Muffler Acoustics-Application to Automotive Exhaust Noise Control

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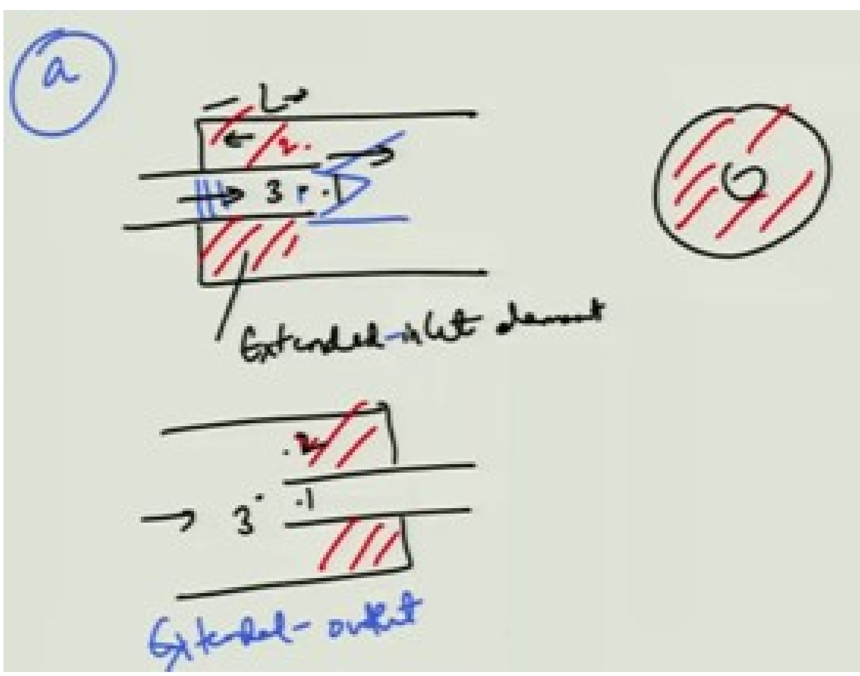
Lecture - 33
Transfer Matrix for Extended – Inlet and Outlet Element and Use of Perforated Elements in Commercial Mufflers

Welcome to lecture 3 of week 7 of this NPTEL course on Muffler Acoustics. So, as informed in the end of the last class, last lecture, lecture 2, I talked about deriving you know the loss factors and the basically the transfer matrix in the presence of mean flow for an extend inlet and outlet element, where we sort of incorporate the loss factors or the loss in the flow that is happening because of the mean flow effect.

So, now towards this end, what we do is that we sort of revisit some of the, you know muffler elements that we probably introduce in the I guess week 3 or probably beginning of week 4. So, we here we have an say let us say we have using the previous nomenclature. We have this muffler element.



Let us call this porters point is point 3 and the part that is right here point 2 and this guy is 1 ok. So, here we have this thing and there is a cavity and here we have a flow. So, this is an extended inlet element. You know the derivation that I am going to talk about now is sort of equally applicable to an extended outlet element.

Here we have pretty much the same nomenclature, that is your, apart from the fact that you know the chamber was the point in the chamber was mentioned as point 1 and here the a point just a the interface of the chamber in the port, but in the port itself is mentioned is point 1 ok. So, the thing is that we would like to develop a relation between a transfer matrix relation between the point 3 and 1 or 3 in 1 the flow is here in this direction. So, when it expands so what happens?

We have already seen, we already know pretty well by now it should be clear that this guy you know, the annular cavity, what does it do? This acts like a quarter wave resonator. It is a quarter wave resonator and it acts like a shunt element. So this transfer matrix whether for this 1 3 2 1 or 1 to 3 for the K, I need to rub this guy this understood here.

That was pretty a straight forward, p_3 V_3 for classical straight variables, this was pretty sort of straightforward. There was

$$\begin{Bmatrix} \tilde{p}_3 \\ \tilde{V}_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_2} & 1 \end{bmatrix} \begin{Bmatrix} \tilde{p}_1 \\ \tilde{V}_1 \end{Bmatrix}$$

$$Z_2 = -jY_0 \cot k_0 L$$

So, this one was pretty clear because p_3 is equal to p_1 and it is also equal to p_2 and velocity, mass velocity enters here gets split into 2 parts, one that goes into the annular cavity another one that propagates downstream.

