FLOWHEAD

Adjoint Spalart Allmaras

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S.A. Adjoint Turbulence Model

- No Frozen turbulence assumption $\frac{\partial \nu_t}{\partial b_m} \neq 0$

- Adjoint S.A.

  – Adjoint continuity stays the same

$$\frac{\partial u_j}{\partial x_j} = -\frac{\partial F_\Omega}{\partial p}$$

  – New term in the adjoint momentum equations

$$-v_j\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{\partial}{\partial x_j}\left[(\nu+\nu_t)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+\frac{\partial q}{\partial x_i}-\widetilde{\nu}\frac{\partial \widetilde{\nu}_a}{\partial x_i}-\frac{\partial}{\partial x_l}\left(e_{jli}e_{jmq}\frac{\mathcal{C}_S}{S}\frac{\partial v_q}{\partial x_m}\widetilde{\nu}\widetilde{\nu}_a\right)=-\frac{\partial F_\Omega}{\partial v_i}$$

  – New equation for adjoint turbulence

$$\frac{\partial \widetilde{\nu}_a}{\partial x_j}v_j + \frac{\partial}{\partial x_j}\left[\left(\nu+\frac{\widetilde{\nu}}{\sigma}\right)\frac{\partial \widetilde{\nu}_a}{\partial x_j}\right] = \frac{1}{\sigma}\frac{\partial \widetilde{\nu}_a}{\partial x_j}\frac{\partial \widetilde{\nu}}{\partial x_j} + 2\frac{c_{b2}}{\sigma}\frac{\partial}{\partial x_j}\left(\widetilde{\nu}_a\frac{\partial \widetilde{\nu}}{\partial x_j}\right) + \widetilde{\nu}_a\widetilde{\nu}\mathcal{C}_{\widetilde{\nu}}(\widetilde{\nu},\vec{v})$$
$$+\frac{\delta \nu_t}{\delta \widetilde{\nu}}\frac{\partial u_i}{\partial x_j}\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}\right) + (-P+D)\,\widetilde{\nu}_a + \frac{\partial F_\Omega}{\partial \widetilde{\nu}}$$

S.A. Adjoint B.C.

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B.C. At Inlet

$$u_{\langle n\rangle} = -\frac{\partial F_{S_I}}{\partial p} \quad , \qquad \mathbf{u}_{\langle t\rangle} = 0 \quad , \qquad \tilde{\nu_a} = 0$$

B.C. At Outlet

– Adjoint pressure

$$q = u_j v_j + u_{\langle n\rangle} v_{\langle n\rangle} + (\nu + \nu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) n_j n_i + \underbrace{\tilde{\nu}_a \tilde{\nu} + \tilde{\nu}_a \tilde{\nu} \frac{C_S}{S} e_{jmq} e_{jli} \frac{\partial v_q}{\partial x_m} n_l n_i} + \frac{\partial F_{S_O}}{\partial v_{\langle n\rangle}}$$

– Adjoint velocity

$$0 = \mathbf{u}_{\langle t\rangle} v_{\langle n\rangle} + (\nu + \nu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) n_j t_i + \underbrace{\tilde{\nu}_a \tilde{\nu} \frac{C_S}{S} e_{jmq} e_{jli} \frac{\partial v_q}{\partial x_m} n_l t_i} + \frac{\partial F_{S_O}}{\partial \mathbf{v}_{\langle t\rangle}}$$

– Adjoint turbulence field

$$0 = -\frac{\delta \nu_t}{\delta \tilde{\nu}} u_i \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) n_j + \tilde{\nu}_a v_j n_j + \left(\nu + \frac{\tilde{\nu}}{\sigma}\right) \frac{\partial \tilde{\nu}_a}{\partial x_j} n_j + \frac{\partial F_{S_O}}{\partial \tilde{\nu}}$$

B.C. At Walls

$$u_{\langle n\rangle} = -\frac{\partial F_{S_W}}{\partial p} \quad , \qquad \mathbf{u}_{\langle t\rangle} = 0 \quad , \qquad \tilde{\nu_a} = 0$$

S.A. Adjoint Sensitivity

- Sensitivity calculation

$$\frac{\delta J}{\delta b_n} = -\int_{\Gamma_W}\left[\nu\frac{\partial u_i}{\partial x_j}n_j - q n_i\right]\frac{\partial v_i}{\partial x_k}\frac{\delta x_k}{\delta b_n}d\Gamma \underbrace{-\int_{\Gamma_W}\nu\frac{\partial\widetilde{\nu_a}}{\partial x_j}n_j\frac{\partial\widetilde{\nu}}{\partial x_k}\frac{\delta x_k}{\delta b_n}d\Gamma + \int_{\Omega}\widetilde{\nu_a}\widetilde{\nu}\,\mathcal{C}_d(\widetilde{\nu},\vec{v})\frac{\partial d}{\partial b_n}d\Omega}$$

- Out of all the terms which have been shown to be negligible, this term is the most costly.

Zymaris A, Papadimitriou D, Giannakoglou K., Othmer C. Continuous Adjoint Approach to the Spalart-Allmaras Turbulence Model for Incompressible Flows. *Computers & Fluids*, 38(8):1528–1538, 2009.

