Texas Water Development Board
Research and Planning Fund Research Grant 2004-483-010

Center for Research in Water Resources
University of Texas at Austin
PI Ben R. Hodges
12 January 2005

FINAL REPORT FOR FY 2004

HYDRODYNAMIC MODELING IN RIVERS WITH SUBMERGED LARGE WOODY DEBRIS

PURPOSE

This report is the deliverable for the Texas Water Development Board under Research and Planning Fund Grant 2004-483. Completed under this project were: 1) literature review of existing modeling techniques, and 2) development of a new hydrodynamic modeling theory including large woody debris. Development of computer code for testing the methodology (a "time permitting" option under the scope of work) was not possible within the present research period. Development of a field survey plan for data collection (an "if necessary and appropriate" option under the scope of work) was not considered appropriate given the present state of the model development.

INTRODUCTION

The important environmental role and significance of large woody debris (LWD) has been indicated in recent research works (Gippel 1995; Marzolf 1978; Harmon et al. 1986; Bisson et al. 1987; Sullivan et al. 1987). The effect of LWD in a river is determined by the flow field near LWD. However, the flow structure around LWD is complicated and usually turbulent (Mutz 2000; Beebe 2001; Daniels & Rhoads 2003). Moreover, there is a large difference in scales between the hydraulic process and the critical ecological processes (Gippel 1995). These complexities have lead us to evaluate the need for a new turbulence model to link the large scale free stream in a river and the small scale flow around LWD.

LITERATURE REVIEW

Turbulence is a phenomenon which is chaotic and unpredictable although it has some statistical quantities. Those properties of turbulence give rise to the exploration of average quantities. In other words, we typically compute the averaged quantities and model the fluctuated part. RANS (Reynolds averaged Navier-Stokes equations) and LES (large eddy simulation) are two representative methods based on this "averaging" idea. RANS employs a time averaging technique while LES is applies a spatial filtering concept (which is subtly different from averaging). In either case, it is the nonlinear term in the Navier-Stokes equations that makes the turbulence "closure" problem both challenging and interesting.

Reynolds-averaged Navier-Stokes models

A century ago, Osborne Reynolds first proposed what are now known as "Reynolds averaged equations." In the Reynolds-averaged approach, the short-time-scale unsteadiness of flow phenomena is removed by averaging. The mean of correlations for the fluctuating components are regarded as turbulence (Lamb, 1945). To derive the Reynolds-averaged Navier-Stokes equations, the flow field is decomposed into average and fluctuating parts and then a time averaging operation is applied to the equations. The decomposition is defined as:

$$u = \overline{u} + u'$$

where $\overline{u} \equiv$ time-averaged velocity and $u' \equiv$ fluctuating velocity. The properties of time averaging imply that if

$$A = \overline{A} + a, \quad B = \overline{B} + b$$

then it follows that

$$\overline{A} = \overline{\overline{A}} + \overline{a}, \quad \overline{B} = \overline{\overline{B}} + \overline{b}$$

As a consequence, the average of an average is unchanged, i.e.

$$\overline{A} = \overline{\overline{A}}, \quad \overline{B} = \overline{\overline{B}}$$

from which it follows that the average of a fluctuation is zero:

$$\overline{a} = 0, \quad \overline{b} = 0$$

From the above, the averaging operator is commutative for interior averages, so that

$$\overline{\overline{A}a} = \overline{A}\overline{a} = 0$$

Note that the above commutation does not hold for LES filters, which creates more complexities for the LES-filtered equations (see LES section below). From the above, it follows that

$$\overline{\overline{A}a} = \overline{\overline{B}b} = \overline{\overline{A}b} = \overline{\overline{B}a} = 0$$

and similar properties are derived as

$$\overline{A^2} = \overline{A}^2 + \overline{a^2}$$
$$\overline{B^2} = \overline{B}^2 + \overline{b^2}$$
$$\overline{AB} = \overline{A}\,\overline{B} + \overline{ab}$$
$$\frac{\partial \overline{A}}{\partial x} = \frac{\partial \overline{A}}{\partial x}, \quad \frac{\partial \overline{A}}{\partial t} = \frac{\partial \overline{A}}{\partial t}$$

