Instability and Transition of Fluid Flows

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Module No. # 01
Lecture No. # 02

Good morning, we have started our discussion on various aspects of transition and turbulence, and what you are looking at there is a course content and we have been basically talking about how historically this subject is developed, so let us get back there. And historically introduction that we have been talking about that following, the experimental observation of Reynolds which was in turn triggered by the observation by stokes that you could not get the pipe flow calculations to match with the experiments was followed by Reynolds in his pipe flow experiments.

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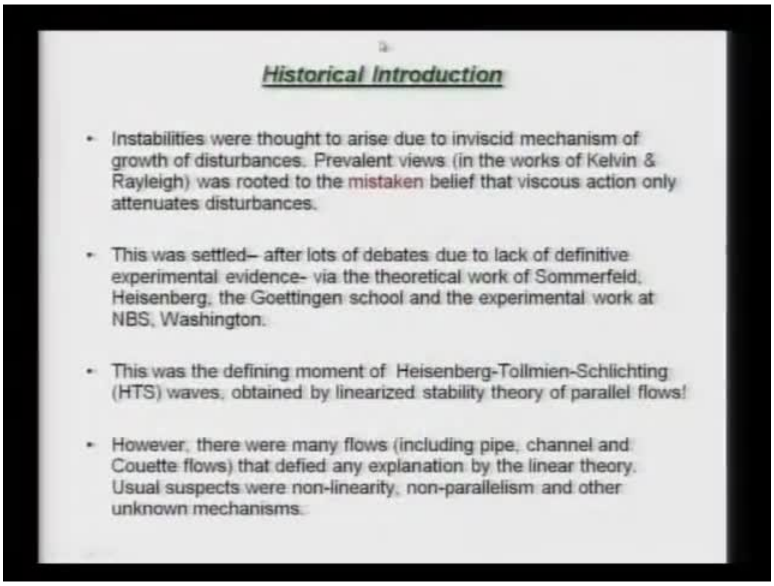

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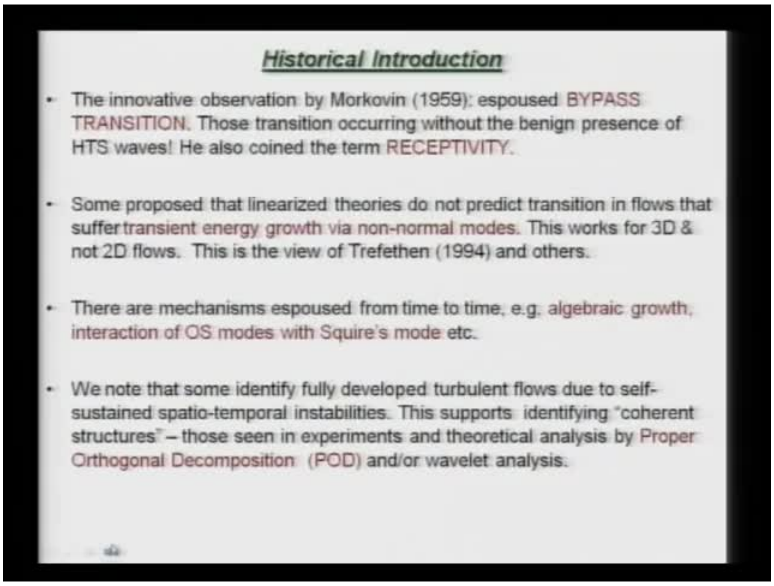

Where he should that, the small ambient disturbances actually magnify and that leads to the settled laminar flow to go from laminar state to turbulence state and the whole idea of that experiment will be revealed to us later.

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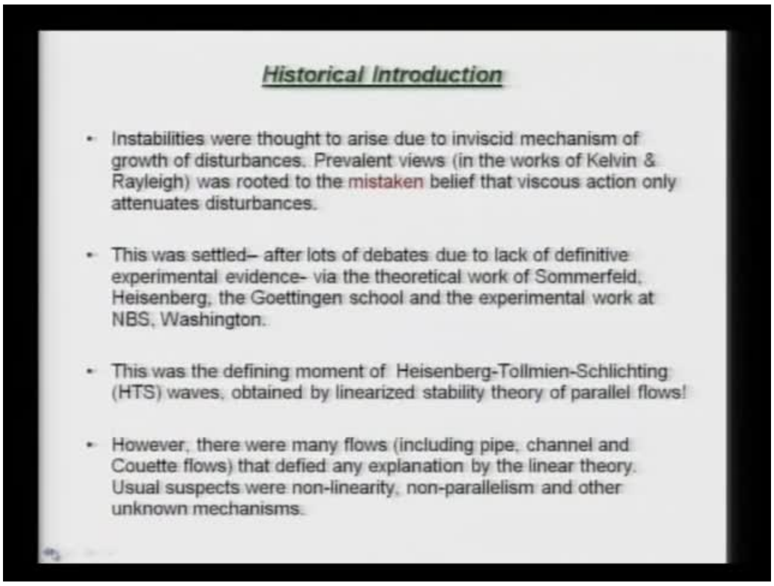

But let us now, basically talk about the other aspect, that the whole stability study was started with the mistaken, believe that viscous action if it is there, it only dubs the disturbances, and this was essentially the idea of Kelvin and Rayleigh. This was settled down after lot of jousting, you can see between various groups from Germany and

Europe in the continent as European continent, in U K and finally settle by experimental observations at NBS Washington by Drigens group. And we concluded that it established the existences of wavy disturbance flow at the onset which we called as a Heisenberg-Tollmien-Schlichting waves or HTS waves which was obtained by linearized stability theory for a parallel flow that is the catch.

However, when the same theory was applied to pipe flow, channel flow and coquette flows in that these are unconditionally stable for all parameter values. So, basically done people started looking at alternate explanations and the suspected that this could be due to the non-linearity of the instability regime or it could be that we had used an assumption that these streamlines are parallel that could be at faults.

So, basically we have to include the growth of the boundary layer into account that is what we mean by non-parallelism, and of course, we may have some kind of other unknown mechanisms, and in this context we come to the work of Morkovin.

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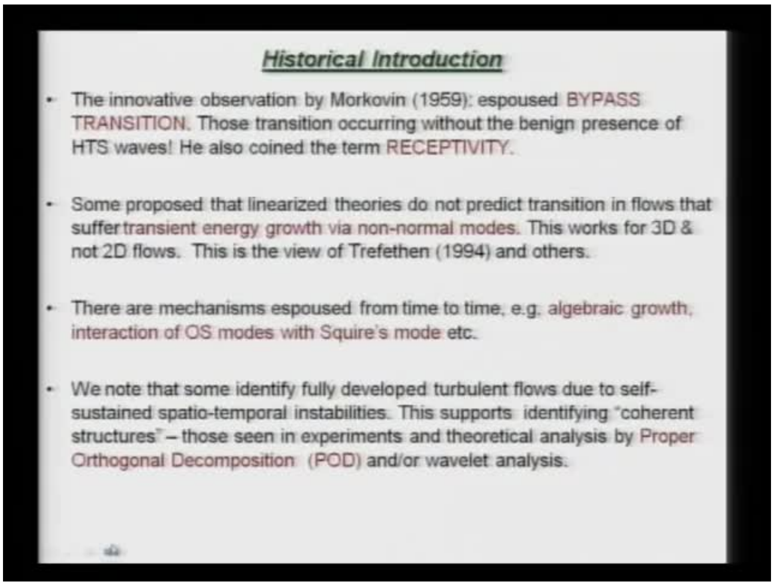

We 1959 espoused what is called as a bypass transition; bypass transition is that scenario which actually occurs without the presence of this waves that Heisenberg -Tollmien-Schlichting waves that we talk to about. And he also followed the experiments of Schuhbauer and Skramstad where it was noted that all kinds of disturbances do not lead to instabilities, you have to be pretty selected.

So, what was observed by him that the flow itself has a property called receptivity that it is receipted to certain class of disturbances; it is not receipted to all kind of disturbances. So, receptivity something that was proposed as oppose to the general theory of stability, which is posed as eigenvalue problem. And as you know that in all eigenvalue problems, you do not need to define what is the disturbance. You have a homogenous differential equation, you also have a homogenous boundary condition, so you have no way of putting in this information that there is some definitive input.

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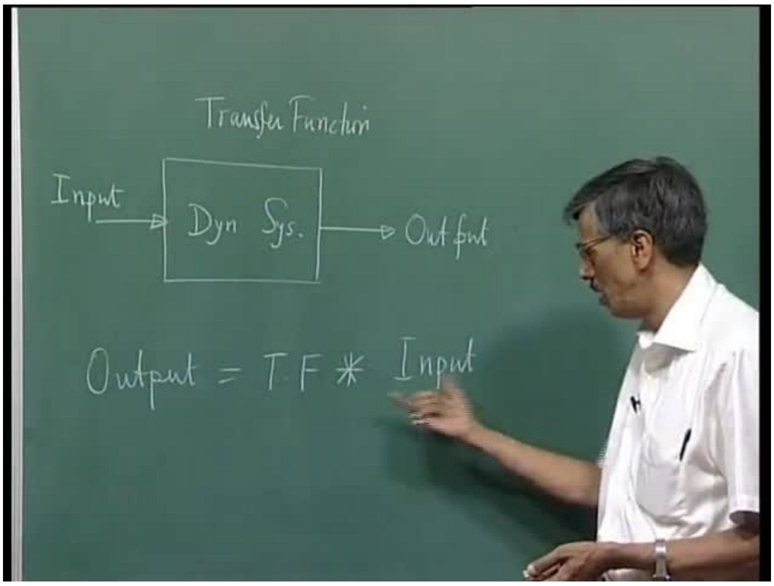

So, basically this is the beginning of a dynamical approach of study of stability through this receptivity analysis, when the receptivity analysis what you do, if you look at the dynamical system, so that is the acted upon by some input and that leads to observable outputs. So, receptivity is the property of the dynamical system and this property is what we called as the transfer function, so in a sense what we are talking about is that the output is nothing but a kind of a product, which I will all use a scientific term called convolution of the transfer function times the input. This is important because you see as long as we cannot include what is causing the perceptible disturbances, the picture remains incomplete, and this is what Morkovin was suggesting that we should talk about it.