S.A. Adjoint Validation

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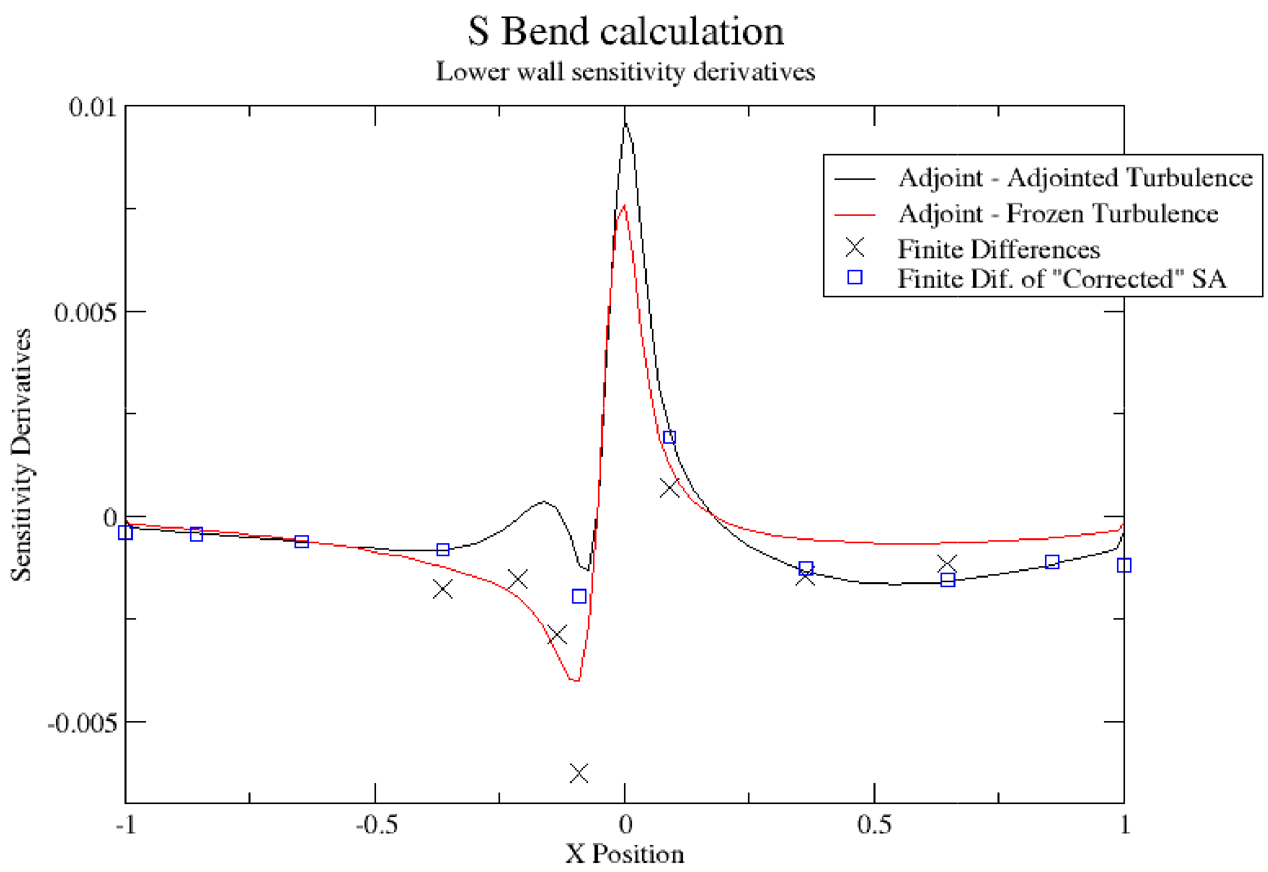
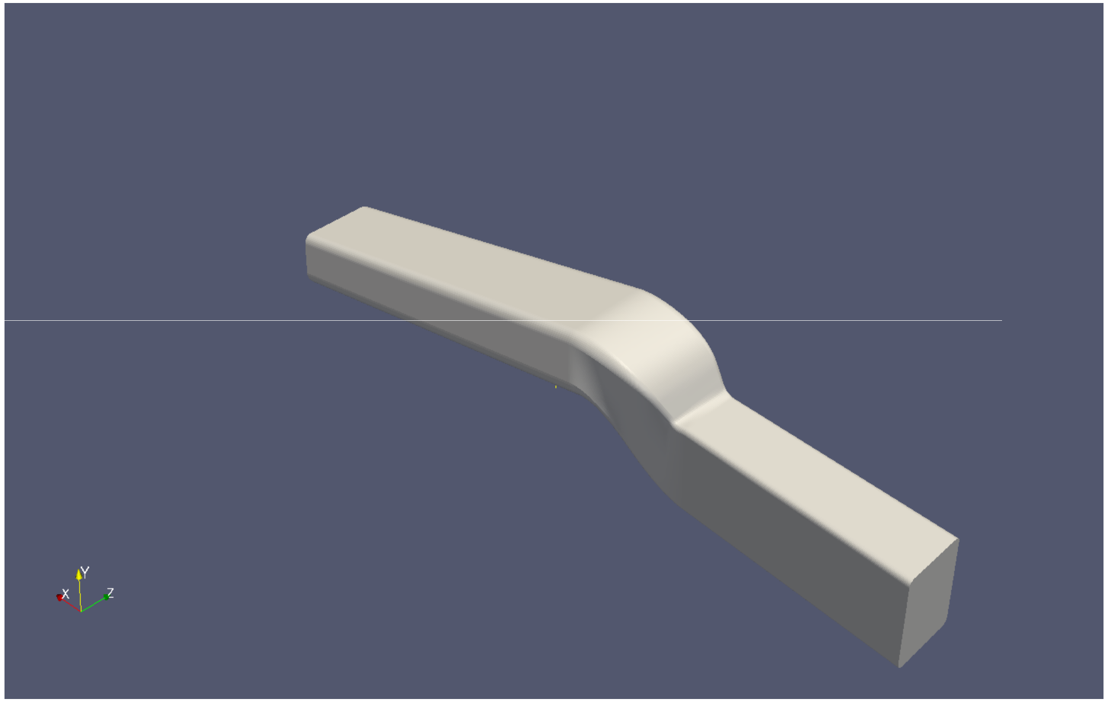


- Validation is tedious through finite differencing.
- Slight modification to the primal SA to obtain “correct” F.D.
- Wrongly signed derivatives with frozen turbulence !