Thus, the Reynolds-averaging for Cartesian velocity terms $\overline{u}$, $\overline{\overline{u}u'}$, $\overline{\overline{u}v'}$, $\overline{\overline{u}w'}$, ... provides $\overline{u}$, 0,0,0… respectively. It follows that (Lamb, 1945)

$$\overline{uu} = \overline{u}\,\overline{u} + \overline{u'u'}, \qquad \overline{uv} = \overline{u}\,\overline{v} + \overline{u'v'}, \qquad \overline{uw} = \overline{u}\,\overline{w} + \overline{u'w'}\,.$$

After manipulating the Navier-Stokes equations with Reynolds-averaging approach, the turbulence closure problem appears because of the nonlinear term. Time averaging of linear terms in the N-S equations causes the fluctuations to disappear. However, time-averaging of the decomposed nonlinear term gives rise to the Reynolds stress term (τ_{ij}), which increases the number of unknowns in the equation set (hence the problem of "closing" the equation set with a model for the Reynolds stresses). The Reynolds stresses can be defined as

$$\tau_{ij} = \overline{u_i' u_j'}$$

where we adopt Cartesian tensor notation such that i,j = 1,2,3 and the conventional (u,v,w) velocity components are represented as

$$u_1 = u$$
$$u_2 = v$$
$$u_3 = w$$

For closing the RANS equations, numerous methods have been developed to model the Reynolds stress. The earliest and most widely used closures are based on the Boussinesq hypothesis: (Speziale 1996, Dubios 1998)

$$D\tau_{ij} = -\nu_T \left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)$$

where $D\tau_{ij}$ is the deviatoric part of the Reynolds stress (τ_{ij}) and ν_T is the eddy viscosity

It can be observed that the Boussinesq's hypothesis ties the Reynolds stress tensor τ_{ij} to the mean velocity field. The earlier approaches to modeling Reynolds stress included the "zero-equation" and "one-equation" models. In zero-equation models, eddy viscosity is given by a function of turbulent length scale and time scale. A good example for zero-equation model is Prandtl's mixing length theory (Prandtl, 1925). Both scales are determined by empirical methods. In the zero-equation model the scales are considered fixed (i.e. there is no transport equation solved for any turbulent component). In one-equation models the time scale t_0 is typically developed from turbulence statistics or a transport model rather than from empirical means. In a one equation $k-l$ model, the eddy viscosity is given as a function of turbulence length scale and the turbulent kinetic energy *k*, which is modeled by the transport equation. A two equation $k-l$ uses transport equations for both the turbulent kinetic energy and the turbulence length scale to parameterize eddy viscosity. A similar basis is used for the popular two equation $k-\varepsilon$ model, which replaces the turbulent length scale with the turbulent dissipation rate ε, where both *k* and ε are again modeled by their transport equation (Speziale 1996).

In summary, the basic idea of RANS is that we compute the averaged motions and approximate the fluctuating motions based on their mean correlations. Hence, RANS will predict good results for a time-averaged state when the coefficients are derived from a sufficiently dense empirical data set. However, in many cases, we need accurate prediction of future state in an unsteady process, where the empirical averaging coefficients cannot be *a priori* obtained, such as for ocean or weather forecasts. This need drove the development of Large Eddy Simulation (LES) methods, first proposed by a meteorologist (Smagorinsky, 1963).

Large Eddy Simulation (LES)

Large eddy simulation treats the large eddies in a turbulent flow more exactly than the small ones. In LES only the large-scale field is directly resolved, while the effect of the small scales on the large-scale motion is modeled. This approach is based on the idea that the large-scale motions are generally more energetic than the small scale ones and are the top-down control on the turbulent cascade of energy from large motions to the small dissipative scales. The critical point in LES is to capture the effects of the subgrid scale (SGS) motion, using simple and "universal" models (Ferziger, 1996).

