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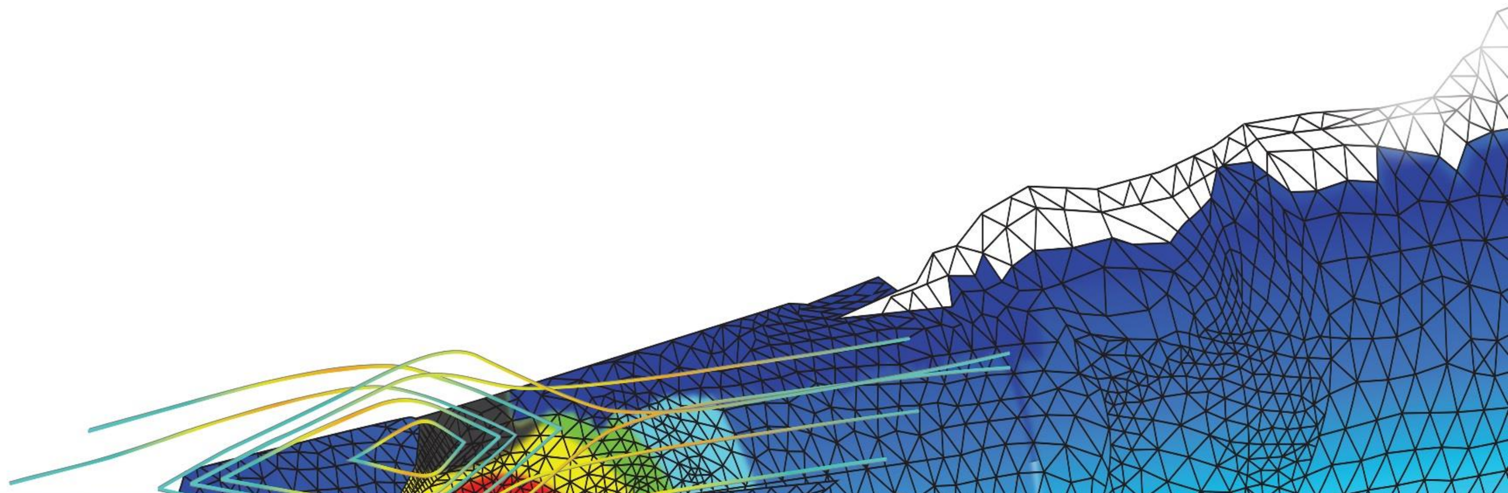
Tools for eddy detection in ANSYS CFD-Post



v1.0

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10/2017

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Description: Detecting vortices

In unsteady calculations, the motion of turbulent eddies is important to characterize the flow dynamics.
SRS calculations solve the motion of eddies in the core flow using a LES approach and revert to RANS approach in the near-wall region.

→ ANSYS CFD-Post 18.2 allows to detect flow eddies using different criteria:

1. Vorticity
2. Helicity
3. Q criterion
4. λ_2 criterion ***NEW IN ANSYS CFD-POST 18.2!**
5. Swirling strength

Main challenge for such methods is to correctly identify vortex cores.

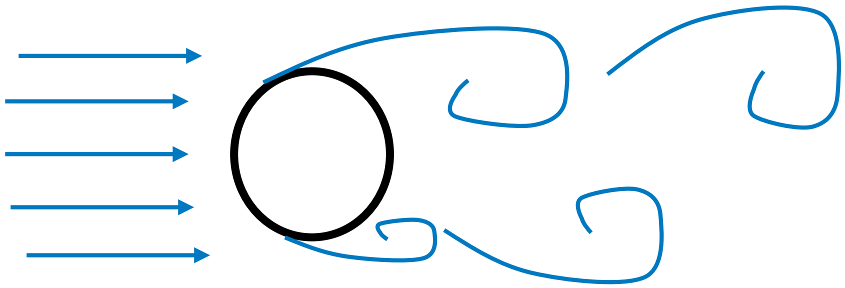
→ Solution 2052121 shows a brief comparison of these criteria performances when detecting eddies in the cylinder wake flow.

Test case

Cylinder
Turbulent wake flow
Re_{Diam} ~ 20 000

Structured grid
12 million hexaedra
Max Y+ = 0.19

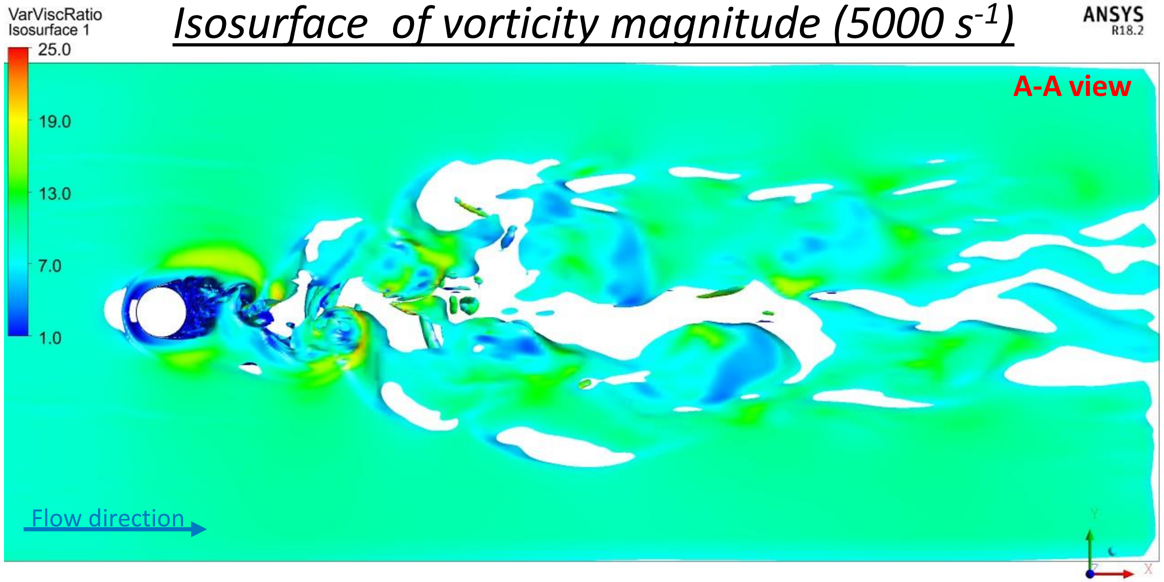
Air at ambiant pressure/temperature
Inlet flow velocity = 15 m/s