S.A. Adjoint Turbulence Model



- Elongated S-Bend Duct case
- 2 million cells
- Y+ < 1 everywhere
- Re = 16000
- Power Dissipation Objective

S.A. Adjoint Turbulence Model

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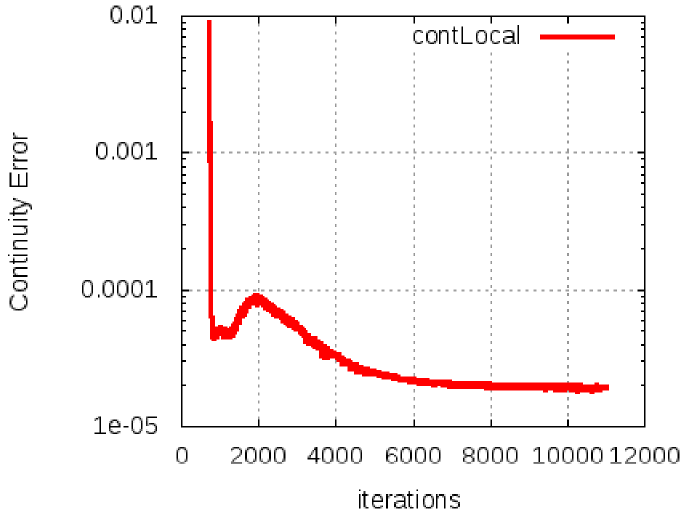
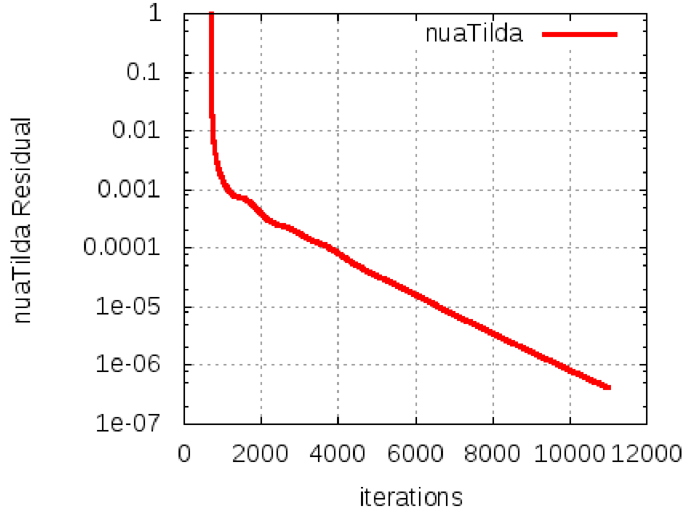
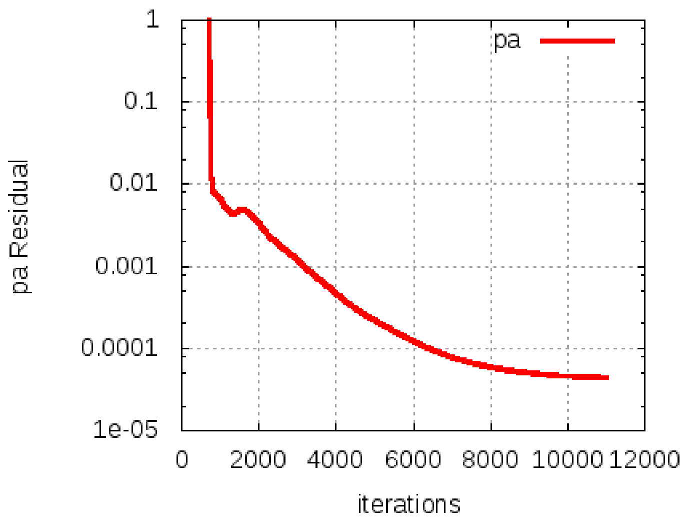
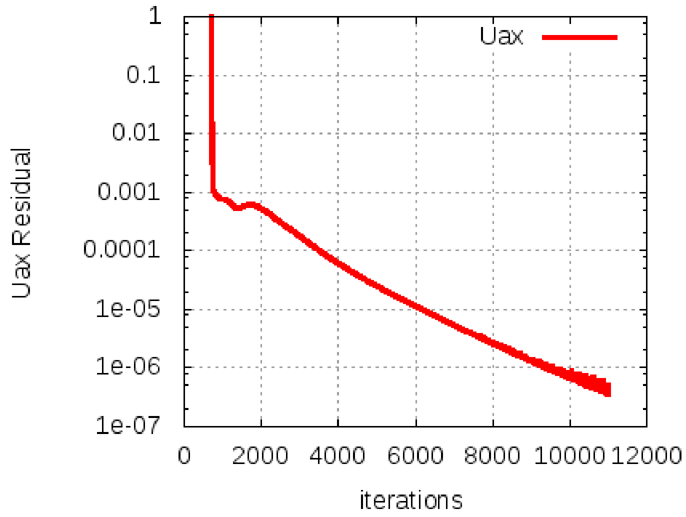
- Good Convergence Obtained – Not without any effort !









S.A. Adjoint Turbulence Model

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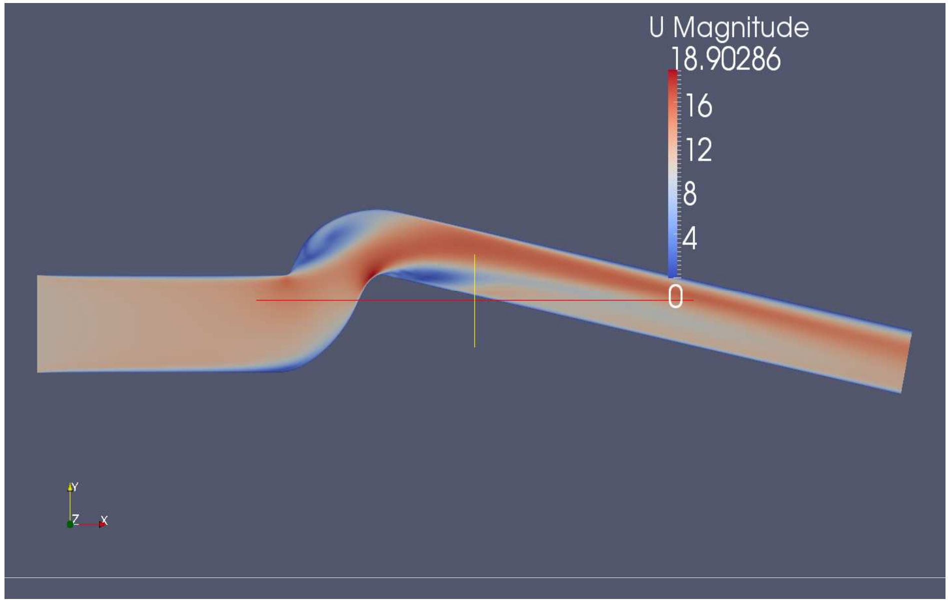

