Large scale Finite Element solvers for the large eddy simulation of incompressible turbulent flows

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Motivation

Thesis motivation

Highly scalable Finite Element (FE) framework for Large Eddy Simulations (LES) of incompressible turbulent flows

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How to get there?

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1. Variational MultiScale (VMS) methods as LES models.
2. Time integration schemes with velocity-pressure segregation.

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How to get there?

1. Variational MultiScale (VMS) methods as LES models.
2. Time integration schemes with velocity-pressure segregation.
3. Highly scalable algorithms based on Domain Decomposition (DD) and block preconditioners.

Motivation

Step by step...

- Residual-based VMS as LES models.

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- Mixed FE formulations LES.

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- Scalable solvers.

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- Application.

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- Application.

Rb-VMS

Implicit LES

ILES: only numerical dissipation (for stabilization) acts as turbulent model

- Not based on filtering of the Navier-Stokes equations
- Rely on numerical artifacts, no modification at the continuous level

Incomp. Navier Stokes equations

Find $\mathbf{u}$ and p defined in Ω

$$\begin{aligned} \partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} + \nabla p - \nu \nabla^2 \mathbf{u} &= \mathbf{f} \\ \nabla \cdot \mathbf{u} &= 0 \end{aligned}$$

with appropriate boundary conditions on Γ.

Incomp. Navier Stokes equations

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$$\nabla \cdot \mathbf{u} = 0$$

with appropriate boundary conditions on Γ.

The weak problem is: $\forall \mathbf{v} \in \mathcal{V}_0$ and $\forall q \in \mathcal{Q}_0$, find $\mathbf{u} \in \mathcal{V}$ and $p \in \mathcal{Q}$ such that

$$(\mathbf{v}, \partial_t \mathbf{u})_\Omega + (\nabla \mathbf{v}, \nu \nabla \mathbf{u})_\Omega + b(\mathbf{u}, \mathbf{u}, \mathbf{v}) - (\nabla \cdot \mathbf{v}, p)_\Omega = \langle \mathbf{v}, \mathbf{f} \rangle_\Omega$$
$$(q, \nabla \cdot \mathbf{u})_\Omega = 0$$

Incomp. Navier Stokes equations

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where

$$b(\mathbf{a}, \mathbf{u}, \mathbf{v}) = \quad \langle \mathbf{v}, \mathbf{a} \cdot \nabla \mathbf{u} \rangle_\Omega$$

Incomp. Navier Stokes equations

Find $\mathbf{u}$ and p defined in Ω

$$\begin{aligned} \partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} + \nabla p - \nu \nabla^2 \mathbf{u} &= \mathbf{f} \\ \nabla \cdot \mathbf{u} &= 0 \end{aligned}$$

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where

$$b(\mathbf{a}, \mathbf{u}, \mathbf{v}) = \frac{1}{2} \langle \mathbf{v}, \mathbf{a} \cdot \nabla \mathbf{u} \rangle_\Omega - \frac{1}{2} \langle \mathbf{a} \cdot \nabla \mathbf{v}, \mathbf{u} \rangle_\Omega + \frac{1}{2} \langle \mathbf{v}, \mathbf{n} \cdot \mathbf{a} \mathbf{u} \rangle_\Gamma$$

VMS decomposition (Hughes 1995)

A decomposition of spaces $\mathcal{V}$ and $\mathcal{Q}$ given by

$$\mathcal{V} = \mathcal{V}_h \oplus \widetilde{\mathcal{V}}, \quad \mathcal{Q} = \mathcal{Q}_h \oplus \widetilde{\mathcal{Q}}$$

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$$\mathcal{V} = \mathcal{V}_h \oplus \widetilde{\mathcal{V}}, \quad \mathcal{Q} = \mathcal{Q}_h \oplus \widetilde{\mathcal{Q}}$$

is applied to the function and test spaces

$$\mathbf{u} = \mathbf{u}_h + \widetilde{\mathbf{u}}, \quad p = p_h + \widetilde{p}$$
$$\mathbf{v} = \mathbf{v}_h + \widetilde{\mathbf{v}}, \quad q = q_h + \widetilde{q}$$

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$$\mathbf{v} = \mathbf{v}_h + \widetilde{\mathbf{v}}, \quad q = q_h + \widetilde{q}$$

We keep all the (eight) contributions from the splitting of the convective term

$$\mathbf{u} \cdot \nabla \mathbf{u} = \mathbf{u}_h \cdot \nabla \mathbf{u}_h + \widetilde{\mathbf{u}} \cdot \nabla \mathbf{u}_h + \mathbf{u}_h \cdot \nabla \widetilde{\mathbf{u}} + \widetilde{\mathbf{u}} \cdot \nabla \widetilde{\mathbf{u}}$$

VMS decomposition (Hughes 1995)

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$$\mathbf{u} = \mathbf{u}_h + \widetilde{\mathbf{u}}, \quad p = p_h + \widetilde{p}$$
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We keep all the (eight) contributions from the splitting of the convective term

$$\mathbf{u} \cdot \nabla \mathbf{u} = \mathbf{u}_h \cdot \nabla \mathbf{u}_h + \widetilde{\mathbf{u}} \cdot \nabla \mathbf{u}_h + \mathbf{u}_h \cdot \nabla \widetilde{\mathbf{u}} + \widetilde{\mathbf{u}} \cdot \nabla \widetilde{\mathbf{u}}$$

and all the (four) contributions from the temporal term

$$\partial_t \mathbf{u} = \partial_t \mathbf{u}_h + \partial_t \widetilde{\mathbf{u}}$$

Semidiscrete problem

FEM equations

$$B\left(\left(\mathbf{u}_h, p_h\right); \left(\widetilde{\mathbf{u}}, \widetilde{p}\right); \left(\mathbf{v}_h, q_h\right)\right) = L\left(\mathbf{v}_h, q_h\right)$$

SGS equations

$$B\left(\left(\widetilde{\mathbf{u}}, \widetilde{p}\right); \left(\mathbf{u}_h, p_h\right); \left(\widetilde{\mathbf{v}}, \widetilde{q}\right)\right) = L\left(\widetilde{\mathbf{v}}, \widetilde{q}\right)$$

Semidiscrete problem

FEM equations

$$(\mathbf{v}_h, \partial_t \mathbf{u}_h)_\Omega + b(\mathbf{a}, \mathbf{u}_h, \mathbf{v}_h) + (\nabla \mathbf{v}_h, \nu \nabla \mathbf{u}_h)_\Omega - (\nabla \cdot \mathbf{v}_h, p_h)_\Omega$$
$$+ (\mathbf{v}_h, \partial_t \tilde{\mathbf{u}})_\Omega + (\mathcal{L}^* \mathbf{v}_h, \tilde{\mathbf{u}})_{\Omega^h} - (\nabla \cdot \mathbf{v}_h, \tilde{p})_{\Omega^h} = \langle \mathbf{v}_h, \mathbf{f} \rangle_\Omega$$

$$(q_h, \nabla \cdot \mathbf{u}_h)_\Omega - (\nabla q_h, \tilde{\mathbf{u}})_{\Omega^h} = 0$$