So, V_3 is equal to V_2 plus V_1. So, that one was a pretty clear and we sort of related eliminated some variables that is variables pertaining to the annular cavity 2 and found out the transfer matrix between 3 and 1. So, in case of 0 min flow this is what we get, we do not have any problems with it. So, whether it is an extend inlet or extend outlet element it does not quite matter. However, when we do have flow things would be a bit different. So, we will see how to incorporate the flow losses that happens here.

So, basically let us first you know, although we are going to talk only in terms of you know a qualitative discussion, because quantitative discussion would involve some flow simulations you know some simulations to simulate the flow field and such a cavity.

But basically, when you know because real fluid will have viscosity, so when you have flow coming in here, so and it is sort of going out again there will be there will be potential core as we are discussing just at the beginning of this week's lecture and there will be that will be shared and it will create some noise ok.

It will definitely create some separation noise, but then there will also be you know something like a head loss. There will be lost associated with sudden expansion of the flow. So that is going to probably aid in later automation, but then the main worrisome feature is the noise that will be occurring due to the free shear layers that are formed here in the after the collapse of the potential core.

So that really is a culprit, and it is from our experimental observation that you never actually allow the flow to separate like this. You actually connected by a perforate bridge just like I was mentioning at the beginning of the last lecture. So, but nevertheless for the sake of completeness of this theoretical development and what is been usually classically taught, we do consider some loss factors.

You know what we can get, basically they are like head the related to head loss when the flow expands suddenly from a pipe and that would actually like I said aid in that animation. So, let us first get that, but obviously one would never allow the flow to expand or constructionally, it sort of it is counter-productive.

But we still derive some theoretical expression at it would you know sort of need much more comprehensive modern experimental validation. Let us begin our derivation for this thing. So, now, let us consider extended inlet element this is your extended outlet ok. So, let us focus on the figure a alright. What happens across this discontinuity?

So, unlike in the case of static medium that is whether it is 0 mean flow where the pressure is constant like I mentioned in the vast mass velocity gets into two parts you know. Here, the stagnation pressure or the perturbation pressure pc decreases across an area discontinuity. So, the stagnation pressure the perturbation pressure the convective pressure pc not $\tilde{p}_c$that decreases across an area discontinuity.

And because as the flow passes certain change the part of the flow acoustic energies converted into heat or basically losses, so that increase that results in an increase in entropy. So, that entropy increase in an up only in an approximate manner can be accounted through a parameter which is again you know sort of measured or experimentally determined for loss stagnation pressure for incompressible flows. So basically, at such a point you have let us

$$p_{S,3} = p_{S,1} + K\left(\frac{1}{\rho_0} U_1^2\right)$$

that is a stagnation pressure at the point 3 which is just upstream is equal to the stagnation pressure at point 1, but you also have a loss, loss factor half into rho naught into let us say U1 is the velocity in the chamber.

So, again continuity will apply we, but we will probably come to that later in a bit. So, here we have this, so K takes a certain form depending on whether a certain expansion or sudden contraction or say reversal cum expansion or a reversal cum contraction based on the elements that we discussed in week 3 I believe or towards the beginning of week 4.

You know K is sort of known from that thing, and although only approximately through classically, but here this will hold when as, for highly subsonic flows.

$$M_1^2 << 1$$

$$M_3^2 << 1$$

So, now if we get to expand this stagnation pressure into the pressure that plus you know your velocity contribution due to the velocity head. But here we have this because stagnation pressure.

$$p_{0,3} + \frac{1}{2}\rho_0 V_3^2 = p_{0,1} + \frac{1}{2}\rho_0 V_1^2$$

$$+K\left(\frac{1}{2}\rho_0 V_1^2\right) \qquad (1)$$

So, now, this loss coefficient I will probably talk about that present a table later, but what we immediately need to do is that since we are doing acoustics, we need to do some you know apply some perturbation. So, this equation needs to be perturbed.

