Wind Energy

Prof. Ashoke De

Department of Aerospace Engineering, IIT Kanpur

Lecture 44: Mechanics: Tower oscillations

Welcome back. So, we'll continue our discussion on this eigenmode analysis of tower and nacelle in combination. So, we have started with the static beam equation. Then, now we are moving to the dynamic beam equation and where we can estimate the kinetic energy. And, this is what the last time we stopped where the kinetic energy expression would contain the component from the tower and then the component from the nacelle both these units both these units have certain mass. So, that is why they are kind of also exposed to this dynamic loading due to the wind forces and other thing so, now going through this particular analysis if you see this kinetic energy expression here what we have taking care of the two components one coming from the tower and then one coming from the nacelle okay so, these two components we consider and so, what we have is now we can write omega square by 2 a naught m tau r by L to the power 5, 0 to L x4 dx m.

Now, further simplification what we can have is that omega square a naught square by 2 one by fib muscle. Now, this is what we get for complete kinetic energy. Then elastic one, what we have half of, zero to l EI a naught square by l dx so, we have A naught square by two EI four by L four into L so, that's gives us A naught square by two EI four by L cube. So, this is elastic potential energy and the kinetic energy that we have.

$$E_{kin} = \omega^2 \cdot \Bigg(\underbrace{\frac{1}{2}\int_0^L \frac{m_{tower}}{L}\left(\frac{A}{L^2}\right)^2 (x^2)^2\, dx}_{\text{Tower}} + \underbrace{\frac{1}{2} m_{nacelle} A_0^2}_{\text{nacelle}} \Bigg)$$

Tower Nacelle

$$= \frac{\omega^2}{2} A_0 \left(\frac{m_{tower}}{L^5} \int_0^L x^4\, dx + m_{nacelle} \right)$$

$$= \omega^2 \frac{A_0^2}{2} \left(\frac{1}{5} m_{tower} + m_{nacelle} \right)$$

$$E_{ela} = \frac{1}{2}\int_0^L EI\left(\frac{A_0^2}{L^2}\right) dx = \frac{A_0^2}{2} EI \left(\frac{4}{L^4}\right) L = \frac{A_0^2}{2} EI\, 4/L^3$$

Equate: $E_{kin} = E_{ela} \Rightarrow \boxed{\omega^2 \underbrace{\left(\frac{m_{tower}}{5} + m_{nacelle}\right)}_{:=\text{ effective mass}} = \frac{4EI}{L^3}}$

So now if equate the kinetic elastic potential energy we have is that omega square, m by five plus m nacelle equals to four EI by LQ. So, this is what we get. So, that's an, so from here, one can estimate the frequency of these things the frequency of oscillation by considering them so, these are i mean, if you look at it so here the i mean, one can kind of estimate this is an sort of an effective mass of that tower and the nacelle in total. So, the oscillation frequency can be estimated. And why these are important? Because, these are important to estimate the frequency of oscillations and then trying to find out what could be the natural frequency of that structural element and since these are exposed to wind loading so there could be effects or, I would say that the structural design consideration would be very, very important.

So the, I mean, the complete procedure, if you think about, see, initially we were looking at it, what would be the estimation of the axial force of the thrust and the effect of the number of blades and all these things. that's what because of the wind and the rotation of the blade you estimate the forces and how much power you can convert so essentially the wind energy in the wind you try to convert to the power but obviously through the calculation of the power coefficient thrust coefficient but those forces are acting on the body of this system That means, the rotor blades, that's a rotating component. Then, you have nacelle which houses all the electrical components, gearbox, all other accessories. Then, you have the tower which is a very important element of this. So, any structural analysis requires the force acting on the body.

And, the force are coming from the wind. one way you can think about or one can think about this is an a nice example of fluid structure interaction problem you have a force which are coming or arising due to the wind now and then different components of the hole in turbine unit and they are exposed to different kind of loading And, that loading would dictate the design. And obviously, when you talk about the design, it's also important to understand the material properties like E, I, and all these things. And then deciding the material is important, which material can resist how much forces and this kind of loading patterns and all these things. So, that's where the, I mean, this analysis becomes important.

Now later on, what you can see that we'll be discussing about the linearized system of considering this analysis, structural analysis, and considering the wind forces. There are not only wind forces, there could be wind shear effect, there could be EOI effect, there could be other effect. Okay. Now, what, see how the side and weights are, weight of turbines are kind of, you can see some example like let's say if tower height is 120 meter so, this is which is 1.8 megawatt power output then you can see their blade length r is 45 meter then you have the nacelle weight which is around 75 ton then three blades weight up to 40 ton so you can see this total gives 150 ton and you have tower height of 152 tons so that kind of gives you an idea about there is another one which you can have that is tower height of 105 meter this Vestas V164 which is 9.

5 megawatt, then blade height is 2 meter which is R then you have nacelle weight 390 ton you have three blades weight one of in total so almost close to 500 ton then you have tower weight which is approximately 400 ton and you have this diameter which is roughly 6.5 meter. So, you can see different these things what you call the site and but, there are other turbines there and nomenclature and things would be different. Now, when you talk about these towers, so, what is important is to talk about this stiff and soft towers and other things. So, we can talk about stiff and soft towers so, we'll be able to find out the lowest extraction excitation frequencies so, lowest excitation frequencies okay, So, we have already discussed that one P which means this is a rotor rotation frequency which one can say blade excitation or blade asymmetries.

Okay. BP is blade passing frequency with number of blades. Then we have tip speed ratio which is lambda that is r omega by u infinity where radius r and wind speed U infinity. So this is. That. So what we have.