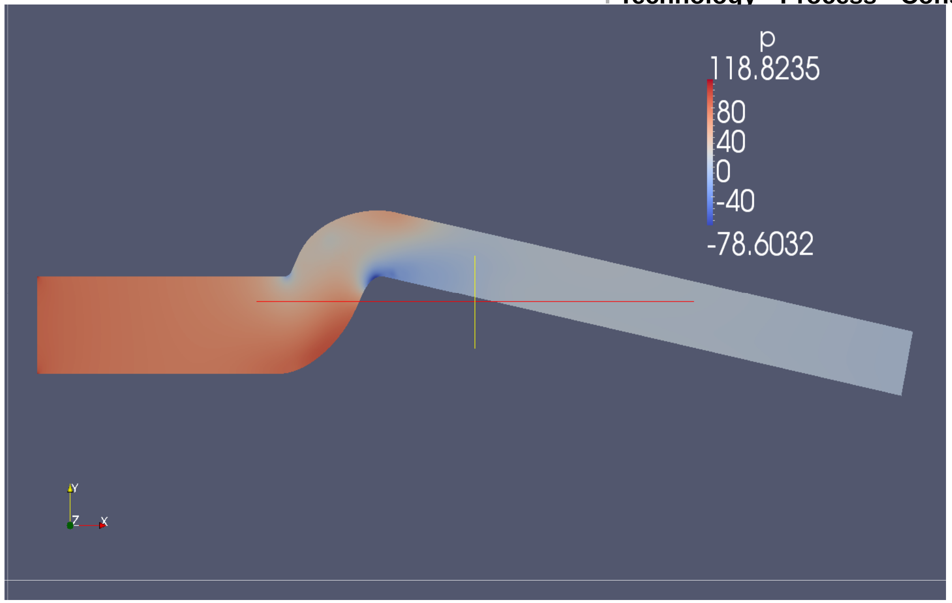

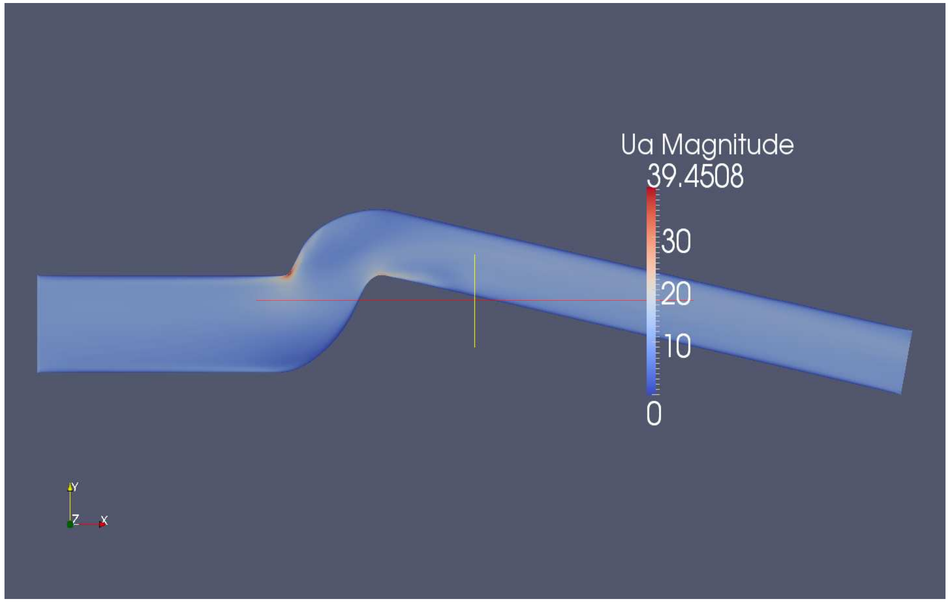

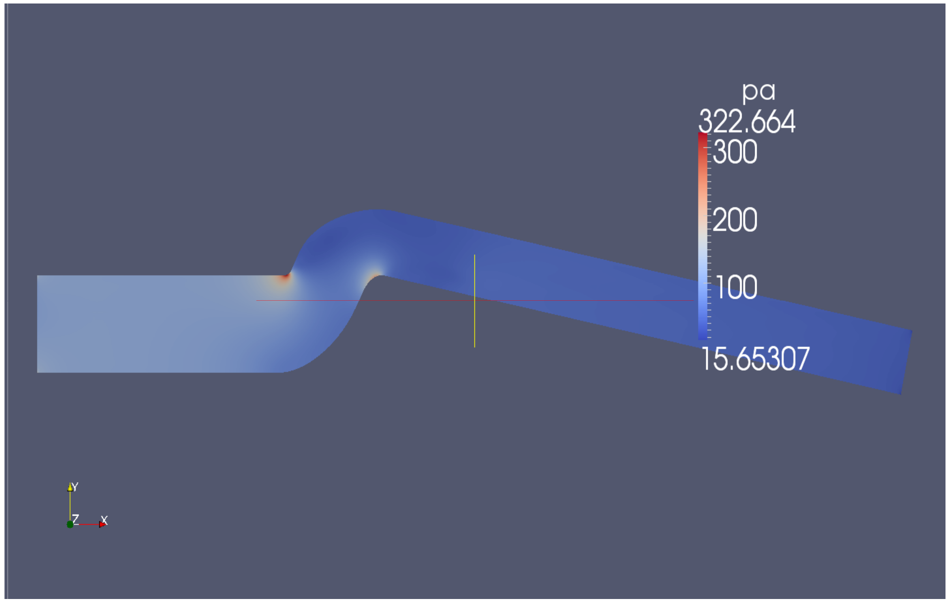

S.A. Adjoint Turbulence Model

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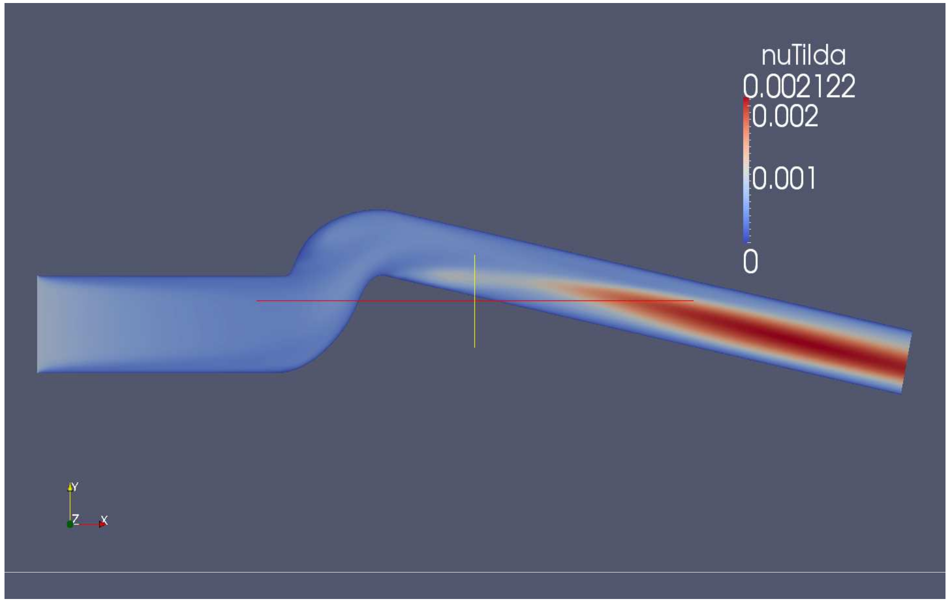