So, how do we do that, how do we exactly you know how about perturbing it? So, basically we get,

$$p_{0,3} + \tilde{p}_3 + \frac{1}{2}\rho_0 \left(U_3 + \widetilde{U}_3\right)^2$$

$$= p_{0,1} + \tilde{p}_1 + \frac{1}{2}\rho_0 \left(U_1 + \widetilde{U}_1\right)^2 + \frac{1}{2}K\rho_0\left(U_1 + \widetilde{U}_1\right)^2 \qquad (2)$$

So now what we need to do is that, let us say this equation (1), this guy is equation (2). So, if you subtract equation (1) from (2) and since look we have a lot of ground to cover, so I will start avoiding the complex simplifications that is there and directly present you the summarized sort of result. So, the idea is there to subtract this entire guy from this particular thing ok. So, 2 - 1 ok.

We will do that, and when you do that and simplify matters do the algebra, so what you will get,

$$\tilde{p}_3 + \rho_0 U_3 \widetilde{U}_3 = \tilde{p}_1 + \rho_0 U_1 \widetilde{U}_1 + K \rho_0 U_1 \widetilde{U}_1$$

And then once we simplify this thing these guys further, we get,

$$= \tilde{p}_3 + M_3 Y_3 V_3 = \tilde{p}_1 + M_1 Y_1 V_1 + KMY_1 V_1$$

Clearly, we can write you know these quantities in terms of the aero-acoustic state variables. So, we need to bring into knowledge or into application, all our things that were doing in the last couple of lectures.

$$\tilde{p}_{c,3} = \tilde{p}_{c,1} + KM_1 Y_1 \quad \frac{\widetilde{V}_{c,1} - M_1 \tilde{p}_{c,1}/Y_1}{1 - M_1^2}$$

So, this happens because you need to basically sort of replace some other classical variables that we have here in terms of the aero-acoustic state variables. So, once we do that we get this particular thing. So all the details you know you can work it out because, let us go back to some of the last slide, where did we define the relation between the classical and the aero-acoustic state variable.

$$\begin{Bmatrix} \tilde{p}_c \\ \tilde{V}_c \end{Bmatrix} = \begin{bmatrix} 1 & M_0 Y_0 \\ \dfrac{M_0}{Y_0} & 1 \end{bmatrix} \begin{Bmatrix} \tilde{p} \\ \tilde{V} \end{Bmatrix}$$

$$\tilde{p} = \vec{A} + \overleftarrow{B}, \ \ \tilde{V} = \frac{A - B}{Y_0}$$

$$p_c = \tilde{p} + \ M_0 Y_0 \tilde{V} \ \ A(1 + M_0)$$

$$+B(1 + M_0)$$

So, it was I guess all written somewhere here, pc is equal to $\tilde{p}$ plus M_0 Y_0 Vc, so clearly this is the guy that we are using. There was yet another one which is basically your velocity was this one ok v tilde plus $\tilde{p}$ M_0 Y_0.

$$M' = \rho_0 S \widetilde{U} + \ \tilde{\rho}\, S U_0$$

$$= \tilde{V} + \frac{\tilde{p}}{C_0^2}\, S U_0$$

$$= \tilde{V} + \ \tilde{p}\ \frac{S}{C_0}\ \frac{U_0}{C_0}$$

$$= \tilde{V} + \tilde{p}\ \frac{M_0}{Y_0}$$

$$M' = \widetilde{V}\ + \tilde{p}\ \frac{M_0}{Y_0} \qquad (1)$$

$$J' = \frac{\cancel{p_0} + \tilde{p}}{\cancel{\rho_0}}$$

$$+ \ \frac{(V_0 + U)^2}{2}$$

$$-\left(\frac{\cancel{p_0}}{\cancel{\rho_0}} + \frac{V_0^2}{2}\right)$$

$$= \frac{\tilde{p}}{\rho_0} + U_0 \widetilde{U}$$

So, you know you just need to get the proper relation using the appropriate subscript and sort of get back. So, once we do all the math's behind it, what we will do is basically put in all the relation in terms of the convective state variables, then simplify the math's and to finally, end up with the following relation,

$$\tilde{p}_{c,3} = \left(1 - \frac{KM_1^2}{1 - M_1^2}\right) p_{c,1} + \frac{KM_1 Y_1}{1 - M_1^2} V_{c,1}$$

So, we get this sort of a relation. So now, like I said for all practical purposes

$$M_1 \sim 0.15, \;\; M_1^2 \ll 1,$$

and said can be neglected with respect to unity or bit other terms which are of first order. So what does it really mean? It basically means that here we have quadratic terms in this equation, so can we sort of neglect this thing.