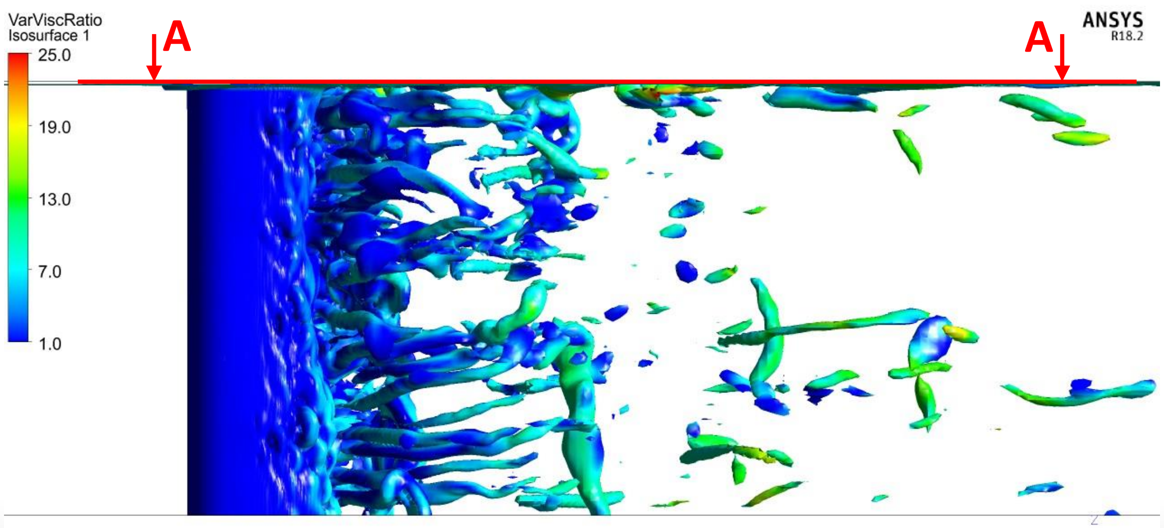


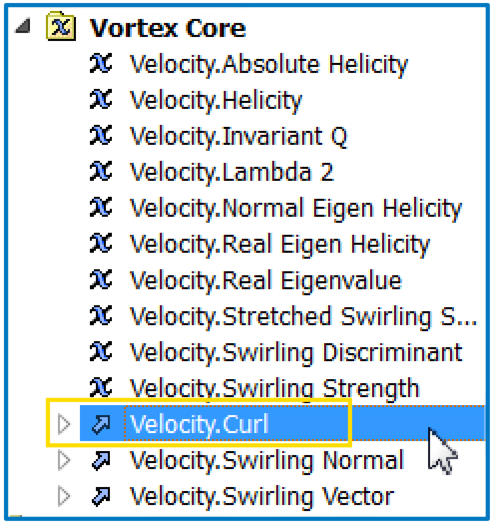
Unsteady calculation
SRS: SBES
Gradient: Green-Gauss Node-Based
2nd order accuracy (space/time)
Mean CFL = 0.3

1.a Vorticity magnitude

Isosurface of vorticity magnitude (5000 s^{-1})







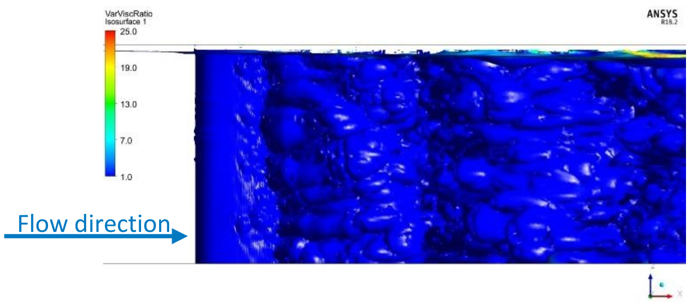
For 3D flow, vorticity (curl) is a vector with 3 components based on transverse velocity gradients:

$$\vec{\omega} = \nabla \times \vec{v} = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) \times (v_x, v_y, v_z)$$
$$= \left(\frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z}, \frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}, \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right)$$

Vorticity allows to quantify how the velocity vector changes when one moves away from the local volume in perpendicular direction.

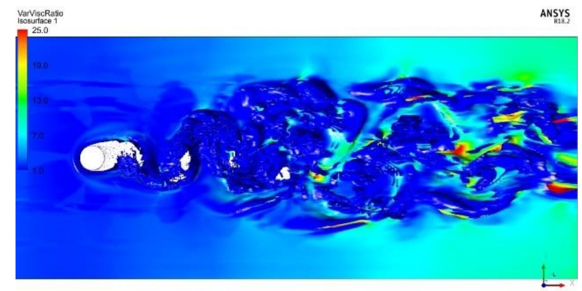
→ Note high values of vorticity near walls: wall shear stress is also detected!

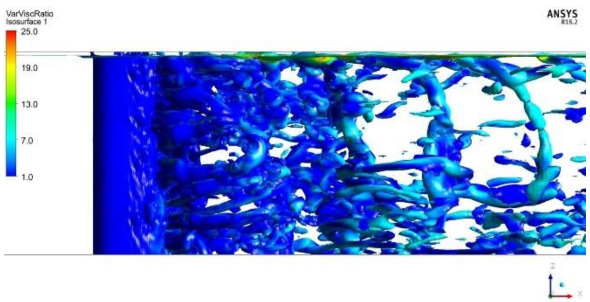
1.a Vorticity magnitude - Influence of value



