Wind Energy

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Lecture 60: CFD and Alternative Wind Energy Systems

Welcome back so we'll continue our discussion on cfd and that is the remaining discussion on cfd that will continue and then we finally talk about the alternative wind energy things and then conclude this so now we talked about the conservation equations and all these things now here what happens is that you have analytical equation that means the physical problem you apply your analytical approach to get the mathematical form and then solving the computer so this mathematical form to form this is what you apply the numerical methods so now you see there is a range of different numerical methods final difference finite element spectral lattice Boltzmann finite volume different methods so the way you apply these methods actually mathematically they are different so the way you define or apply this numerical methods you get different solutions in different ways so eventually you will get the same type of solution so just to quickly talk about what finite difference does it's a there are advantage because it's a simple to do it solves in a structure orthogonal system but when you have a complicated geometry and all these things then there is a problem with this method then you have finite element method which can be applied to any realistic complicated geometry but this is not straightforward so you need to have a in depth insight about this the mathematical rigors are quite high so obviously programming could be challenging but this can be applied to apply to complicate i mean complex problems and all this but in fluid flow finite element applications are not very popular the third one spectral method this is again it can be combined with fdms and things like that but this is relatively complex in comparison to standard fdms so implementation of complex boundary conditions could be difficult in spectral method that's why it's not quite popular for wide range of fluid flow problem where you need them whereas this pilot volume method which is also it has physical soundness not as straightforward like fdm but it can capture any realistic geometry by so commercial softwares are also mostly on based on finite volume method because this is quite popular in that sense which allows you to solve the complicated problem now in finite volume what you do you have this so essentially you get this del del of rho phi del t plus rho u i phi minus gamma del phi by del xi dot n i d s and this is q p dot dv so this is first term so this is for del of del xi equal to p dot so this is how you convert so this is your complete transport equation which could be continuity equation this could be continuity equation momentum equation so now what you can do is that this is how you get this system and then finally that equation that we rho phi by del t dv plus rho ui t minus gamma del phi by del xi dot equals to u phi dot dv so this is um kind of So this is what the domain where you solve this finite volume method. So these are you can see this is how numerically I mean we can skip this.

FVM-I

General Form of Navier-Stokes Equation

$$\frac{\partial(\rho\Phi)}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho U_i\Phi-\Gamma_\Phi\frac{\partial\Phi}{\partial x_i}\right)=q_\Phi \qquad \Phi=\{1, U_j, T\}$$

Local change with time **Flux** **Source**

Integrate over the Control Volume(CV)

$$\int_V \frac{\partial}{\partial x_i}\Phi\, dV=\int_S \Phi\cdot n_i\, dS$$

Integral Form of Navier-Stokes Equation

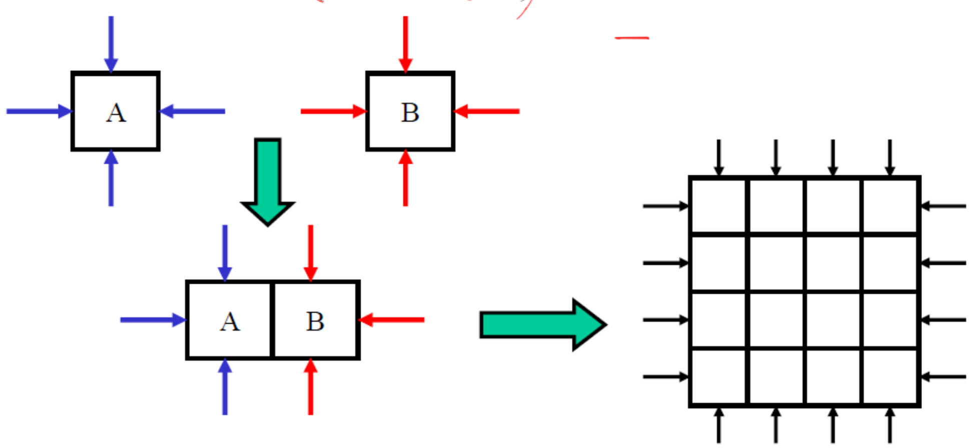
$$\int_V \frac{\partial(\rho\Phi)}{\partial t}dV+\int_S\left(\rho U_i\Phi-\Gamma\frac{\partial\Phi}{\partial x_i}\right)\cdot n_i\, dS=\int_V q_\Phi\, dV$$