So, if this transfer function is not receptive to that class of our disturbances, then even in the presence of that input is not going to do anything.

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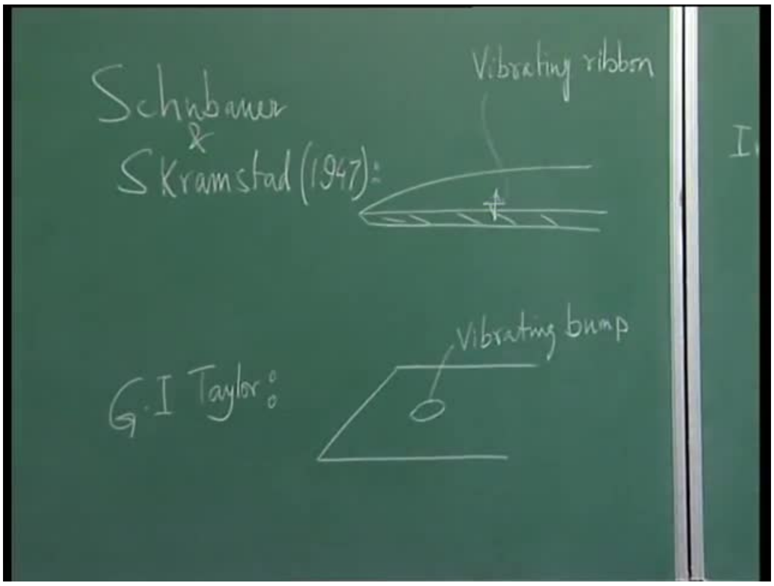

This is rather important because, when Schuhbauer and Skramstad in the experiment in the tunnel try to basically excite those waves by acoustics and we are not successful, then they used a kind of a vibrating ribbon. So, what they did as the following that if you have, let us say, a flow past a flat plate, then the boundary layer grows like this and what they did was, they put in a kind of a vibrating ribbon here, which is close to the boundary and then started vibrating it.

So, this is what you may call as the vibrating ribbon, these are made of bronze and it has vibrated at some specific frequency which was actually used in Tollmien and Schlichting calculation. We talk to about in the last class, the G I Teller also wanted to do some experiments, what G I Teller did was this, we have a plate and then you put in kind of a vibrating bump.

So, this is like a circular patch flexible which goes up and down, and this was the experiment that was conducted by G I Taylor in 30's - early to mid 30's - and this was the experiment that was done by Schuhbauer and Skramstad. This was published in 1947, but it was done long time before, it remains classified during the warriors and it got published afterwards.

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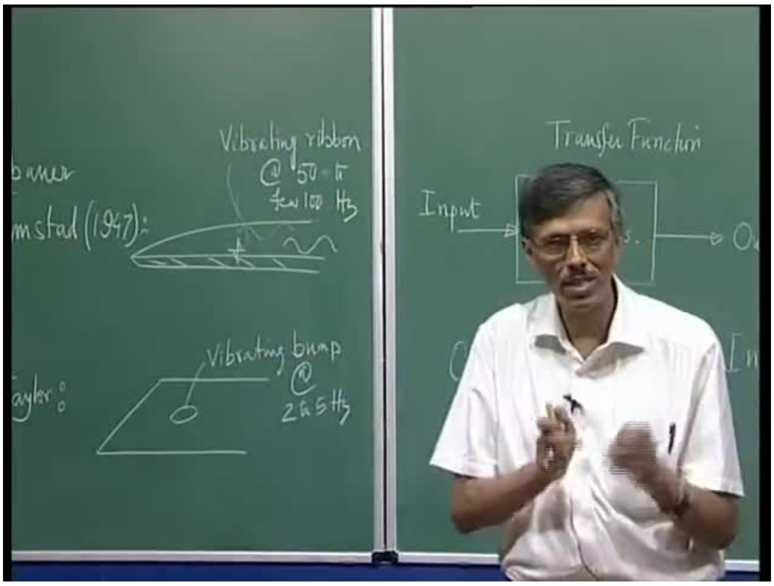

So, this vibrating ribbon was excited at frequencies of let say 50 to few 100 hertz, whereas in this case this was vibrated at 2 to 5 hours. So, this could not produce Tollmien-Schlichting wave, but this could. The reason is this eigenvalue calculations of Schlichtings did show that the flow is not receptive at low frequencies of this kind, but they are indeed, receptivity this frequency, and this was something that one needs to do, in experiments you just do not simply do a qualitative experiment and then make value judgment, so we understand, all though I must tell you that G I Taylor was outstanding fluid dynamic system of his time.

It is said that he never took any sponsored project he is to do science for its own sake is in his own money and resource, and he was a professor at Cambridge. So, he never did any sponsored research, so he used to do it for the love of the subject, whether the same time even the person of that Caliber can also, some time take a wrong step and here is an example. So, this was the something that was very good that Morkovin suggested that we should look at the receptivity approach, so we need to understand the transfer function very clearly. Stability theory only looks at the transfer function, whereas receptivity studies look at this full thing, because that also includes the information of the input.

We mentioned that there was something like some flows, the coquette flows, pipe flows, which does not show linear stability. So, what happened is, some researchers commented that those flows actually undergo transition because they suffer transient energy growth via some modes which they call as non-normal. Well, we will go through these details, the Eigenvalue analysis looks at one frequency or one wave number at a time, so those individual frequencies or wave numbers are called normal modes. So, here this people are talking about some kind of an energy growth not growing like a wave, but it is growing like - in time.

And that is transient it just grows and then, it is not there - I mean - it directly takes the flow from laminar to turbulence state. So, it is not like a gradual growth that is you associated with the Heisenberg-Tollmien-Schlichting wave transition route.

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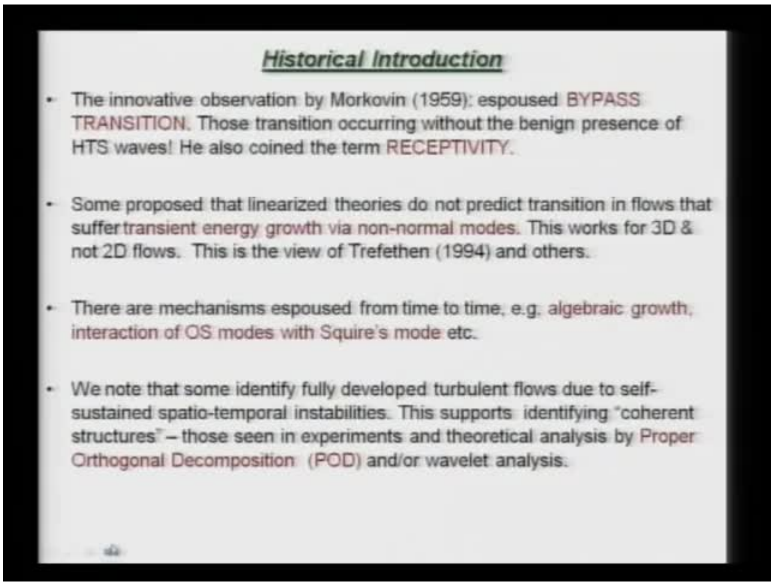

So, maybe you know this is the attempt to explain one particular type of bypass transition; we define the bypass transition at that transition which bypasses the wave and its growth. So, this was that, and this is the view propose by and his colleagues in this paper, and they were other attempts by Landaul, where he and Trefethen his colleagues talked about algebraic growth of disturbances and interaction of different types of instability mode etcetera, we will talk about this.

Now, we also note that some researches identify that you get fully developed turbulent flow due to some kind of a self-sustain instabilities, mean for that you do not have to do anything, it will just become unstable to grow become turbulent and then, it may decay but then again another set of disturbances will pick up. So, that process is self-sustain and they said that during this process, you create some kind of a discrete structure which has been called as coherent structure, it is like think of eddies, vortices, so they are talking about some vortices or eddies forming, and those are what are called as the coherent structures, they have been seen actually in various experiments, some theoretical analysis done by proper orthogonal decomposition or wavelet analysis also shows presents of coherent structures.