$\Omega_0 = 500\ s^{-1}$

0.1% of max

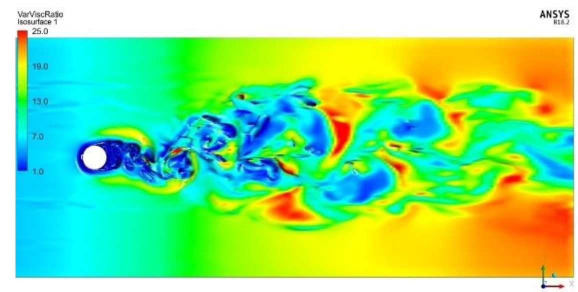


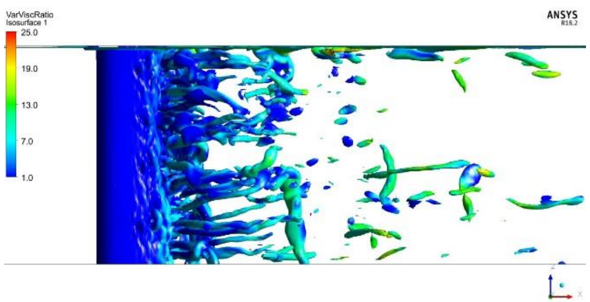


Ω_0x5

$\Omega = 2500\ s^{-1}$

0.5% of max

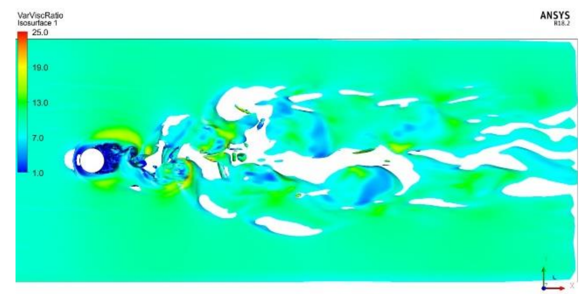




Ω_0x10

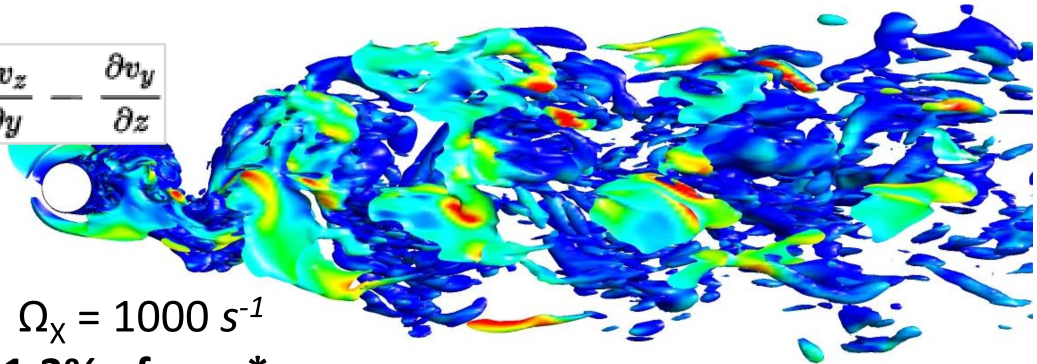
$\Omega = 5000\ s^{-1}$

1% of max



1.b Vorticity components

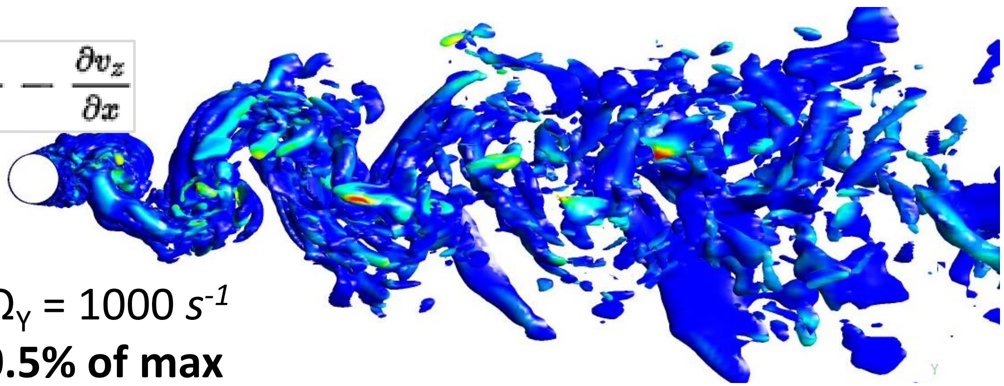
$$\frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z}$$



$\Omega_X = 1000\ s^{-1}$

1.3% of max*

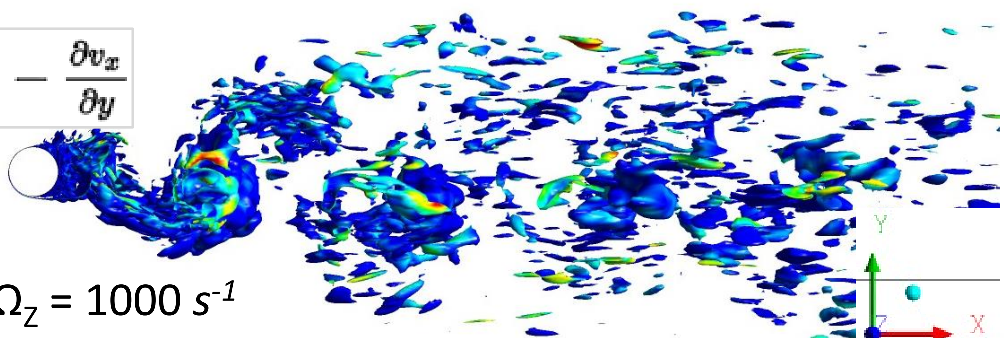
$$\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}$$



$\Omega_Y = 1000\ s^{-1}$

0.5% of max

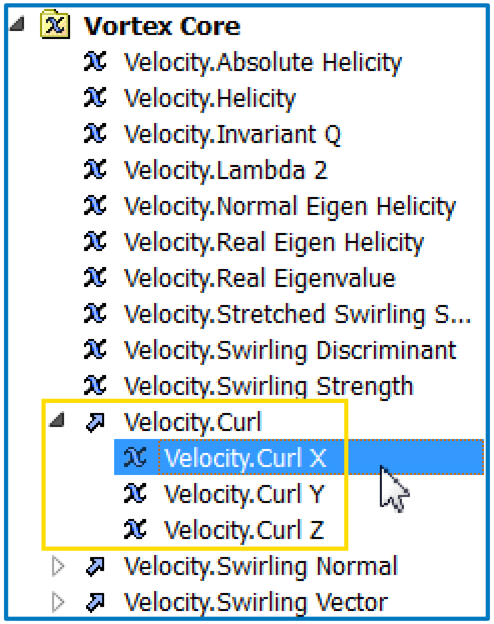
$$\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}$$



