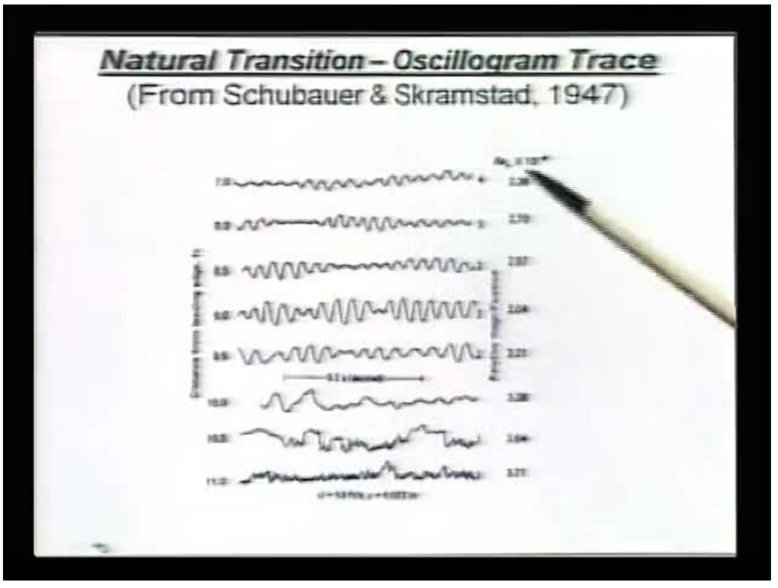
**Instability and Transition of Fluid Flows**

**Prof Tapan K. Sengupta**
**Department of Aerospace Engineering**
**Indian Institute of Technology, Kanpur**

**Lecture No # 12**

Last week, we were talking about what really happens in a real flow. The theory that we have talked about so far refers to normal mode. That means we look at single frequency and the corresponding wave numbers as selected by the eigenvalue such.

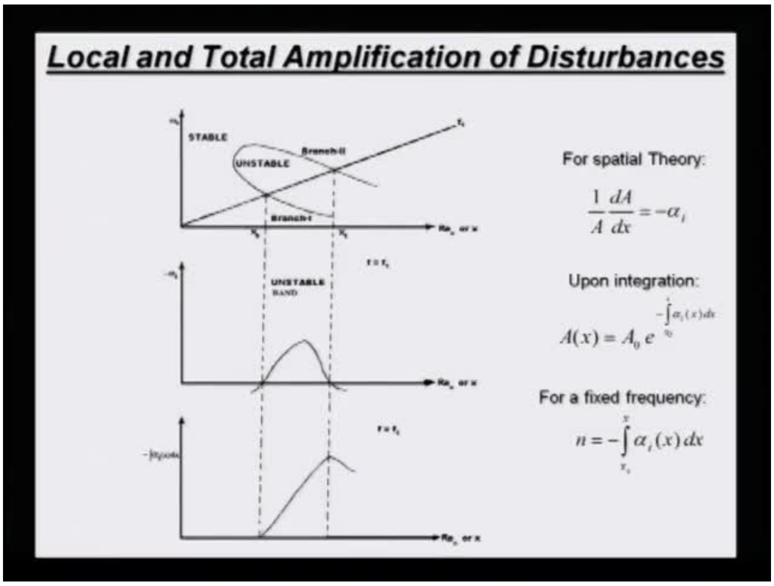
(Refer Slide Time: 00:46)




In a natural flow, this is how you would see the trace. If you put a probe at a particular point, then this is how it would be as a function of time. These are at different locations from the leading edge of the plate. So, distance is growing in this direction. Corresponding Reynolds numbers based on current length goes on like this. What I mentioned last time also to you that at the early stages, signals are weak. That is why, for example, this signal has been magnified four times; this has been magnified three times; same here; three times; three times; this one has been magnified two times; and, last three are not magnified at all. To give you an idea what really happens, few things become readily apparent that they are not monochromatic. If it was so, you would have seen a single frequency even. So, it looks like collection of many frequencies and they are mutually interacting. That is why you get wave packet-like features of the flow. And, what happens secondly is that, when you go downstream, these increases in amplitudes, all these disturbances, show their amplitude increasing. And, after a certain distance, what you notice, the flow is characterized by very high frequency oscillations. These are very high frequency oscillations. So, this is one of the characteristic of all natural flows.

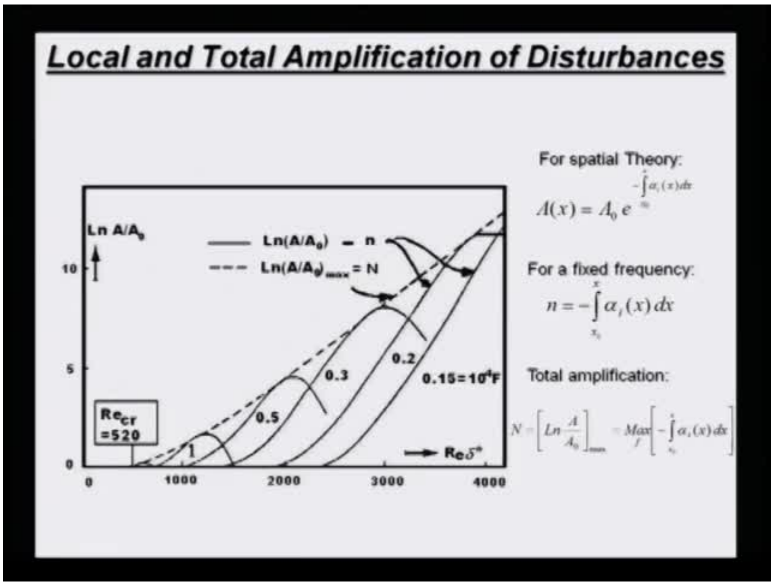
Nonetheless, what happens here is that in this scenario, if you want to validate those stability theories as it was done by these two gentlemen Schubauer and Skramstad, what you need to do is that, remove any sort of trace or background disturbances, because what you are seeing is the effect of background disturbances. So, if you can create a wind tunnel, for which the background disturbance is minimal and then you excite the flow at a particular frequency, then you should be able to check for all those waves those have been predicted by the stability theory.

(Refer Slide Time: 03:09)



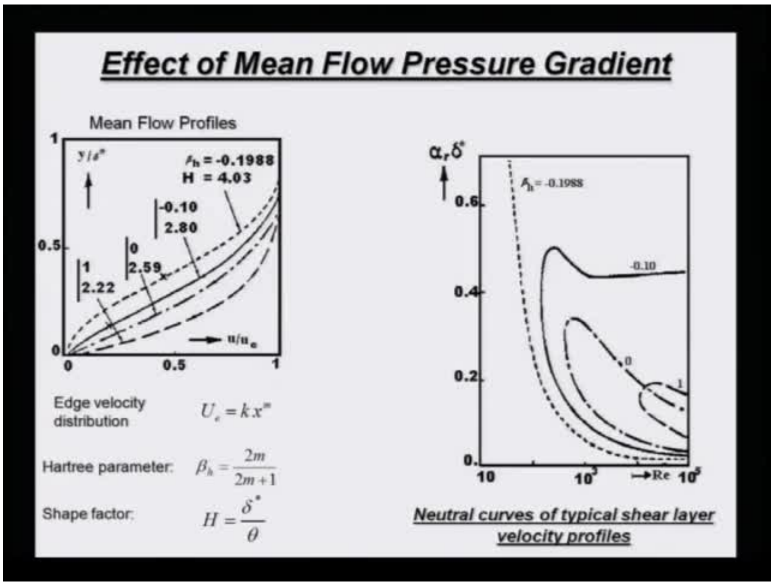

And, if you do that, this is the way that we said we follow a fixed frequency disturbance that those are the rays starting off from the origin. On this side, we have plotted the non-dimensional frequency; on this side we have plotted the Reynolds number or x. So, a constant frequency disturbance goes like this. It is only during its so (( )), during this unstable part given by this branch 1 and branch 2 of the neutral curve that the amplitude increases. And, that is what we have done here, because the relative growth rate is given by minus of alpha i, so that if we integrate, we get A at any station x in terms of the amplitude at some reference station and e to the power minus alpha i dx, starting from that reference station to the current station. So, what happens is, for this flow, then what we could do is, we can plot minus alpha i; that is the quantity of interest. And, within the unstable band, you would see that they will be amplified. And, if I now perform that integral that is given in the exponent here, that is what we have done here; (Refer Slide Time: 04:33) alpha i x dx. Then, we are going to see that amplitude is going to grow. And, this is what we called as the n factor for that particular fixed frequency.