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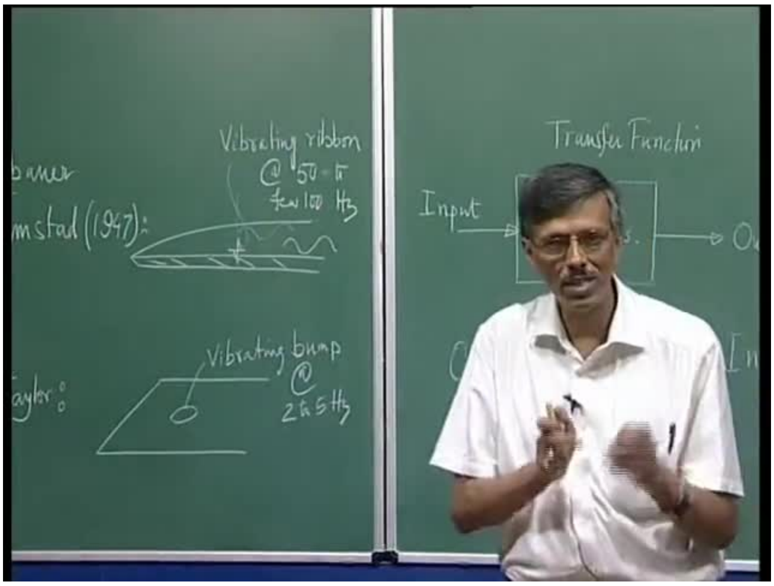

So, this is a precisely the status now, we are now in a time where we see that there are the possibilities that you have this transition taking place to the growth of waves or you can have bypass transition; a bypass transition is basically a basket, so it has many roots we have talked about couple of them one was the transient energy growth another was algebraic growth of disturbances, there could be multiple instability modes interacting and those also did not necessarily show you waves. But, let me add at this point in time that this experiment that we talk about was very specially designed experiment and this ribbon was excited at a fixed frequency.

So, what we are doing? We are creating a monochromatic wave, so we create a monochromatic wave and we see some kind of waves that grow downstream. Now, what happens in the immediate vicinity of the exciter is not talked about a great deal before 1990’s people used to think that, that is not important, even you will see some of that books or monograph, they actually erroneously show as if that there is nothing up to air and all of a suddenly you start getting some finite waves growing, that is a wrong picture, the in fluid flow especially at low speed, you cannot have such kind of a discontinuities, you will see that it has to be a smoothly growing solution.

In fact, when we first did all this receptivity calculations, we identify 2 distinct components of those solutions; one we call as a near field which is in the immediate neighborhood of the exciter where we are exciting the flow and if far field. In the far field you see those waves the HTS waves that you talked about, but in the near field you may see some kind of a totally a different structure, will talk about it in greater detail, so this is the picture that we see. Now, let saw go through the formal description of the subject through this introduction.

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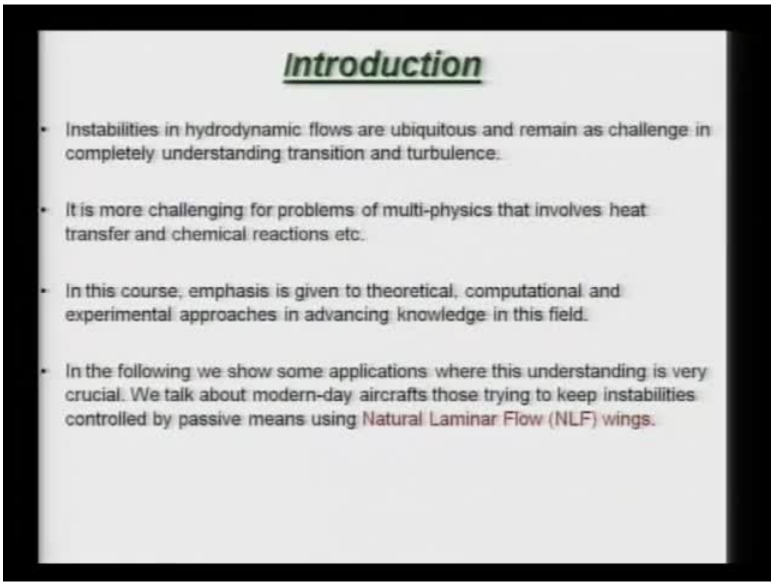

What we see as instability in a flew dynamical flows, they are always that is what we say that they are ubiquitous, and even today they remain as challenge, because we still do not completely understand transition and turbulence. We understand bits and pieces, and we are also going to do that, however, will try to integrate the whole thing together, and as we can see that you have a laminar flow, then you have transitional flow and then you have turbulent flow, in this course we will try to go from the laminar flow side to that side. We will not put the cart before the horse, we will not talk about turbulence and then we will say make some assumption most of the time people who actually spend all the effort in studying turbulence, the back of their mind, they basically think about some kind of a universality of turbulence.

What it means is, irrespective of whatever input you have the eventual output you will get only one turbulence, one kind of turbulence, all though they described it not in a deterministic manner, the described it in a stochastic fashion, but they say that in a stochastic picture also you have a universality or which is debatable and which we do not agree or some of us do not agree. So, that is why what we do is, we go from the laminar flow side first it becomes unstable in a primary mode, then he could have a secondary instability, then he could have partial instability, he could have non-linear stages and then you have fully turbulence, so that is what we are talking about.

So, you know, for pure dynamical flow we are saying that they are everywhere, but if you add some additional parameter - I mean - physical events into it, for example, if we add heat transfer or if we add chemical reaction, as you may see in an engine, those also suffer instabilities and those instabilities are going to be even more complicated. So, we will probably spend some time talking about heat transfer, chemical reaction we are not going to discuss at all.

And of course, we are going to emphasize a various theoretical computational developments, we will talk about experimental results, how experiments have to be design, this is an example, that you want to see something if you are not careful you end up doing this kind of experiments instead of this.

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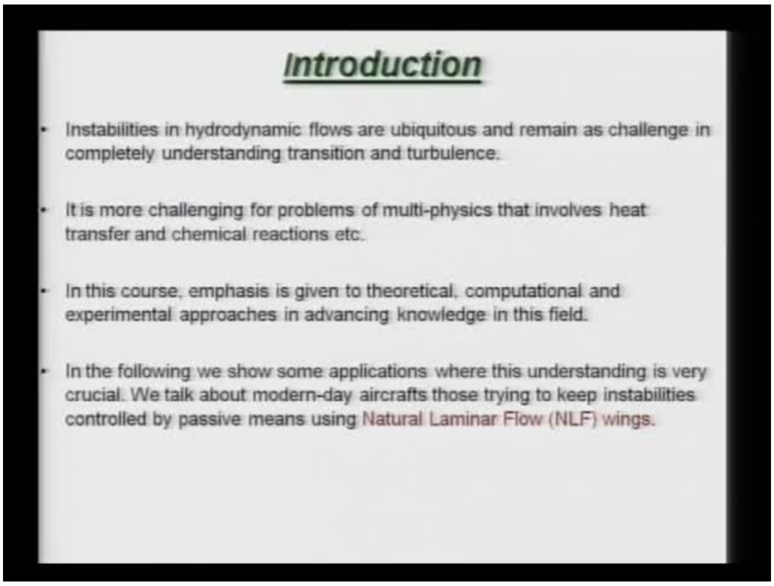

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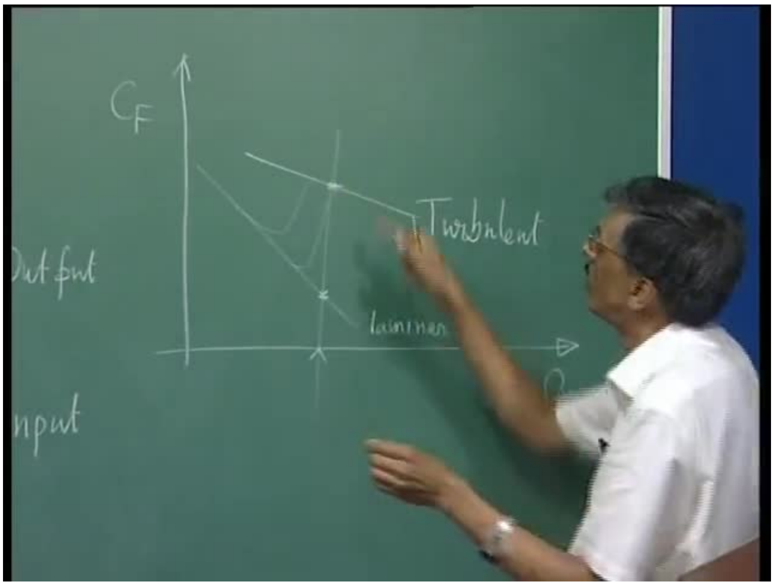

So, experimental approaches also important, so if you are going to work as a theoretician it is necessary that you communicate to your friends who will do those experiments and should to tell them how to design the experiments, this is rather important. So, let us talk about one of the application that should motivate most of you, where this understanding of the flow transition is very, very, crucial, for example, we are talking about modern day aircraft, where we basically want to keep the flow laminar as long as possible why? Because of the reason that if I plot, let say, the drag or one component of it the skin friction, versus Reynolds number, then we know, even for flow positive flat plate, the laminar flow - if I do it in log scale laminar flow - it will goes like this.

So, this is the C F versus the Reynolds number for laminar flow and then, depending on the kind of disturbance that you have, it actually goes on to a turbulent branch. So, the way the transition process takes place depends on the background disturbances and it goes connects like this, it connects like this. So, depending on different H levels of disturbances, so that is where the receptivity factor comes in, where would you continue up to this laminar flow depends on how you control the disturbance environment. If you can control it well, then instead of flow become in turbulent here you can delay it, and it can happen later.

And you can see that we are talking about a log scale, so if I look at a position, then I can see for laminar flow, the skin friction is here and for that corresponding turbulent flow if it is fully developed turbulent flow it is there, this difference is quite significant, we will give you an example, you find this is significantly ahead, so one of the goal for any good aircraft designer would be to keep the flow laminar as far as possible.