SGS equations

$$\partial_t \tilde{\mathbf{u}} + \tau_m^{-1} \tilde{\mathbf{u}} = \mathcal{P} \mathbf{R}_m$$

$$\tau_c^{-1} \tilde{p} = \mathcal{P} R_c$$

$$\tau_m = \left(\frac{c_1 \nu}{h^2} + \frac{c_2 |\mathbf{a}|}{h} \right)^{-1}, \quad \tau_c = \frac{h^2}{c_1 \tau_m}$$

$$\mathbf{a} = \mathbf{u}_h + \tilde{\mathbf{u}}$$

Semidiscrete problem

FEM equations

$$(\mathbf{v}_h, \partial_t \mathbf{u}_h)_\Omega + b(\mathbf{a}, \mathbf{u}_h, \mathbf{v}_h) + (\nabla \mathbf{v}_h, \nu \nabla \mathbf{u}_h)_\Omega - (\nabla \cdot \mathbf{v}_h, p_h)_\Omega$$
$$+ (\mathbf{v}_h, \partial_t \widetilde{\mathbf{u}})_\Omega + (\mathcal{L}^* \mathbf{v}_h, \widetilde{\mathbf{u}})_{\Omega^h} - (\nabla \cdot \mathbf{v}_h, \widetilde{p})_{\Omega^h} = \langle \mathbf{v}_h, \mathbf{f} \rangle_\Omega$$
$$(q_h, \nabla \cdot \mathbf{u}_h)_\Omega - (\nabla q_h, \widetilde{\mathbf{u}})_{\Omega^h} = 0$$

SGS equations

$$\partial_t \widetilde{\mathbf{u}} + \tau_m^{-1} \widetilde{\mathbf{u}} = \mathcal{P} \mathbf{R}_m$$
$$\tau_c^{-1} \widetilde{p} = \mathcal{P} R_c$$

$$\mathbf{R}_m := \mathbf{f} - \partial_t \mathbf{u}_h - \mathcal{L} \mathbf{u}_h - \nabla p_h, \quad R_c := -\nabla \cdot \mathbf{u}_h$$

Semidiscrete problem

FEM equations

$$(\mathbf{v}_h, \partial_t \mathbf{u}_h)_\Omega + b(\mathbf{a}, \mathbf{u}_h, \mathbf{v}_h) + (\nabla \mathbf{v}_h, \nu \nabla \mathbf{u}_h)_\Omega - (\nabla \cdot \mathbf{v}_h, p_h)_\Omega$$

$$+ (\mathbf{v}_h, \partial_t \widetilde{\mathbf{u}})_\Omega + (\mathcal{L}^* \mathbf{v}_h, \widetilde{\mathbf{u}})_{\Omega^h} - (\nabla \cdot \mathbf{v}_h, \widetilde{p})_{\Omega^h} = \langle \mathbf{v}_h, \mathbf{f} \rangle_\Omega$$

$$(q_h, \nabla \cdot \mathbf{u}_h)_\Omega - (\nabla q_h, \widetilde{\mathbf{u}})_{\Omega^h} = 0$$

SGS equations

$$\partial_t \widetilde{\mathbf{u}} + \tau_m^{-1} \widetilde{\mathbf{u}} = \mathcal{P} \mathbf{R}_m$$

$$\tau_c^{-1} \widetilde{p} = \mathcal{P} R_c$$

$$\mathcal{P} = I \quad \text{(ASGS)}, \qquad \mathcal{P} = P_h^\perp = I - P_h \quad \text{(OSS)}$$

Semidiscrete problem

FEM equations

$$(\mathbf{v}_h, \partial_t \mathbf{u}_h)_\Omega + b(\mathbf{a}, \mathbf{u}_h, \mathbf{v}_h) + (\nabla \mathbf{v}_h, \nu \nabla \mathbf{u}_h)_\Omega - (\nabla \cdot \mathbf{v}_h, p_h)_\Omega$$

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$$(q_h, \nabla \cdot \mathbf{u}_h)_\Omega - (\nabla q_h, \widetilde{\mathbf{u}})_{\Omega^h} = 0$$

SGS equations

$$\partial_t \widetilde{\mathbf{u}} + \tau_m^{-1} \widetilde{\mathbf{u}} = \mathcal{P} \mathbf{R}_m$$

$$\tau_c^{-1} \widetilde{p} = \mathcal{P} R_c$$

$$\mathcal{P} = I \quad \text{(ASGS)}, \qquad \mathcal{P} = \mathrm{P}_\mathrm{h}^\perp = \mathrm{I} - \mathrm{P}_\mathrm{h} \quad \text{(OSS)}$$

$$\mathbf{a} = \mathbf{u}_h + \widetilde{\mathbf{u}}$$

Summary

	Sgs space	Sgs dynamics	Advection
1	ASGS	Static	Linear
2	ASGS	Dynamic	Linear
3	ASGS	Dynamic	Nonlinear
4	OSS	Static	Linear
5	OSS	Dynamic	Linear
6	OSS	Dynamic	Nonlinear

1 It is the most standard method (SUPG for linear elements) up to the choice of the stabilization parameters. Unknown stability properties.

4 Strictly pointwise positive for linear elements (no backscatter).

5 Convergent to weak solutions of NS equations (Badia & Gutierrez 2012).

Energy statements

FE counterpart:

$$B\left(\left(\mathbf{u}_h, p_h\right); \left(\widetilde{\mathbf{u}}, \widetilde{p}\right); \left(\mathbf{u}_h, p_h\right)\right) = L\left(\mathbf{u}_h, p_h\right)$$

SGS counterpart:

$$B\left(\left(\widetilde{\mathbf{u}}, \widetilde{p}\right); \left(\mathbf{u}_h, p_h\right); \left(\widetilde{\mathbf{u}}, \widetilde{p}\right)\right) = L\left(\widetilde{\mathbf{u}}, \widetilde{p}\right)$$

TOTAL:

$$\begin{aligned} & B\left(\left(\mathbf{u}_h, p_h\right); \left(\widetilde{\mathbf{u}}, \widetilde{p}\right); \left(\mathbf{u}_h, p_h\right)\right) \\ + & B\left(\left(\widetilde{\mathbf{u}}, \widetilde{p}\right); \left(\mathbf{u}_h, p_h\right); \left(\widetilde{\mathbf{u}}, \widetilde{p}\right)\right) = L\left(\mathbf{u}_h, p_h\right) + L\left(\widetilde{\mathbf{u}}, \widetilde{p}\right) \end{aligned}$$

Energy statements

FE counterpart:

$$\frac{1}{2} d_t \|\mathbf{u}_h\|^2 + \nu \|\nabla \mathbf{u}_h\|^2 + b(\mathbf{a}, \mathbf{u}_h, \mathbf{u}_h)$$
$$+ (\partial_t \widetilde{\mathbf{u}}, \mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h, p_h), \widetilde{\mathbf{u}}) - (\nabla \cdot \mathbf{u}_h, \widetilde{p}) = \langle \mathbf{f}, \mathbf{u}_h \rangle$$

SGS counterpart:

$$\frac{1}{2} d_t \|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1} \|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1} \|\widetilde{p}\|^2$$
$$+ (\mathcal{P}(\partial_t \mathbf{u}_h), \widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h, p_h)), \widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla \cdot \mathbf{u}_h), \widetilde{p}) = \langle \mathcal{P}(\mathbf{f}), \widetilde{\mathbf{u}} \rangle$$

TOTAL:

Energy statements

FE counterpart:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + b(\mathbf{a},\mathbf{u}_h,\mathbf{u}_h)$$
$$+ (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle$$

SGS counterpart:

$$\frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$
$$+ (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

TOTAL:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2$$

Energy statements

FE counterpart:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + b(\mathbf{a},\mathbf{u}_h,\mathbf{u}_h)$$
$$+ (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle$$

SGS counterpart:

$$\frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$
$$+ (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

TOTAL:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \nu\|\nabla\mathbf{u}_h\|^2$$