(Refer Slide Time: 04:50)



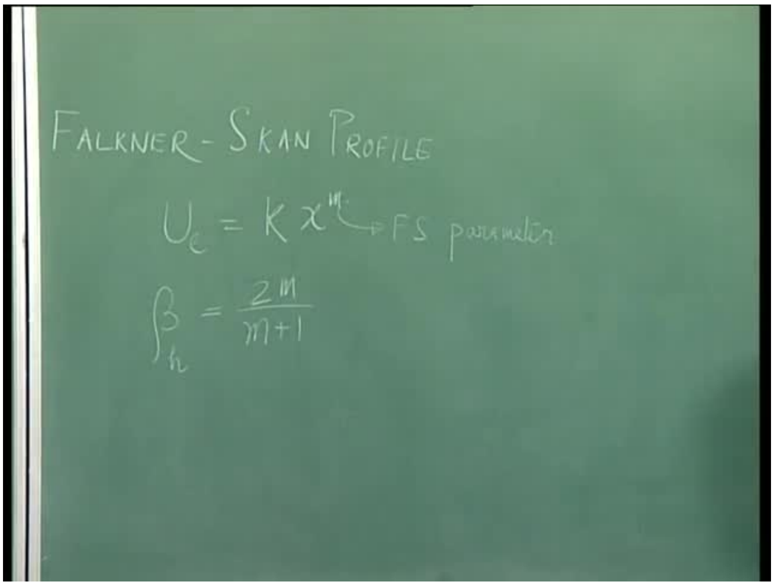

Look at the behavior of different frequencies; and, this also we explained that as the frequency increases, the flow becomes unstable at earlier location. However, it also comes out of the unstable part earlier. So, that is why, you see it is growing and then it flattens off and then amplitude start decaying; whereas, if you look at the figure here, the lower frequencies are the ones which start off late. But, once they are inside, they amplify to significantly larger values. If we draw an envelope correcting the maxima of different frequencies; that is what we show here by the dotted line; that is what we call as the total amplification. Total amplification is then a natural algorithm of A by A naught, the maximum value. So, in trying to represent the flow instability, then we start off with the critical point, below which everything is stable. And, from here on, (Refer Slide Time: 06:13) some high frequencies start becoming unstable. And, you assume that in actual flow, what happens is kind of interchangeably, the disturbance is migrated across frequency. How it is done? It is never explained, but this is empirically projected. That is why we really do pay heed to this capital N factor.

(Refer Slide Time: 06:48)



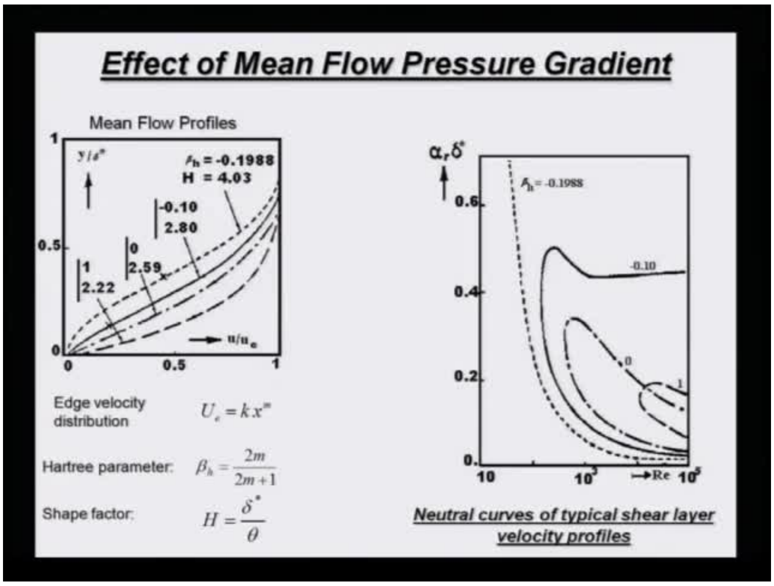

And, lots of experiments have been done and people have tried to correlate this factor, capital N and they tried to figure out whether the flow has undergone transition or not. For example, for a zero pressure gradient boundary layer, people have found out when this capital N takes a value of about 8 to 9. That is where you should to expect the transition to occur. But, let me sort of warn you upfront that this is too empirical, because this does not tell you anything about A naught. Are we saying that irrespective of any tunnel or even in the same tunnel and different speed? Are we going to see the same kind of behavior? That is something will discuss.

(Refer Slide Time: 08:04)




However, what we are next going to focus about is what happens if we look at the flows of different kind. Flows of different kind are characterized by what the velocity distribution is in the inviscid path of the flow. So, that is what we are representing here by the Falkner-Skan profile. The Falkner-Skan profile is characterized by the external edge velocity distribution given by U e as equal to some constant K times x to the power m. And, this is what is called as a Falkner-Skan parameter. However, lots of work have been done and artery or specifically nodes that what is of interest is this parameter called beta h or the artery parameter, which is equal to 2 m divided by m plus 1.

(Refer Slide Time: 06:48)

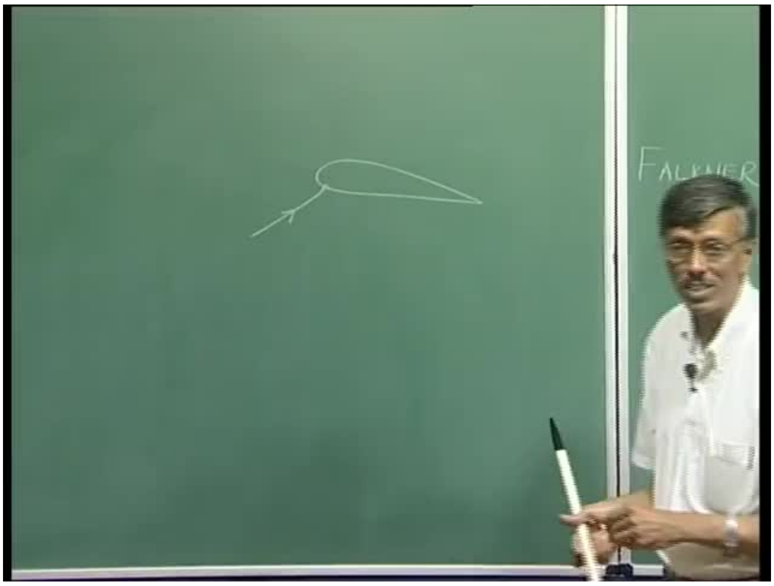



When a boundary layer develops in a shear layer, then there are two thicknesses, which we talked about, are of interest: one is the displacement thickness, delta star; the other is the momentum thickness. So, one basically gives you an estimate for mass displacement or defect due to the presence of the boundary layer; other one gives you the momentum deficit. So, H is equally important parameter called the shear factor. And, what you are seeing here is basically a velocity profile. So, what you are noticing here, you have plotted U by U e versus the height. Height also we have plotted; y over delta star. So, you expect that the flow to reach close to value of 1 at delta star, but at the boundary layer thickness, which would be probably 2 or 3 times this delta star. That is where you would really get 99.9 percent or so on and so forth.