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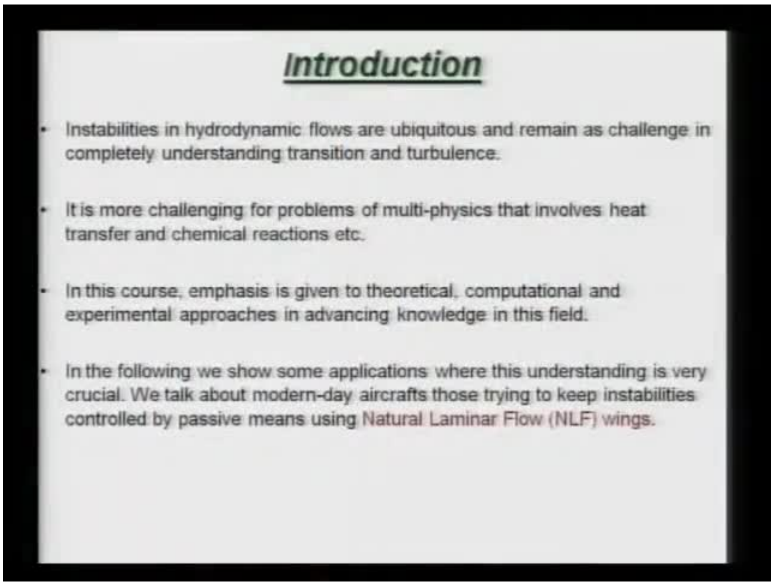

And there is a technology which is called natural laminar flow technology which tries to design and alter the wing geometry such that you can control the transition process. So, that is those wings are called NLF wings or Natural Laminar Flow wings, and you understand also, that in designing those wings we are not depending upon active devices, why not, because for active device, if you does not work then will be in deep trouble operationally. Think of that you have designed an aircraft thinking the flow will be laminar, so you have put in some engine and then up there in this sky, while it is flying, your active device fails and flow becomes turbulent and engine does not have sufficient power, then your flight is in jeopardy.

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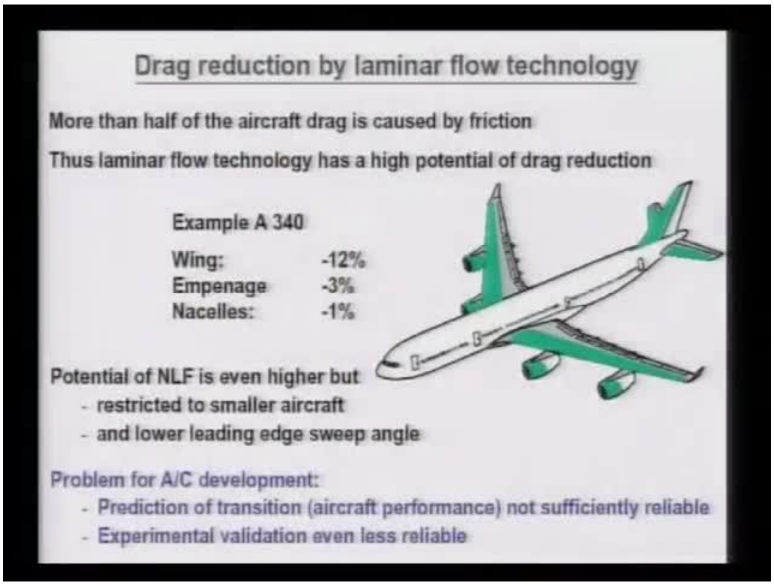

So, in aerospace engineering we are always very conservative, we always try to go for passive device instead of active device. All does not preclude that we do not basically look at active devices, lot of research is goes on using various active devices and here I have shown you a picture of an air bus 340, so this is asymmetric view of that aircraft that you can see. The green part of in this diagram indicates where you could try to keep the flow laminar, so you have not tries to keep the flow laminar over the full wing; it is only part of it you try to keep it.

And if you can do that, one is talking about 12 percent gain, 12 percent reduction in a drag and that is a quite significant. And as I told you that apart from the fuselage, most of the aircraft actually, I experience is drag that is due to skin friction viscous action, it is not as much as due to the pressure component, you know, we have 2 components of drag; skin friction drag and pressure drag. So, it a fuselage actually that gives a significant amount of a pressure drag, I will give you an estimate, so you will see that estimate.

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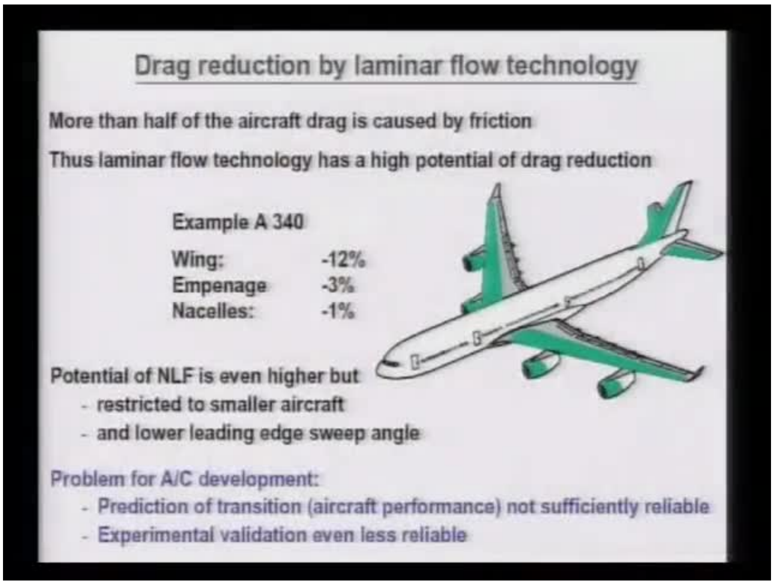

So, you can actually think of reducing the wing drag by 10 to 12 percent and that is quite significant, empenages are those controls of a site, the horizontal stabilizer and the vertical stabilizer they are also wing like body. So, you could basically keep the flow laminar over those also, whatever works in the wing, they would also work in the horizontal and vertical stabilizer. In addition, you could also keep part of the flow about this nacelle which houses the engine laminar, and there you cannot think of get a one percent reduction in drag.

So, basically, it is quite possible to do that but you notice that this is aircraft the wing is swept back; it is making some angle with the fuselage direction. So, that is swept back wings, I am not too amenable for keeping the flow laminar that becomes better if you have a sweep back angles smaller, that is why you will see many of the aircrafts that people are thinking of designing; they would not like to have the sweep back too larger, a rule of thumb is try to keep your sweep back angle less than equal to 20 degrees than that should be ok.

Why do we need sweep back? Most of these aircrafts fly at what speed do you know, it is about 0.8 and they are about, so if the aircraft is moving at about at a mark number of 0.8 then in some part of the wing then you could get a shock. So, the good news is, if you can keep the flow laminar and design the contour in such a way that also helps in controlling the shock.

So, those are called super critical wings, super critical wings are design for keeping the shock weak, it so happens that what works for super criticality, also works for natural laminar flow. So, all this aircrafts that you see, modern day aircrafts like A 340 or Boeing 7 5 7 7 6 7, and the higher models they all have NLF wings which are also supper critical wings. So, you try to push the frontier, you try to go as high as possible in terms of mark number, and to avoid shock forming you have to provide the sweep back.

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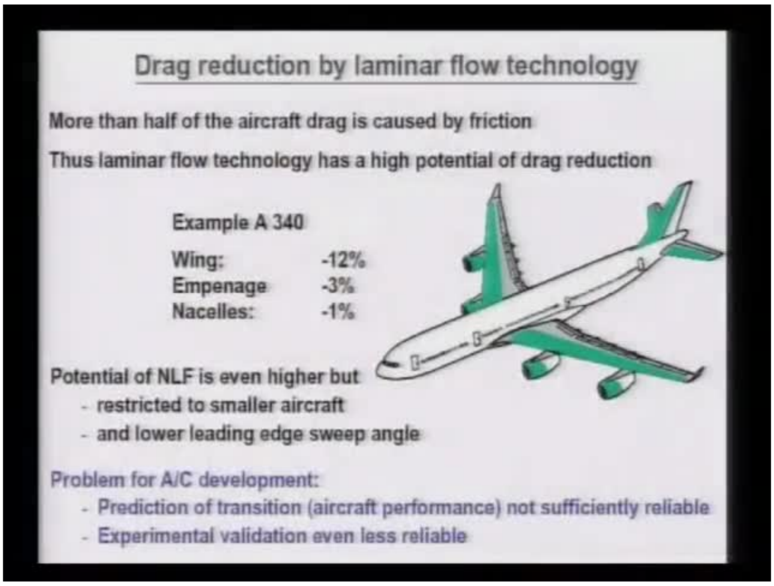

So, what matters most is the mark number normal to the leading edge, not parallel to the fuselage, so that is why sweep it back, so that the mark number normal to the wing becomes lower, so that is the whole idea.