In early LES calculations, the most widely used SGS model was proposed by Smagorinsky (1963), which parameterized the subgrid scale stresses in terms of an eddy viscosity and local strain rates, calculated locally from the resolved velocity scales. All such models are based on the notion that the principal effects of the SGS Reynolds stress are increased transport and dissipation (Salvetti, 1995). The anisotropic part of The SGS stress in Smagorinsky model is (Ferziger,1999).

$$\tau_{ij} - \frac{\delta_{ij}}{3}\tau_{KK} = -2\nu_T \overline{S}_{ij}$$

where the eddy viscosity is

$$\nu_T = C\overline{\Delta}^2 \left|\overline{S}\right|$$

This model can be obtained in different ways (Ferziger, 1996): 1) presuming production and dissipation of subgrid scale turbulent kinetic energy in equilibrium; 2) direct interaction approximation (DIA) turbulence theory (Leslie, 1973, Ferziger, 1996); 3) the eddy damped quasi-normal Markovian (EDQNM) approximation (Lesieur, 1992, Ferziger, 1996), and 4) renormalization group theory (RNG) (Yakhot and Orszag, 1986, Ferziger, 1996).

However, the LES model, though very popular, has some notable drawbacks, which include that it (a) requires an input model coefficient C which is flow dependent; (b) predicts incorrect asymptotic behavior near a wall or in a laminar flow; (c) does not allow SGS energy backscatter to the resolved scales; (d) assumes that the principal axes of the SGS stress tensor are aligned with those of the resolved strain rate tensor, a result which is not supported by direct numerical simulation data (Piomelli, 1990); and (e) the basic Smagorinsky model is too dissipative in LES of wall-bounded transitional flows (Zang et al., 1993).

A scale similarity model was proposed by Bardina el al. (1980). The idea of this model is that the small scales resolved in a simulation are similar in many ways to the still smaller scales that are treated via the model. The principal argument is that the important interactions between the resolved and unresolved scales involve the smallest eddies of the former and the largest eddies of the latter. Arguments based on this concept lead to the following model:

$$\tau_{ij}{}^{s} = -\rho(\overline{\overline{u}_i\,\overline{u}_j} - \overline{\overline{u}}_i\,\overline{\overline{u}}_j)$$

where the superscript ‘s’ is a reminder that this is a scale similarity approximation of the e Reynolds stress, and the double overline indicates a quantity that has been filtered twice. The model constant of the Smagorinsky approach does not appear in the above as it is required to be unity to satisfy the Galilean invariance (Ferziger,1999). This model cannot be directly correlated with eddy viscosity models and is not dissipative. However a mixed model, which is a linear combination of the scale similarity and eddy viscosity models, predicts turbulence statistics better than eddy viscosity models for homogeneous isotropic, rotating, and sheared turbulence (Bardina, 1980). Also the scale similarity term in this model provides SGS backscatter transfer of energy.

The dynamic subgrid stress model (DSM) proposed by Germano et al (1991) overcomes several of the limitations of the Smagorinsky model. In the DSM, the unknown Smagorinsky coefficient is dynamically computed using the information from the resolved scales instead treated as a given constant. The DSM model has correct asymptotic behavior near a wall and in laminar flow and permits energy backscatter from small scales to large scales. In spite of these desirable features, the DSM has some aspects that are not ideal. Because the Smagorinsky model is used as the base model, the principal axes of the SGS stress tensor are assumed to be aligned with those of the resolved strain rate tensor, which may not reflect the realities of turbulence. Zang et al, 1993, combined the DSM with the scale similarity model to create the Dynamic Mixed Model (DMM), which retains the favorable features of DSM and has two additional advantages: 1) the scale similarity term enables the SGS model to have a better representation of the local flow dynamics; 2) the SGS stress tensor and the strain tensor are not required to be aligned. The DMM has been successfully applied to the LES simulation of flows in lid-driven cavity, using a finite-volume method and a "box filter" in physical space. The results show better agreement with experiment data than obtained using the DSM (Zang et al.,1993).