Because here you have if you neglect this guy you still have a second order term in the numerator, which should be much sort of smaller than the unity term because K ultimately is a loss factor, it is sort of you know it is small it is less than unity. So, basically this entire term is much smaller than 1, provide that $M_1^2 \ll 1$. That is what we do and then we also ignore or neglect the M_1^2 the numerator. So, what we get is basically,

$$\tilde{p}_{c,3} = \tilde{p}_{c,1} + KM_1 Y_1 V_{c,1}$$

So we get this relation. So now after this, we probably would also like to note: that density perturbation we have your quantities like $\tilde{\rho}_2$, that is related to the acoustic pressure fluctuations by your isotropicity relation.

You know the relation basically what happens between the upstream and downstream variable? So, this is always there, and at a downstream

$$\tilde{\rho}_2 = \frac{\tilde{p}_3}{C_0^2} \qquad \tilde{\rho}_1 = \frac{\tilde{p}_1 - S_1 \rho_0}{C_0^2}$$

So, what are all these quantities these probably are these quantities that we are looking at the first time. Well, S_1 is the entropy S_1 is not the cross sectional area here it is the entropy term in the chamber, because it is an extended inlet element as we sort of see here. Now, this is what we get, p_0 is ambient pressure and cV is the specific heat at constant volume.

So, these are all sort of thermodynamic relations, I probably would not go deep into this part or just say that well you know this is what we get when we have entropy term generation in the downstream. But you know it is been fortunately is been found out that the entropy contribution is only of the older M_1^2 that is you know all this entire term the one circled here, this has is of the order M_1^2.

So, basically does not contribute that much as the this term, so we would sort of neglected one is sort of referred to the previous papers by Panicker and Munjal published long time back probably in the journal of Indian science published 1981 I believe where they where they did all these thermodynamic derivation ensured that these quantities are of order M_1^2.

$$\tilde{\rho}_1 = \frac{\tilde{p}_1}{C_0^2}$$

So eventually, what is the purpose of all this thing is that we are going to have this, and our thing isotropicity relation between p 3 rho 3 and p 3 and rho 1 and p 1 ok. So, we will keep this handy, now another thing that comes to our mind while doing all this is the continuity relation.

So, we have rho naught, basically whatever mass flux goes here it has to come out of 1. So, continuity is I mean it is very important, so it has to be maintained. Now, as usual we go about a business of doing perturbation,

$$= \rho_0 S_3 U_3 = \rho_0 S_1 V_1 \qquad (1)$$

$$(\rho_0 + \tilde{\rho}_3)S_2\left(U_3 + \tilde{U}_3\right) = (\rho_0 + \tilde{\rho}_1)S_1\left(U_1 + \tilde{U}_1\right) \qquad (2)$$

so this is what we get?

So, again we drop the second order term like $\tilde{\rho}_3$ and $\tilde{U}_3$ and the first order terms cancels out, because you know again, the equation (1) equation (2) subtract expand the equation (2) out completely they will be 0 order term or the ambient terms first order term then second order term. Second order terms like $\tilde{\rho}_1$ into $\tilde{U}_1$ that will be very small compared to the first order term, so ignore that, drop of that, alright, and retain only the first order terms.

It subtracts equation (1) from (2). So, the resultant equation would look something like this

$$= \rho_0 S_3 \widetilde{U}_3 + \tilde{p}_3 S_3 V_3 = \rho_0 S_1 \widetilde{U}_1 + \tilde{\rho}_1 S_1 V_1 + \tilde{\rho}_1 S_2 V_2$$

Now, what we immediately realize this is nothing but the mass velocity,

$$= \tilde{V}_3 + \frac{\tilde{p}_3}{C_0^2} S_3 U_3 = \tilde{V}_1 + \frac{\tilde{p}_1}{{C_0}^2} S_1 U_1 + \tilde{V}_2$$

We get that kind of a thing. So, we get here the is the mean flow thing and this is nothing but $\tilde{V}_1$ and you know here this is really your p_1. So, here we get p1 by ${C_0}^2$. S_1 into U_1 and perturbation of the acoustic mass velocity in the angular cavity.