$\Omega_Z = 1000\ s^{-1}$

0.3% of max

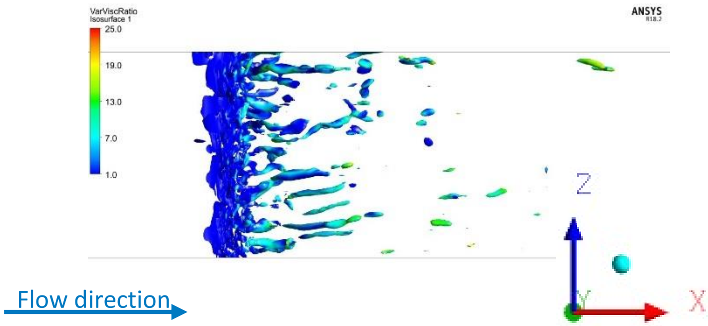
*max of each vorticity component



Vorticity components allow to identify vortices that are created along the different directions of the flow.

Maximum of each vorticity component is also different, confirming the anisotropic nature of the flow eddies.

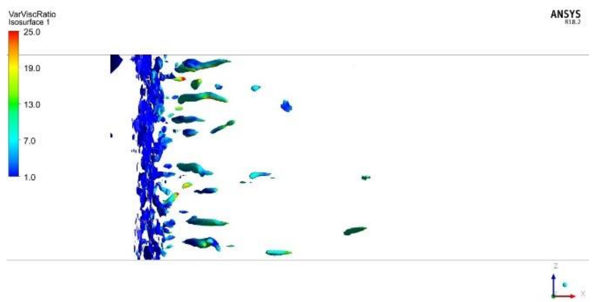
1.b Vorticity components



$$\frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z}$$

$\Omega_X = 5000\ s^{-1}$

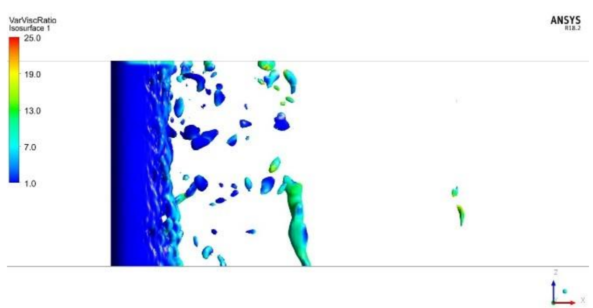
6.3% of max*



$$\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}$$

$\Omega_Y = 5000\ s^{-1}$

2.7% of max



$$\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}$$

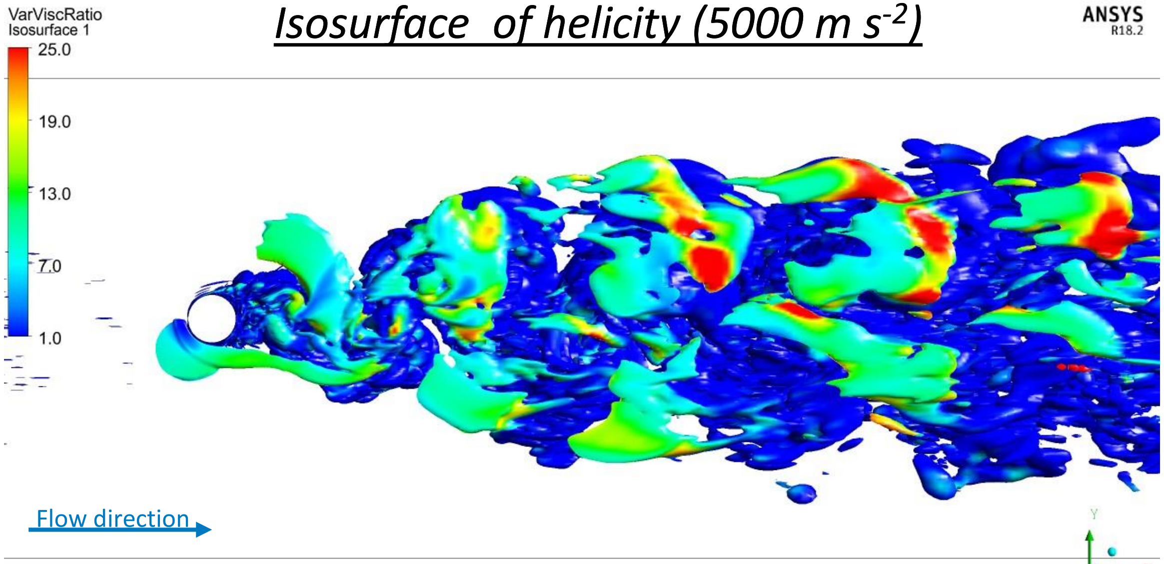