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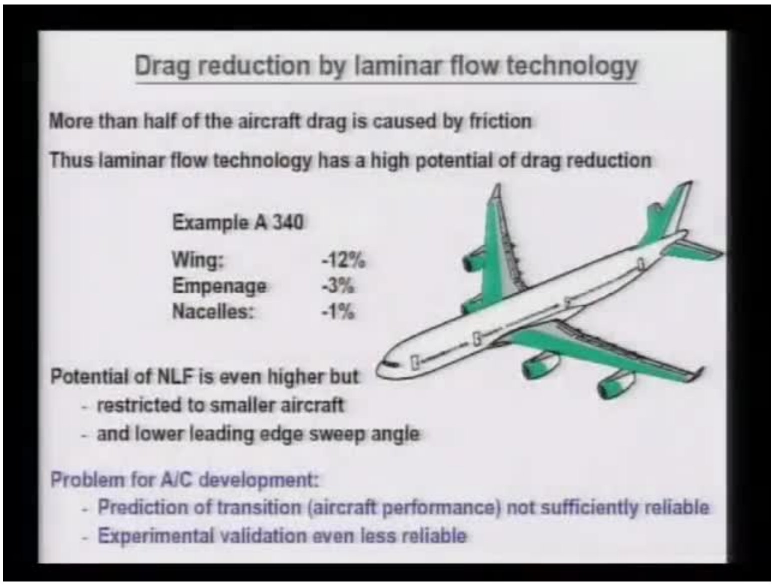

Now, if you are trying to design a new aircraft these are the problem areas, even today we do not predict transition very well, we simply do not, and even if we do they are not very reliable. And if you are talking about problem of prediction, experiment is virtually impossible. It is simply because of the fact, that every wing tunnel brings its own signature, you take the same aircraft model and do experiment to 2 different tunnel you will find a very disappointing result because there will be all different.

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So, this is what we try to keep in mind when we go along, so we are going to look at how things are work, and this is an example of a beautiful design, this is, I am not very sure if it is still out yet, it was supposed to have been inaugurated this year, this is an aircraft design by Honda. And you can see, unlike any other aircraft the surface finish of this aircrafts is superb, and this has happen the automobile sectors, they have better manufacturing ability then what we do in making their airframes. If you come close to an aircraft is see those rebates, the gaps, they look very ugly and they also actually create a big potential for transition.

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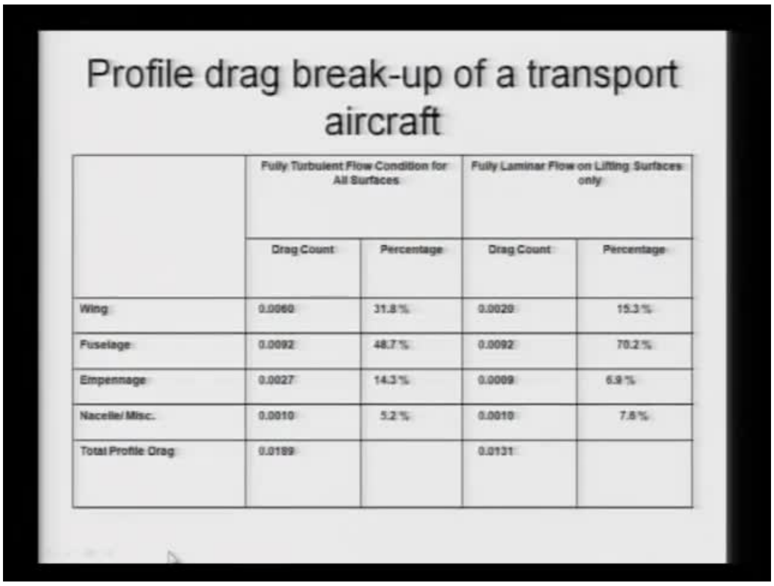
Profile drag break-up of a transport aircraft

	Fully Turbulent Flow Condition for All Surfaces		Fully Laminar Flow on Lifting Surfaces only	
	Drag Count	Percentage	Drag Count	Percentage
Wing	0.0060	31.8 %	0.0020	15.3 %
Fuselage	0.0092	48.7 %	0.0092	70.2 %
Empennage	0.0027	14.3 %	0.0009	6.9 %
Nacelle/ Misc.	0.0010	5.2 %	0.0010	7.6 %
Total Profile Drag	0.0189		0.0131	

Whereas, this people have design the wing as a NLF wing, I will show you some clip today itself, and not only that, they have also position this nestle with respect to the fuselage in such a way it is a beautiful design, because if you calculate the drag of the nestle, you calculate the drag of the fuselage, add that 2 up together and then, you go to the tunnel and do the experiment with the fuselage and nestle together that total drag is lesser than sum, so this is what is called synergy in design. So, this is one of the most of a beautiful aircraft that has been design, we have studied it to some extent, I will show you some of the work that is done by Yogesh here, you will see some of those calculations. Now, I was telling you what is the actual scenario? Now, this is the scenario, on the left hand side of this table we have shown you, if the flow condition was fully turbulent at all surfaces, and what happens is, the aircraft designers talk about the drag in terms of counts.

So, for example, the wing contributes a drag component which is 0.006, these are drag coefficients, so it is a non-dimensional number well defined, but let us get the relative idea. Compare to that you can look at the fuselage that continues 2.0092. So, you can see, it is the fuselage which actually contributes more drag than given wing, then the stabilizer gives you a drag of the order of the value of 0.0027.

So, now flee about half of what you get from the wing, so it is not to negligible. And look at the other nacelle, another miscellaneous contribution that is about 0.001, this all adds up to I think 0.0198 or something, and this column tells you that percentage component. So, wing drag is roughly about 32 percent, the physiologies about 48 to 50 percent, and the empennage contributes about 14, 15 percent drag and then another quantities define about 5 to 8 percent of drag that you talk about.

Now, if I showed you that picture, where we show for the airbus 340, and suppose, we manage to keep the flow fully lamina on all lifting surfaces, not part lifting surfaces - so lifting surfaces are just the weighing on the empennages, nothing else - so if we can keep that then you see the drag of the way would come down from 0.006 to 0.0028, so that is one third the value that is what we shown here.

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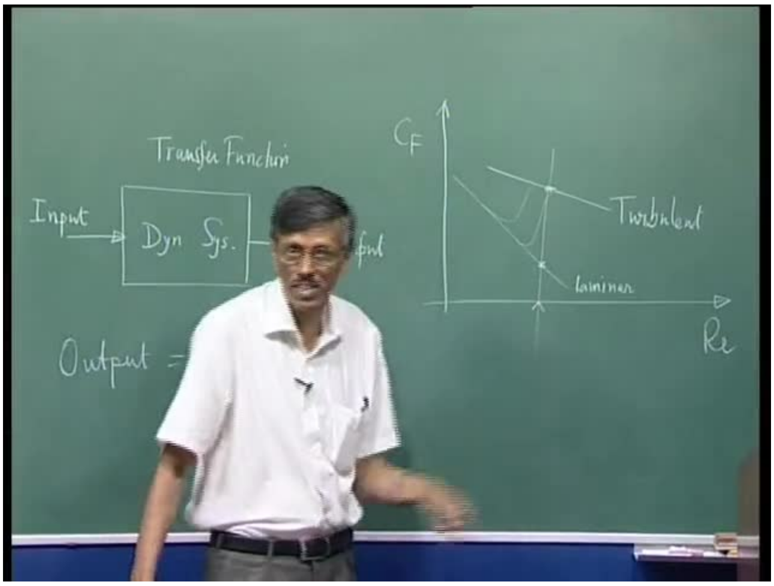

So, actually this jump for a flap plate is about 5 to 10 times, so you try to keep the flow laminar as far as possible, and further you keep it, you can see the dramatic growth, so suppose, it becomes turbulent here, then this differential is not very much but if you can keep it like this, so you can actually get a very significant reduction and drag, so that is what you see that the drag becomes one third for the wing.

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Profile drag break-up of a transport aircraft

	Fully Turbulent Flow Condition for All Surfaces		Fully Laminar Flow on Lifting Surfaces only	
	Drag Count	Percentage	Drag Count	Percentage
Wing	0.0060	31.8 %	0.0020	15.3 %
Fuselage	0.0092	48.7 %	0.0092	70.2 %
Empennage	0.0027	14.3 %	0.0009	6.9 %
Nacelle/ Misc.	0.0010	5.2 %	0.0010	7.8 %
Total Profile Drag	0.0189		0.0131	

Now, fuselage of course remains the same 0.0092, and the empennages also become almost one third, and other things kept as it is, so you see the drag as remains from 0.0189 to 2.0131. And now you see what is happen? The wing contributes about 15 percent of the drag, but the fuselage contribution as gone up to 70 percent and empenages always so come down, and the nacelle has also down.

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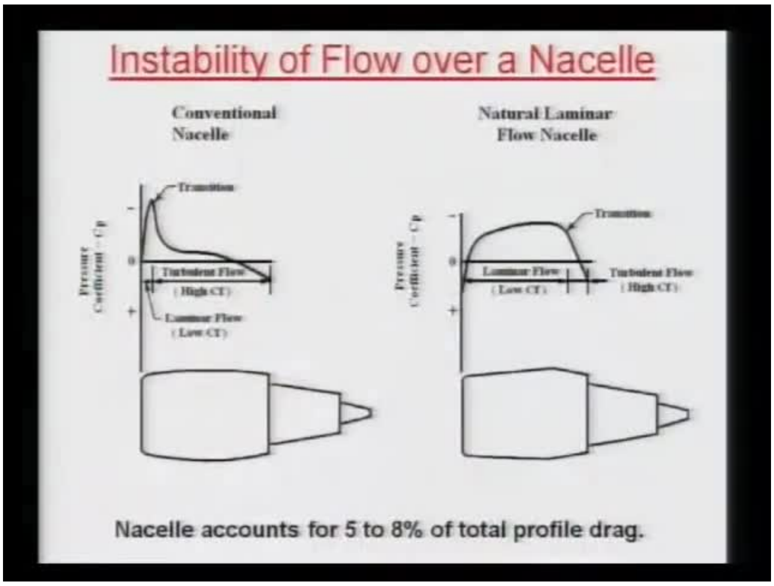

So, however, we have seen in that picture what the current thinking in Europe is, that you are not going to a fully laminar flow about the whole lefting surface, you are going to get part of it, so this is an optimistic picture what would happen if you could do that. So, talk about, let say, the flow where a nacelle, there also people have done something, you see what really matters is the pressure radiant in the flow.