So, here we have you know this relation, again using your convective state variables what we figure out U_3 by $C_0$is nothing but M_0 or M_3. A Mach number in the extend the tube and C_0 by S_3 is your Y, the same argument goes for this particular term and these two terms.

So basically, we are in a good position to write these guys as,

$$\tilde{V}_{c,3} = \tilde{V}_{c,1} + \tilde{V}_2 \; *$$

The convective state variables. So, you see we have got these guys, ok this one other equation was this one. Let us call this a star and let us call this is cross. So, we have got these star and cross equations.

Look, what is our aim? Our aim is to first you know relate things between point 3 and 1, so we are we have got two equations. We have we now K depending on the kind of discontinuities whether it is an extended inlet discontinuity your extended outlet discontinuity and so on.

So, here we in this equation pretty much there is no unknown here in the sense that there is no variable in for the annular cavity, we just have things in the point 3 and 1 and the loss factor, and here we have V_2. Now, V; however, to eliminate a V_2 you would need one more equation. So, how do we go about doing that?

So, here the momentum equation then comes in handy, and what we do is that for the extended inlet element like the one that is sort of seen here, 3 and 1, we must apply certain relations alright. So, what do we do? We basically put

$$p_0 S_3 + \rho_0 S_3\, U_3^2$$

So we have got this thing,

$$-(p_0 S_1 + \rho_0 S_1\, U_1^2) + p_0 S_2 = 0$$

$$(p_0 + \tilde{p}_3) S_3 + (\rho_0 + \tilde{\rho}_3) S_3\, \left(U_3 + \widetilde{U}_3\right)^2$$

we have this momentum equation, now this minus sign here in the plus 1 I know that goes on here that is only for an extended inlet element.

For an extended outlet you know here we will have minus. Let us a first deal with an extended inlet the figure that I had just drawn back in this slide the figure a, for figure b it will be minus. Anyhow, so what we will do that will perturb the equation as usual we go about doing a perturbation business,

$$-\left\{(p_0 + \tilde{p}_1) S_1 + (\rho_0 + \tilde{\rho}_1) S_1\, \left(U_1 + \widetilde{U}_1\right)^2\right\}$$

So, what you know as we usually we do, we I will skip some other algebraic simplification with the understanding that you guys would take it out take it up at some stage. So, this thing will be

$$+(p_0 + \tilde{p}_2) S_2 = 0$$

So we get that. Now, again we will subtract the star mark equation from double star equation, and you know one can do the algebra to dropping second order terms and first order zero-th order term any ways cancel out.

$$S_3 \tilde{p}_3 + 2\, \rho_0 \frac{S_3}{C_0}\, M_3 \widetilde{U}_3 + \tilde{\rho}_3 S_3 U_3^2$$

$$-\left\{S_1\tilde{p}_1 + 2\,\rho_0 S_1 U_1 \widetilde{U}_1 + \rho_1\, S_1 U_1^2\right\}$$

$$+S_2\,\tilde{p}_2 = 0$$

So we get that. Again, we sort of make use of the convective state variables and with the understanding that we had in the last few equations, what we eventually get,

$$=> S_3\left(p_{c,3} + M_3 Y_3 V_{c,3}\right)$$

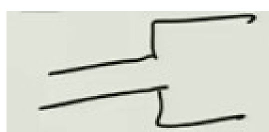
$$-S_1\left\{p_{c,1} + M_3 Y_3 V_{c,1}\right\}$$

$$+S_2\,\tilde{p}_2 = 0$$

Now,

$$\frac{p_2}{V_2} = \frac{Z}{2}$$

So, what do we do now? Z_2 to that is the impedance seen at the right at the entrance of the annular cavity, and that we know is nothing, but $-\,jY_0 \cot k_0 l_2$ in annular cavity there is no mean flow. So that is why we are getting k_0.



