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Turbulence-Methods

Relatório interno

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A-Turbulence

Turbulent flow is a type of fluid (gas or liquid) flow in which the fluid undergoes irregular fluctuations, or mixing, in contrast to laminar flow, in which the fluid moves in smooth paths or layers. In turbulent flow the speed of the fluid at a point is continuously undergoing changes in both magnitude and direction.

To model turbulence it is necessary to concern with an unsteady, irregular motion in which transported quantities (mass, momentum, scalar properties) fluctuate in time and space. It is also necessary to pay attention to fluid properties and velocity random variations. Energy transfer is performed from larger eddies to smaller eddies and in smallest eddies turbulent energy is converted to internal energy through viscous dissipation.

B-Models

The main classes of computational models approaches for modeling turbulent flows are:

- Reynolds-Averaged Navier-Stokes Models (RANS)
- Large Eddy Simulation (LES)
- Direct Numerical Simulation (DNS)

The first category, RANS, solves time-averaged N-S equations and allows all turbulent length scales .They is used for calculating industrial flows.

The second type of models, LES, solves spatially averaged N-S equations. Large eddies are directly resolved and eddies smaller than the mesh are modeled. This category is less expensive than DNS but most expensive tan RANS.

DNS models can simulate all turbulent flows by numerically solve the full N-S equations. This process is not implemented in FLUENT.

With the two first classes of models FLUENT presents several possible combinations of computational models:

- Transition models- used to predict boundary layer development and calculate transition onset;
- Coupling models;
- Reynolds Stress Model (RSM);
- Scale-Adaptive Simulation (SAS) Model Reynolds Averaged N-S Equations (RANS);
- Detached Eddy Simulation (DES);
- Near Wall Treatment for Wall Bounded Turbulent Flow

1. Reynolds-Averaged Navier Stokes (RANS) Equations

1.1 The Closure Problem: Boussinesq Approach v.s Reynolds stress

Boussinesq Hypothesis (B-H) is applied by eddy viscosity models. Here Reynolds (Re) stresses are modeled using a turbulent (or eddy) viscosity. This Hypothesis is used in Spalart-Allmaras Model (one equation), and all k-ε and k-ω models (two equations).

- The disadvantage is that this hypothesis assumes the viscosity to be an isotropic quantity which is not strictly true. The B-H works well for shear flows dominated by Re of the turbulent shear stresses which covers wall boundary layers, mixing layers, round jets and channel flows.

RANS with Reynolds stresses requires modeling for many terms in the transport equations.

- The only advantage is in the presence of turbulent flow with large streamline curvature and swirl, being more difficult to converge.

1.2 The Spalart-Allmaras Model

This Model is a low-cost RANS model solving a transport equation for a modified eddy viscosity. When in modified form the eddy viscosity is easy to resolve near the wall. Designed specifically for aerospace application involves wall bounded flows. It has been proved to give good results for boundary layers subjected to adverse pressure gradients.

1.3. k-ε Turbulence Models

There are three differences in the k-ε models:

- the calculating method of turbulent viscosity;
- the Prandtl numbers that are present in k and ε;
- The generation and destruction of terms in equation in ε.

These models, when a nonzero gravity and temperature gradient are simultaneously present, account for the generation of k due to buoyancy and the corresponding contribution to the production of ε.

In transport equation for k turbulent kinetic energy for k tends to be augmented in unstable stratification. For stable stratification buoyancy tends to suppress the turbulence.
In ANSYS the effects of buoyancy on the generation of k are always included when considering both a nonzero gravity and a nonzero temperature or density gradient.

Convective Heat and Mass Transfer Modeling uses an analogy to turbulent momentum transfer. Energy equation may have additional terms depending on the underlying physical model.

1.3.1 Standard k-ε (SKE) Models (Launder and Spalding)

(SKE) model is the most used model for industrial applications. It is robust and accurate. Contains sub models for compressibility, buoyancy combustion among other.

Limitations:

- One term of ε equation cannot be calculated at the wall;
- The performance for flows with strong separation is poor.

1.3.2 Renormalization k-ε (RNG) Models

Equations are derived using the statistical technique called renormalization group theory. It is more accurate than SKE model, for more complex shear flows and flows with high strain rates, swirl and separation.