LES has become the preferred approach when turbulence at large scales is resolved on the model grid and the mostly-isotropic small scales are modeled by closure algorithms. However, the key weakness to LES is the need for the model to create the correct large-scale turbulence structures: that is, LES is the preferred approach to capturing the down-scaling of the turbulent energy cascade from large turbulent eddies. However, when such large eddies are created by an upscaling from small scales (e.g. boundary layer 'sweep' and 'burst' events, Nezu and Nakagawa, 1993), LES models may produce the wrong number and size of large-scale eddies (Hodges, 1997, pg. 76-77). Thus, LES models in the presence of upscaling are faced with a conundrum: if the model correctly represents the dissipative energy of a single turbulent structure, the overall flow will be insufficiently dissipative as insufficient structures are created (leading to an accelerated flow); alternatively, if the model gets the correct large scale dissipation, it must have overpredicted the dissipation of the individual simulated turbulent structures (Hodges, 1997). In the context of modeling rivers with LWD, the turbulent structures created by the LWD are inherently an upscaling phenomena, so it cannot be expected that simple application of LES methods at coarse grid scales can solve the problems associated with RANS modeling.

Summary of literature review

The most widely-used turbulence models are RANS and LES. In LES, the nonlinear term in the Navier-Stokes equations requires the "closure" to capture the effects of the subgrid scale (SGS) motion, using simple and "universal" models (Ferziger, 1996). However, for a coarse model grid, eddies generated from a subgrid-scale obstruction cannot be resolved at the grid scale, and their effects cannot be predicted from the resolved flow; thus, LES cannot resolve the effects of subgrid-scale physical feature. In RANS, all the unsteadiness is averaged out i.e. all unsteadiness is regarded as part of the turbulence (Lamb, 1945) and the resulting affect is considered locally homogeneous, which requires sufficiently dense empirical data to provide the modeling coefficient. The crucial task for "closure" in RANS is capturing the temporal unsteadiness of motions (Ferziger, 2002) rather than the spatial heterogeneity. Hence, RANS cannot satisfactorily account for subgrid-scale inhomogeneity in physical features that are below a model grid scale.

PROGRESS – A NEW MODEL FORMALISM

The crucial effort in accounting for subgrid-scale inhomogeneity is developing a new scaling theory to link the coarse grid scale and fine grid scale, thereby making the new turbulence model independent of the grid size. To solve this problem, we propose a new conceptual model that applies a spatial filter to the Reynolds-averaged Navier-Stokes equation, effectively combining

RANS and LES. The advantage of this approach is it allows heterogeneity in the subgrid-scale turbulence structure to be modeled independent of grid size in the new model.

To better understand the new approach, it is useful to go a little deeper into the differences between a RANS approach an LES approach. A RANS formalism implies a time average of the equations of motion, which are then discretized on a model grid. Thus, within the RANS approach the discrete equations are an approximation of the complete spatial structure of the time-averaged flow, and the spatial error associated with homogenization of subgrid-scale features is part of the model spatial truncation error (turbulence is considered sub-*time* scale). In contrast, the LES formalism applies a spatial filter to the equations of motion. This creates a continuous smooth velocity field that is resolvable at the filter scale, so the subfilter-scale features can be modeled explicitly and are separate from the model spatial truncation error. The key observation is that the spatialnfiltering of the equations of motion is significantly different than time averaging since spatial filters of nonlinear terms do not behave the same as simple time averaging for nonlinear terms (Leonard, 1974).