Energy statements

FE counterpart:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + b(\mathbf{a},\mathbf{u}_h,\mathbf{u}_h)$$
$$+ (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle$$

SGS counterpart:

$$\frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$
$$+ (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

TOTAL:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \nu\|\nabla\mathbf{u}_h\|^2$$

Energy statements

FE counterpart:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + b(\mathbf{a},\mathbf{u}_h,\mathbf{u}_h) + (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle$$

SGS counterpart:

$$\frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2 + (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

TOTAL:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$

Energy statements

FE counterpart:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + b(\mathbf{a},\mathbf{u}_h,\mathbf{u}_h)$$
$$+ (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle$$

SGS counterpart:

$$\frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$
$$+ (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

TOTAL:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$
$$+ (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}})$$
$$- (\nabla\cdot\mathbf{u}_h,\widetilde{p}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p})$$

Energy statements

FE counterpart:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + b(\mathbf{a},\mathbf{u}_h,\mathbf{u}_h)$$
$$+ (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle$$

SGS counterpart:

$$\frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$
$$+ (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

TOTAL:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$
$$+ (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}})$$
$$- (\nabla\cdot\mathbf{u}_h,\widetilde{p}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle + \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

Energy statements

FE counterpart:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + b(\mathbf{a},\mathbf{u}_h,\mathbf{u}_h) + (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle$$

SGS counterpart:

$$\frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2 + (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

TOTAL: **Static subscales**

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2 + (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle + \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

Energy statements

FE counterpart:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + b(\mathbf{a},\mathbf{u}_h,\mathbf{u}_h) + (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle$$

SGS counterpart:

$$\frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2 + (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

TOTAL: **Dynamic subscales - ASGS**

$$\frac{1}{2}d_t\|\mathbf{u}_h+\widetilde{\mathbf{u}}\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2 - 2\,(\nu\Delta\mathbf{u}_h,\widetilde{\mathbf{u}}) = \langle\mathbf{f},\mathbf{u}_h\rangle + \langle\mathbf{f},\widetilde{\mathbf{u}}\rangle$$

Energy statements

FE counterpart:

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + b(\mathbf{a},\mathbf{u}_h,\mathbf{u}_h)$$
$$+ (\partial_t\widetilde{\mathbf{u}},\mathbf{u}_h) + (\mathcal{L}_a^*(\mathbf{u}_h,p_h),\widetilde{\mathbf{u}}) - (\nabla\cdot\mathbf{u}_h,\widetilde{p}) = \langle\mathbf{f},\mathbf{u}_h\rangle$$

SGS counterpart:

$$\frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$
$$+ (\mathcal{P}(\partial_t\mathbf{u}_h),\widetilde{\mathbf{u}}) + (\mathcal{P}(\mathcal{L}_a^*(\mathbf{u}_h,p_h)),\widetilde{\mathbf{u}}) - (\mathcal{P}(\nabla\cdot\mathbf{u}_h),\widetilde{p}) = \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

TOTAL: **Dynamic subscales - OSS**

$$\frac{1}{2}d_t\|\mathbf{u}_h\|^2 + \frac{1}{2}d_t\|\widetilde{\mathbf{u}}\|^2 + \nu\|\nabla\mathbf{u}_h\|^2 + \tau_m^{-1}\|\widetilde{\mathbf{u}}\|^2 + \tau_c^{-1}\|\widetilde{p}\|^2$$
$$- 2\,(\nu\Delta\mathbf{u}_h,\widetilde{\mathbf{u}})$$
$$= \langle\mathbf{f},\mathbf{u}_h\rangle + \langle\mathcal{P}(\mathbf{f}),\widetilde{\mathbf{u}}\rangle$$

Numerical experiments

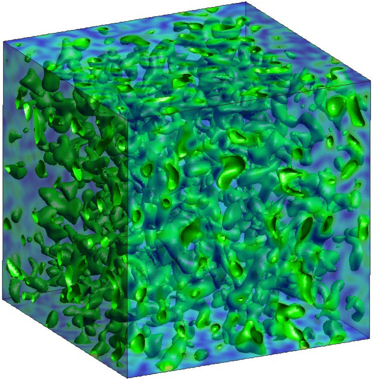
Three different turbulent benchmarks:

- Decaying of Homogeneous Isotropic Turbulence (DHIT).
- Taylor-Green Vortex (TGV) flow.
- Turbulent Channel Flow (TCF).

DHIT Decay of Homogeneous Isotropic Turbulence

Problem setting:

- Prescribed initial energy spectra corresponding to $Re_\lambda = 952$.
- Setting defined in AGARD database (Mansour & Wray 1993).
- A (very simple) time step adaptation technique is used.
- Different mesh discretizations (Q_1/Q_1 and Q_2/Q_2).



DHIT Decay of Homogeneous Isotropic Turbulence

Energy espectra (models):

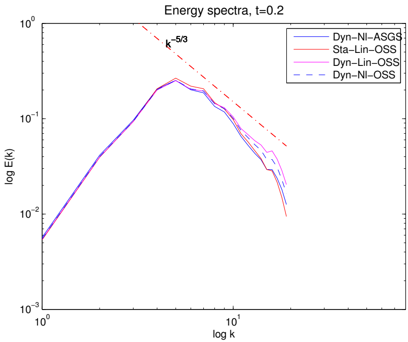


Figure : $32^3 - Q1,\ t = 0.2s$

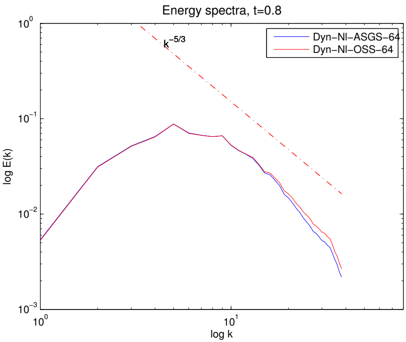
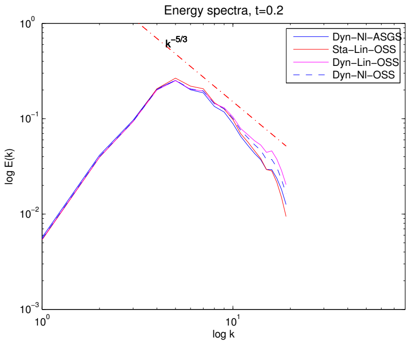


Figure : $64^3 - Q1,\ t = 0.8s$

DHIT Decay of Homogeneous Isotropic Turbulence

Energy espectra (models):



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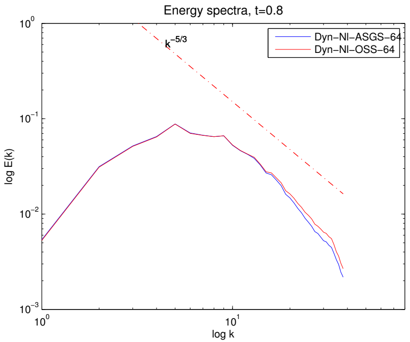
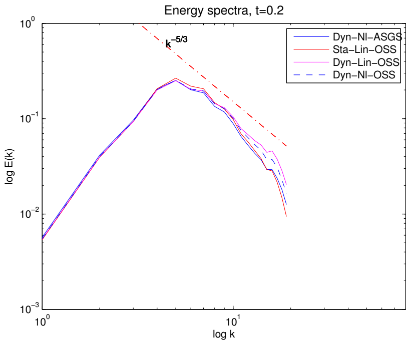


Figure : $64^3 - Q1,\ t = 0.8s$

- Small differences between methods (physical sense).