- RNG has an additional term in the equation in ε that improves the accuracy for strain flows;
- Re effect on turbulence is induced enhancing accuracy for swirling flows;
- Differential viscosity to account for low Re effects;
- Analytically derived algebraic formula for turbulent Prandtl number.

1.3.3 Swirl Modification k-ε (RNG) Model

This model is applied when turbulence is affected by rotation or swirl in the mean flow.

RNG provides an option to account for the effects of the swirl or rotation by modifying the turbulent viscosity appropriately. This model is applicable to asymmetrical swirling flows and 3D flows when RNG is chosen. The principal difference between RNG and SKE is in the fourth term in ε equation. RNG models yields a lower turbulence viscosity than SKE.

1.3.4 Realizable k-ε Model

The term realizable means that the model satisfies certain mathematical constrains on the Re stresses, consistent with the physics of turbulent flows: positivity of normal stresses and Schwarz inequality for Re shear stresses. This model contains an alternative formulation for the turbulent viscosity.

In the equation of transport the forth term represents better the spectral energy transfer and the third term doesn't have a singularity as in previous models. It has a modified transport equation for the dissipation rate ε which has been derived from an exact equation for the transport of the mean square vorticity equation.

Limitations:

- Produces non-physical turbulent viscosities in situations when the computation domain contains both rotating and stationary fluid zones. This is due to the fact of this model includes the effects of mean rotation in the definition of the turbulent viscosity;
- This extra rotation effect has a behavior that must be taken into account;
- Turbulent viscosity is modeled in a different way being not a constant.

Advantages:

- Predicts more accurately the spreading rate of both planar and round jets;
- Also provide superior performance for flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and recirculation.

1.4. k-ω Turbulence Models

In this class there are Standard, (BSL)-Baseline, and (SST)-Shear Transfer models.
All of them have similar transport equations for k and ω. Turbulence damping is available only in with k- ω models.
The k- ω of turbulent models have gained popularity mainly because:

- The model equations do not contain terms which are undefined at the wall, that is they can be integrated to the wall without using wall functions;
- They are accurate and robust for a wide range of boundary layer flows with pressure gradient.

k- ω of turbulent models are divided in:

- Standard k- ω (SKW)model
    - Most adopted in the aerospace and turbo-machinery problems;
    - Compressibility effects, transitional flow and shear flows corrections.
- (SSTKW) model (Mentor)
    - The SST k- ω model uses a blending function to gradually transition from the SKW near the wall to a high Re number version of the k-ε model in the outer portion of the boundary layer;
    - Contains a modified turbulent viscosity formulation to account for the transport effects of the principal turbulent shear stress.

1.4.1 Standard k-ω (SKW) Model (Wilcox)

This model is based on Wilcox formulation. It incorporates modifications for low Re numbers effects, compressibility and shear flow spreading.

The weak points of the model are the sensitivity of the solutions to values for k and ω outside the shear layer.

It is also an empirical model based on model transport equation for the turbulence kinetic energy k and the specific dissipation rate ω (That can be seen as ε/k).

- A limitation of this model is that compressibility effects have not been calibrated for a sufficient number of experiments thus they are disabled by default.

1.4.2. Baseline (BSL) k-ω Model (Mentor)

The main problem with the Wilcox model is its well-known strong sensitivity to free stream conditions. The BSL model designed by Mentor was developed to blend the robust and accurate formulation of the k-ω model in the near wall region within the free stream independence of the k-ε model in the far field. So k-ε was converted in k-ω formulation.

This model is similar to Standard but includes some refinements:

- Model constants are different;
- Standard k-ω model and transformed k-ε model are both multiplied by a blending function and both models are added together;

- BSL incorporates a damped cross diffusion derivative term in ω equation.

1.4.3 Shear Stress Transport (SST) k-ω Model

This model includes the refinements of the BSL k-ω model and accounts for the transport of the turbulence shear stress in the definition of the turbulent viscosities. The model is more accurate for a class of flows like adverse pressure gradient flows, airfoils transonic shock waves than the standard and the BSL k-ω models.