Local change with time in CV **Flux Over the CV Surface** **Source in CV**

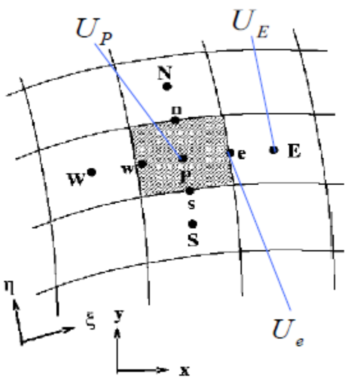
FVM-II

Conservation of Finite Volume Method

$$\int_V \frac{\partial(\rho\Phi)}{\partial t}dV+\int_S\left(\rho U_i\Phi-\Gamma\frac{\partial\Phi}{\partial x_i}\right)\cdot n_i\, dS=\int_V q_\Phi\, dV$$



FVM-III



Approximation of Volume Integrals

$$m = \int_{V_i} \rho \, dV \approx \rho_p V; \qquad mu = \int_{V_i} \rho_i u_i dV \approx \rho_P u_P V$$

Approximation of Surface Integrals (Midpoint Rule)

$$\int_{V_i} \nabla P \, dV = \oint_{S_i} P \, dS \approx \sum_k P_k \, S_k \qquad k = n, s, e, w$$

Interpolation

Upwind $U_e = \begin{cases} U_P & \text{if } (\vec{U} \cdot \vec{n})_e > 0 \\ U_E & \text{if } (\vec{U} \cdot \vec{n})_e < 0 \end{cases}$

Central $U_e = U_E \lambda_e + U_P (1 - \lambda_e) \qquad \lambda_e = \dfrac{x_e - x_P}{x_E - x_P}$

So essentially any complicated geometry if you have so there you can apply and finally you get this you finally get this linear system. So any this different numerical technique that you apply they would eventually give you the linear system to solve so that linear system so this is probably nicely summarized in this slide this is the omega plus c plus d minus this so you have one unsteady term you have convection term you have diffusion term you have source term and And then you have this time discretization, which you can do in terms of implicit or explicit, whatever, so essentially. So important aspect is that when I apply these numerical methods, the whole system turns to a linear system that I have to solve. This is where computer comes into the picture.

Discretization of Cont. Eqn

One Control Volume

$$a_P u_P + a_N u_N + a_S u_S + a_W u_W + a_E u_E = 0$$

Whole Domain

$$\begin{bmatrix} a_{11} & a_{12} & & & a_{1l} & & & & & \\ a_{21} & a_{22} & a_{23} & & & a_{2,l+1} & & & & \\ & \cdot & \cdot & \cdot & & & \cdot & & & \\ & & \cdot & \cdot & \cdot & & & \cdot & & \\ a_{k1} & & & \cdot & \cdot & \cdot & & & a_{l-1,n-1} & \\ & a_{k+1,2} & & & \cdot & \cdot & \cdot & & & a_{l,n} \\ & & \cdot & & & \cdot & \cdot & \cdot & & \\ & & & \cdot & & & \cdot & \cdot & \cdot & \\ & & & & a_{n-1,n-k-1} & & & a_{n-1,n-2} & a_{n-1,n-1} & a_{n-1,n} \\ & & & & & a_{n,n-k} & & & a_{n,n-1} & a_{nn} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ u_{n-1} \\ u_n \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ 0 \\ 0 \end{bmatrix}$$