DHIT Decay of Homogeneous Isotropic Turbulence

Energy espectra (models):



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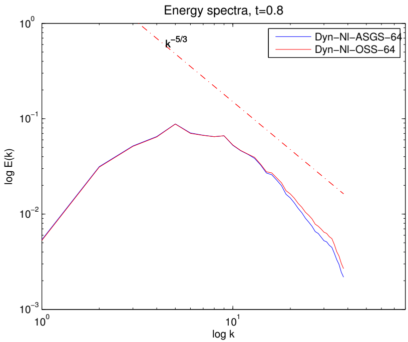


Figure : $64^3 - Q1,\ t = 0.8s$

- Small differences between methods (physical sense).
- Even more similar when we refine the mesh.

DHIT Decay of Homogeneous Isotropic Turbulence

Computational cost (models):

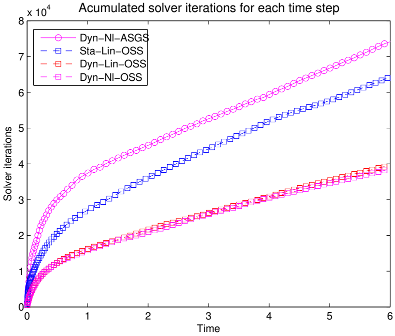
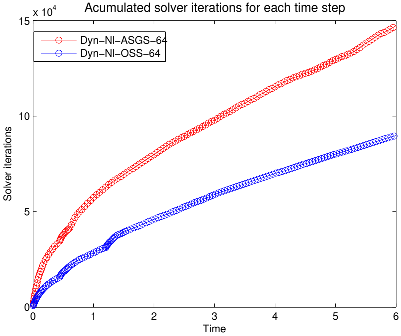


Figure : $32^3 - Q1$



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DHIT Decay of Homogeneous Isotropic Turbulence

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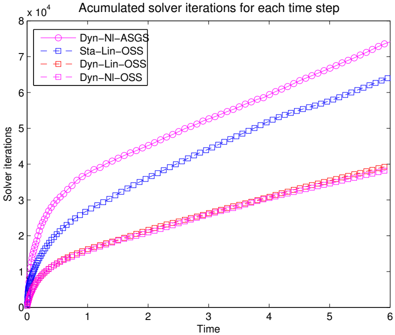

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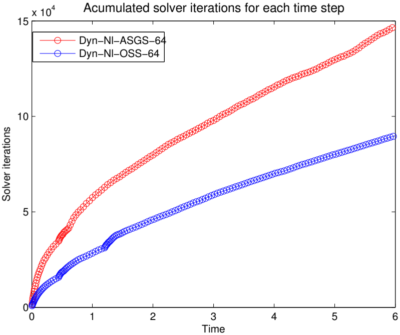

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DHIT Decay of Homogeneous Isotropic Turbulence

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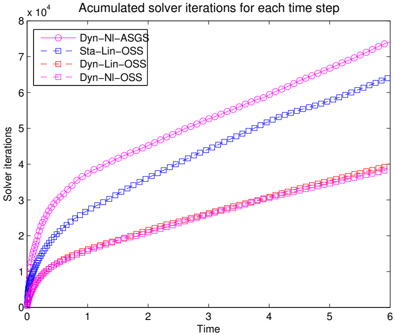

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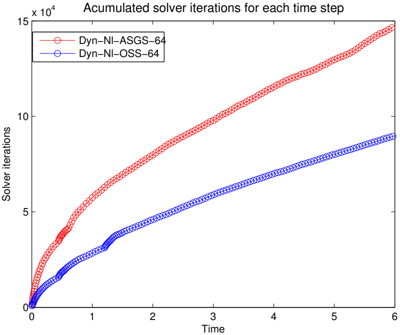
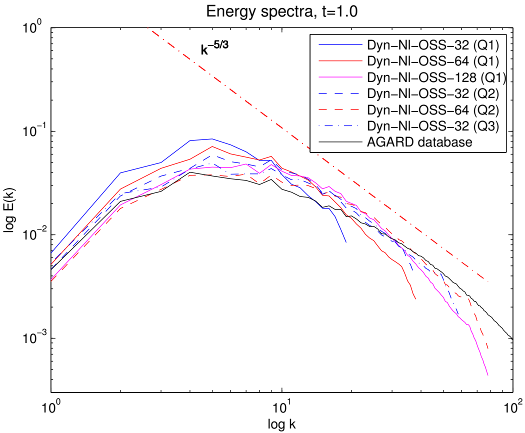


Figure : $64^3 - Q1$

- Big differences between methods (computational sense).
- Dynamic versions of OSS method are the most efficient.

DHIT Decay of Homogeneous Isotropic Turbulence

Energy espectra (refinement):



- Results become closer to the DNS when we refine the mesh.

TGV Taylor-Green Vortex flow

Problem setting:

- Prescribed initial condition.
- $Re = 1600$.
- Different mesh discretizations (Q_1/Q_1 and Q_2/Q_2).

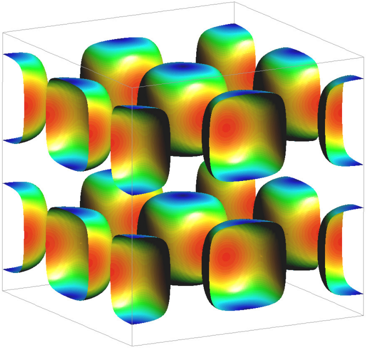


Figure : Initial vorticity isosurface $|\omega| = 1$

TGV Taylor-Green Vortex flow

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- $Re = 1600$.
- Different mesh discretizations (Q_1/Q_1 and Q_2/Q_2).

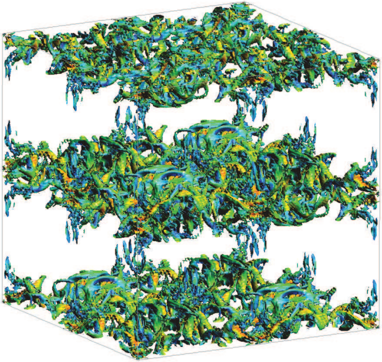


Figure : Vorticity isosurfaces $|\omega| = 9.0$

TGV Taylor-Green Vortex flow

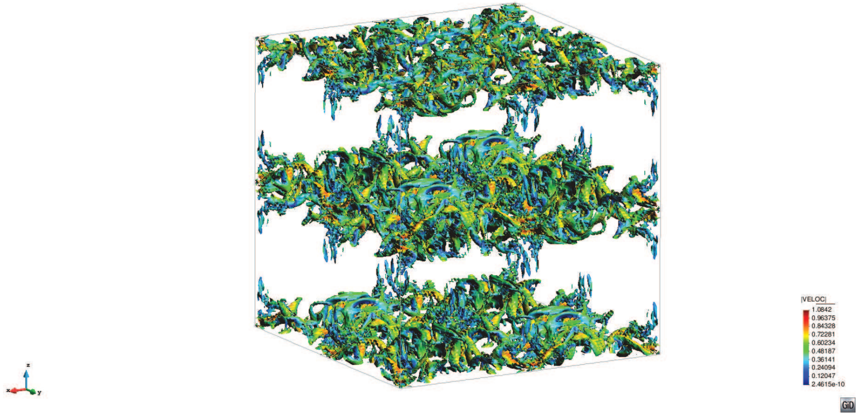


Figure : Velocity isosurface

TGV Taylor-Green Vortex flow

Energy dissipation rate (refinement):