$\Omega_Z = 5000\ s^{-1}$

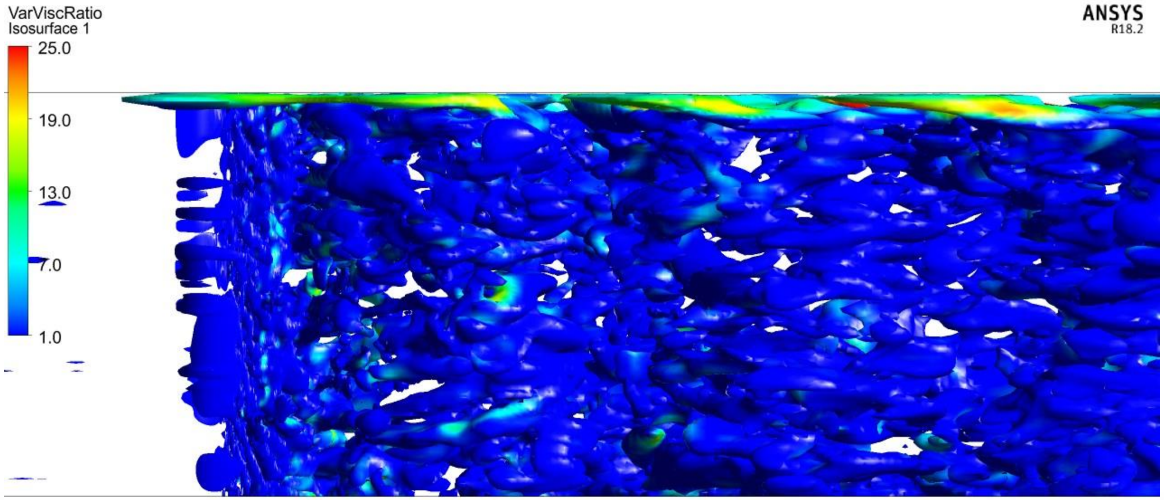
1.5% of max

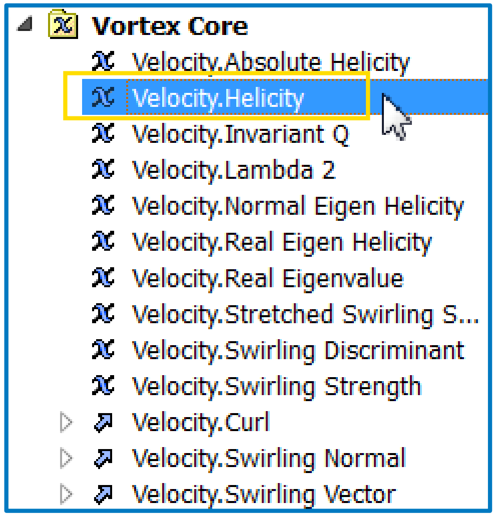
*max of each vorticity component

2. Helicity

Isosurface of helicity (5000 m s^{-2})







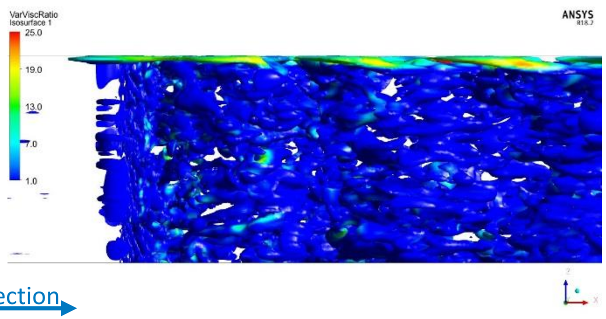
Helicity is a scalar that is the dot product between vorticity and velocity :

$$h = \vec{\omega} \cdot \vec{v}$$

Helicity allows to quantify how the vorticity vector is transported by the velocity field.

Thus, helicity is influenced by the velocity field. A vortex having a non-zero axial velocity is characterized by a non-zero helicity: such vortex is detected as a *helical* structure.

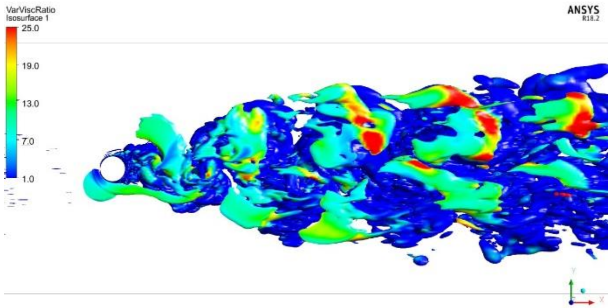
2. Helicity - Influence of value on detection