So after doing all these things and substituting you know making use of this relation, what we get after significant you know algebra is that V_{c3}, so you know the just let us go back just a little back and we see that V_{c3} equal to V_{c1} plus V_2 ok, and we did all this algebra and finally after a significant you know sort of simplifications, we will get

$$V_{c,3} = \frac{1}{S_2 Z_2 + S_3 M_3 Y_3} \times \left\{S_2 p_{c,1} + (S_2 Z_2 - M_1 Y_1)\left(-S_1 + K S_3 V_{c,3}\right)\right\}$$

We will get that. And this is multiplied by

So, we get this relation, and once you put this in the convective state form it is a it is going to be a rather complicated thing. Because now you know we in this, by the time we arrive at this point we would have neglected the m square terms.

Now, all these things can be further writing an approximate manner as

$$\begin{Bmatrix} p_{c,3} \\ V_{c,3} \end{Bmatrix} \simeq \begin{bmatrix} 1 & KM_1Y_1 \\ \cancel{\dfrac{S_2}{S_2Z_2 + S_3M_3Y_3}}\ 0 & \dfrac{S_2Z_2 - M_1Y_1(-S_1 + KS_3)}{S_2Z_2 + S_3M_3Y_3} \end{bmatrix} \begin{Bmatrix} p_{c,1} \\ V_{c,1} \end{Bmatrix}$$

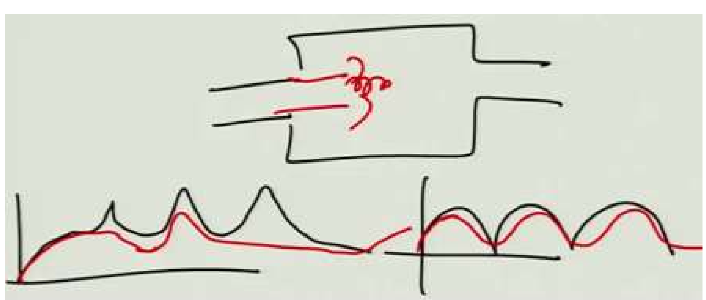
And this thing will be eventually related to p_{c1} V_{c1}. This is a lot of algebra there are few important cases as or corollaries that we would like to probably note here.

You know when this guy, we have this particular thing ok. Now, when what happens if your thing is flush mounted if you are inlet pipe flush mounted, so basically impedance right here that is called $k_0 l$, is 0, so cot at 0, that is your extending to infinity, is not it. This guy is going to infinity and this is tending to a very large number and all these terms are very small in comparison. So, basically the result will be, that this guy will be 0.

What about the things here? Here also you have Z_2 in the numerator in the denominator and these are all finite terms. So basically, you will be having sort of 1 here, is not it, you will be having 1 here. So, that is the case of a certain expansion ok. So, we are deriving the case of certain expansion in a very simple manner using this. So, you have 1 and

$$\begin{Bmatrix} p_{c,3} \\ V_{c,3} \end{Bmatrix} = \begin{bmatrix} 1 & KM_1Y_1 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} p_{c,1} \\ V_{c,1} \end{Bmatrix}$$

The relation between the convective variables across a sudden expansion incorporating the loss factor.



So this loss factor will actually, what it will do? For a simple expansion chamber incidentally you know the loss factor for sudden you know contraction would be would be different from that of a certain expansion.

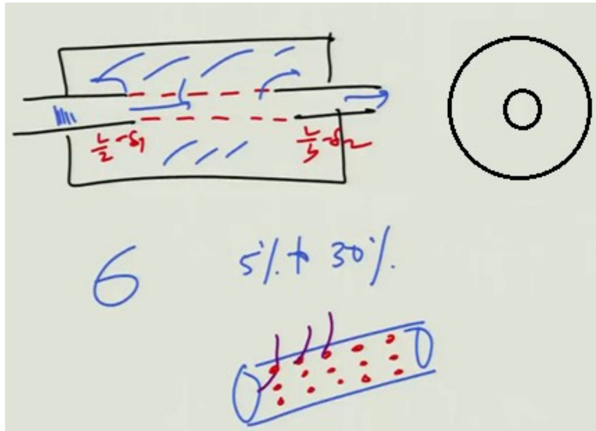
But whatever it is you know this kind of a transmission loss you are getting for a case of a 0 mean flow. So, in case of non-zero mean flow the trough will be slightly lifted you know based on theoretical predictions, but and the peeks will be slightly lower this at derivation, but these are all theoretical things experimentally and pretty much the same thing you now will happen for a this thing.