Spatially-filtered Reynolds-averaged Navier-Stokes equations

For the new model formalism, we begin with the RANS equation, derived by decomposing the velocity into time-average and fluctuating parts then time-averaging the entire equation. The result is:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_i \overline{u}_j\right) = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} - g\frac{\partial x_i}{\partial z} + \frac{1}{\rho}\frac{\partial \overline{\tau_{ij}}}{\partial x_j} - \frac{\partial}{\partial x_j}\left(\overline{u_i' u_j'}\right)$$

where $\overline{u}$ is a time-averaged velocity and u' is a velocity fluctuation defined respectively as

$$\overline{u} \equiv \frac{1}{\Delta t}\int_{\Delta t} u \, dt$$

$$u' \equiv \overline{u} - u$$

We apply a LES spatial filter to the RANS equations, where the filter is indicated by $\langle \; \rangle$. This new approach provides a set of equations for continuous velocity and pressure fields that are resolvable at the spatial filter scale:

$$\frac{\partial}{\partial t}\left\langle \overline{u}_i \right\rangle + \frac{\partial}{\partial x_j}\left\langle \overline{u}_i \overline{u}_j \right\rangle = -\frac{1}{\rho}\frac{\partial}{\partial x_i}\left\langle \overline{p} \right\rangle + g\frac{\partial x_i}{\partial z} + \frac{1}{\rho}\frac{\partial \left\langle \overline{\tau_{ij}} \right\rangle}{\partial x_j} - \frac{\partial}{\partial x_j}\left\langle \overline{u_i' u_j'} \right\rangle$$

However, the nonlinear term cannot be simulated in this form, so we move it to the right-hand side and add to both sides of the equation a resolvable nonlinear term:

$$\frac{\partial}{\partial x_j}\left\langle \overline{u}_i \right\rangle \left\langle \overline{u}_j \right\rangle$$

which results in:

$$\frac{\partial}{\partial t}\left\langle \overline{u}_i \right\rangle + \frac{\partial}{\partial x_j}\left\langle \overline{u}_i \right\rangle\left\langle \overline{u}_j \right\rangle = -\frac{1}{\rho}\frac{\partial}{\partial x_i}\left\langle \overline{p} \right\rangle + g\frac{\partial x_i}{\partial z} + \frac{1}{\rho}\frac{\partial\left\langle \overline{\tau_{ij}} \right\rangle}{\partial x_j} - \frac{\partial}{\partial x_j}\left\langle \overline{u_i' u_j'} \right\rangle + \frac{\partial}{\partial x_j}\left\langle \overline{u}_i \right\rangle\left\langle \overline{u}_j \right\rangle - \frac{\partial}{\partial x_j}\left\langle \overline{u}_i \overline{u}_j \right\rangle$$

In a model, the spatially-filtered time-averaged velocity is the velocity resolved on the model grid, so for simplicity in notation let us define

$$U \equiv \left\langle \overline{u} \right\rangle$$

The sub-filter-scale velocity (i.e. what cannot be resolved on the model grid) can be defined from

$$\tilde{u} \equiv \overline{u} - U$$

Note that an unconventional tilde is applied to indicate the sub-filter scale velocity to remind us that this velocity is time-averaged and therefore does not include turbulent (i.e. sub-time scale) fluctuations. A similar simplified notation can be made for the resolved pressure as $P = \left\langle \overline{p} \right\rangle$.

Substituting provides

$$\frac{\partial U_i}{\partial t} + \frac{\partial}{\partial x_j} U_i U_j = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + g\frac{\partial x_i}{\partial z} + \frac{1}{\rho}\frac{\partial\left\langle \overline{\tau_{ij}} \right\rangle}{\partial x_j} - \frac{\partial}{\partial x_j}\left\langle \overline{u_i' u_j'} \right\rangle + \frac{\partial}{\partial x_j} U_i U_j - \frac{\partial}{\partial x_j}\left\langle \left(\tilde{u}_i + U_i\right)\left(\tilde{u}_j + U_j\right) \right\rangle$$