Now, as I said that we will characterize the flow profile by these two parameters: (Refer Slide Time: 10:07) beta H and A; capital H. And, that is what you have seen. Please note that a zero pressure gradient flow will correspond to m equal to 0; that is, corresponding to beta H equal to 0. And, that is what this is (Refer Slide Time: 10:27); see this top quantity, beta H equal to 0. So, that is for the Blasius profile; the second last figure from the bottom. And, the corresponding shear factor of Blasius profile happens to be about 2.59. Above these two curves we are seeing two more profiles for which beta H is negative and H is greater than the Blasius profile value. Beta H negative means the flow is decelerating. And, if flow decelerates, what happens is you do get an inflection point. Remember we talked about Rayleigh’s theorem. We said that if we have an inflection point, those flows are unstable to inviscid mechanism. And, you notice that depending on the value of beta H, you would have a different location, where you are going to have the inflection point marked by the crosses here; this is one here and the other 1 is there.

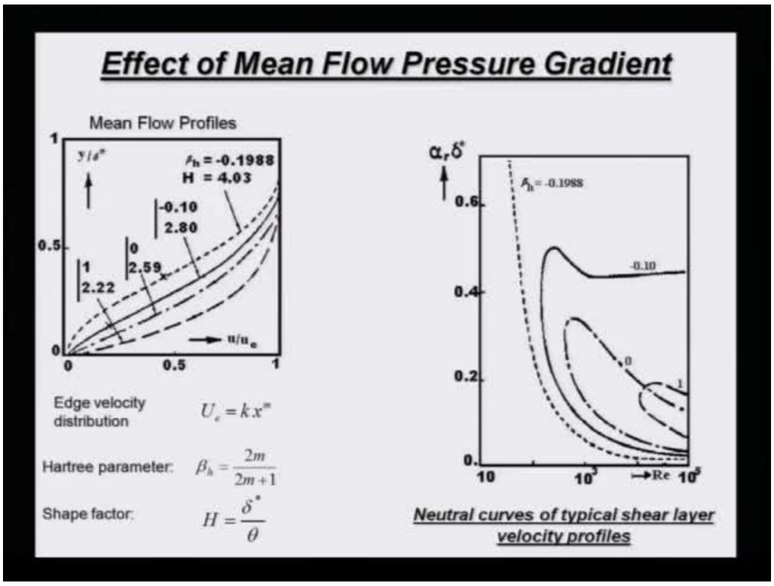
I asked you the question last time also; you can remember that for Blasius profile, a point of infection is actually on the surface; which is of no consequence, because a Rayleigh’s theorem does not consider that flow to be unstable; whereas, this last curve that is shown here for which beta H is equal to 1 corresponds to stagnation flow.

(Refer Slide Time: 12:12)



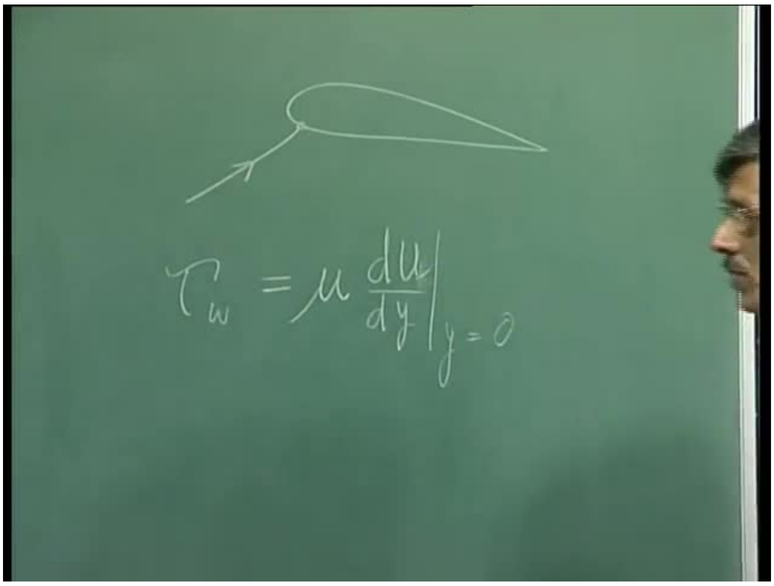
So, if we are talking about flow past, let say a dynamic shape like this, you will have a stagnation point. So, in the vicinity of the stagnation point, you will have a velocity profile for which beta H is equal to 1 (Refer Slide Time: 12:25) and the shear factor is rather low.

(Refer Slide Time: 12:23)




This top-most curve that you are noticing that corresponds to beta H equal to minus 0.1988 and the H value is for 4.03. So, you can understand that if the flow is experiencing adverse pressure gradient, then you have the inflection point. So, those flows are inherently more unstable. And, this is the situation, where the flow is about to separate. That is what you are seeing; (Refer Slide Time: 13:05) the behavior of the flow at the wall will give you some indication of whether the flow is attached or separating.

(Refer Slide Time: 13:25)



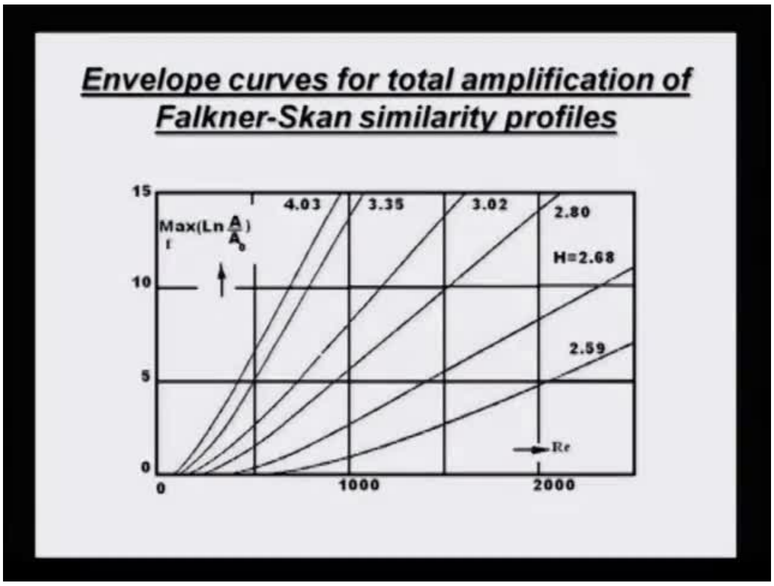
Recall the Prandtl's condition that separation is indicated when the wall shear is equal to 0. So, what is wall shear? That is given by tau w; that we will write it as mu d U by dy at y equal to 0.

And, that is what you have seen in the last curve. This goes off tangentially up. So, this is a profile for incipient separation. Now, what does this really do? This is a qualitative description that we talked about. We can do the same thing. We can really draw the neutral curve for various kinds of velocity profile. And, one standard reference neutral curve is this one (Refer Slide Time: 14:13) corresponding to Blasius profile, that is that beta H equal to 0. And then, you notice that if I take the stagnation point profile, a neutral curve is like this. And, please note, this is in a log scale. So, what you are seeing here (Refer Slide Time: 14:38) is, this 10; this is 1000; this is 10 to the power 5. And, what you notice that this value was… We earlier indicated this about 519 or so. That is the tip of this neutral curve for Blasius profile.