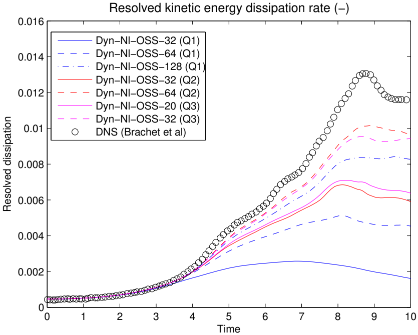


Figure : Resolved scales

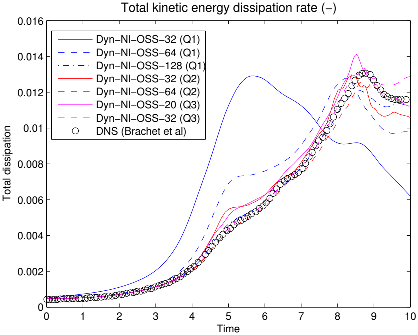
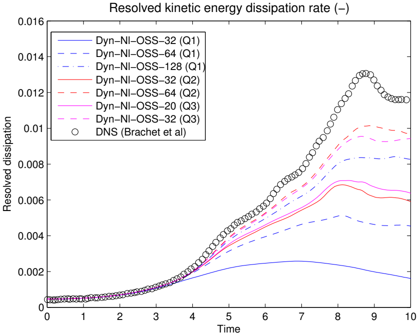


Figure : Total

TGV Taylor-Green Vortex flow

Energy dissipation rate (refinement):



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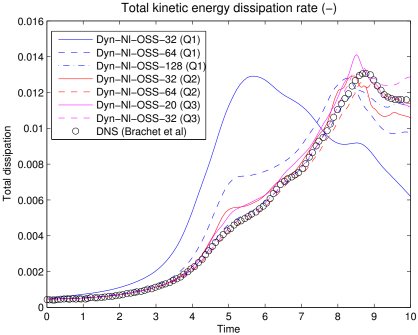

Figure : Total

- Good agreement with the DNS taking account the subscales.

TGV Taylor-Green Vortex flow

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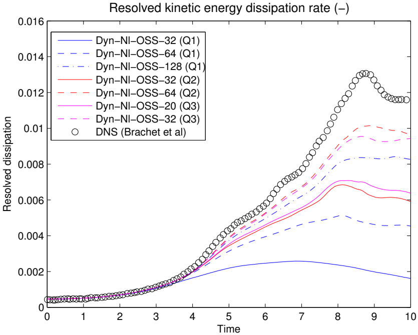

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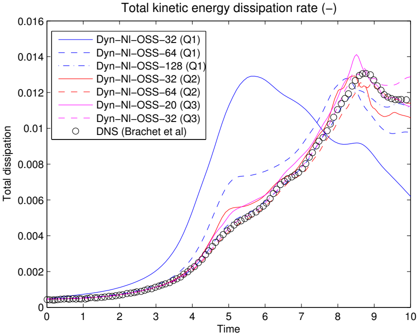

Figure : Total

- Good agreement with the DNS taking account the subscales.
- More accurate results increasing the order of approximation.

TGV Taylor-Green Vortex flow

- All results until now are compared against **DNS**.
- Are our methods comparable with **LES** models?

TGV Taylor-Green Vortex flow

Energy dissipation rate (against LES model):

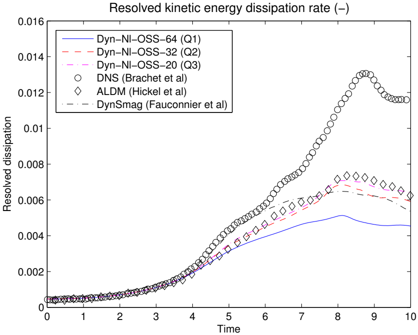

Figure : Resolved scales

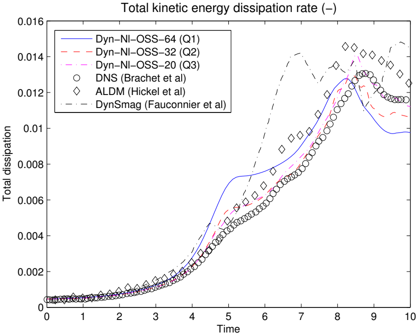

Figure : Total

TGV Taylor-Green Vortex flow

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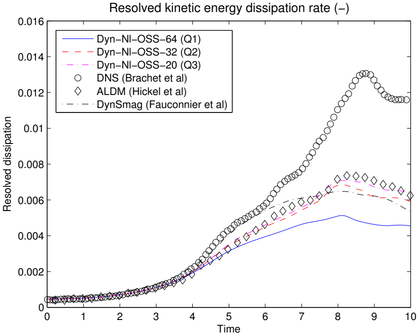

Figure : Resolved scales

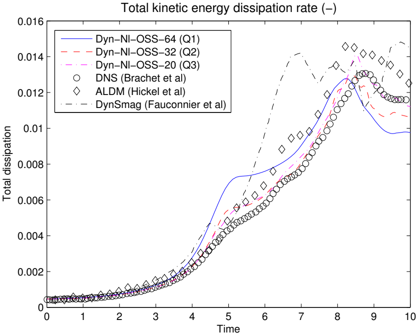

Figure : Total

- Good agreement with the LES models on resolved scales.

TGV Taylor-Green Vortex flow

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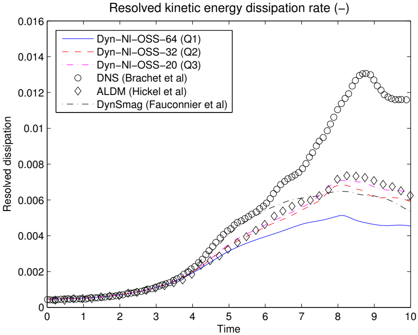


Figure : Resolved scales

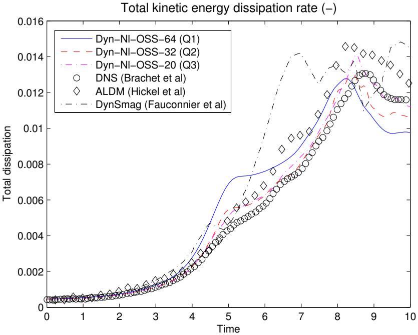


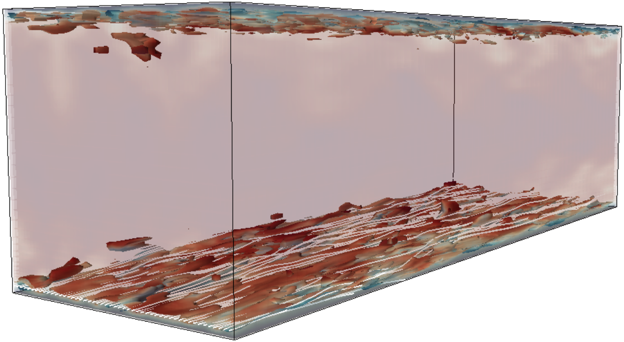
Figure : Total

- Good agreement with the LES models on resolved scales.
- Better results than LES models adding subscales counterpart.

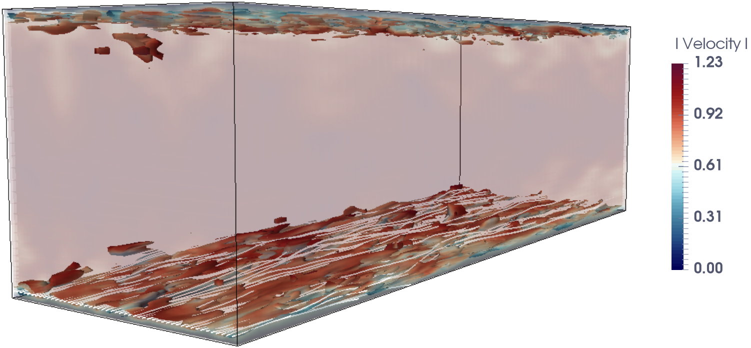
TCF Turbulent Channel Flow

Problem setting:

- Wall bounded flow.
- $Re_\tau = 180$ and $Re_\tau = 395$.
- Mesh resolution: $32^3 - Q1$.