As in the Spalart-Allmaras model the concept of wall turbulent viscosity has been adopted.

1.4.4 k-kl-ω. Transition Model

This model is used to predict boundary layer development and calculate transition onset. It can be used to effectively address the transition of the boundary layer from a laminar to a turbulent regime.

k-kl-ω model is a three equation eddy viscosity that includes transport equations for turbulent kinetic energy , laminar kinetic energy and the inverse turbulent time scale.

1.4.5 Transition SST Model

The transition SST model (Y-Re_Θ model) is based on coupling:

- SST k-ω model transport equations:
- Two other transport equations;
  -One for intermittency
  -One for transition onset criterion in terms of momentum thickness Re number.

Limitations for this model are:

- This model is only applicable to wall bounded flows and not to transition in free shear flows. It will predict free shear flows as fully turbulent;
- The Transition SST model is not Galilean invariant and should therefore not be applied to surfaces that move relative to the coordinate system for which the velocity field is computed; for such cases the intermittency model should be used instead.
- The Transition SST model is designed for flows with a defined nonzero free stream velocity (that is the classical boundary layer situation);
- The transition SST has not been calibrated in combination with other physical effects that affect the source term of the turbulence model like buoyancy and multiphase turbulence.

1.4.6 Intermittency Transition Model

This model has the following advantages in comparison with the previous one:

Advantages:

- It reduces the computational effort (by solving one transport equation instead of two);
- It avoids the dependency of the Re_Θ equation on the velocity, which makes the Y transition model Galilean invariant. It can therefore be applied to surfaces that move relative to the coordinate system for which the velocity field is computed.

- The model has provisions for cross flow instability that are not available for the k-kl-ω or the y- Re$_\Theta$.
- The model formulation is simple and can be fine-tuned based on a small number of user parameters.

Like the Re$_\Theta$ .the Intermittency model is based on local variables.

Limitations:

- Y-Transition Model is only applicable wall-bounded flows. To other flows the model will predict free shear flows as fully turbulent;
- This model has only been calibrated for classical problems. To other types of bounded flows may require some modifications;
- The model has not been calibrated with the combination of the effects of buoyancy and multiphase turbulence.

1.4.7 The V2F Model

V^2-f model (V2F) is similar to k-ε model but incorporates near wall turbulence anisotropic and non-local pressure strain effects. It cannot be used to solve Euclidian problems. Is a low Re numbers turbulence model that is valid all the way up to solid walls. It also simulates flows dominated by separation. It is used to a velocity scale $\bar{v}^2$ instead of kinetic energy k.

1.4.8 Reynolds Stress Model (RSM)

This model is the most elaborate type of RANS turbulence model of ANSYS. It solves the transport equation for Re stress together with an equation for dissipation rate. In 2D flows it needs to five equations and in 3D it needs to seven equations

The RSM model accounts for the effects of streamline curvature, swirl, and rotation, rapid changes in strain rate in a more rigorous manner than the models with one or two equations.

However fidelity prediction is limited by closure assumptions employed to model various terms in the exact transport equation terms (because they are exact). Pressure-strain and dissipation rate terms modeling are responsible to compromise the accuracy of this method.

1.4.9 Scale- Adaptive Simulation (SAS) Model Reynolds Averaged N-S equations (RANS)

SAS is an improved RANS formulation which allows the resolution of the turbulent spectrum in unstable flow conditions. Von Karman length scale into the turbulent scale equation allows SAS models to dynamically adjust to resolved structures in a URANS (unstable-RANS) simulation.

SAS can be combined with other models:

- K- ω , BSL K- ω, Transition SST;
- ω based Reynolds stress model (RSM).

SAS model does not include compressibility effects.

2 LES - Large Eddy Simulation Models

LES has been successful for high-end applications where the RANS models fail. They are used in Combustion, Mixing and external Aerodynamics.

The implementation in FLUENT was done through subgrid scale (SGS) turbulent models like Wall-Adapting Local Eddy-Viscosity and Dynamic Kinetic Energy transport, Detached Eddy simulation (DES) model. LES is applicable to all combustion models. Basic statistical tools are available: time averages, RMS values of solution variables, built-in fast Fourier transform FFT.