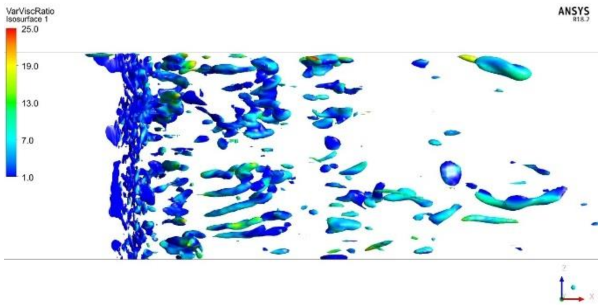


Flow direction

$H_0 = 5000\ m\ s^{-2}$

1% of max

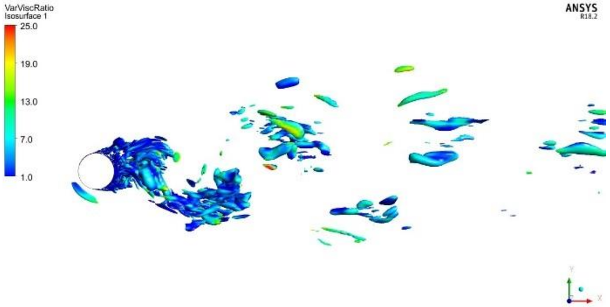




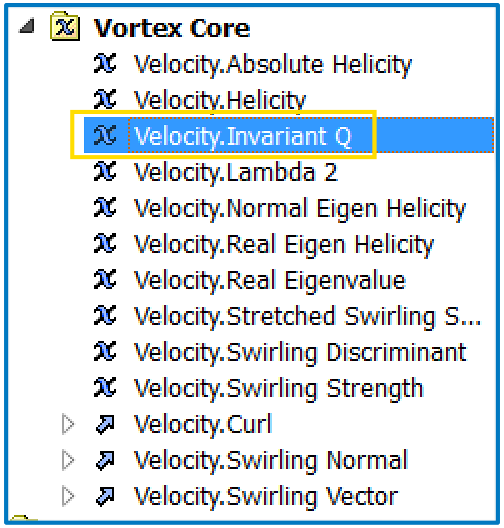
H_0x10

$H = 50000\ m\ s^{-2}$

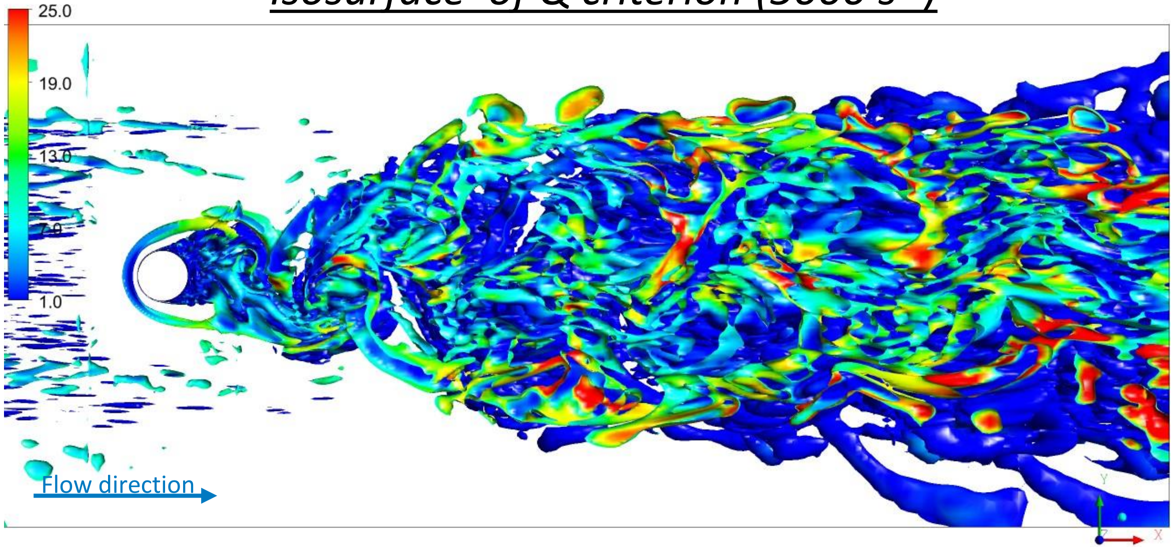
10% of max

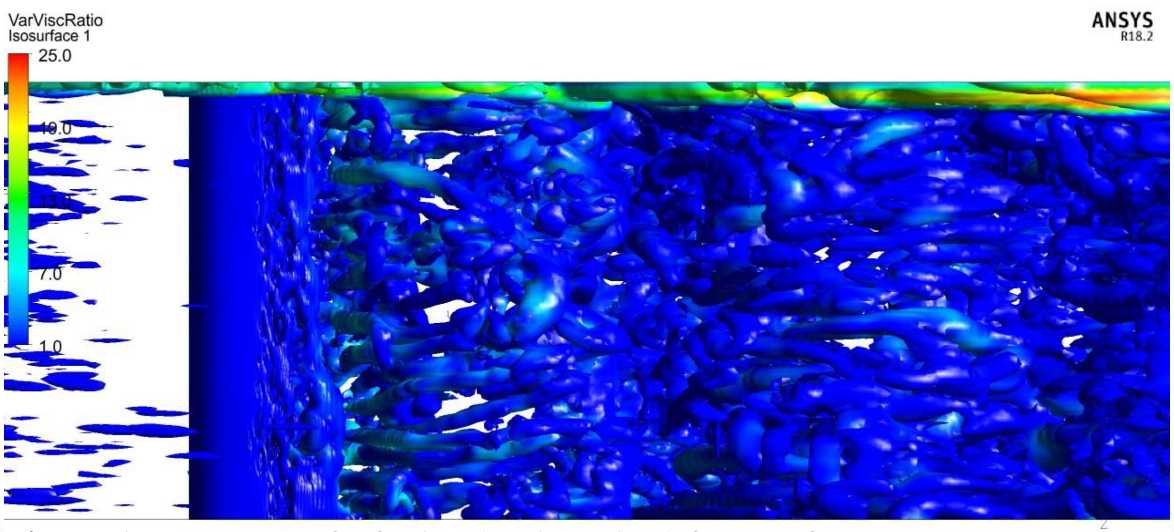


3. Q criterion



Isosurface of Q criterion (5000 s^{-2})





Q criterion* is a scalar that calculates the difference between the squares of rotation rate and strain rate:

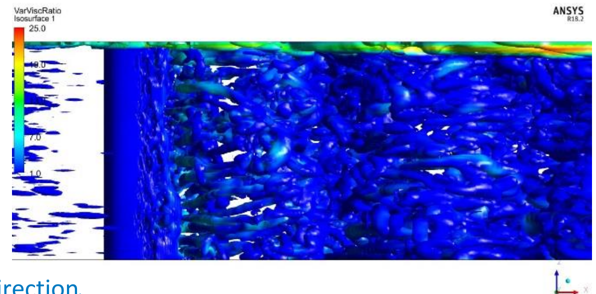
$$Q = \frac{1}{2} * (\Omega^2 - S^2)$$

Q > 0 corresponds to $\Omega^2 > S^2$ and is usually set as the detection threshold for turbulent eddies. A condition on pressure is added.

Besides, Q criterion involves the products of spatial velocity derivatives compared to previous methods 1 and 2, which allows the detection of finer structures.

*See solution **2041496** for further details on the definition of Q criterion.

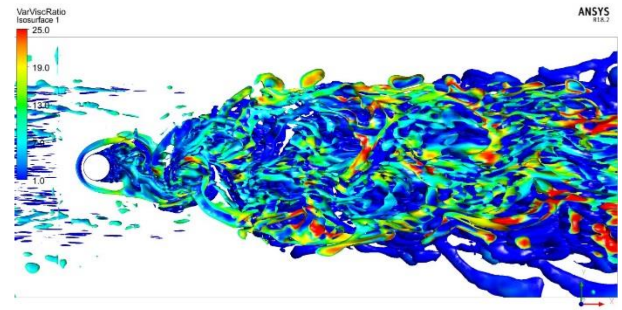
3. Q criterion - Influence of value on detection