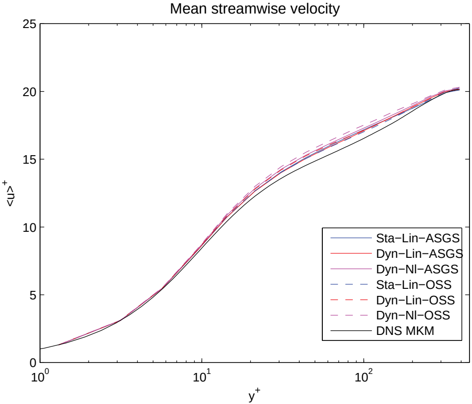


TCF Turbulent Channel Flow



TCF Turbulent Channel Flow

Mean streamwise velocity (models):



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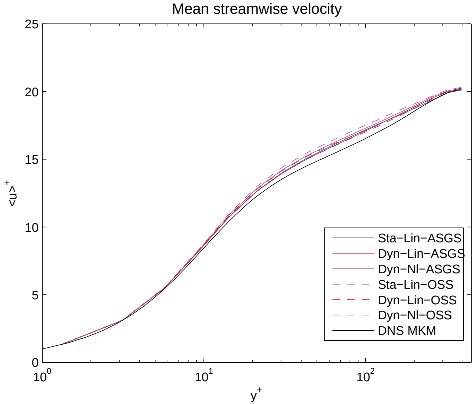

- Small differences between methods.

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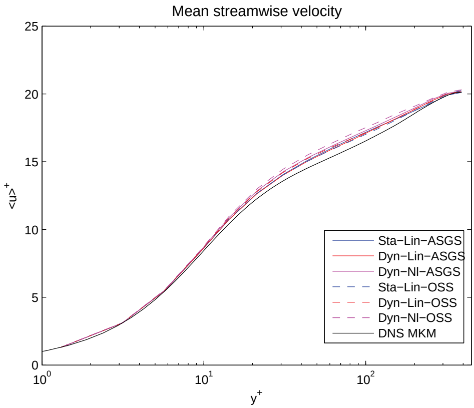

- Small differences between methods.
- Very accurate results compared against the DNS.

TCF Turbulent Channel Flow

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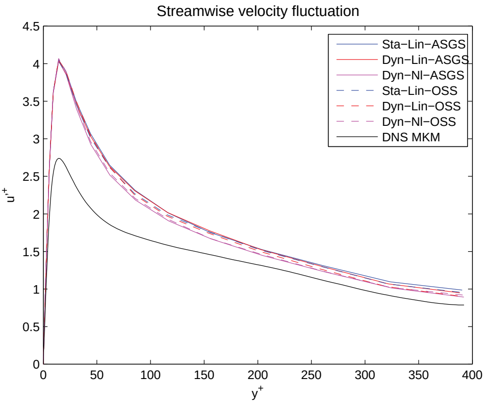

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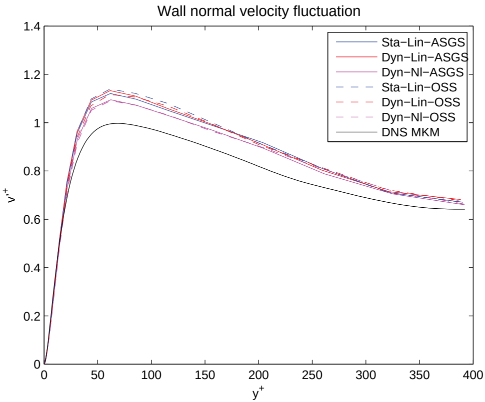

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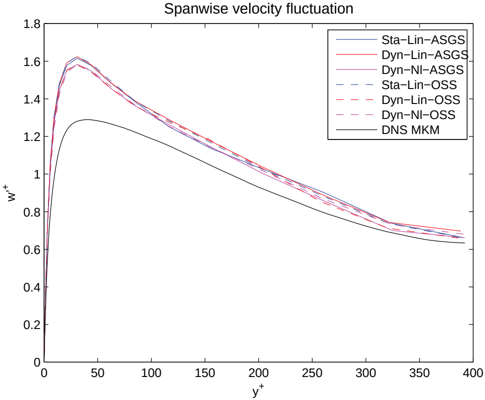

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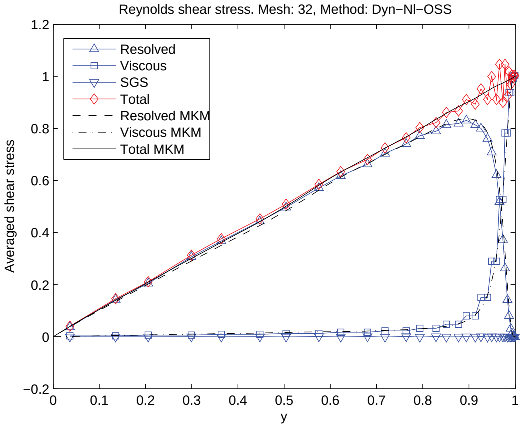
TCF Turbulent Channel Flow

Reynolds shear stress (models):



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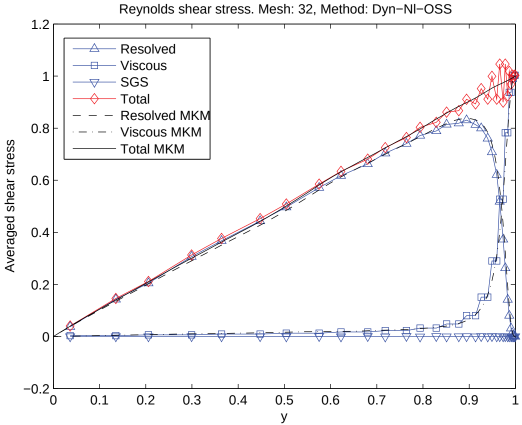
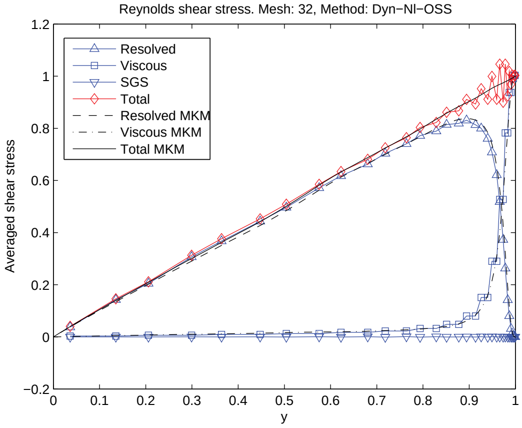


- Almost identical to the DNS.

TCF Turbulent Channel Flow

Reynolds shear stress (models):



- Almost identical to the DNS.
- SGS counterpart does not contribute to the Reynolds shear stress.

RB-VMS Conclusions

- VMS formulations of NS equations can be used for the numerical simulation of turbulent flows.

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- Our particular VMS modelling ingredients
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  - Nonlinear subscales
  - Orthgonal subscales

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RB-VMS Conclusions

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  seem to be important to simulate turbulent flows.
- Among them dynamic and orthogonal subscales (linear or nonlinear) are the most effective.
- The skewsymmetric formulation is important to keep stability.