Large Eddy Simulation (LES) that falls between DNS and RANS can be summarized as follows:

- Momentum, mass, energy and other passive scalars are transported mostly by large eddies;
- Large eddies are more problem depended;
- Small eddies are less depended on geometry ,tend to be more isotropic and so more universal;
- The chance of finding a universal turbulence model is much higher for smaller eddies.

Resolving the large eddies – coarse mesh and large time step sizes in DNS (Direct Numerical Simulation). But to obtain stable statistics of the flow needs more time of computation, more memory (RAM). A high performing computing (that is MPI) is necessary for LES.

2.1 Inlet Boundary Conditions to the LES model

This model is used to model to model the velocity fluctuations of velocity inlet boundary or pressure inlet boundary. If no perturbation is set ANSYS neglects the velocity. In such cases individual instantaneous components velocity are set to the mean value.

2.2(ELES) – Embedded Large Eddy Simulations

LES proved to be a very expensive model to be applied in industrial field. So Hybrid models like Scale Adaptive Simulation (SAS), DES and SBES have been developed.

ELES is a combination of LES and RANS models joined by appropriated interface conditions. The most critical are interfaces where it is necessary to select methods to convert modeled turbulence kinetic energy into resolved energy:

- No perturbations: Turbulent fluctuations are not present at the inlet;
- Vortex Method
- Spectral Synthesizer.

Can be used for RANS/LES zonal hybrid approach.

2.3(DES) – Detached Eddy Simulation Models

There are five types of models in this class: Spalart-Allamaras, Realizable k-ε, BSL k-ω, SST k-ω, and Transition SST.

Turbulent flows are characterized by eddies with a wide range of length and time scales. The largest eddies are typically comparable in size to the characteristic length of the mean flow. The smallest scales are responsible for the dissipation of turbulence kinetic energy.

- For high Re wall bounded flows, LES are too expensive to resolve near wall region;
- Using RANS in near wall regions would significantly mitigate the mesh resolution requirement;
- RANS/LES hybrid model based on the Spalart-Allamaras turbulence model is a one equation that in equilibrium is reduced to an algebraic model.

DES is a practical alternative to LES for high Re number flows in external aerodynamic applications.

3 Wall Treatments

The k-ε family and RSM models are not valid in the near wall region, but Spalart-Allamaras and k-ω models are valid provided the mesh is sufficiently fine. To work with this there are two approaches:

- Wall Function Approach: for equilibrium and non-equilibrium turbulent boundary layers;
- Enhanced Wall Treatment Option: blended law-of-the-wall and a two-layer zonal model.

3.1 Near-Wall Treatments for Wall Bounded Turbulent Flow

Turbulent flows are not affected by the presence of walls. Mean velocity is affected through the non-slip condition that has to be satisfied at the wall. Very close to the wall viscous damping reduces the tangential velocity fluctuations. The near wall modelling significantly impacts the fidelity of numerical solutions as walls are the main source of mean vortices and turbulence.

There are Wall Functions and Near Wall Models

Wall Functions comprise: Semi-Empirical Formulas: Standard Wall Functions (That arise with k-ε models and Re-Stress models), Scalable Wall Functions, Non-Equilibrium Wall Functions (k-ε models and Re-Stress Transition models and User Defined Wall Functions.

Limitation to Wall Functions:

- Severe pressure gradients leading to bounding layers separations
- Strong body forces (flow near rotating disks, buoyancy driver forces)
- Highly 3D flows in the near wall region

3.2. Enhanced Wall Treatment ε- Equations (EWT- ε)

The wall functions in this model have a momentum boundary condition based on a blended law of the wall. Pressure gradient effects and thermal including compressibility are also included. Is a two layer zonal model: a blended two layer model is used to determine near wall ε field

- Domain is divided into viscosity-affected (near-wall) region and turbulent one region;
- High Re turbulence model used in outer layer;
- Simple turbulence model used in inner layer.

The Enhanced Wall Treatment option is available for the k- ε and RSM models.