Look at the stagnation profile. That is very stable, because flow is (( )) stable up to such a large extent. In contrast, when you look at any adverse pressure gradient profile; for example, here if I take beta H equal to minus 0.1, what you notice that two features that critical Reynolds number falls off significantly. So, this is roughly close to may be 100 or so for this particular value. And, the second thing is you notice that for Blasius profile, when it becomes unstable, it is due to a viscous mechanism, because Rayleigh's theorem says that even if you look at the inviscid mechanism, it is stable. So, this is inherently a viscous mechanism. And, what is interesting is if I draw this curve far down, then the upper branch and the lower branch of the neutral curve for Basius profile will approach towards each other. That is one of the features. That is what you see in all viscous flow instability, you see a sort of a limited region. And, that region shrinks again increasing with Re.

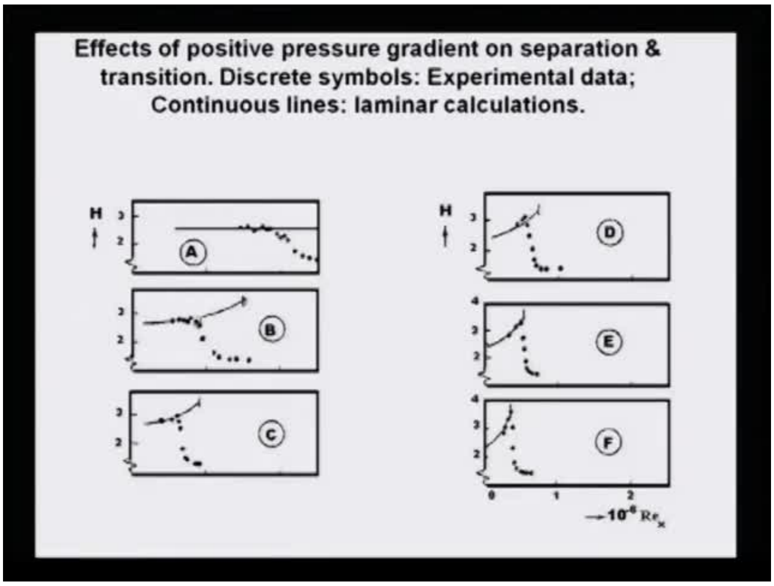
In contrast, for adverse pressure gradient, what you notice that this line is (Refer Slide Time: 16:21) kind of parallel. So, it means what? That this is going to remain unstable. So, that is one of the indication that why adverse pressure gradient flows are not good from the point of view of instability and transition. And, look at the value for the incipient separation profile. There the neutral curve does not even close; and, just remains open. So, it is going to remain unstable from a very low frequency to a very large frequency.

(Refer Slide Time: 17:23)



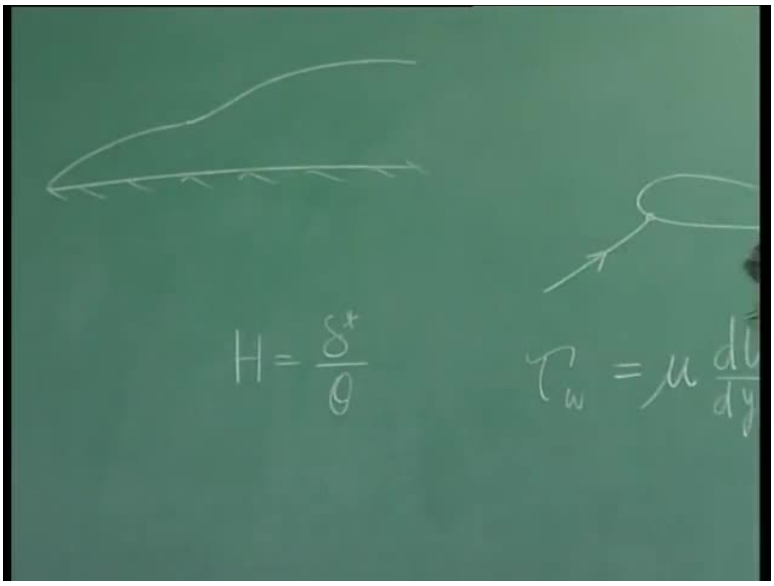

This is an attribute of linear theory. So, this basically gives you an idea of how to interpret flow instability from linear theory. This was done by (( )) and his group. And, this picture reveals quite a few of the features that one would expect directly coming out from the linear theory. Recall, we plotted that capital N factor, which was nothing but maximum of Ln; A by A naught scanned over all possible frequencies. Now, what we have done here, we have plotted that n factor variation with Re for different values of shear factors. So, this is the Blasius profile; H is equal to 2.59. And, any value above this corresponds to unstable profile, because H is more than the Blasius profile. And, that is what you are also noticing that their same station, if the H is larger, the capital N factor is significantly larger. So, you can see that for a Blasius profile to go unstable and if I say e to the power 9, you can see it would have to travels much longer distance. But, if you look at 2.68, it would indicate that by this time that value n is equal to 9 has reached here. So, if you look at 2.8, it is so unstable. And, as you approach the incipient separation profile, you can see, it basically, virtually goes out. So, basically, then one should be in a position to talk about flow being stable or unstable by looking at the local pressure gradient. So, we are essentially studying the effect of pressure gradient of flow instability. That is why we are considering all these flows.

(Refer Slide Time: 19:08)



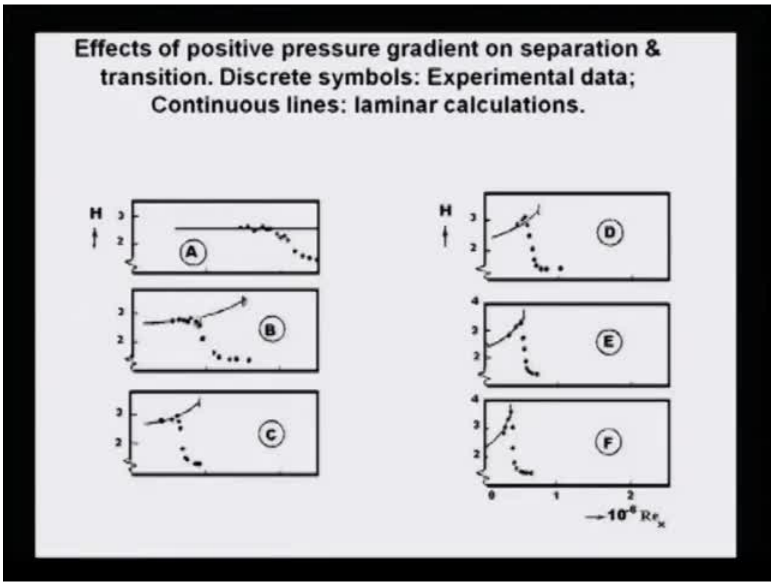

Now, what we are seeing here is lot of H versus Re; on the y-axis, we plot H, shear factor; on the x-axis, we plot Re, scale down by the factor of Malian. And, this discrete data points that you are seeing – those are the corresponding experimental observation. And, this solid line indicates some effort for calculating the boundary layer. We can solve the boundary layer equation and then we calculate its H; and then, we see what happens. What about this A? A corresponds to a case, where we are talking about a zero pressure gradient boundary layer. So, corresponding to that, there H value remains flat at 2.59. But, if I go the lab and do the experiment, I do not see that remaining flat. It actually fluctuates a little bit and then it drops. Now, what does it signify for the H to drop? Which flow would you expect to have higher H? Laminar or turbulent flow; see what we saw that when we have adverse pressure gradient, H values were larger and the boundary layer was thicker. Now, what happens? When you have a turbulent flow, what do you expect to happen? You would have larger (( )) fluctuations. So, there will be more mixing. If you are going to have more mixing, then what will happen? The boundary layer will be somewhat relatively thinner. But, at the same time, because of the larger mixing, we are also going to experience larger losses; drag; turbulent flows invariably will have more drag.