RB-VMS Limitations

- **ASGS:**

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  - Poorly matrix conditioning ⇒ High number of solver iterations.

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RB-VMS Limitations

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- **OSS:**
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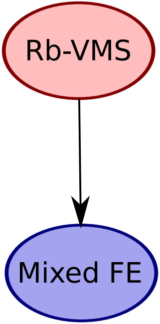
- **Desired:**
  - OSS with implicit projections.


Rb-VMS
Mixed FE

Semidiscrete problem

FEM equations

$$(\mathbf{v}_h, \partial_t \mathbf{u}_h)_\Omega + b(\mathbf{a}, \mathbf{u}_h, \mathbf{v}_h) + (\nabla \mathbf{v}_h, \nu \nabla \mathbf{u}_h)_\Omega - (\nabla \cdot \mathbf{v}_h, p_h)_\Omega$$

$$+ (\mathbf{v}_h, \partial_t \widetilde{\mathbf{u}})_\Omega + (\mathcal{L}^* \mathbf{v}_h, \widetilde{\mathbf{u}})_{\Omega^h} - (\nabla \cdot \mathbf{v}_h, \widetilde{p})_{\Omega^h} = \langle \mathbf{v}_h, \mathbf{f} \rangle_\Omega$$

$$(q_h, \nabla \cdot \mathbf{u}_h)_\Omega - (\nabla q_h, \widetilde{\mathbf{u}})_{\Omega^h} = 0$$

SGS equations

$$\partial_t \widetilde{\mathbf{u}} + \tau_m^{-1} \widetilde{\mathbf{u}} = \mathcal{P} \mathbf{R}_m$$

$$\tau_c^{-1} \widetilde{p} = \mathcal{P} R_c$$

$$\mathcal{P} = I \quad \text{(ASGS)}, \qquad \mathcal{P} = \mathrm{P}_\mathrm{h}^\perp = \mathrm{I} - \mathrm{P}_\mathrm{h} \quad \text{(OSS)}$$

$$\mathbf{a} = \mathbf{u}_h + \widetilde{\mathbf{u}}$$

Semidiscrete problem

FEM equations

$$(\mathbf{v}_h, \partial_t \mathbf{u}_h)_\Omega + b(\mathbf{a}, \mathbf{u}_h, \mathbf{v}_h) + (\nabla \mathbf{v}_h, \nu \nabla \mathbf{u}_h)_\Omega - (\nabla \cdot \mathbf{v}_h, p_h)_\Omega$$
$$+ (\mathcal{L}^* \mathbf{v}_h, \widetilde{\mathbf{u}})_{\Omega^h} - (\nabla \cdot \mathbf{v}_h, \widetilde{p})_{\Omega^h} = \langle \mathbf{v}_h, \mathbf{f} \rangle_\Omega$$
$$(q_h, \nabla \cdot \mathbf{u}_h)_\Omega - (\nabla q_h, \widetilde{\mathbf{u}})_{\Omega^h} = 0$$

SGS equations

$$\tau_m^{-1} \widetilde{\mathbf{u}} = \mathcal{P} \mathbf{R}_m$$
$$\tau_c^{-1} \widetilde{p} = \mathcal{P} R_c$$

$$\mathcal{P} = \mathrm{P}_\mathrm{h}^\perp = \mathrm{I} - \mathrm{P}_\mathrm{h} \quad \text{(OSS)}$$

$$\mathbf{a} = \mathbf{u}_h$$

Term-by-term OSS

FEM equations

$$(\mathbf{v}_h, \partial_t \mathbf{u}_h)_\Omega + b\left(\mathbf{a}, \mathbf{u}_h, \mathbf{v}_h\right) + (\nabla \mathbf{v}_h, \nu \nabla \mathbf{u}_h)_\Omega - (\nabla \cdot \mathbf{v}_h, p_h)_\Omega$$
$$+ (\mathcal{L}^* \mathbf{v}_h, \widetilde{\mathbf{u}})_{\Omega^h} - (\nabla \cdot \mathbf{v}_h, \widetilde{p})_{\Omega^h} = \langle \mathbf{v}_h, \mathbf{f} \rangle_\Omega$$

$$(q_h, \nabla \cdot \mathbf{u}_h)_\Omega - (\nabla q_h, \widetilde{\mathbf{u}})_{\Omega^h} = 0$$

Term-by-term OSS

Term-by-term OSS (Codina 2008)

$$(\mathbf{v}_h, \partial_t \mathbf{u}_h)_\Omega + b\left(\mathbf{a}, \mathbf{u}_h, \mathbf{v}_h\right) + (\nabla \mathbf{v}_h, \nu \nabla \mathbf{u}_h)_\Omega - (\nabla \cdot \mathbf{v}_h, p_h)_\Omega$$

$$+ \left(\tau_m \mathbf{a} \cdot \nabla \mathbf{v}_h, \mathcal{P}_h^{\perp}(\mathbf{a} \cdot \nabla \mathbf{u}_h)\right)_{\Omega^h}$$

$$+ \left(\tau_c \nabla \cdot \mathbf{v}_h, \mathcal{P}_h^{\perp}(\nabla \cdot \mathbf{u}_h)\right)_{\Omega^h} = \langle \mathbf{v}_h, \mathbf{f} \rangle_\Omega$$

$$(q_h, \nabla \cdot \mathbf{u}_h)_\Omega + \left(\tau_m \nabla q_h, \mathcal{P}_h^{\perp}(\nabla p_h)\right)_{\Omega^h} = 0$$

Term-by-term OSS

Term-by-term OSS (Codina 2008)

$$(\mathbf{v}_h, \partial_t \mathbf{u}_h)_\Omega + b(\mathbf{a}, \mathbf{u}_h, \mathbf{v}_h) + (\nabla \mathbf{v}_h, \nu \nabla \mathbf{u}_h)_\Omega - (\nabla \cdot \mathbf{v}_h, p_h)_\Omega$$

$$+ (\tau_m \mathbf{a} \cdot \nabla \mathbf{v}_h, \mathbf{a} \cdot \nabla \mathbf{u}_h)_{\Omega^h} - (\tau_m \mathbf{a} \cdot \nabla \mathbf{v}_h, \boldsymbol{\eta}_h)_{\Omega^h}$$

$$+ (\tau_c \nabla \cdot \mathbf{v}_h, \nabla \cdot \mathbf{u}_h)_{\Omega^h} = \langle \mathbf{v}_h, \mathbf{f} \rangle_\Omega$$

$$(q_h, \nabla \cdot \mathbf{u}_h)_\Omega + (\tau_m \nabla q_h, \nabla p_h)_{\Omega^h} - (\tau_m \nabla q_h, \boldsymbol{\xi}_h)_{\Omega^h} = 0$$

$$\boldsymbol{\eta}_h := \mathcal{P}_h(\mathbf{a} \cdot \nabla \mathbf{u}_h)$$

$$\boldsymbol{\xi}_h := \mathcal{P}_h(\nabla p_h)$$

$$\mathcal{P}_h(\nabla \cdot \mathbf{u}_h) \approx 0$$

Matricial form

- ASGS:

$$\begin{bmatrix} M\dot{\mathbf{U}} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} K + C + A_\tau & G \\ D & L_\tau \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_u \\ \mathbf{0} \end{bmatrix},$$

Matricial form

- ASGS:

$$\begin{bmatrix} M\dot{\mathbf{U}} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} K + C + A_\tau & G \\ D & L_\tau \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_u \\ \mathbf{0} \end{bmatrix},$$

