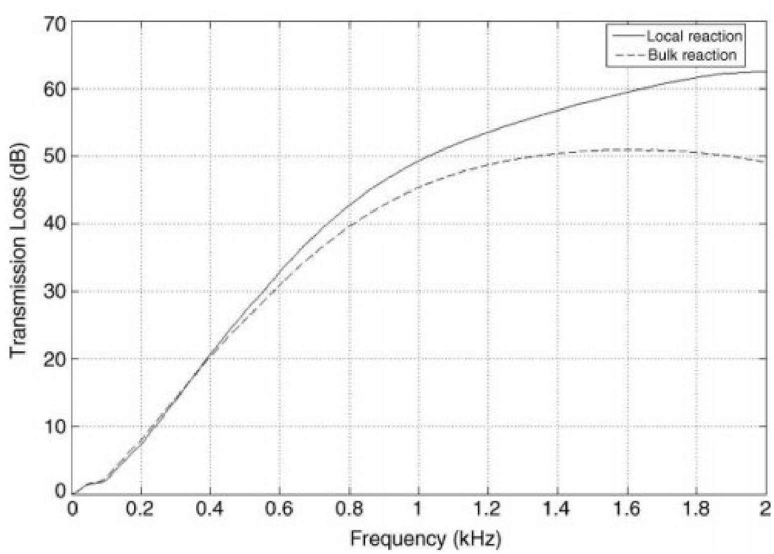


Figure 6.9: Effect of model on transmission loss of a 1-m lined circular duct with d = h = 50mm, protected by a steel plate with porosity of 0.39.

You know low frequencies are you know that dissipative mufflers are sort of less effective at low frequencies and more effective towards higher frequency. So, you typically combine reactive muffler with hybrid muffler a hybrid sorry, reactive muffler with your dissipative thing. You typically put that dissipative element in the downstream of the reactive elements and control the attenuation, after the first cut on frequency where high order mode start and that there is a difference between local reaction and bulk reaction.

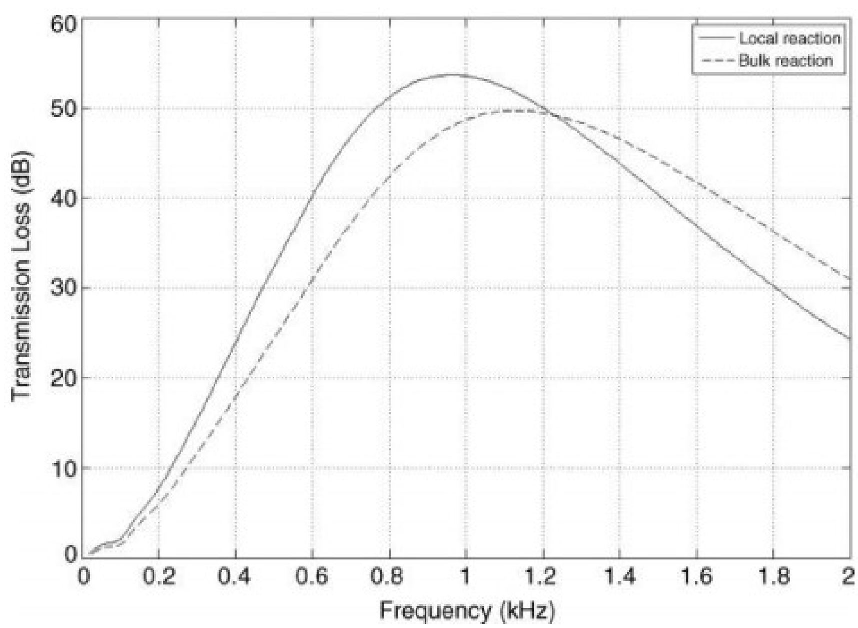


Figure 6.10: Effect of model on transmission loss of a 1-m lined circular duct with d = h = 50 mm, protected by 0.04mm thick Mylar layer.