Expanding the last term gives

$$\begin{aligned}\left\langle \left(\tilde{u}_i + U_i\right)\left(\tilde{u}_j + U_j\right) \right\rangle &= \left\langle \tilde{u}_i\tilde{u}_j + U_i\tilde{u}_j + \tilde{u}_i U_j + U_i U_j \right\rangle \\ &= \left\langle \tilde{u}_i\tilde{u}_j \right\rangle + \left\langle U_i\tilde{u}_j \right\rangle + \left\langle \tilde{u}_i U_j \right\rangle + \left\langle U_i U_j \right\rangle\end{aligned}$$

Substituting we obtain

$$\begin{aligned}\frac{\partial U_i}{\partial t} + \frac{\partial}{\partial x_j} U_i U_j = &-\frac{1}{\rho}\frac{\partial P}{\partial x_i} + g\frac{\partial x_i}{\partial z} + \frac{1}{\rho}\frac{\partial\left\langle \overline{\tau_{ij}} \right\rangle}{\partial x_j} - \frac{\partial}{\partial x_j}\left\langle \overline{u_i' u_j'} \right\rangle + \frac{\partial}{\partial x_j} U_i U_j \\ &- \frac{\partial}{\partial x_j}\left\langle \tilde{u}_i\tilde{u}_j \right\rangle - \frac{\partial}{\partial x_j}\left\langle U_i\tilde{u}_j \right\rangle - \frac{\partial}{\partial x_j}\left\langle \tilde{u}_i U_j \right\rangle - \frac{\partial}{\partial x_j}\left\langle U_i U_j \right\rangle\end{aligned}$$

We can regroup terms to write this as

$$\begin{aligned}\frac{\partial U_i}{\partial t} + \frac{\partial}{\partial x_j} U_i U_j = &-\frac{1}{\rho}\frac{\partial P}{\partial x_i} + g\frac{\partial x_i}{\partial z} + \frac{1}{\rho}\frac{\partial\left\langle \overline{\tau_{ij}} \right\rangle}{\partial x_j} - \frac{\partial}{\partial x_j}\left\langle \overline{u_i' u_j'} \right\rangle + \\ &- \frac{\partial}{\partial x_j}\left\langle \tilde{u}_i\tilde{u}_j \right\rangle - \frac{\partial}{\partial x_j}\left\{\left\langle U_i\tilde{u}_j \right\rangle + \left\langle \tilde{u}_i U_j \right\rangle\right\} - \frac{\partial}{\partial x_j}\left\{\left\langle U_i U_j \right\rangle - U_i U_j\right\}\end{aligned}$$

The filtering operation passes through the derivatives, so this can be written as

$$\frac{\partial U_i}{\partial t} + \frac{\partial}{\partial x_j} U_i U_j = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + g\frac{\partial x_i}{\partial z} + \frac{1}{\rho}\frac{\partial \left\langle \overline{\tau_{ij}} \right\rangle}{\partial x_j} - \left\langle \frac{\partial}{\partial x_j} \overline{u_i' u_j'} \right\rangle +$$
$$- \left\langle \frac{\partial}{\partial x_j} \tilde{u}_i \tilde{u}_j \right\rangle - \left\langle \frac{\partial}{\partial x_j} \left\{ U_i \tilde{u}_j + \tilde{u}_i U_j \right\} \right\rangle - \frac{\partial}{\partial x_j} \left\{ \left\langle U_i U_j \right\rangle - U_i U_j \right\}$$

We can define the classic LES terms derived by Leonard (1974):

$$L_{ij} \equiv \left\langle U_i U_j \right\rangle - U_i U_j$$
$$C_{ij} \equiv U_i \tilde{u}_j + \tilde{u}_i U_j$$
$$R_{ij} \equiv \tilde{u}_i \tilde{u}_j$$