- Term-by-term OSS:

$$\begin{bmatrix} M\dot{\mathbf{U}} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} K + C + A_\tau & G & B_{\eta,\tau} & 0 \\ D & L_\tau & 0 & B_{\xi,\tau} \\ -B_{\eta,\tau}^T & 0 & M_{\eta,\tau} & 0 \\ 0 & -B_{\xi,\tau}^T & 0 & M_{\xi,\tau} \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \mathbf{P} \\ \boldsymbol{\Upsilon} \\ \boldsymbol{\Xi} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_u \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix},$$

Matricial form

- ASGS:

$$\begin{bmatrix} M\dot{\mathbf{U}} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} K + C + A_\tau & G \\ D & L_\tau \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \mathbf{P} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_u \\ \mathbf{0} \end{bmatrix},$$

- Term-by-term OSS:

$$\begin{bmatrix} M\dot{\mathbf{U}} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} K + C + A_\tau & G & B_{\eta,\tau} & 0 \\ D & L_\tau & 0 & B_{\xi,\tau} \\ -B^T_{\eta,\tau} & 0 & M_{\eta,\tau} & 0 \\ 0 & -B^T_{\xi,\tau} & 0 & M_{\xi,\tau} \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \mathbf{P} \\ \boldsymbol{\Upsilon} \\ \boldsymbol{\Xi} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_u \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix},$$

- Term-by-term OSS with Inf-sup stable elements (mixed FE):

$$\begin{bmatrix} M\dot{\mathbf{U}} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} K + C + A_\tau & G & B_\tau \\ D & 0 & 0 \\ -B^T_\tau & 0 & M_\tau \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \mathbf{P} \\ \boldsymbol{\Upsilon} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_u \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix},$$

Block-recursive preconditioning

General case:

$$\begin{bmatrix} M\dot{\mathbf{U}} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} K + C + A_\tau & G & B_{\eta,\tau} & 0 \\ D & L_\tau & 0 & B_{\xi,\tau} \\ -B^T_{\eta,\tau} & 0 & M_{\eta,\tau} & 0 \\ 0 & -B^T_{\xi,\tau} & 0 & M_{\xi,\tau} \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \mathbf{P} \\ \boldsymbol{\Upsilon} \\ \boldsymbol{\Xi} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_u \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix},$$

Block-recursive preconditioning

General case:

$$\left[\begin{array}{c} M\dot{\mathbf{U}} \\ \mathbf{0} \\ \hline \mathbf{0} \\ \mathbf{0} \end{array}\right] + \left[\begin{array}{cc|cc} K+C+A_\tau & G & B_{\eta,\tau} & 0 \\ D & L_\tau & 0 & B_{\xi,\tau} \\ \hline -B_{\eta,\tau}^T & 0 & M_{\eta,\tau} & 0 \\ 0 & -B_{\xi,\tau}^T & 0 & M_{\xi,\tau} \end{array}\right] \left[\begin{array}{c} \mathbf{U} \\ \mathbf{P} \\ \hline \boldsymbol{\Upsilon} \\ \boldsymbol{\Xi} \end{array}\right] = \left[\begin{array}{c} \mathbf{F}_u \\ \mathbf{0} \\ \hline \mathbf{0} \\ \mathbf{0} \end{array}\right],$$

Block-recursive preconditioning

General case:

$$\left[\begin{array}{c} M\dot{\mathbf{U}} \\ \mathbf{0} \\ \hline \mathbf{0} \\ \mathbf{0} \end{array}\right] + \left[\begin{array}{cc|cc} K + C + A_\tau & G & B_{\eta,\tau} & 0 \\ D & L_\tau & 0 & B_{\xi,\tau} \\ \hline -B_{\eta,\tau}^T & 0 & M_{\eta,\tau} & 0 \\ 0 & -B_{\xi,\tau}^T & 0 & M_{\xi,\tau} \end{array}\right] \left[\begin{array}{c} \mathbf{U} \\ \mathbf{P} \\ \hline \boldsymbol{\Upsilon} \\ \boldsymbol{\Xi} \end{array}\right] = \left[\begin{array}{c} \mathbf{F}_u \\ \mathbf{0} \\ \hline \mathbf{0} \\ \mathbf{0} \end{array}\right],$$

- Outer block matrix:

$$\tilde{A} = \left[\begin{array}{cc|cc} M_{\eta,\tau} & 0 & -B_{\eta,\tau}^T & 0 \\ 0 & M_{\xi,\tau} & 0 & -B_{\xi,\tau}^T \\ \hline B_{\eta,\tau} & 0 & K + C + A_\tau & G \\ 0 & B_{\xi,\tau} & D & L_\tau \end{array}\right]$$

Block-recursive preconditioning

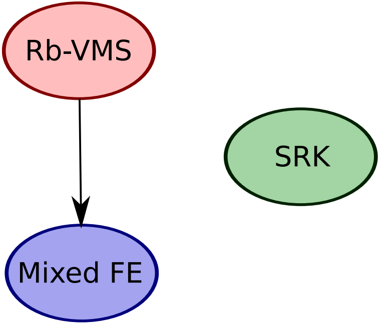
General case:

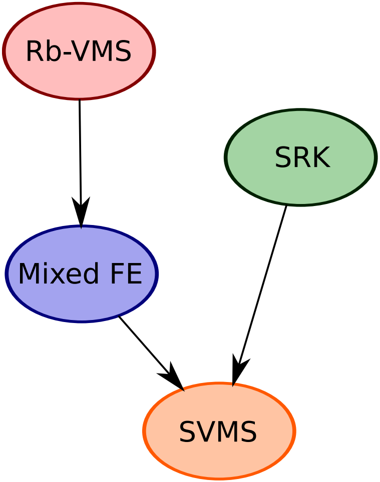
$$\left[\begin{array}{c} M\dot{\mathbf{U}} \\ \mathbf{0} \\ \hline \mathbf{0} \\ \mathbf{0} \end{array}\right] + \left[\begin{array}{cc|cc} K+C+A_\tau & G & B_{\eta,\tau} & 0 \\ D & L_\tau & 0 & B_{\xi,\tau} \\ \hline -B_{\eta,\tau}^T & 0 & M_{\eta,\tau} & 0 \\ 0 & -B_{\xi,\tau}^T & 0 & M_{\xi,\tau} \end{array}\right] \left[\begin{array}{c} \mathbf{U} \\ \mathbf{P} \\ \hline \boldsymbol{\Upsilon} \\ \boldsymbol{\Xi} \end{array}\right] = \left[\begin{array}{c} \mathbf{F}_u \\ \mathbf{0} \\ \hline \mathbf{0} \\ \mathbf{0} \end{array}\right],$$

- Outer block matrix:

$$\tilde{A} = \begin{bmatrix} \tilde{M}_\tau & -\tilde{B}_\tau^T \\ \tilde{B}_\tau & \tilde{K} \end{bmatrix} = LUdecomposition...S = ...$$

$$P(\tilde{A}) = ... \begin{bmatrix} \tilde{M}_\tau & -\tilde{B}_\tau^T \\ \tilde{B}_\tau & \tilde{K} \end{bmatrix}, S \approx ...$$


Rb-VMS
SRK
Mixed FE


Rb-VMS
SRK
Mixed FE
SVMS

Outline

- Line 1.

Outline

- Line 1.
- Line 2.
  Less formal

Outline

- Line 1.
- Line 2.
  Less formal
- Line 3.
  Less formal, different color.

Blocks

Standard Block

This is a standard block.

Example Block

This is an example block.

Alert Block

This is an alert block.

Questions?