So, if I just simply take a cylindrical nacelle, then its pressure distribution is given like this, so you have a section peak here, so following a section peak you have a severe deceleration of the flow. Advance special gradient is very, very, large in this part, that actually triggers transition immediately, so one rule of term is avoid advance special gradient as much as possible.

If you guys are aware of this NACA 5 digit series and 6 digits series airfoils those were designed, they knew about this, that you have keep the flow favorable pressuring as long as possible, and one of the team in the development of those aero foils sections in 1920's and 30's, first to keep the maximum thickness point as aft as possible.

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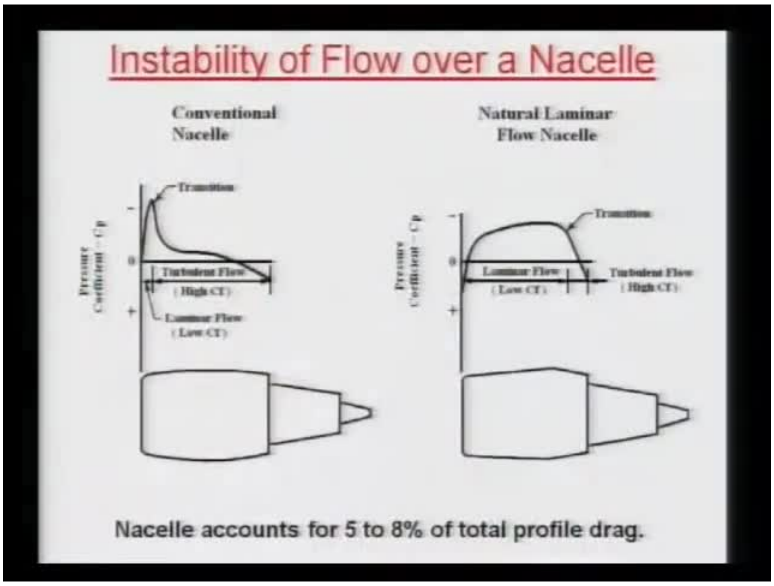

So, they did push the maximum thickness point to say a 35 percent to 50 percent and so and so forth. So, that is the story of 6 digit series airfoils, so here also you can do the same thing, now you can see the concluding instead of having a flat diameter. Now, it has been increased and if you are looking at a flow less than mark number 1, then such a contour would create flow acceleration up to the maximum thickness point.

So, you get a very smooth C P distribution has compared to this P K C P distribution. So, this is one of the way people have been talking about reduction of drag over nacelle and we have already said that it accounts for 5 to 8 percent. So, whatever you get its good enough, somebody say, it sometime ago that if you can reduce drag by 1 percent, the drag actually comes down, the operation cost come down a few billion dollars.

We just saw that for an aircraft like airbus people are talking about some amount of drag reduction by promoting laminar flow, what we also saw the Honda jet which look gleaming and which has a very fantastic of drag polar which is very good. I told you about surface finish, now surface finish is not something that you only see with your naked eyes, sometimes you would also worry about the roughness which you can only measure using profilometers.

So, then those effect of even the small scale roughness could be very perform and the people have known about it, and this effect of roughness is a function of Reynolds number, you see all those NACA 6 digit airfoils which we design they somehow work for gliders, but they do not work for powered aircraft, why? Because those unpowered aircrafts do what a smallest speed, so Reynolds numbers are lower of the order of few hundred thousand, whereas even if you look at that business jet that we saw Honda jet, the cruse Reynolds number is something like 10.3 million. So, the aircraft that you have in our flight lab they would also have a cruse Reynolds symbol of the order few millions if not 10 it would be few millions. So, at those high Reynolds numbers to small roughness is act like an amplifier, they really promote turbulence.

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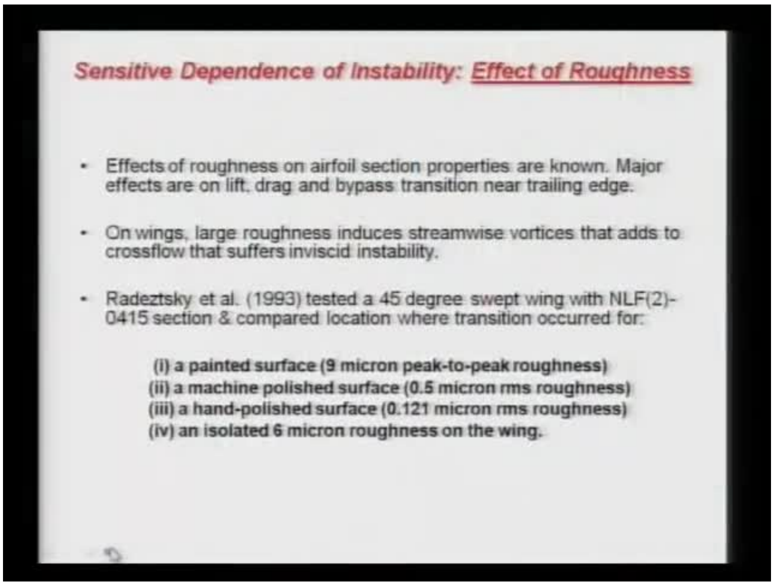

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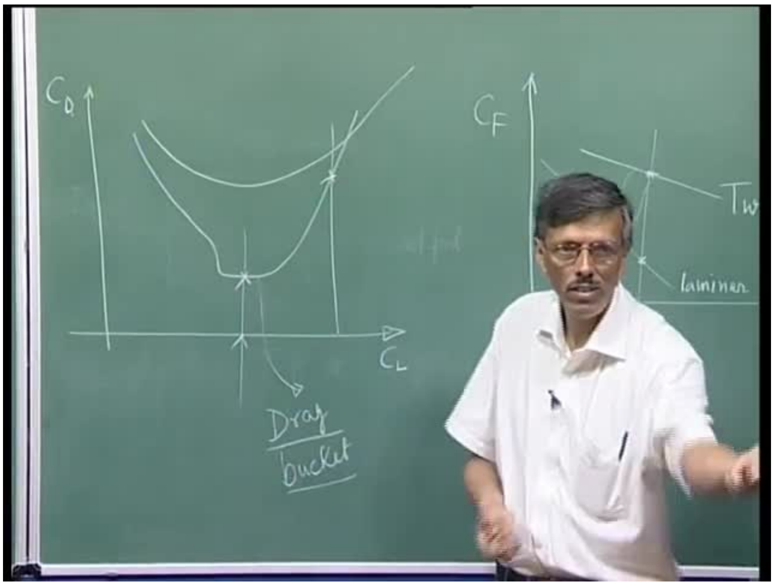

So, effect of roughness on aerofoil section is quite well known, that is why 6 digits series airfoils are not used to any commercial aircraft that you would see. They have major effects on lift drag and bypass transition may have been leading edge. Now, let me tell you some what about the property of this natural lamina flow airfoils, they have the following property 35 flopped, the section property on this side I will plot one dimensional lift coefficient and on this side, I will plot the non-dimensional drag coefficient, and this envelop aero foils are now 6 digits series airfoils those were design in 20's and 30's they have this following type of property.

So, what happens is, you design it for say point here, so this is your design point, so at the design point your drag is quite nice, so this could be a cruse configuration, but suppose when you are landing or taking off for there is a some other off design condition, you can see that if you are here then this drag and this drag are quite. And roughness actually, changes this come out together if you have roughness, you could see that this could actually go like this. So, this is what is called as a drag bucket, so most of the 6 digit series aerofoils have a drag bucket, a drag polar looks like a bucket.

So, if you are working in this region it is all verify, you are outside that region drag increases very, very, badly, So, that is why it was drag whereas, the modern day NLF aero foils would be somewhat something like this. So, it is not a single point design, it is a multi-point design, you try to design it not only for cruse configuration you also try to design it for let say landing and taking off and so on and so forth.

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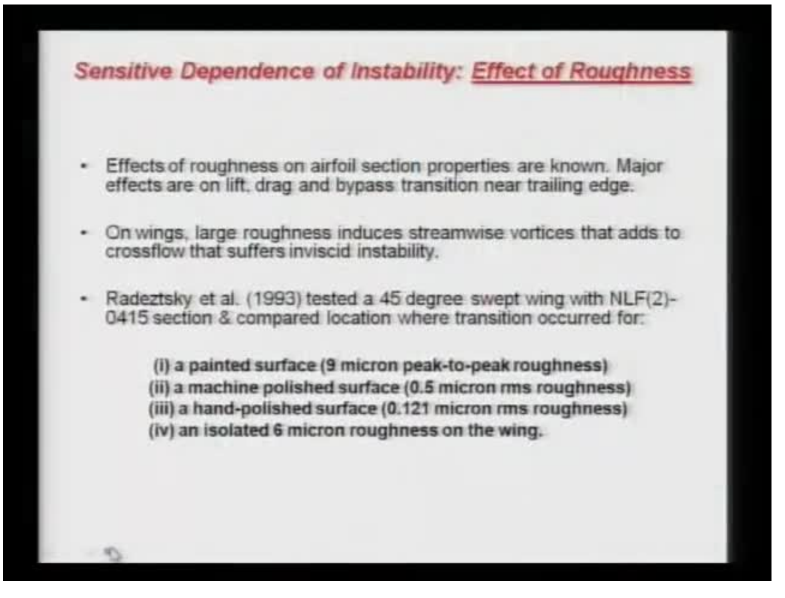

However, we have seen that this rapid increase in drag is contributed by roughness for those 6 degree digit series aero foils. What it does actually, this roughness element where it sits; it is almost like this, like a bump and you create some kind of stream wise vertices. So, vertices which are like helical structure in the stream wise direction and those stream wise vertices actually create an in instability which is called the cross flow instability and which is basically inviscid in nature.