(Refer Slide Time: 21:46)




If I now look at an expression for H, is delta star over theta. Now, if I take a flow over flat surface like this, then what do I see in an experiment? I have a laminar flow profile; then, flow becomes turbulent; and then, goes like this. So, what you are noticing that delta star increases also for the turbulent flow, because you are giving now v, velocity fluctuate. So, shear layer would appear thicker. But, what is happening, that corresponding growth or theta is much larger than the growth in delta star. So, the two together actually conspires to give you a value of H, which is much lower for turbulent flow as compared to laminar flow.

(Refer Slide Time: 19:08)



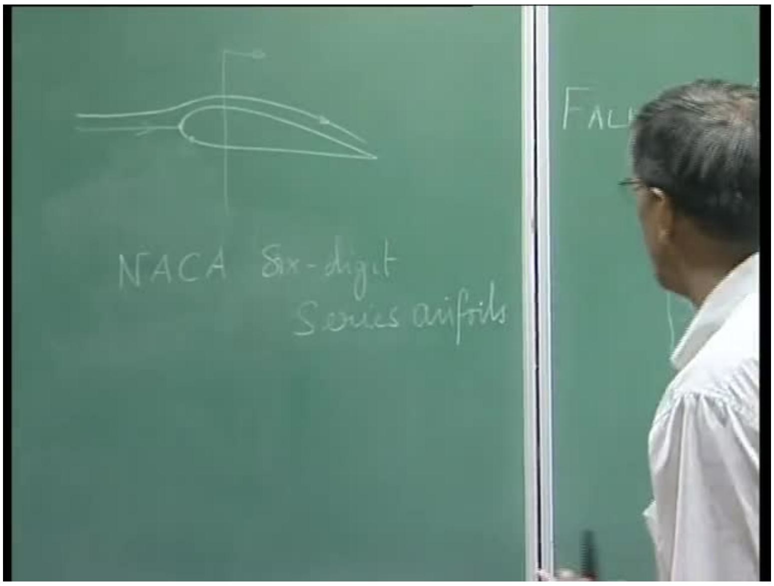

So, whenever you see such a thing happening, that H falls off. That is an indication of transition. So, we are talking about a physical understanding of features of the mean flow, the equilibrium flow that helps us identify what is going on in the flow. We do not need to really do those detailed stability calculations to comment upon things. But, if I do plot, let say, experimentally H versus Re and if I see that this is falling off, (Refer Slide Time: 23:29) this indicates there is a sort of a gradual transition that has taken place, so that the value of H has fallen from 2.59 to somewhere in between 1.3, 1.5; within that range.

Now, that was the zero pressure gradient scenario. Now, let us look at adverse pressure gradient effect scenario. Now, what will happen, you see, if you do a boundary layer calculation, what you would find? Because it is an adverse pressure gradient, the H increases as we indicated. Then, in fact, you would notice that after some distance, you would have this (Refer Slide Time: 24:14) criteria satisfied. So, you would have a flow separation. That is indicated by this (Refer Slide Time: 24:21) vertical barrier, so that the boundary layer calculation cannot go beyond this. What happens to the experimentally observed shear factor? That you can see it falls off; so, while this is a theoretical laminar flow, but actual flow undergoes transition earlier and that is what you are noticing here.

Now, make the pressure gradient even more stronger. Then, you would see that the laminar flow calculation will break down earlier. However, you would also notice that transition would have occurred even earlier than that. What you notice that further increase of the adverse pressure gradient brings a situation, where the point of separation and point of transition becomes virtually the same like the case E and F. So, basically, then gives you an understanding that looking at the boundary layer diagnostics itself, you can talk about what is really happening; what actually are the difference between the place where the flow separates and where the transition occurs progressively becomes small and smaller with the strength of the adverse pressure gradient. So, if you have sufficiently strong adverse pressure gradient, you do not need to do many fancy calculations; you can very safely say, the point of separation and point of transition are synonymous; they are same.

Now, you also notice one interesting thing is this fall of H is rather instantaneous here with larger adverse pressure gradient; whereas, for milder adverse pressure gradient, what you notice, the transition is rather gradual; it just does not happen instantaneously like what you see on these right-hand side frames. So, do understand that this is both sort of information as well as a message of warning for us, how we should look at a flow past bodies, where we would like to control transition. For example, if I look at flow past this airfoil, (Refer Slide Time: 27:14) then what happens?

(Refer Slide Time: 27:46)

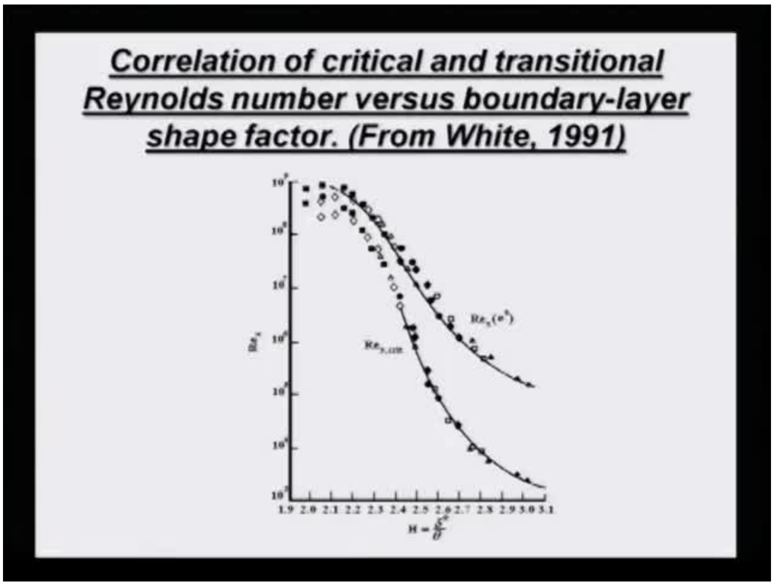



If I look at zero angle of attack case, what we would expect to happen? We will expect to see the following scenario that flow will approach the airfoil and there would be some kind of a stagnation point here. Then, if you follow the flow on the top surface and the bottom surface, you are going to see some qualitative difference. But, what will happen if I look at another nearby stream line, it would go like this. So, what does it mean here in the early part of the flow? This is where the stagnation point means flow has stagnated there; and then, the flow actually starts accelerating from there and the acceleration will go on till the position of the maximum thickness. Beyond the position of the maximum thickness, what happens? The streamlines diverge. So, that means the flow experiences adverse pressure gradient. So, you would see that in real flows like what one may be interested, you would get admixture (( )) This is what you are going to expect. What you are going to expect that at least up to the maximum thickness point, flow is accelerating. So, if there are any background disturbances, they will be reduced. That is what we have seen, that the accelerated flows are more stable than decelerated flows.