W1P. Would be. Omega. Which is lambda. U infinity.

By R. And similarly. W. BP. b dot omega that means, b into lambda U infinity by R so, which means we always have WBP B into W1P typically varies with wind speed. One can think about like there would be no problem if the WBP become equal to our Eigen frequencies.

lowest excitation frequencies

1P : "Rotor rotation frequency" (blade excitation, blade asymmetries)

B.P : "Blade passing frequency" (with B = no. of blades)

tip-speed ratio $(\lambda) = \frac{R\Omega}{U_\infty}$, radius R and wind speed U_∞

$$\omega_{1P} = \Omega = \frac{\lambda U_\infty}{R}, \quad \omega_{B.P} = B.\Omega = B.\frac{\lambda U_\infty}{R}$$

we always have: $\boxed{\omega_{B.P} = B.\omega_{1P}}$ → ω_{1P} typically varies with wind speed.

So, we have to avoid with a power design and b controller design so, Essentially, what one has to do, this rotor rotation frequency and blade passing frequency can be equal to the tower eigenfrequencies. But importantly, one has to avoid the resonance. So, while designing the tower and the controller, one has to be careful that this blade passing frequency and rotation frequency should not come in resonance. Otherwise, they can be equal. And so, now what, so, these are typical constant while doing the structural design.

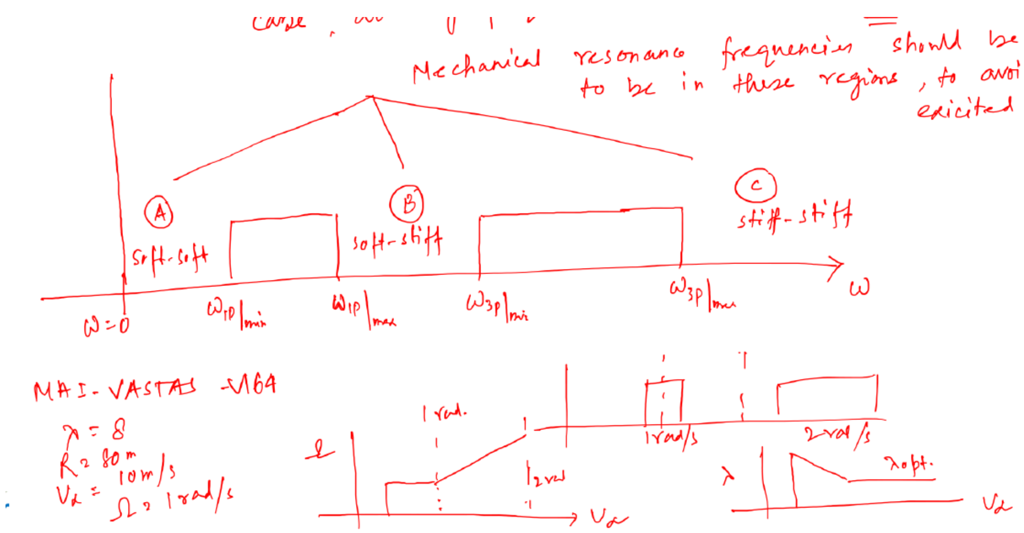
And, if there are resonance that occurs and which is always a likelihood possibility because there could be catastrophic failure of the whole unit so, it is always a good idea to avoid those kind of resonance occurrence of resonance things like that while doing the design through analysis so, as i mentioned earlier this is quite interdisciplinary in nature and also it is quite a bit of involved in a sense that this is a real example of fluid structure interaction problem now, what we can see let's say for let's say we have some given operational speeds. Let's say one radian per second, two radian per second. So, let's say given range of power, can be updated in the frequency domains. So, here you can see there could be soft-soft which is if it's lowest eigen frequency W tower is in region A. Then we have soft-stiff, if W is in region B. C, it could be stiff-stiff if Omega tower is in region C, that means it is higher than BP rate crossing frequency In this case. All. I again.

Frequencies. Are. Omega BP max. Okay. So. what one can draw. This is for varying omega.

You have zero. So, you can have omega 1p min, omega 1p min. Max. And then we can.

Keep him in. Omega. Max. So this is the June. This is June B. This is June C. Which is.

Typically, steep, steep. This is soft, stiff. This is soft, soft. So, the mechanical resonance frequencies would be designed to be in this region to avoid being excited so, that means when this design has to be done then one has to take that into consideration that where the mechanical resonance frequencies to be falling so that you can avoid this resonance so, whole idea of all these analysis or the discussion is that you have a rotor blade which is rotating so once it rotates there would be rotation frequency then there could be a blade passing frequency when the blade passes for a single revolution since these are dynamical system they kind of exposed to some dynamical loading and they are typical eigenvalues, eigenvectors and things like that. So, in the design, one has to take that into consideration that these are the things are going to be very, very important.



in a sense. So, I mean, one can see an example, which like, that the one that this, that's just 160 v 164, where we have already seen that, let's say one rad per second, this could be 2 rad per second where you have lambda equals to 8 r equals to 80 meter u infinity equals to 10 meter per second omega equals to 1 rad per second so, you will have a variation of omega over u infinity like like this okay, so, and then similarly one can see the variation with u infinity the lambda that goes up comes down stays there, that is number optimum. So, this is between, I mean, essentially one rad and two rad per seconds. So, this would be two rad per second. This is the line for one rad per second. So, this is an example where you can see how these things that is okay.

So we'll continue this discussion in the next session. Okay.