So, these are the things for a circular duct with different values of d and h, certain parametric values.

And then they are things like; I will quickly go to parallel baffle mufflers where what happens here that in the flow passage, the flow you know this split into number of parts, number of segments, depending upon baffles or which are lined baffles and as the waves goes through these baffles they are attenuated and typically an engineering from an, purely from an engineering perspective what happens is that you know have a look at this graph.

$$\frac{S}{P} = \frac{W \times 2h}{2W} = h$$

Now acoustic attenuation is known to be proportional to P=S, the ratio of the lined perimeter and flow area, and, of course, length l. Thus one could write

$$TL_l = TL_h \cdot l/h$$

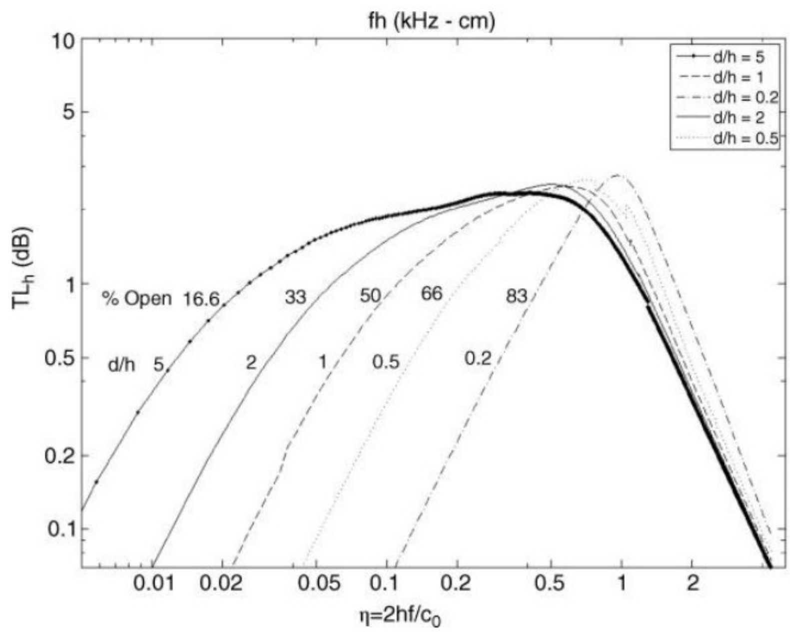


Figure 6.14: Normalized attenuation versus frequency curves for parallel-baffle mufflers, illustrating the effect of percentage open area on attenuation bandwidth for $R = \frac{Ed}{\rho_0 c_0} = 5$ (adapted from [7])

So, this is the graph where we can probably do some engineering based calculation.

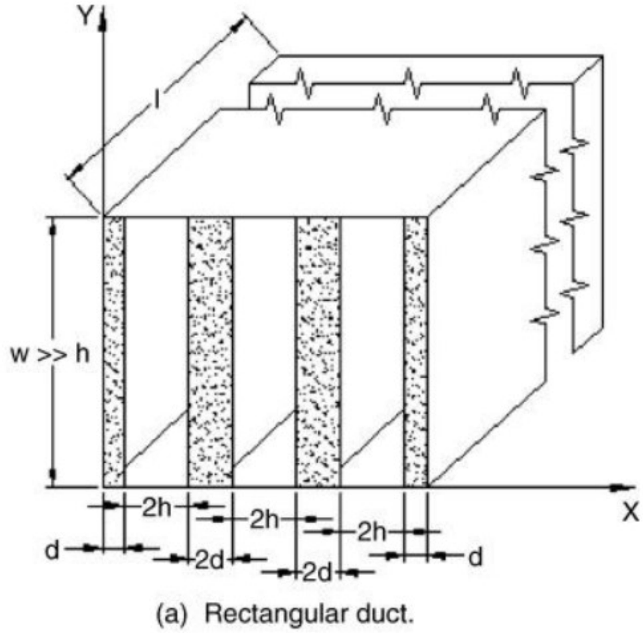


Figure 6.13 Parallel-baffle ducts or mufflers

So, h is the; h is the h is nothing, but the passage two times 2 h the passage length between the two successive baffles. w you know, w is the overall width and is much greater than the thickness of the and it is much greater than the passage length and d is a is the thickness of the baffle ok.