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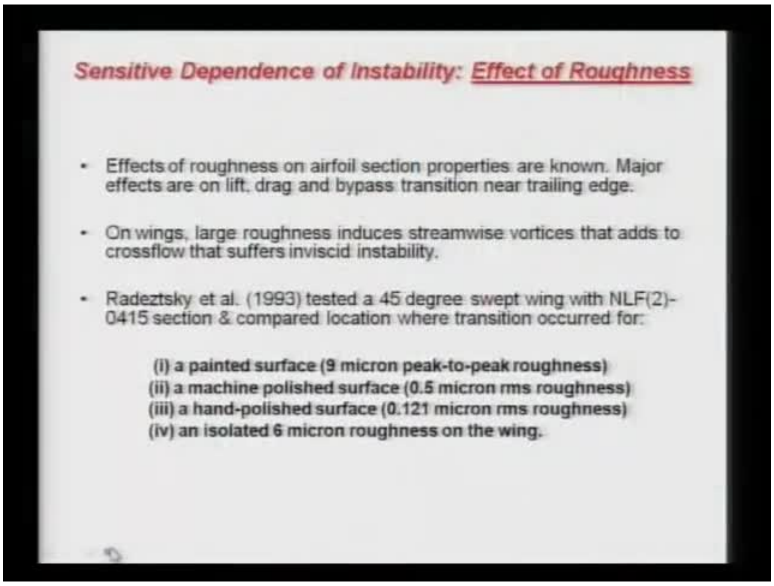

So, you have no way of controlling, inviscid mechanisms are the most vertices create some kind of a inviscid instability and they are going to triggered transition immediately. So, that is why you try to avoid having roughness, this was investigated by group Radeztsky and his a co-authors actually test a 45 degrees swept wing with this particular natural laminar flow section, this is what is called also they General Aviation Wing GAW wing. So, that is the number code for it 0415 these are 15 percent thick aero foil, and they actually compare the location where transition occurred for the following 4 cases.

You take a painted surface, you want it probably think painting its make a smoother where, still despite that if you look at peak to peak a roughness height that is of the order of 9 micron is not too large isn't, but even for a transition point of view they could be disasters. Now, you could also machine polisher of a surface, so you can bring down the peak to peak roughness from 9 micron to 0.5 micron this is the RMS value. So, you can bring it down, but what works best the life is the individual ability to do it by hand.

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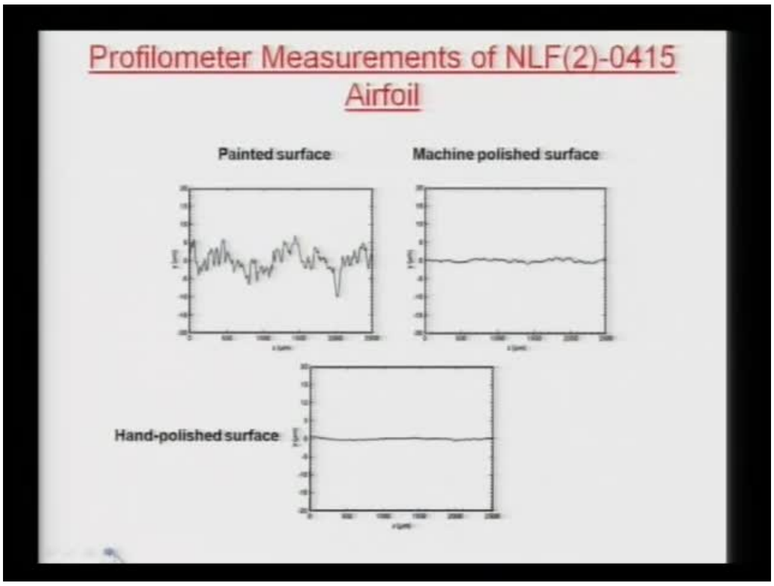

So, a hand-polished surface actually brings down the roughness height to even lower values, and they also studied something like a bump here by a 6 micron isolated roughness element. And what you would notice that this kind of a picture that you would see here, this is your painted surface, so it is like talking a cart and taking looking at sideways.

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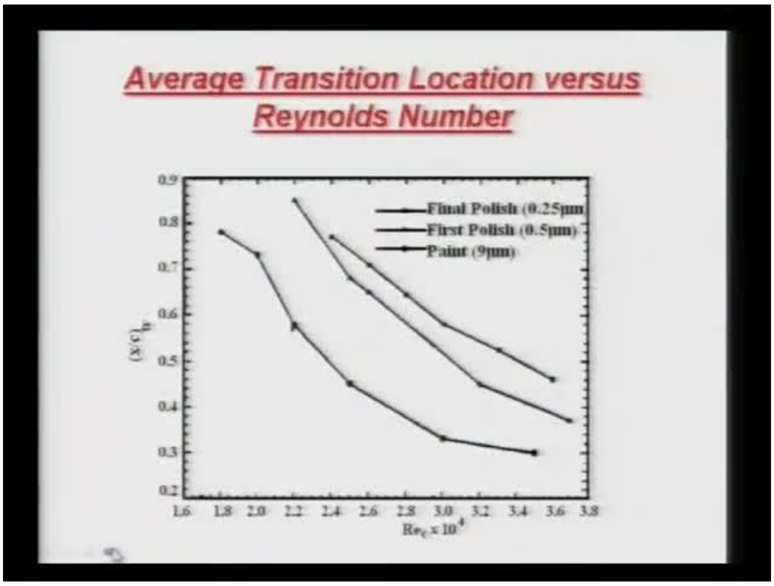

You can see those jagged nature of the painted surface, this is all in we are talking about micron level variation, and this is what you get when you machine polished to the right, on the bottom one is the hand polished. So, you can see that this 3 arcs some more different, and although there is a problem with hand polishing, you can get polish it better where it is the curvature is less, if you try to look at near the stagnation point near the leading edge, then the polishing may not be as good as this, it would be slightly degraded, but still it will be better than machine polishing. So, even today lots of model making for transition experiments one does take care of that and this is what you get. This is the story average or transition location plotted against Reynolds number and you can see this is your painted surface and then, if you do a first polishing which is about 0.5 micron.

So, this is your painted, this is your first polish and this is your final polish, so fix your attention on a particular Reynolds number, you see the painted surface a critical Reynolds number location is somewhere around here about between 30 and 45 percent, so if I look at, let say 3 million Reynolds number I think this is a 10 to the power 4, so this is a 10 to the power 4, so 3 into 10 to the power 4 the transition is occurring somewhere around 32 percent. But if you go to that first polish surface, then it actually goes from here to here, so that is about 50 percent and if you do hand polish it can actually even take it even better towards to 60 percent.

So, you can see that it is not trivial that you are talking about keeping the flow laminar for 30 percent to all the above up to 60 percent. So, effect of roughness is profound and what do you do? When we do calculations, we always calculate uniform flow past a smooth surface, so you understand why we do not do such well, when it comes to computing also, because we do not have where we that into put this input into your computations, surely some of us try to do, but rest of the people spatially those commercial packages have no way of really even comprehending this problem.

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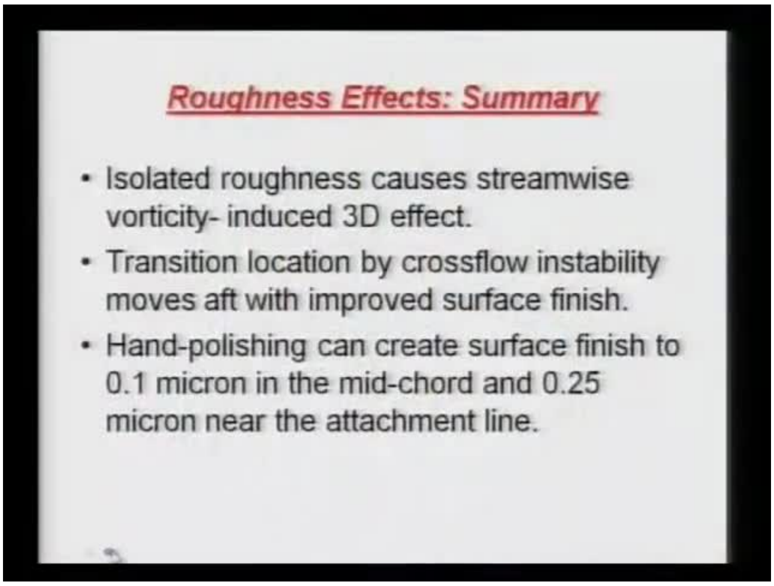

So, we understand the what it is, so if I summarize the effect of roughness, if I have isolated roughness like what we have shown here induces three dimensional effect via this streamwise vorticity, and this streamwise vertices actually creates a in the series instability. You can prevent transition occurring early by cross flow instability, if you remove this isolated roughness by proper surface finish. And hand polishing can really create surface finish up to 0.1 micron near the mid-chord region at 0.25 near the attachment line, attachment line is there the leading is right, so there you have a curve surface, you can do better than that.