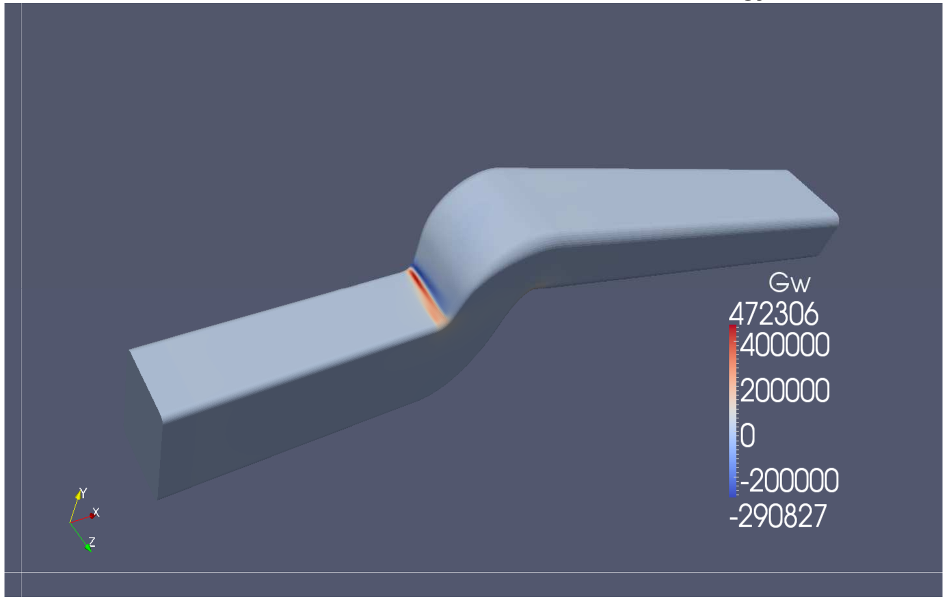

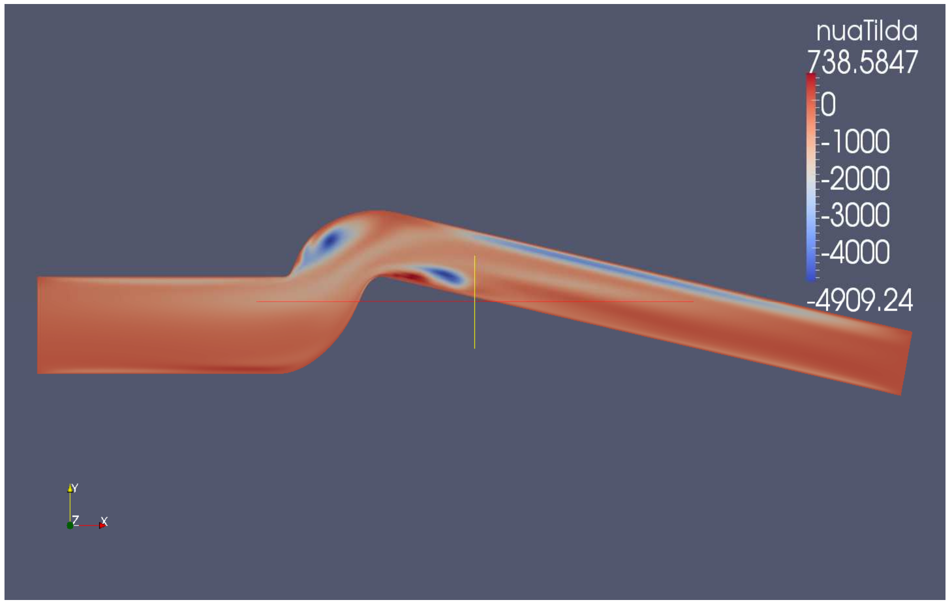

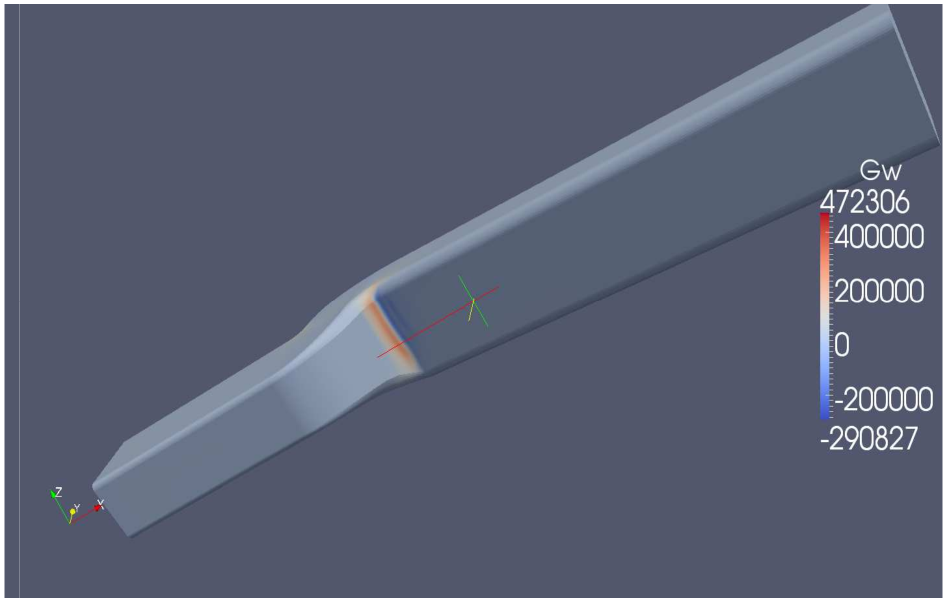

Adjoint Turbulence Model Usage

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```
adjointTurbulenceModel adjointSpalartAllmaras;
turbulence      on;
adjointLaminarCoeffs
{
}
adjointSpalartAllmarasCoeffs
{
    alphaNut        alphaNut [0 0 0 0 0 0 0] 1.5;
    Cb1             Cb1 [0 0 0 0 0 0 0] 0.1355;
    Cb2             Cb2 [0 0 0 0 0 0 0] 0.622;
    Cw2             Cw2 [0 0 0 0 0 0 0] 0.3;
    Cw3             Cw3 [0 0 0 0 0 0 0] 2;
    Cv1             Cv1 [0 0 0 0 0 0 0] 7.1;
    Cv2             Cv2 [0 0 0 0 0 0 0] 5.0;
}
```