However, beyond the position of the maximum thickness point, flow will experience more and more adverse pressure gradient. And, this is where you can draw inferences from this kind of study (Refer Slide Time: 29:25). So, you can see that in a profile like this, it is virtually impossible to keep the flow laminar indefinitely. What happens is, this was known to people, experimentalists that maximum thickness value on the location determines the sectional property of this kind of airfoils. This prompted those people at NACA (National Advisory Committee for Aeronautics); they designed a series of airfoils, which are called NACA six-digit series airfoils, which benefitted from this observation that you have to postpone the maximum thickness point. That is what you should look at any airfoils data book. And, you would notice that how the maximum thickness in the position of maximum thickness point has changed during that period. These six-digit series airfoils try to push the maximum thickness point as far back as possible.

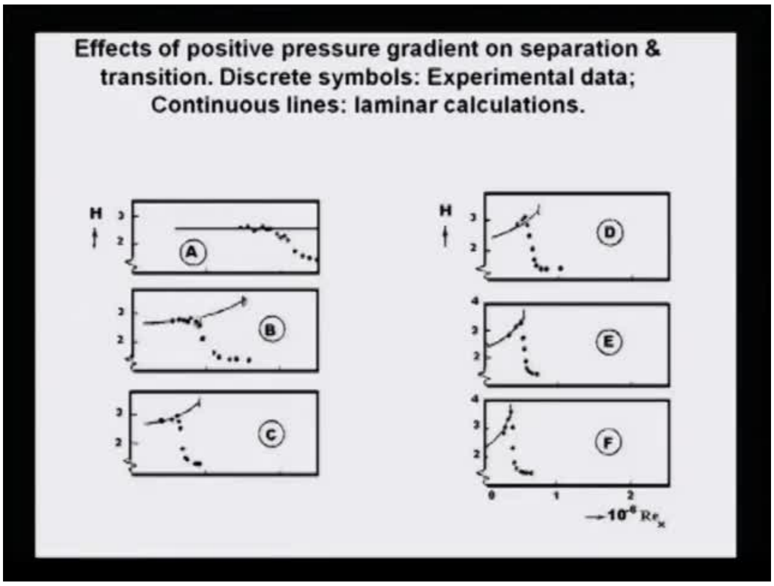
In fact, those pictures that we saw of HondaJet, which I said, uses natural laminar flow airfoil; there also, you would notice, for the maximum thickness point location; whereas, this six-digit series are little earlier. Now, this is all there is to your common sense applied to understanding of the flow. We will talk about this as we go along. But, you can see that in actual flow, it will virtually be possible to keep the flow laminar over the full extent of the body. So, this is something that we must keep in mind.

(Refer Slide Time: 31:55)



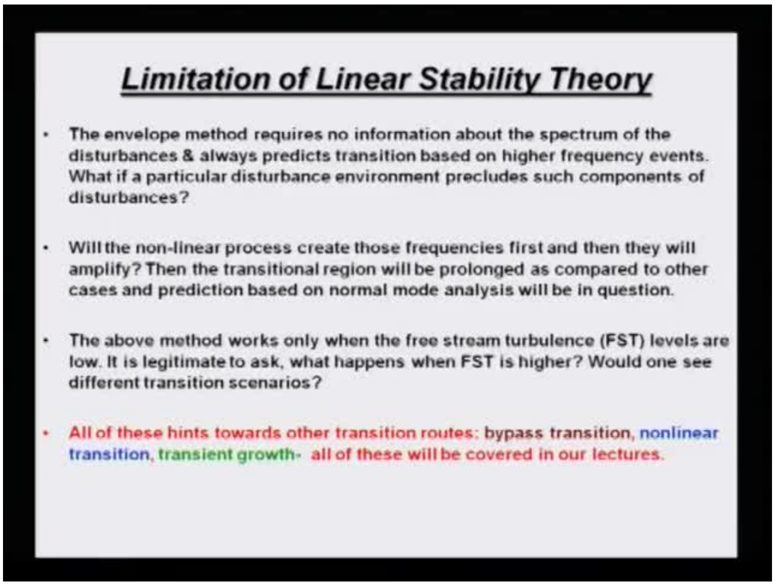

Let us now talk about other effects. We have now just talked about effect of pressure gradient. What else can affect transition? The main thing is going to be the background disturbances. Here, what we have done is what we just now discussed. We have plotted i, Reynolds number versus the shear factor. And, there are collections of data. Those have been plotted here. This is the first line corresponds to where the flow becomes critical. For different values of H, it happens at different location; whereas, the second curve corresponds to where the flow becomes turbulent. So, what you really need to understand, instability does not necessarily mean transition. As we saw in the previous frame also, if you recall, we did talk about it that if our (Refer Slide Time: 33:24) value of pressure gradient is not too adverse, then there is a distinction between where the flow becomes unstable; where the flow becomes unstable, H has the tendency to fall, but it reaches that turbulent value much further down.

(Refer Slide Time: 33:32)




So, there is this difference between the point of instability and point of transition. This thing (Refer Slide Time: 33:58) sort of disappears with adverse pressure gradient; and, that is what this nice figure is (Refer Slide Time: 34:10). This is a compilation of data from various flows taken from White's book. What you notice that this is the locus of point of instability and this is the locus of point of transition as predicted by e to the power 9 theory. You see, we did talk about the total amplification rate; when this is about 9, then where does it happen. So, this is this. So, depending on the value of H, if H is a smaller, then you can see that this critical, i x, calculated from e to the power 9 kind of comes closure. But, this into open out – what does it imply actually? This is just opposite to what we have been talking about. This basically tells you the limitation of e to the power 9 theory. E to the power 9 theory may say that for larger value of H, which means the distillated flow, there would be a significant difference, but that does not happen so. So, please do understand that these linear theories do have their limitations.

(Refer Slide Time: 35:40)




That is what we are talking about – limitations of linear stability theory. This envelope method that we did talk about – e to the power n method – does not require any information about the frequency content or that is what we are calling about the spectrum of the disturbance. We just somehow said that it is a mishmash of the whole thing. Whenever it reaches the value of n equal to 9, we are done. And, it also predicts transition based on high frequency (( )) But, suppose I talk about a disturbance environment, which do not have this kind of component, then what do we see? Basically, we are talking about nothing but the background disturbance environment; that is going to play a significant role. This is what Reynolds did in the early part of the development of the subject. He used to, I told you, come past midnight doing those experiments and he used to use that bellmouth to control the input disturbances. But, the linear theory does not really give you any room to put in there directly although one can (( )) If you know a fact, you can always create some kind of a empirical correlation and you can put it in. What we need to really talk about then is basically the background disturbances.

In addition, linear theory may not be everything. What we mean it to know is basically non-linear theory, because we can see the growth, the spectrum. All these things depend upon the amplitude of the disturbance; higher the amplitude, we may actually see a growth, which will depart significantly from what the linear theory predicts. And, we have also seen that this linear theory, the way it was developed, it did not talk about where the disturbance originated; whether the disturbance was applied from inside the shear layer or outside the shear layer; did not, because how we got the Eigenvalue formulation? We get those disturbance values to be equal to 0 at y equal to 0 and y going to infinity. That is one of the serious theoretical drawbacks of all Eigenvalue theories. However, those experiments by Schubauer and Skramstad specifically reported that they could create, validate the linear theory only when they created a disturbance inside the shear layer. But, suppose you are flying in aircraft; you will know the wing surface vibrates, because of structural vibration that can create a seed of disturbances from inside.