So, for an extended inlet or extended outlet element what one would typically imagine is that for tuned thing that we are kind of thinking, the first order trough will be lifted, the second order trough will be lifted, third one will be lifted and so on. So, these flow what it will do?

It will basically lower their troughs and these things will go up in basically wherever there is a trough will try to lift it up. So, it has a smoothing effect or leveling effect you know, but typically these are all predictions with how it really considering the flow and use noise at the expansion, that is here or you know at these points like I was mentioning.

There will be water is being shred will which will be interacting with the duct create a lot of noise. So, all these things are sort of very classical ways of predicting the losses that will be generated but then one really has to you know develop newer expressions for the actual flow and you know actual situation when you have a non-zero mean flow the flow is allowed to expand suddenly.

Actually we not be very productive, I will be counterproductive. Especially when your muffler shell is very thin and it radiates noise outside. And the transmission loss of course, will also come down because of this. We have some experimental proof for the recently conducted work, but you know the main thing this basically brings bring us to the premise of why we should go for a perforated system.



So, we have typically you know, we would never allow the flow to expand so freely I mean. So, what we do is that, so this bring us to the topic of perforated mufflers and right now we are just going to discuss very briefly the next couple of minutes of 5 minutes about why do we need to have perforates, what purpose does it serve and maybe I show you some nice photos available in the internet.

About some cool perforated mufflers chambers and, so basically what you have, what you do is that you connect the while you know we have tuned the chamber L / 2 and this is L / 4 for instance. So, we typically it will be higher order modes generate, so in the at later points in the course we will hopefully do some derivation of the high order modes for without the perforates, but the ideas that higher demotes be generated.

So, you can tune this by slightly reducing the length here, the geometrical length and so on. Now, the perforated bridge length will increase ok. So when it does so, so I mean this is this gap will increase. So basically, what you need to do is that connect the inlet and outlet pipe with a perforated bridge, we will connect that.

And, so we do not allow the flow to sort of expand, we never allow the flow to expand it just goes away and it interacts with the annular cavity. It interacts with the annular cavity ok. The waves interact the annular cavity and they have resonances here and resonances here, but the flow itself just goes smoothly.

So will be a minimum pressure drop, and because there will be no free shear layers from there will be no that are found in the wave which would have which would otherwise form if the perforate bridge were not there. So, the flow and use noise, the counterproductive noise will not be there.

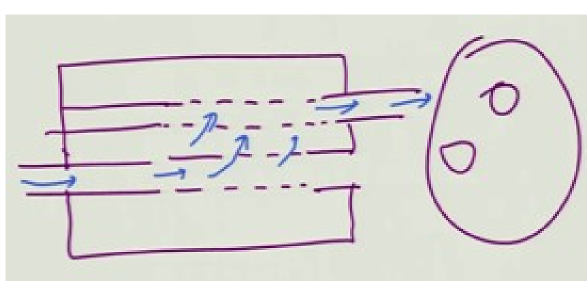
So, the flow can smoothly go away like this and leave the outlet here, but at the same time a highly perforated bridge, so you know we will discuss all the parameters that are relevant to discussion of perforate, especially when you talk about impedance one other important parameters is sigma or the porosity which typically you know sort of varies between you know 5 percent to about 30 percent, 30 percent porosity means it is basically the open area ratio.

So, basically is nothing but a pipe in on the surface of which their holes, small small holes are there at some interval they have been different you know manners in which perforated things are drill. So, through these waves, I am sorry through these holes the waves are allowed to interact with the outer cavity.

So, if this 30 percent then it is highly pore is virtually like it is a acoustically transparent, but the same time mechanically is allowing the flow to go through. So, these holes are very small about roughly 2 to 4 mm diameter and placed at a certain spacing. So, these series perforate things very commonly I show you some photographs of the perforated stuff that we did some time back.