Discretization of NS Eqn

➢ FV Discretization of Incompressible N-S Equation

$$Mu_h = 0$$

$$\Omega \frac{du_h}{dt} + C(u_h)u_h + Du_h - Mq_h = 0$$

Unsteady Convection Diffusion Source

➢ Time Discretization

$$\frac{du_h^{n+1}}{dt} = \begin{cases} f(u_h^n) & \text{Explicit} \\ f(u_h^n, u_h^{n+1}) & \text{Implicit} \end{cases}$$

But to solve the problem, I need to have, so like this is an airfoil geometry, this is some cylinder, you need to have grid. so simple grid is structure grid or you can have unstructured grid you can have block structure grid so the way you generate so this grid generation is another challenging task because when you have complicated geometry then this grid generation becomes also complicated and and and also uh depends how you generate the grid it that is kind of dictated by the kind of method that you are going to use whether it's a finite difference or finite element of final volume so different methods allow certain flexibility advantage or disadvantage over this grid so grid has to be generated based on your tool that you have okay and obviously when you try to define a problem your boundary conditions are those things just to solve any partial differential equation you need boundary condition so effectively the solvers could be direct solver or it could be iterative solvers and then you can have other things to have convergence and things like that then partial differential equations that you obviously define the order of discretizations and all these things where you classify any generic partial differential equation del x by del o i plus e del two phi by del y two uh del phi by del x plus e del p by del y f v plus g equals to zero so that's any so i mean importantly you have elliptical equation there is a solution pattern there is a parabolic hyperbolic equations but importantly our navier-stokes equation so if you look at it the navier-stokes equation has different behavior the pressure diffusion term is elliptic in nature but the convection term is parabolic in nature

Classification of PDEs

Linear second-order PDEs: **elliptic, parabolic, and hyperbolic**.

The general form of this class of equations is:

$$a\frac{\partial^2\phi}{\partial x^2}+b\frac{\partial^2\phi}{\partial x\partial y}+c\frac{\partial^2\phi}{\partial y^2}+d\frac{\partial\phi}{\partial x}+e\frac{\partial\phi}{\partial y}+f\phi+g=0$$

where coefficients are either constants or functions of the independent variables only.

The three canonical forms are determined by the following criteria:

- $b^2 - 4ac < 0$ *elliptic*
- $b^2 - 4ac = 0$ *parabolic*
- $b^2 - 4ac > 0$ *hyperbolic*

Classification of PDEs

PDE	Example	Explanation
Elliptic	Laplace's equation: $\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}=0$ Poisson's equation: $\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}=g(x,y)$	In elliptic problems, the function f(x, y) must satisfy both, the differential equation over a closed domain and the boundary conditions on the closed boundary of the domain.
Parabolic	Heat conduction $\frac{\partial\phi}{\partial t}=\alpha\frac{\partial^2\phi}{\partial x^2}$	In parabolic problems, the solution advances outward indefinitely from known initial values, always satisfying the known boundary conditions as the solution progresses.
Hyperbolic	Wave equation $\frac{\partial^2\phi}{\partial t^2}=\gamma^2\frac{\partial^2\phi}{\partial x^2}$	The solution domain of hyperbolic PDE has the same open-ended nature as in parabolic PDE. However, two initial conditions are required to start the solution of hyperbolic equations in contrast with parabolic equations, where only one initial condition is required.