```
dimensions      [0 0 -1 0 0 0 0];
internalField   uniform 0;
boundaryField
{
    inlet
    {
        type            fixedValue;
        value           uniform 0;
    }
    outlet
    {
        type            adjointOutletNuaTilda;
        value           uniform 0;
    }
    wall
    {
        type            fixedValue;
        value           uniform 0;
    }
}
```

- Additional equation and B.C. for nuaTilda.
- Additional terms in the adjoint momentum equation.
- Adjoint pressure equation and B.C. are unaffected.
- Adjoint SA model activated through constant/adjointTurbulenceProperties file.

External Aero case

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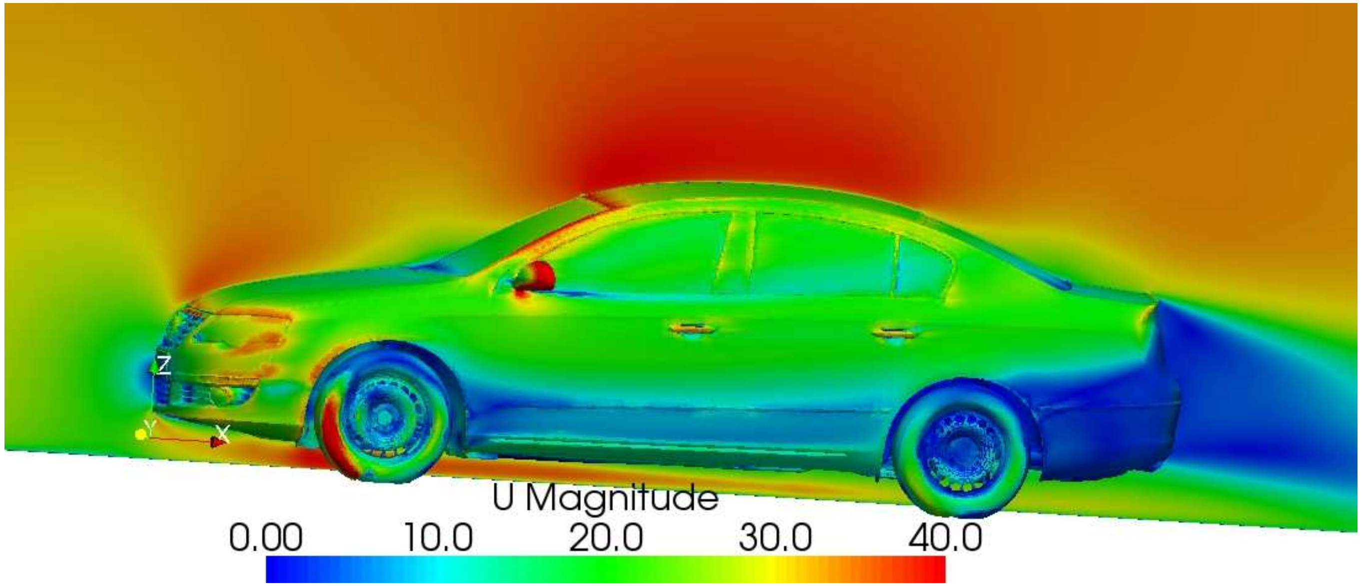
- B6 test case
- Steady RANS calculation
- foamProMesh:~5m cells – 3 surface layers (less than normal)
- Surface mesh was priority!



External Aero case

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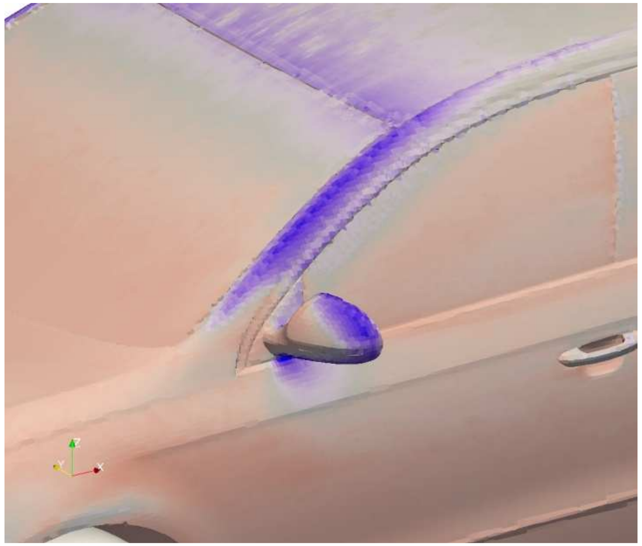
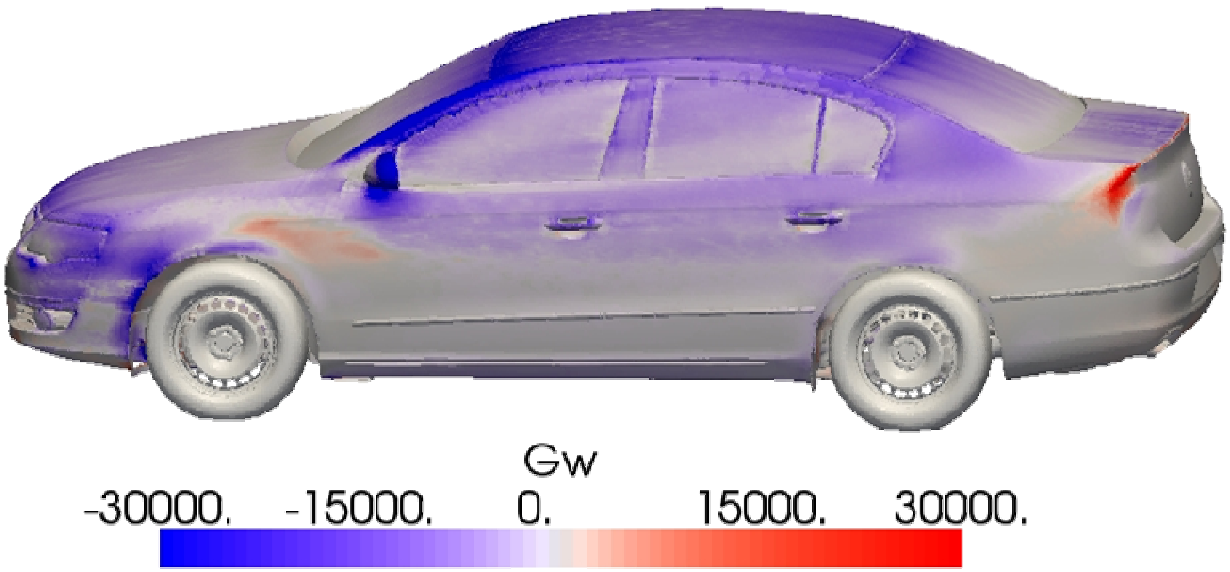
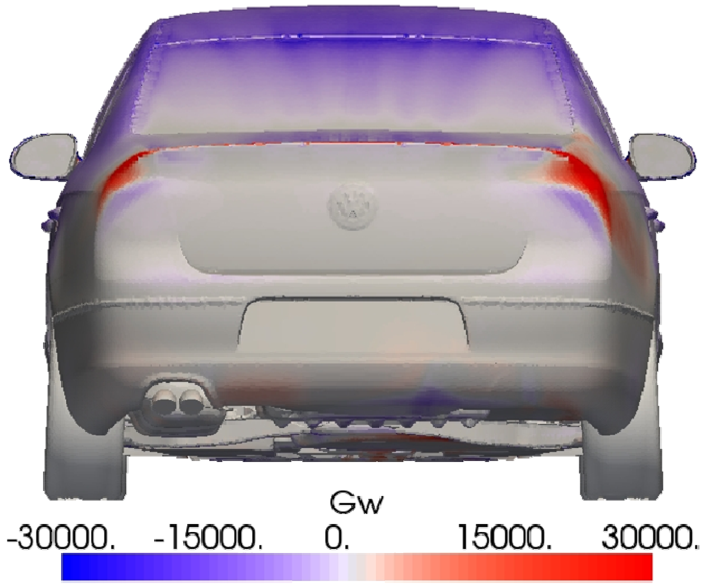