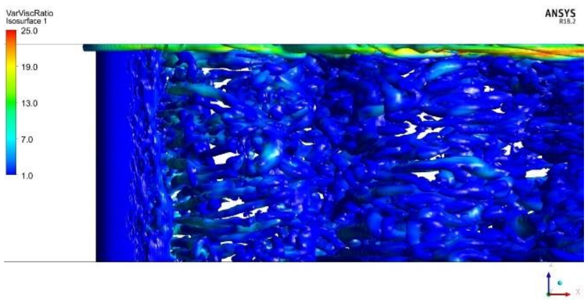


Flow direction

$Q_0 = 5000\ s^{-1}$

0.0005% of max

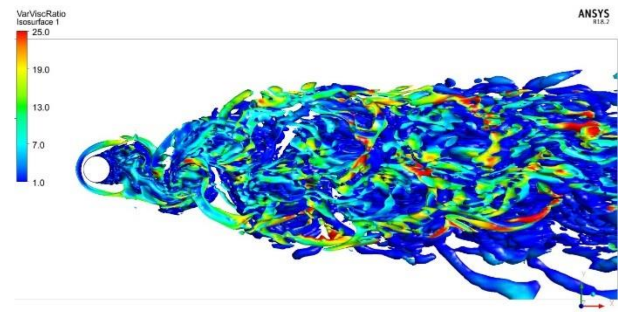




Q_0x10

$Q = 50000\ s^{-1}$

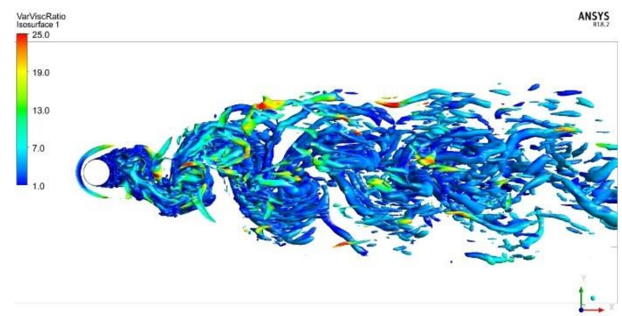
0.005% of max



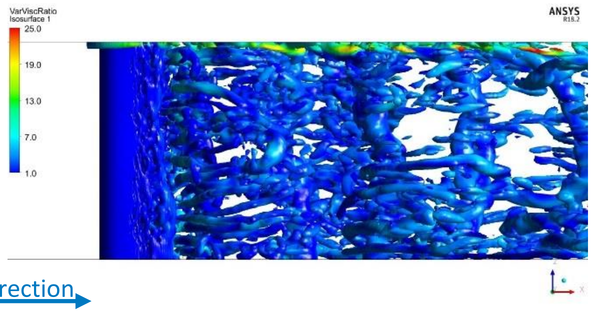
Q_0x100

$Q = 500000\ s^{-1}$

0.05% of max



3. Q criterion - Influence of value on detection

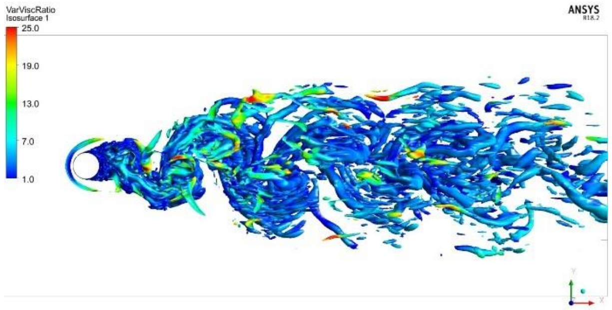


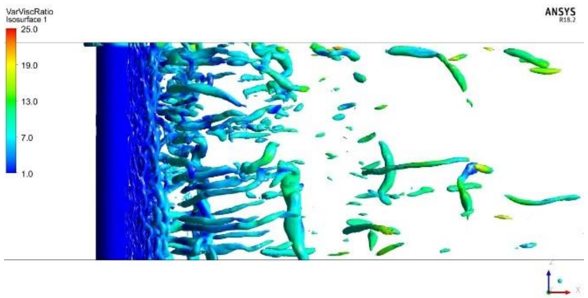
Flow direction

Q_0x100

Q = 500000 s^{-1}

0.05% of max





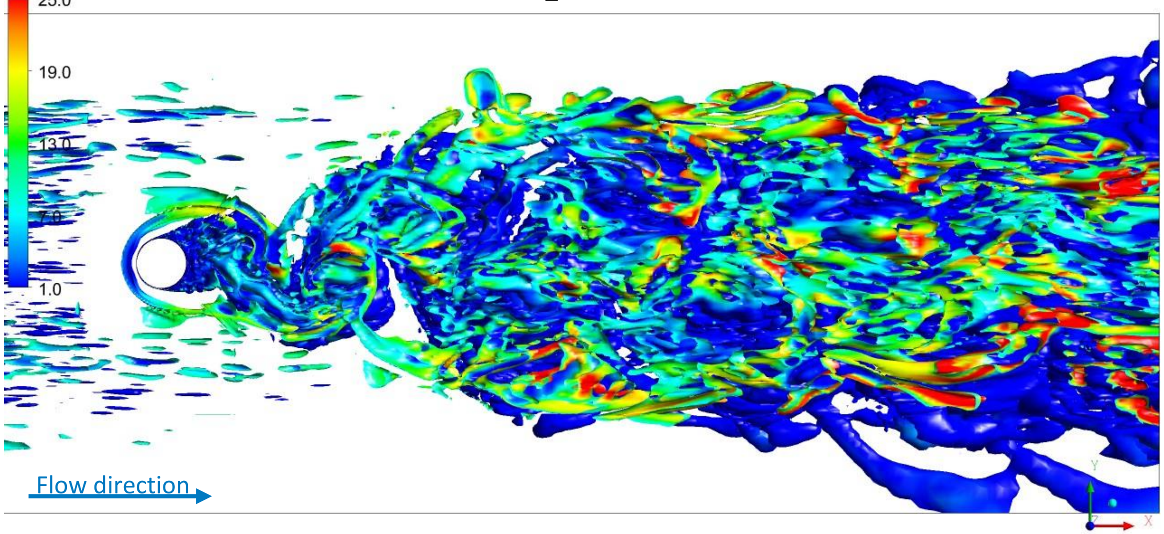
Q_0x1000

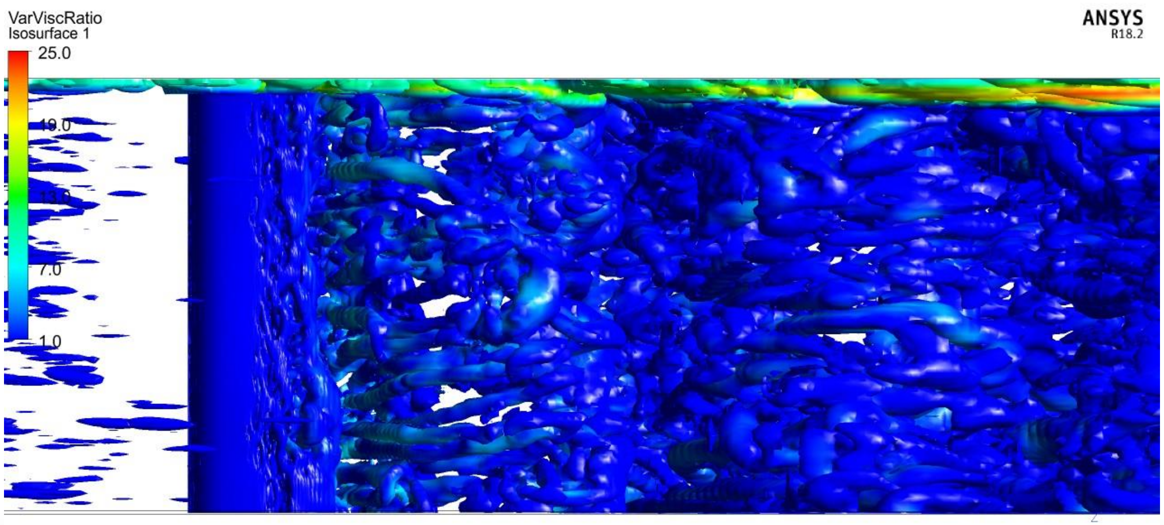
Q = 5000000 s^{-1}

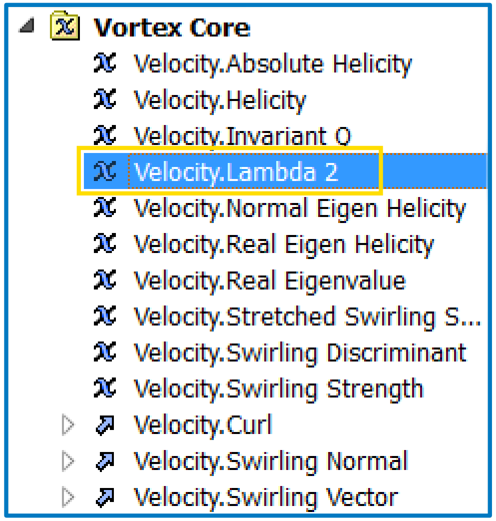
0.5% of max

4. λ_2 criterion

Isosurface of λ_2 criterion (-5000 s^{-2})





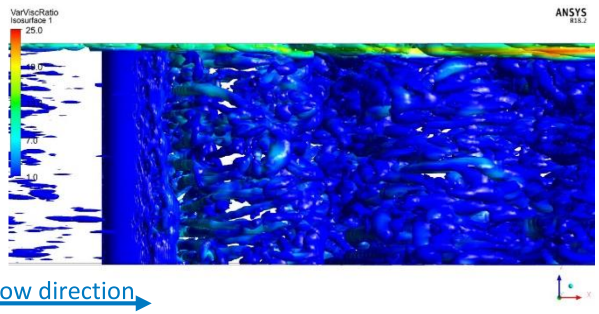