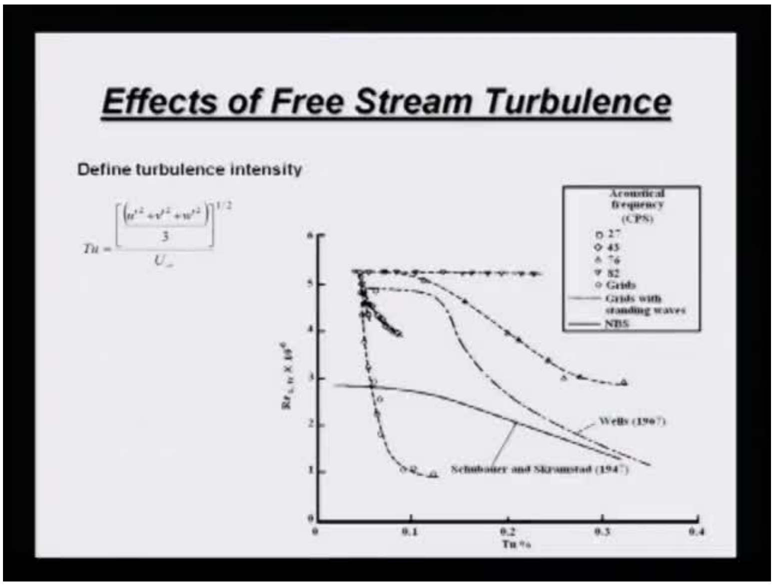
What is other possibility? The possibility would be the background disturbances are with the oncoming flow. Those disturbances are what are called as free stream turbulence. So, the free stream what we are all used to taking as U is equal to U infinity, etcetera, they are a hardly (( )). So, there would be always disturbances riding with the uniform flow. And, all these theories seem to work if this level of free stream turbulence is low. Then, you are free to ask the question – what happens if the free stream turbulence is (( )) So, we are asking a very legitimate question that if free stream turbulence level is higher, will our linear theory work? That is a very neat question to ask; or, even the mechanism by which we have talked about these disturbances grow is through the viscous mechanism. Will that mechanism follow the same route when the amplitude increases? This exercises the mind of many researchers; one of the best minds in the field is Markovian. He did study this problem very intensely and he noticed that this linear theory works for shear-driven flow like a boundary layer to some extent. But, if you look at internal flows like flow inside a pipe or a quiet flow; you know, the quiet flow is if you have a fixed plate and have another moving plate, the flow is completely shear-driven. There linear theory says flow is stable even using the viscous flow analysis.

Then, if you talk about flow inside a channel, which is called the posiflow; in the posiflow, the linear theory predicts (( )) which is close to 5770. However, people have done experiments and they have seen that channel flows can be destabilized at a lowest number something like 1000 also. These are the earlier indications that linear theory is OK for external flow, shear-driven flow like a problem of this kind of engineering interest and it did do a lot of good work. However, if the disturbances are not low, then you may get a mechanism of transition, which does not create those instability waves, which we called as the tollmien-schlichting waves. It will completely bypass that route.

And, those transitions are what are called as bypass transition. So, we will spend talking about some of the bypass transition mechanism. Then, there could be nonlinear effects; nonlinear effects could be significant. And, to that, we will add a third element; this is rather very important, which was not greatly appreciated even couple of decades ago.

All the people have talked about transient growth through mathematical subtleties of talking about non-normal modes, etcetera. But, in some of our work, we did show that when we look at even stable boundary layer, there is a possibility at the onset of disturbance; we could get a very large spatiotemporal wavefront; spatiotemporally growing wavefront. This was postulated by Brilon in the context of electromagnetic wave propagation. But, never very successfully it was detected. Fortunately enough that when we started looking at this problem ourselves, we looked at it from not a stability perspective, but from a receptivity perspective; if we create a localize disturbance and the flow is say stable from the spatial theory, we still can create this maximum growing disturbance. A good analogy would be for it is like what you may actually see in a tsunami; you would get on two, three peaks and valleys, and it grows very rapidly as it go down stream. We will talk about this. This we are going to cover in this course.

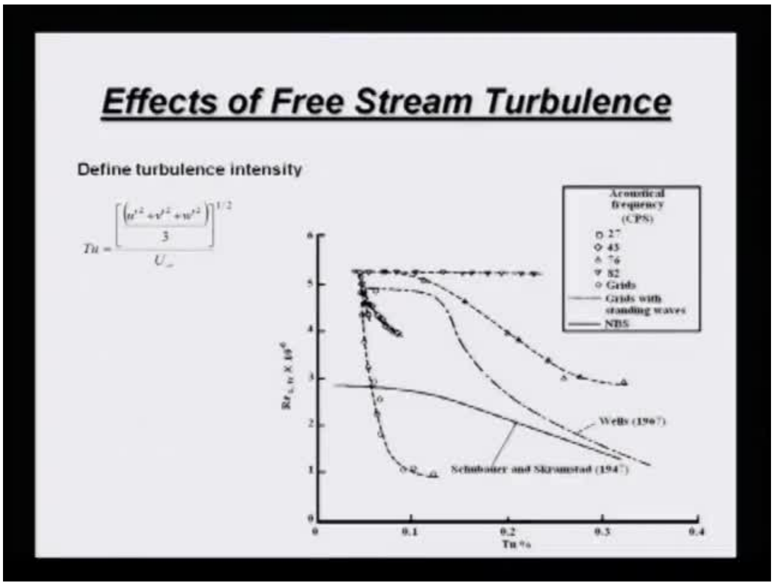
(Refer Slide Time: 44:13)




Now, one of the things that characterize the disturbance level is as I told you, is called the free stream turbulence. How do you define free stream turbulence? There is an age-old definition of turbulence intensity Tu, which is nothing but u prime square v prime square w prime square divided by 3. So, that is a kind of mean square fluctuation; on that you take a square root. So, it is a root mean square fluctuation scaled by oncoming flow velocity. That is how we define turbulence intensity. In this respect also, I would like to sound a word of caution that despite what all the experimentalists trade data among themselves by saying I have a tunnel of turbulent intensity of this value and that value; please be aware. Please be aware; they may not know what they are talking about, because the turbulent intensity is also a function of the oncoming flow velocity. So, it is quite unusual that people have depended so long to try to define a phenomenon of turbulence, which is essentially stochastic in terms of a single moment. What is this moment? This is the second moment; RMS value.

What happens to other quantities? Of course, the mean is taken care off; that is what you calculate. Second moment is OK. What about the higher moments? This we will talk about and we will see and we will show that it is very significant that you should not lose sight of this; and also, the fact that this is not something that you can just simply talk about. We will show you some experimental results, experiments done in the same tunnel. So, from the experimentalist's perspective, has the same Tu so-called, because that is what they all have tried to coach you a single number. But, in the same tunnel, we did experiment with flow past a cylinder of two different diameters. So, to keep the Reynolds number same, what we had to do for different diameters, we had to change the speed; and, what we saw as a totally different frequent of transition. We will come to that. Nonetheless, historically, people have gone through it or let us show you what we get. This is a plot of a transition Reynolds number (Refer Slide Time: 47:12) versus turbulence intensity. On this solid line is the classical experiment of Schubauer and Skramstad, which shows that as turbulent intensity increases, that Re transition comes down.