but then again depending on the flow this pattern changes or the behavior changes okay so that is something very very important that like you see this parabolic elliptic and mixed flows so effectively when you talk about the complete fluid flow problem realistic geometry this could be now this is how you boundary conditions you could define in either you could have a display boundary conditions where you specify the exact value you could have gradient conditions or normal conditions or you could have mixed condition so these are the ways or robin conditions now the problems could be you can have initial value problem you could have boundary value problem this is how you now coming back to that uh when you talk about the turbines and all these important thing is the turbulence because the whole flow around wind turbine is turbulent so understanding of turbulence and turbulent models are very very important so what happens is that the flow which is turbulent in nature when it passes over the turbine which is rotating then try to get a proper load now here i would like to mention that this is where your simplified linearized model would lag because it doesn't include turbulence and things like that so that's not where the full safety becomes useful because it can use this turbulence model so that turbulence models which are to use for the turbulent flows you can use the correlation based system integral equations or neurons reynolds average navier stokes equations larger dissimulation these are high fidelity one but most of the engineering applications is done with this okay runs equation so because turbulent has a property on nature that the it see you have a large scale structure to small scale structure you can see the dns for realistic problem is quite expensive even with the given computing resources for our problem of interest even today's date that is very difficult so that is why this is not expected alias is also expensive so that is why it's an engineering problem as preferred to solve using rams so uh what it does so now this gives you the include as you go along this direction you include more physics but at the same time you increase the computational cost you increase the complications so dns for realistic problems are still difficult today le is possible but primarily this box where the engineering applications are done in general so there are the range of runs equations i mean one can look at that in any textbook there are two equation model one equation model i mean there they have their advantage the disadvantage um i mean you can see their uses at different context their behavior so it's not that any particular model can be applied to any kind of flow that is very difficult so that is what i mean usually not done So depending on the flow pattern and how would you, I mean, this also list the strength and weaknesses of these different turbulence model. So that kind of gives you an idea of where to use what. So these are pretty standard, but there is another thing near all treatment, because when you talk about, let's say turbine, flow around the turbine there would be boundary layer around those so how you resolve that so you need near wall treatment so either use some kind of a standard wall function non equilibrium so there are ways to treat that so effectively this gives you an idea that how one can handle those uh near all treatment and things like that but these are part of your turbulence modeling that one has to do that so the standard wall function uses certain correlations which are kind of one has to incorporate in the turbulence model the non-ecliptogram wall function in the certain correlations which one has to incorporate there so what is that now these are enhanced wall function which also uses some correlations but these are uh again to say that how much physics you would like to capture or not uh that's what it turns into and those are the things one and two So these are some recommended strategy that one can I mean, the first point, what could be there and how you do that.

And based on that, certain recommended strategies, therefore, different kind of problems and also the boundary conditions for turbulence models are also there because I mean, that's quite important because when you talk about this turbulence model, so quickly you see this what is your requirements then what model and narrow treatments you require then the procedures to follow which turbulence model and what not so with that if you look at the application that is what we said that in aerospace you see that flow around the aircraft and all these things these are really solving a large scale problem of nature so when you go to appliances you see that full spectrum of the domain of these appliances can be obtained you go to automotive industries so in internal dynamic behavior external fluid dynamic behavior everything has been kind of simulated you go to biomedical applications which is very very emerging today's date that medical device design and all these things where cfd is becoming a key ingredient at this moment this is chemical processing industry you go to age vac where heating air conditioning air conditioning and all these things this is hydraulics where you see the dam sheep and all these things there are marine applications where CFD can be used oil and gas applications power generation this is where you have wind turbine is one of that when you do this poor aerodynamics which is another very interesting part where you have this applications of to estimate this drag and all these things so that this is how you can see this these are some of the in-house applications that where you try to solve this kind of vertical axis wind turbine you see how this rotating systems is handled so the complete so it gives you the complete picture of the fluid dynamic behavior and all these things so this is another picture of the same thing so here you see that different kind of design these applications could be for hydro turbine as well but the important thing is that the whole rotating frame of reference has been taken and considering these things to predict this so this is another application and this shows you Again, this is a hydroturbine application where you see both. But the similar thing can be done even in the horizontal, vertical axis wind turbine as well. This hybrid or variable pitch. Now also interesting area is that AI/ML applications because now there are a lot of sites which has a lot of data. So the wind power forecasting can be a handy exercise and one could do.