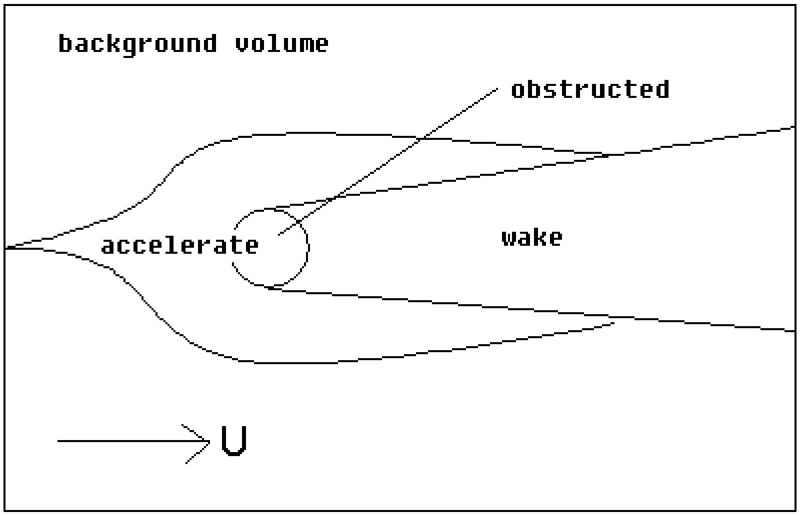
Substituting, the spatial filter applied to the RANS equations provides:

$$\frac{\partial U_i}{\partial t} + \frac{\partial}{\partial x_j} U_i U_j = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + g\frac{\partial x_i}{\partial z} + \frac{1}{\rho}\frac{\partial \left\langle \overline{\tau_{ij}} \right\rangle}{\partial x_j} - \left\langle \frac{\partial R_{ij}}{\partial x_j} \right\rangle - \left\langle \frac{\partial C_{ij}}{\partial x_j} \right\rangle - \frac{\partial L_{ij}}{\partial x_j} - \frac{\partial}{\partial x_j} \left\langle \overline{u_i' u_j'} \right\rangle$$

The above equation is similar to prior LES forms, but includes a filtered Reynolds stress term $\left\langle \overline{u_i' u_j'} \right\rangle$ and the LES terms are considered correlations of time-filtered, spatially resolved (U) and subgrid-scale ($\tilde{u}$) quantities.

Flow regions around LWD

The new model treats the flow field around LWD differently from the conventional approaches, allowing us to relate the small scale and the large scale physical quantities. As an example, we consider the simple turbulent flow around a circular cylinder. This canonical flow has four different regions based on Prantl's boundary layer theory (Prantl,1925; Zdravkovich, 1997). We consider a grid cell of volume $\forall_{cell}$ that can be divided into 4 sub-volumes: 1) a background volume $\forall_b$ that is unaffected by sub-grid scale inhomogeneity, 2) an obstructed volume $\forall_o$ in which the flow is slowed, 3) an accelerated volume $\forall_a$ in which the obstruction leads to local flow acceleration, and 4) a wake volume $\forall_w$ where the sub-filter scale velocity is fairly close to the resolved velocity, but the turbulence is enhanced by the wake of the object.



The characteristic scale of the time-averaged velocity in each subregion are sub-filter scale velocities: $\tilde{u}_{background}, \tilde{u}_{obstructed}, \tilde{u}_{accelerated}, \tilde{u}_{wake}$. Let us consider the simplest possible model where the resolved flow is only in the U direction (V=0) such that the flow is decelerated through an obstruction and accelerated around the obstruction. The characteristic velocity in each region is modeled by an empirical parameter and the resolved velocity such that

$$\begin{array}{llllll}
\tilde{u}_{background} & = U & \tilde{v}_{background} & = 0 & \tilde{w}_{background} & = 0 \\
\tilde{u}_{obstructed} & = \alpha U & \tilde{v}_{obstructed} & = 0 & \tilde{w}_{obstructed} & = 0 \\
\tilde{u}_{accelerated} & = \beta U & \tilde{v}_{accelerated} & = \gamma U & \tilde{w}_{accelerated} & = 0 \\
\tilde{u}_{wake} & = U & \tilde{v}_{wake} & = 0 & \tilde{w}_{wake} & = 0
\end{array}$$

where the model coefficients are: $\alpha < 1$, $\beta > 1$, and $-1 < \gamma < 1$. Thus, the new approach is based on empirically linking the subgrid-scale velocities to the resolved velocity and the subgrid-scale obstruction.