So, basically not allowing the flow to expand freely, but at the same time allowing the ways to interact with the cavity is what the perforate does and it really kills or does not does not bring into picture the a separation noise. On experimental evidence has it that you know this is much better than just allowing the flow to expand.

And in real life also no one really uses a bare extended inlet and outlet chamber you know people really need to use some perforate and that is why it is perforate element are studied a lot. And in all commercial vehicles I will show you couple of photographs they are there and there is other element also perforated thing, there something like this is here the flows graces the surface you know.



But there are other elements which something like let me just sort of draw it quickly for you guys. So, here we can have a solid pipe and we have a overlapping element and ok, so the flow has to go through this, flow has to go through this ok. So, basically such an element is called a cross flow expansion chamber.

So here, cross expansion takes place is no longer a grazing flow, flow has to go through this. So, the perforate impedance expression sort of changes significantly so, hopefully we should be able to do that as well. Now, let me show you some nice photographs of the interiors of how the typical in a perforated element looks like.

So, we see these perforated tube, so these are something that we fabricated sometime back, this is nothing but something like 2 and a half a 3 mm MS Steel pipes and a number of holes are drilled at regular intervals as you can see here about 2 mm, 3 mm holes and the regular regulated. This is definitely highly porous because you know porosity is about 28 to 30 percent somewhere between that and this is about only 12 percent.

So, you acoustical properties, the final thing that matters is transmission loss from muffler, which is highly dependent on the porosity. So, we did some experiment, some time back and figured out that this is highly porous and this is as good as you know acoustically this being not there. But, the presence of such a perforated thing is very crucial because this is what eventually will happen.

You know you see, this is the part and this connects of course, this is a you know let us say this inlet this is the outlet where my mouse is pointing, the flow comes in here and its smoothly guided by the perforated pipe and leaves outside, it does not allowed to expand. I mean not allow to freely expand the acoustic wave, nevertheless allowed to interact with the cavity and the cavity is not empty now.

As you can see it is surrounded by some sort of a glass wool and mineral wool and all that, so these are nothing but dissipative materials they completely kill or dissipate the acoustic signal. So, basically the this is a completely fully perforated muffler, but it is also the annular areas will filled with absorptive sort of materials.

So it is fully dissipative. So the crucial idea is that the perforated thing acts like a guide, it does not allow to the flow to expand out freely and it interacts with the annual cavity and then that is what happens. So, this is a straight through muffler with a least pressure drop and the flow noise that I was talking about will not be there.

And then, this is yet another more complicate mufflers hopefully we will be doing some plane wave analysis of this thing next week. So basically, you know the flow comes in here as it is shown somewhere here inlet and this is an outlet, but in the process it has to negotiate number of turns like the flow is reversed here is end chamber.

We you know remember in your last assignments you dealt with propagation along these axis and, similarly along this axis because we have propagation is here. And in the annular area it is filled with absorbent materials. So, the idea behind all this is that the flow has to essentially you know crossover this thing, the flow has to basically bend around and some part of the flow kind of interacts with the material and interacted the annular cavity which is filled with absorbent material.

But if it is not filled with absorbent material, it can still the flow necessarily has to also go through some part in here. And will be a number of passages through which the flow has to pass and then we will be a cross flow you know expansion chamber. So, different expressions will involve.

So, you know this photo really tells you how complicated real time muffler can be. So, this involves multiple interactions with the annular cavity and produces the desired transmission loss. So, there is lots to be done; obviously, with this end this note I will have to end this today's lecture, which is a bit large, but there is lots to be done there is still lot of areas not quite explode and with so many dimensions perforated it really adds a lot of dimension to our thing.

So, especially it with the number of more elements like shot and chambers and dissipate materials and all that. So, not everything can be covered in these scores, but only glimpses of these things probably can be given. So, tomorrow what we probably would be doing is for the first time we will be talking about concentric perforated expansion chamber in which only plane waves will propagate and get some equations.

And finally, do some hopefully transmission loss calculations. But before that, we would also need to thoroughly have a decent idea of the different perforate impedance available in the literature. So, we will try to present that in the lecture 4 and lecture 5 of week lecture before moving on to the next week.

So, thanks a lot, stay tune, I will see you in lecture 4.