But for that, one has to have certain data to team their AI/ML based model. And then you can forecast that what could be the prediction in a few minutes, happen on our day here. so long term forecast short term forecast so these are the things one can do so where you can see certain models how they predicted the actual value because in denmark and sweden there are a lot of wind farm they collect a huge amount of data to support this kind of things so in conclusion this is a powerful tool and this can provide a wide range of scientific applications and engine problems to solve but yes you have to use it carefully because it can provide meaningful legend as long as you have set up the problem correctly so there are certain funny things you calculate therefore you are so you are fully conscious you think about you are the god because i tend to fool the resources least to calculate a lot more and more unsteady understand few less but that is not how things work important thing is that you may have a robust and efficient tool but it is always important to estimate each point of view of the project if you want to obtain a result so you have to take proper care of the whole thing so computational fluid dynamics is essentially not colorful fluid dynamics so you have to have a proper balance between these things this is the scientist who said that no one will receive the result except one who performed on the calculation and then another great scientist who is no more said greatest disaster one can encounter in computation is not instability or lack of convergence but results that are simultaneously good enough to be believable but bad enough to question so all models are wrong but some are useful so essentially what it says that you have to look at your competence witness of your stakeholder and the smart fair testing so that you can have a good robust tool so that you can solve this kind of engineering problem okay so that's how it gives you that perspective of the cfd and how you can or cfd as well as some CAE based tool which can be used for the design purposes okay so now we'll move to the alternative concept so we'll move to the alternative concepts what is there and to see how things are so this is again going back to the horizontal axis will form so you have a overview of that you have the wind turbine connected at the offshore then you have a substation cables connected with that this is an again an image where offshore installations are done so offshore horizontal axis wind turbine is a better wind sources which we have talked because of very low roughness offshore construction have almost no restriction limited variability of land so obviously these are there you can have high wind energy production offshore installation only this much so i mean these are some of the advantages that you have in the offshore installation that you can do so typical loads that is acting you can estimate all this these are again you see that net passing frequency rotor frequency so these things we have discussed enough uh these are again uh complete uh unit which is uh i mean this is the dynamics part of it that is why we spend enough time to analyze that but option carbon installations also can have depending on the water depth you can see the then this is 30 meter greater than 60 meter you see that depending on the different depth you can have different kind of installation these are floating installations so floating installations how they are connected with the cables and things like that so these are the structure which is visible above surface but underneath there are other construction and all these things there at the seabed and this is the spacing of wood turbine in site layout so there are certain things that is coming out of this thing this is a vertical axis wind turbine where there is a rotor this is a rotor this we have seen also some of the application then it's not large in size and all these things these are uh sabonius wind turbine this is a top view of it so the interesting alternative concept that is going to be airborne wind energy this is something one can think about it how it is that now there is a comparison first thing that a typical european needs five kilowatt because of electricity transport heating this equals this much of 12 liters of petrol one return flight of europe to china consumes about this much of so this is an electric heater so this much of power requirement you can see how much power requirement but five megawatt installed capacity delivered an average about one megawatt so this would be enough to cover all energy needs of 200 people so what we can do we can have a solar plant like that or wind in north sea a turbine of 150 meter height so this would provide you could we harvest wind power in high altitudes with less material that is a big question so that's the advantage so what it is there as we know when you try to increase i mean see this is a small turbine is a large turbine obviously the power output of this power would be higher than power of this so but again you have a long lever arm to large torque so this is how the wind this is the wind shear that is going to impact the whole turbine okay and that can have difficult so the idea is that if you have a huge long tower if you have big long tower then it can get the fresh wind so that your power production increases but obviously the question is that structural stability so idea is that in the mean slightly away from the earth surface where the wind shear also gets little reduced you have a clean wind or available we can extract out the energy but then we have to construct a long tower like this so long tower is very difficult to build at the same time this will not have structural serenity but can we do something like that if we connect this turbine only to a thing and then instead of the tower and extract out that energy this is the this is how you would like to do that you get rid of the tower there is no power only the turbine is there in the air so this is a very visionary ways to think about it that the only thing is that the turbine is there you connect with this thing so this is what the kite flies faster loop in crosswind direction very strong so but where could we generator be driven so this is the crosswind kite power the similar concept that so we can attach a small wind turbine to the kite it will transmit the power then there are pros it's light light speed generator propeller can be used to start and land cable needs to transmit power generator so that means the idea is that we put some turbine in the on the air. And then, so this is an artistic vision in 1992, that how these things can be done. And the cycle consists of two phases, power generation phase, and then the retraction phase, okay.