(Refer Slide Time: 44:13)



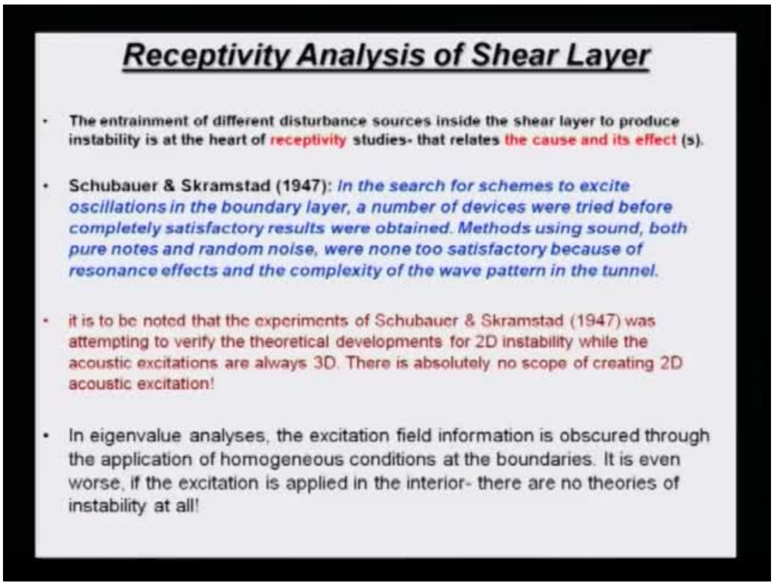

But, please do note that in their experiment, they did not see effect of turbulent intensity below a level of 0.1 percent. So, there has been a kind of a myth gone around say, which says that if the turbulent intensity is less than 0.05 or so, you have extremely low turbulent intensity (( )). And, that is quite OK. However, if I am seeing a fluctuation, this is what; any disturbance in a fluid flow can be classified into few generic components. One of the components would be the vertical disturbances; I can create small eddies. Those could give rise to this u prime, v prime, w prime. That is the vertical disturbance. However, I could also create even acoustic disturbance; noise – acoustic noise. At these tools, think same; common sense tells us no. But, unfortunately, when you talk about Tu, this Tu does not tell you that this Tu has been calculated, is based on the vertical disturbance or acoustic disturbance. So, people do actually try to rationalize saying that this insensitive path (Refer Slide Time: 49:00) at the lower level is due to acoustic disturbance. I mean, those kinds of disturbances or turbulent intensity are due to acoustics and they do not affect. It is only when it becomes vertical, they start affecting the transition location.

Here, we are seeing some results, which were reported by various people; the acoustical disturbances were created in a wind-tunnel experiment for flow positive flat plate. And, these are different frequencies: (Refer Slide Time: 49:39) 27, 43, 76, 82. And, this is one case, where some grids are put; the beginning of that (( )) section. This grid data is this one. And, this grid data tells you a very good story here; what does grid create? Vertical disturbances; eddy is directly. And, the moment you do that, you can see that it actually brings down the transition location very (( )) That is what it is. So, if I create a particular grid of this particular experiment, this was the curve (Refer Slide Time: 50:25).

Now, we are seeing lots of other interesting data. And, this is what (Refer Slide Time: 50:34) is for acoustic disturbance of frequency 76 hertz (( )) And, this is for 82 hertz and those two sets of data are here. So, why did Schubauer-Skramstad fail in creating instability and transition by acoustic excitation while this data shows, there is some dependence. Why? Please do understand that Schubauer experiment's main aim was to validate linear theory. The linear theory for what/why we are studying? We are studying a 2 dimensional mean flow with 2 dimensional disturbance failing. Acoustic disturbances – can it be 2D? So, you can understand that you will have to study the flow from the perspective of 3 dimensional disturbances. And, we cannot use the square theorem; that is what we have said. For a 3 dimensional flow, if you are looking at spatial instabilities, squares theorems does not work; you will really have to study a 3 dimensional… Despite that, this result seems somewhat perplexing that while some frequencies, you see dependence on the turbulent intensity; whereas, for this case, (Refer Slide Time: 52:19) it remains flat. Why is that so?

If I create acoustic frequency of a particular frequency, where is it that I am getting different value of T infra? It is not due to acoustics. Acoustics is a fixed frequency; or, is it that they have increased the amplitude of acoustic excitation and by that they are controlling Tu; or, if I create a very large amplitude acoustic disturbance, first it creates a vertical disturbance and that inturn destabilizes. There are so many unanswered questions in this area. So, this is something that you should keep in mind and there are some results, which also talked about basically where you created a kind of a standing wave. See what happens; if I am doing an experiment in a wind tunnel; so, it is a closed section wind tunnel and I put a model inside; then, the waves. If I create acoustics, that will continually reflect from top and bottom. And, depending on the condition, I can also create a standing wave and that is what one of the results are; see this one (Refer Slide Time: 53:42). This data is due to waves, which says that there was a grid, but in addition, there was some standing waves noted.

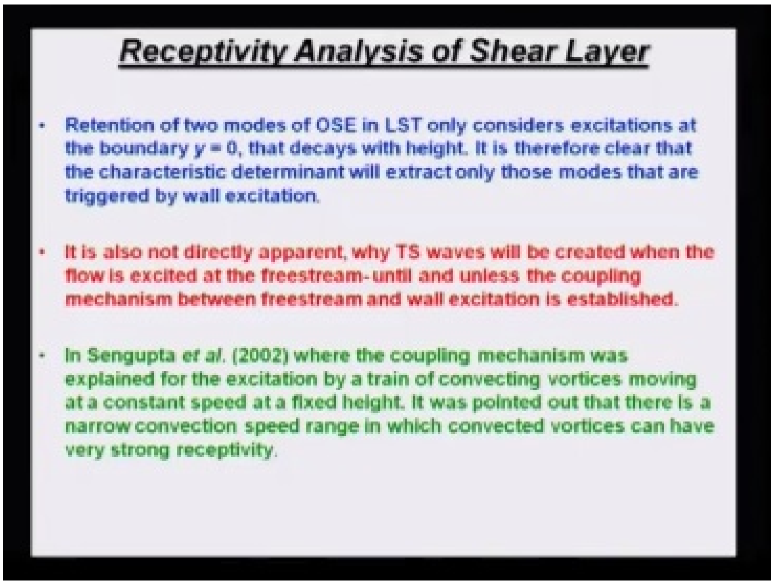
(Refer Slide Time: 53:56)




This tells us that we need to do something different from linear stability theory. And, I am drawing your attention to what is known as the receptivity analysis. In receptivity analysis of the shear layer, what we need to do is, we relate the cause and effect. So, that means what? We are talking about the background disturbances, etcetera; whatever is the source of excitation, you try to find out. And, you can see what Schubauer and Skramstad noted themselves; that in the search for schemes to excite oscillations inside the boundary layer, they did try a number of devices before they completely obtained satisfactory results. What they noted that methods using sound, both pure notes as well as random notes, were not satisfactory, because of some kind of resonance effect. And, those also create a complex wave patterns. And, I told you that their experiment was geared towards validating a 2D instability while acoustic excitations are all 3D. And, you would agree with me, there is absolutely no scope of creating 2D acoustic excitation; absolutely, no.

Then, this part we need to keep in mind that in eigenvalue analyses, the excitation field information is completely lost, because of our insistence upon satisfying homogeneous condition. It is even worse, if the excitation is applied in the interior – there are no theories of instability. So, we always create disturbances on the boundary. Suppose I put a sort of a vibrator somewhere in between, instability theory, eigenvalue theorem; then, it has no clue; cannot say what is going on. So, it was the situation till the mediate is also. Then, some of us tried to rectify the situation.

(Refer Slide Time: 56:24)




Then, what we are tried to figure out that when we retain already two modes in linear stability theory, we are actually considering excitation at the boundary y equal to 0, which decays with y. So, that is what we called as the wall mode. We will start from here in the next class and will see how we can systematically develop a theory of receptivity and find out lot more meaningful information than what is given out by the eigenvalue theorem.