- Surface sensitivities for Drag minimisation
- Special interest in the rear of the car and the mirror
- Why Not S.A. Adjoint ?





New Objective Function

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- In general the obvious cost function to directly optimise wrt turbulence is

$$J = \int_V k dV$$

- However, the Spalart-Allmaras model was chosen for adjointing because of its (relative!) simplicity. This doesn't give *k* directly.

- Adjoint of k-epsilon model is one of the next steps

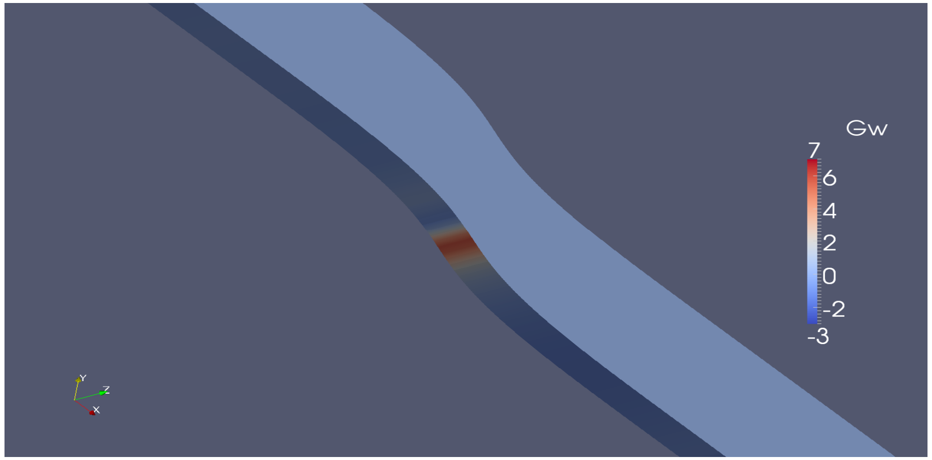
Turbulence based cost function

- We needed to construct a suitable equivalent.
- The only turbulence information directly available is $\tilde{\nu}$, which we need to drive towards zero
- So the obvious cost function is $\int_V C\tilde{\nu}^2 dV$ where C is an arbitrary constant scaling factor
- In practice we defined $C = 1/d^2$ where d is interpreted as a turbulence length scale.
- This gives us dimensional consistency with the original idea of using turbulent kinetic energy.

Turbulence based cost function