So, and the h the and another parameter one very important parameter in such a context is basically the attenuation produced per unit length h, per unit length per unit length h of the of the baffle, it is called the specific attenuation and so once we know the length, overall length or attenuation produced per unit thickness of the of the baffle.

$$\frac{S}{P} = \frac{W \times 2h}{2W} \qquad (6.97)$$

Now acoustic attenuation is known to be proportional to P /S, the ratio of the lined perimeter and flow area, and, of course, length l. Thus one could write

$$TL_1 = TL_h . l/h \qquad (6.98)$$

So, once we know it, we can multiply this by the overall length and find out the total attenuation produced over a length l, once we know the specific attenuation for a thickness equal to h, where h is the half the transverse dimension of the flow passage as I was mentioning. So, once we know TL_h , we can find out for any length T L. So, how do you find out once we are given different h values and different d value? So, from these charts.

So, once you know what is d value for a perforated sorry, parallel baffle muffler so, parallel baffle muffler as it looks like here, you know this is the thickness of the perforated sorry, the thick baffles and 2 h is the twice is the thickness of the air passages through, air goes through the passage is where I am pointing my mouse cursor here, here, and this is the absorbent material of each of thickness d ok.

So, we look at a specific transmission loss for given d by h say for a d by h 5 is the ratio of the thickness of the thickness of the baffle, dissipative baffle sheet to the passage distance is 5 so that is you know that is basically this curve and it is plotted versus non dimensional frequencies. 2 h passage length f / C_0 sound speed ok. So, f / C_0 is the frequency by sound speed.

So, basically by second and this is meter by this is meter by second and this is c naught. So, this is also meter by second so, a eta is the non-dimensional frequency is apologies for the small confusion. So, if we consider d / h 5 and if you take a particular non dimensional frequency say 0.1 and we know the value of; if we know the value of h and d. So and d / h we know that the dimensions are in the d/ h is equal to 5 or something like that.

So, we consider that curve and for a given non dimensional value, we find out the specific attenuation, then multiplied that with the length, overall length that is required or the muffler to get the attenuation at that frequency ok, from these non-dimensional curve. So, suppose if it is between 5 and 1 so the 5 of 5 or 2 or something like that. So, we interpolate between for a given frequency we can interpolate between this value and this value to get a specific d l h and multiply with the length. Figure 6.14 as a function of the normalized frequency,

$$\eta \equiv 2hf/C_0$$

for parallel-baffle mufflers, with baffles of a normalized flow resistance,

$$R \equiv Ed/\rho_0 C_0 = 5$$

So, using such a thing you can find out the from an engineering perspective what will be the attenuation for a parallel baffle muffler. So, these are the normal attenuation curves for this thing.

Now, all this parallel baffle muffler concept and line chambers, plenum chambers, line ducts, all these things have to be you know considered in the much greater detail more formally, this is called this is not really something that I was justice to, because of lack of time.

What we really need to do in a next course is that consider at length, dissipative mufflers, hybrid mufflers and combination of this dissipative mufflers with this reactive mufflers to control specially high frequency noise. So, and; obviously, one challenge is always there to design or get an absorbent material which can control low frequencies as well, you know ah.

So, basically the idea is that we will cover a lot of topics in the next advanced course, but for now, I will just sort of stop here and in the next class we will summarize all that has been done and the course so far. So, I hope you really like the course and with this thing it brings and to the technical and to the technical presentation of the course.

So, hope to see you very soon in the future and please send your feedbacks. So, thanks a lot who attending, I am very grateful for all of you guys who have taken the course and do send your feedback and do complete the assignments and hopefully people who are registered for the exam should do well in the exam and thanks a lot.