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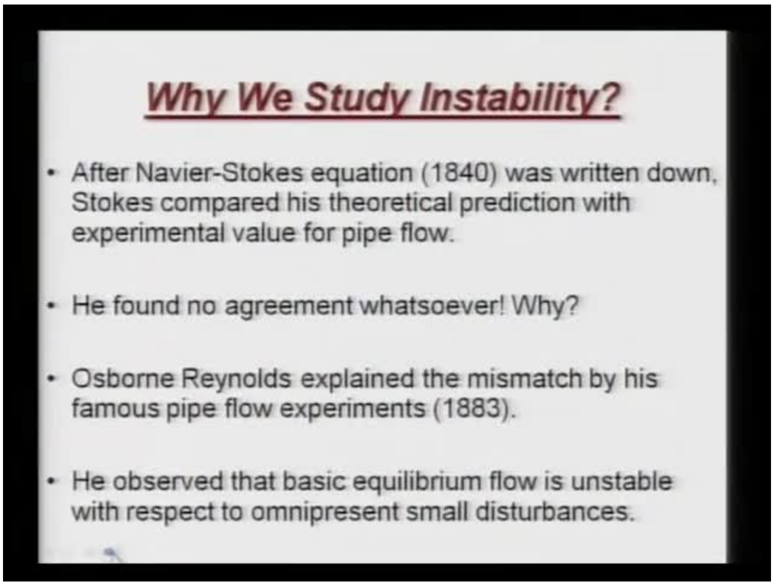

Now, why we study, we have talked about enough about this, so we know what we are talked about, but here I want to show you, but as Osborne Reynolds did. Osborne Reynolds performs some experiments, his famous pipe flow experiments, he notice that the basic equilibrium flow is unstable with respect to the back ground disturbances.

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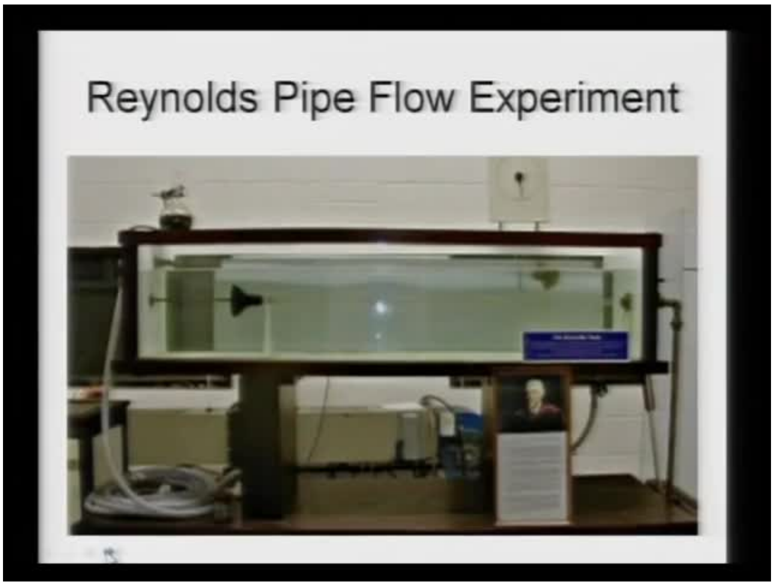

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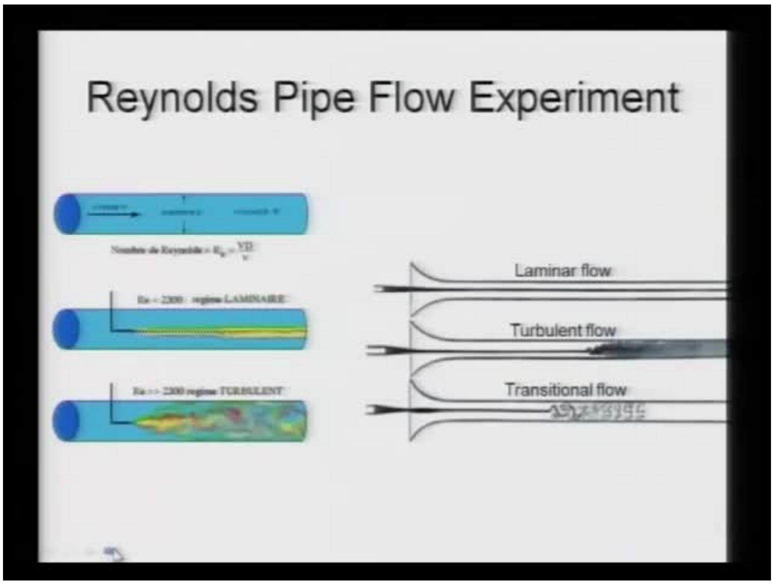

So, let see what he did in his experiment, this is a sketch of his experimental facility it is probably taken from some museum where it is displayed and this is the pipe in the middle, I will show you better sketch later, but to understand the pipe is here, the pipe entrance is through this bell mouth, so the bell mount is visible. And at the center of the bell mouth dye is injected; this is where the dye is kept on top. And what happens is, one notices the following scenario which has been sketched here on the right hand side, that if the flow was completely laminar the dye injected in the center would remain and go through the pipe.

But what actually happens is something like this, it remains laminar then it brings down to turbulent flow very rapidly, and then, this dye gets mixed up in the surrounding fluid. So, that is a signature of turbulence there right - kiotic nature of the flow. Sometimes were happens is, if you do take some care then you do not immediately go to fully developed turbulent flow.

Instead you get something like this; these are like what they call as puffs or slugs. So, you get something like a puff of disturbances going so that is what has been sketched here, you see this like a smoke ring kind of a thing that goes one after the other and this is what actually you see in the experiment. So, this is what happens when you have laminar flow it does diffuse, the dye diffuses, but if it becomes turbulent you get this.

So, what happens is, here is a case whether transition is occurred rapidly here, it has is going to happen little delayed rather, so this part of the flow starting from here till the end we will call it as a transitional flow.

So, this was the famous experiment, and if we look at it and recall what we see in the text books; in the text books it says that if you have a Reynolds number around up to 2300 or so, you can keep the flow laminar, anything largely in excess up that Reynolds number flow becomes turbulent. We have seen that in the experiment of Reynolds he could keep it flow laminar for a Reynolds number of 12,840 and here to do all kinds of things one of the thing that we have noticed is this bell mouth, this bell mouth what does it do, again, it is a in comprisable flow you are reducing error, reducing the diameter, so you have basically imposing a favorable pressure gradient or your accelerating the flow.

In the presents of favorable pressure gradient the back ground disturbances strength comes down that is how you do it. And unfortunately, the lab where prof Reynolds work in Manchester it was next to a main road, those days they are no automobiles, but there is to horse drawn coaches etcetera, and these too give rise to equisetic excitation and that is why he used to come back and do the experiments in the middle of the night and he could keep the transitional Reynolds number as high up to 12830 and this we are talking about 1880s.

Subsequently, I think (( )) did experiments and he reported (( )) they did experiments and they reported that they could delay the transition all the way have to Reynolds number hundred thousand.

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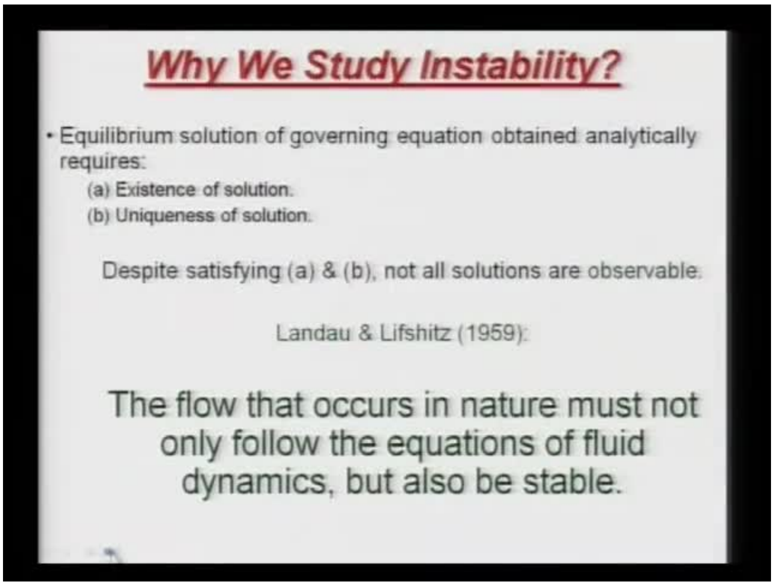

So, this is something we must keep in mind that disturbance plays a major role and that is what we wrote that input, if you stave the input of disturbances, the corresponding things will be milder, this is what we see.

So, in summary of this experiment we say that equilibrium flow that is a laminar flow, if we have obtained it analytically, we already worry about these two things, the mathematicians all is likes to think in terms of existence and uniqueness of the solution, but that story is not complete, because even if you shown that solution exist and its unique you may not observe it in nature that is related to what Landau and Lifshitz are said very clearly that the natural flow that you would see, they not only follow the equations of fluid dynamics, but they would also have to be robust enough to withstand all those back ground disturbances they have to stable, then only you will notice that flow.

So, this is at the heart of an instability studies and we said that Reynolds could keep his transition Reynolds number up to 12,830 that prompted him to say this, that the condition that he could do achieve is one of instability for disturbances of a certain magnitude. And if the magnitude is lower than flow is stable, if magnitude is larger it is unstable. So, what is this? This is the non-linear aspect where you have the phenomena depends on amplitude that is non-linear instability. This is a something that he could prophetically say that because we have said that subsequently after him where linear theory came and people investigated it was found to be stable, so why pipe flow becomes unstable? So, Reynolds himself gets this suggestion, I think we will stop here.