```
SIMPLE
{
    nNonOrthogonalCorrectors 0;
    solvePrimal     yes;
    solveAdjoint    no;
    adjointTurbulence yes;
            …
    turbEnergyOptimisation yes;
    turbEnergyLengthScale 0.001;
}
```

- 2 Additional options in the system/fvSolution file



- Example of sensitivity field obtained using this cost function.

Turbulence based cost function

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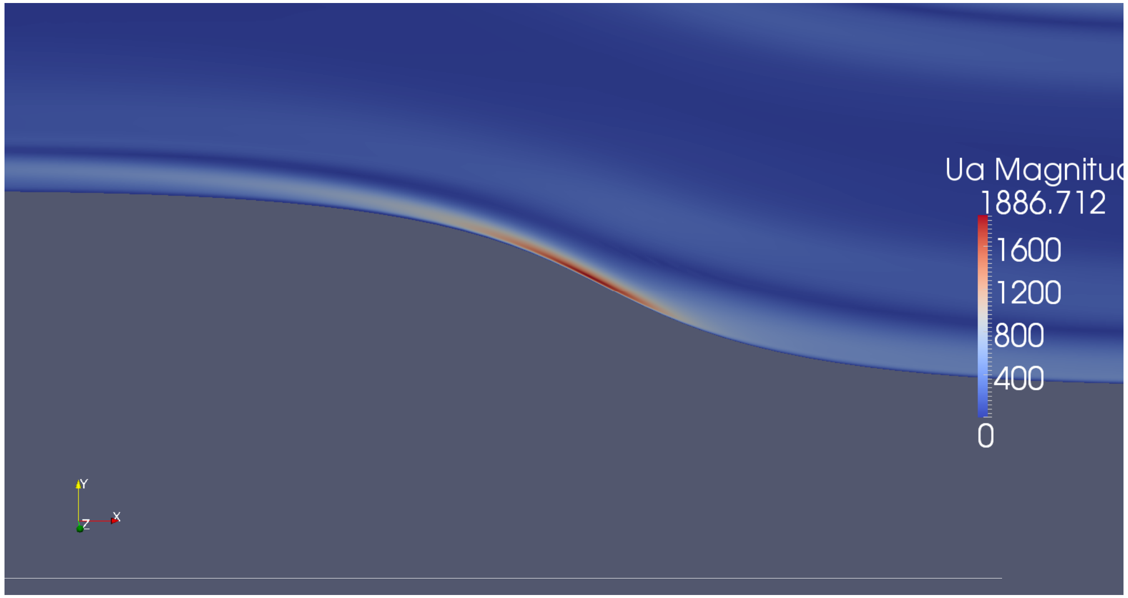
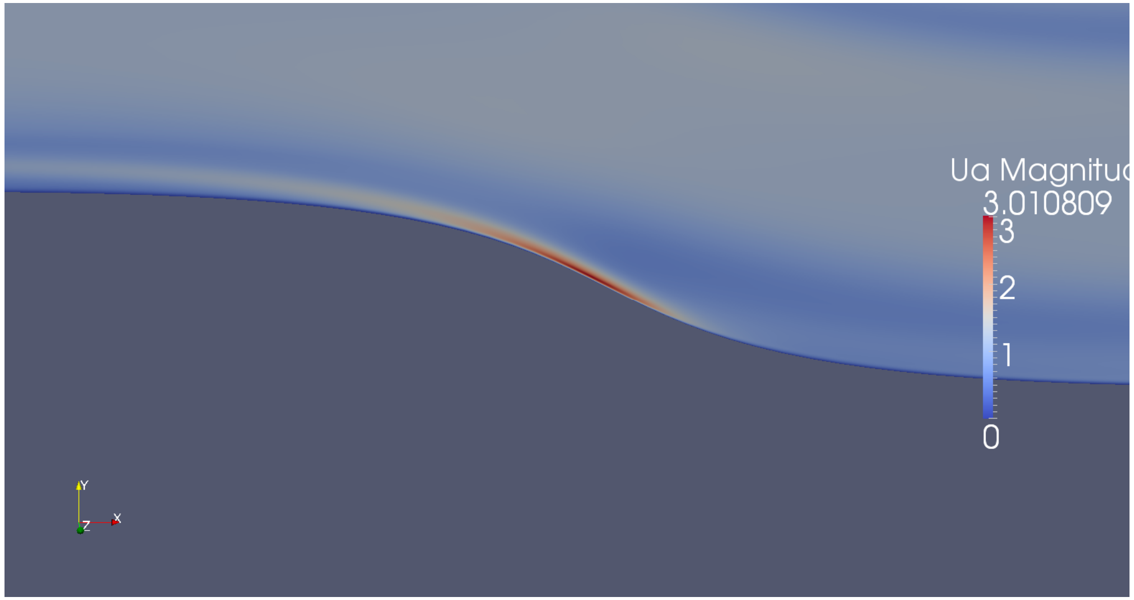


- Turbulence Cost Function



- Power Dissipation Cost Function

Summary

- Low-Re Adjoint S.A. Implemented
  - High constraints on mesh quality

- New Cost function for turbulence minimization

- Requirement for High-Re adjoint turbulence model

For any information or inquiry please contact:

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Special thank you to NTUA

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