3.3. Menter-Lechner ε- Equations (ML- ε)

Near the wall it consists in a wall function approach together with a low Reynolds approach. Limitations:

- The formulation is complex, involving highly nonlinear damping terms;
- The formulation produces multiple solutions for the same application;
- Produces pseudo transitions of results (unphysical).

3.4. k-ε Turbulence Models

Today two formulations arrived: the k-ε Turbulence Models. The idea is to add a source term to the transport equation of the turbulence kinetic energy k that accounts the near wall effects.

Shear wall is only active in the viscous sub-layer and account to low Reynolds number effects.

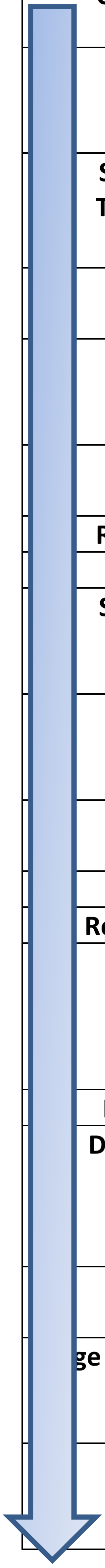
3.5. Curvature Correction for the Spalart-Allmaras and Two Equations Model

Eddy viscosity models are insensitive to streamline curvature and system rotation. Modification to the turbulence production in the following models:

- Spalart-Allmaras one-equation;
- Standard, RNG, Realizable k ε models;
- K-ω models;
- Scalable Adaptive Simulation (SKL with BSL) SST/DES-SST, DES/BST, SDES.

The limitations to the two equations models are the fact of generating excessive turbulence energy.

Table 1-Description and Application of RANS/DES Turbulence Models The arrow shows the Increase in computational cost per iteration of the referred models.



RANS-Models	**Description and Application**
Spalart-Allamaras **One Equation Model**	Single transport equation model solving directly for a modified turbulent viscosity .Include strain rate in k production term. Aerospace applications involving wall bounded flows near wall mesh. Use of coarse meshes.
	Economical for large meshes. Suitable for quasi-2D external/internal flows and boundary-layer flows Applicable to airfoils, wings, airplanes, missiles.
Standard k-ε **Two Equation Model**	Two transport equations model for k and ε. Coefficients are empirical derived. Account for viscous, heating, buoyancy, and compressibility. Valid for fully developed flows.
	Robust. Widely used. Suitable for initial iterations, initial screening of Alternative designs and parameterized studies.
RNG k-ε	Equations and coefficients are analytically derived. Improved the ability to model strained flows. Options to swirl and low Reynolds number flows modelling.
	Applied to shear flows involving rapid strain moderate swirl, vortices and local transitional flow.
Realizable k-ε	Improvement to SKE to obtain a better performance.
	Similar applications as RNG. More accurate. Easier to converge.
Standard k-ω	A two transport equation in k and ω, the specific dissipation rate (ε/k). Superior performance for wall bounded low Reynolds number flows. Predict transition. Option for free shear and compressible flows.
	Applicable to complex boundary layer flows under adverse pressure gradient and separation: aerodynamics and turbo -machinery. Used for transitional flows.
SST- k-ω	Combines the SKW near the wall and SKE away from the wall using a blending function. Limits turbulent viscosity.
	Dependency on wall distance. Suitable for free sheer flows.
Reynolds Stress	Solved directly using transport equations for highly swirling flows.
	Avoid isotropic eddy viscosity assumption. More CPU time and memory required Suitable for complex 3D with strong streamline curvature, strong swirl, rotation like cyclones.
DES- Models	**Description and Application**
Detached Eddy Simulation	One equation SGS subgrid scale turbulence model. In equilibrium it reduces to an algebraic model. RANS/LES Hybrid model based on the Spalart Allmaras turbulence models.
	DES is an alternative to LES for High –Reynolds number flows in external aerodynamic application.
ge Eddy Simulation **LES**	Implementation is done through a (SGS) turbulence models. Momentum, mass energy are transported by large eddies- Small eddies are less depended on geometry. More universal.
	Applicable to all combustion models. Basic tools are available. Coarse meshes and large time step size in DNS. To obtain convergence needs more time of computation and memory RAM