Using the scale relations proposed above, we can calculate the cross term in the spatially-filtered RANS equation as:

$$\left\langle \frac{\partial C_{11}}{\partial x} \right\rangle = \frac{1}{\forall_{cell}} \left[\forall_b \frac{\partial C_{11(b)}}{\partial x} + \forall_o \frac{\partial C_{11(o)}}{\partial x} + \forall_a \frac{\partial C_{11(a)}}{\partial x} + \forall_w \frac{\partial C_{11(w)}}{\partial x} \right]$$

where subscripts indicate: b = background, o = obstructed, a = accelerated, w = wake. It follows that

$$\begin{aligned}
C_{11(b)} &= U\tilde{u}_b &&= U^2 \\
C_{11(o)} &= U\tilde{u}_o &&= \alpha U^2 \\
C_{11(a)} &= U\tilde{u}_a &&= \beta U^2 \\
C_{11(w)} &= U\tilde{u}_w &&= U^2
\end{aligned}$$

which provides

$$\left\langle \frac{\partial C_{11}}{\partial x} \right\rangle = \frac{U^2}{\forall_{cell}} \left[\forall_b + \alpha \forall_o + \beta \forall_a + \forall_w \right]$$

Thus, once we have the empirical coefficients for the relationships between the background (free-stream) flow and the flow in the object-affected regions, the cross term is analytically calculable. Similar approaches can be used for the other cross, Leonard and Reynolds terms. The key insight is that the modeling relationships (i.e. values for model coefficients such as α, β, γ) are determined empirically without regard to the model grid spacing, but their implementation implicitly includes the effect of the grid scale. Note that the above is simply an illustrative example, and the appropriate forms for the relationships between the characteristic and resolved velocities requires further investigation.

Conclusions

This project has successfully developed the theoretical underpinnings of a new model formalism for representing large woody debris in river models. That is, the formal mathematical structure of spatial filtering applied to RANS equations provides a basis for multiple modeling approaches (much as RANS and LES themselves are formalisms that admit a multitude of models). The principle advantage of the new theory is that it can explicitly represent the relationships between model grid scales and empirical data collected in the field and laboratory. Future work to develop and test this approach will provide a more effective methodology for modeling the flow effects of large woody debris.

FURTHER COURSE OF WORK

The LWD modeling framework derived in this report needs further development, implementation and testing/validation against theory, other model predictions, laboratory experiments, and field data. Model development/implementation requires: 1) selecting a workable framework for relating the characteristic subgrid scale flows and the large-scale flows for submerged objects; 2) choosing a suitable existing base model for hydrodynamic solution, and 3) coding a basic structure for the new model. Initial model testing should be conducted with simple geometry (perhaps flow around a circular cylinder) that has been previously modeled and for which the fundamental flow features are well-understood. Initial testing should be against theory and model results for simple geometries to demonstrate how knowledge of the turbulence field around an object can be transformed into empirical coefficients that improve the modeling of a large-scale flow field. The second level of testing should be against flow fields for more complex geometries that are studied in a laboratory flume. The laboratory testing effort should demonstrate the robustness of the model for capturing the large-scale flow around a variety of object shapes. The third level of testing/validation should be against field data collected in a river. For field validation purposes, a river reach should be selected for study and hydrodynamic modeling using standard TWDB practices. In addition to the data typically collected for modeling, an effort should be made to collect detailed velocity data around 8 or 10 pieces of LWD. The data from 50% of this collection should be used to calibrate the empirical coefficients for all the LWD features in the river reach. The remaining data should be used for evaluating the model performance. The key issue to be analyzed is whether or not the new model provides a better representation of the large-scale flow than is obtained by a model using standard RANS approaches for turbulence closure.

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