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$$\boxed{P = \frac{2}{27}\,\rho\, A\, w^3\, C_L \left(\frac{C_L}{C_D}\right)^2}$$

So slow down kite reduce force pull back line, all electric parts on ground and slow turning so this is the concept and as per the lloyd formula this is how you can have the power and this is cl by cd so that means if my cl by cd is high this one can see the curve this is the tension this is power tension so roll out speed and so maximum power reached at one third of the wind speed so this is what one can now how far does it kite fly compared to the real wind so this is how you can estimate okay and then find out the power out of that obviously this is where you would like to uh this is a 40 kilowatt per meter square uh this if you compare one meter square wind surface correspond to 250 meter square photovoltaic cell in solar power plant so but this man say this size can produce 40 kilowatt so this is an advantage that you have now airborne wind energy vision so you can replace tons of steel and concrete structure so this offshore turbine and this today which are the primary contributor from the wind energy production but this could be replaced by this kind of so you have this huge concrete structure infrastructure building all this could be replaced by that so what are the categorization you have ground-based generation that means the kite will fly and you connect with the cable you have a ground or onboard generation that means you have the turbine on the onboard either you can have soft twin fixed twin you can have like this onboard generation you have turbine sitting on the wing you have soft twin which is like in parachute so the companies which are doing this that a maxi power in Canada and Mckinney power in California, diesels from Hamburg. So these are the industry which are kind of there is a book there one can look at this airborne wind energy. So for simple plane attached to a tether, you have 20 differential states, and then you connect with tether and then then it goes in a loop or it goes in a particular around the system finally you extract out the so this is what in a high wind picture that rotation to power orbit so they are going to fly this thing so this is another flight experiment in lebanon that what is the other planes follow certain paths so the flight path estimation is important and then one could have a dual kite system so then you have a main tether then you have a secondary tether so that it can stabilize each other and they go in a cyclic path where we start out the energy so this is quite interesting concept and this is an example of dual kite system you can see this is one here this is one here which is connected and the cable is connected there So there are Amoxy Power is a startup from TU Delft, they are venture capital. This is pumping cycle to harvest to import. This is another capsule start of this.

This is again going to the EBIT. to have this kind of things which are flying there so that you could this is soft kites with the ground-based generator that means this connected and you have a ground where things are on generator this is an example of an sky cell that it is in 2001 so that means this shop structure is connected to the cable when the ship is sailing so these are some fun things at riverbed where you can see where ground based generator can be used now this is an example of rigid wing based generator uh this is in makhani power turbines on board so you see these things which are there this is how i mean this design could be optimized or it could be kind of this is connected with the wing how so when the things are flying this is makhani power 600 kilowatt utility scale this was in april 2015 so they have kind of tested it and these are some of the pictures in 2017 these are the system tests they had uh where they wanted to and this is the picture you can see when this is flying and you have this onboard turbine generators which are doing this job so what it does that the airborne wind energy quite promising concept which you can utilize the wind power available at the linear uh obviously some non-linear control optimization all this so it could have a different way one board ground based generator stop twin fixed twin but this is a very handy concept and this is kind of connected with the uav kind of things where you can have these turbines and uh i mean obviously these are talking about some futuristic technology and that one could have that pretty much i would say conclude the complete discussion on this wind energy so we started with basic fluid mechanics then went into the discussion of energy scenario energy perspective horizontal axis wind turbine vertical axis wind turbine then wind turbine both horizontal and vertical axis wind turbine aerodynamics then we talked about the dynamics which is more like a structural for design purposes and then finally talked about the CFD perspective and the alternative concept like airborne wind energy. I thank you very much for listening and attending this - thank you