λ_2 criterion relies on the search of a local minimum of pressure. The transport equation for strain-rate reads:

$$\frac{DS_{ij}}{Dt} - \nu S_{ij,kk} + \Omega_{ik}\Omega_{kj} + S_{ik}S_{kj} = -\frac{1}{\rho} p_{,ij}$$

where the pressure Hessian $p_{,ij}$ contains the information needed on local pressure. For a local pressure minimum to happen, two positive eigenvalues of $p_{,ij}$ are required.
This condition is translated as two negative eigenvalues for $\Omega^2 + S^2$. If eigenvalues are ordered: $\lambda_1 > \lambda_2 > \lambda_3$, that means $\lambda_2 < 0$.

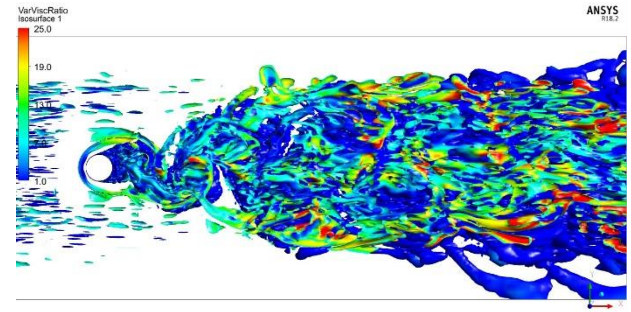
4. λ_2 criterion - Influence of value on detection



Flow direction

$\lambda_{2\,0}$ = -5000 s^{-1}

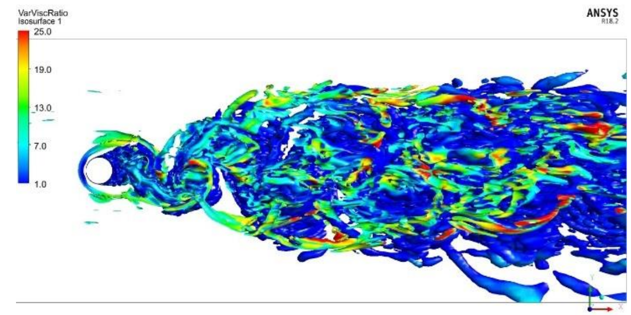
0.0006% of max*

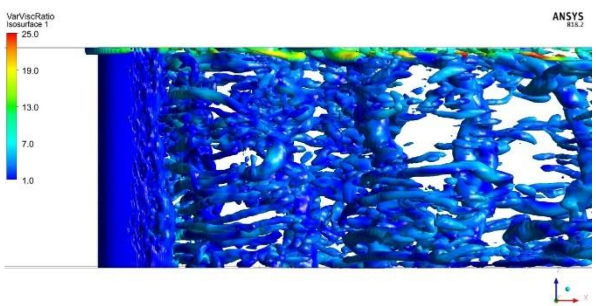


$\lambda_{2\,0}$x10

λ_2 = -50000 s^{-1}

0.006% of max

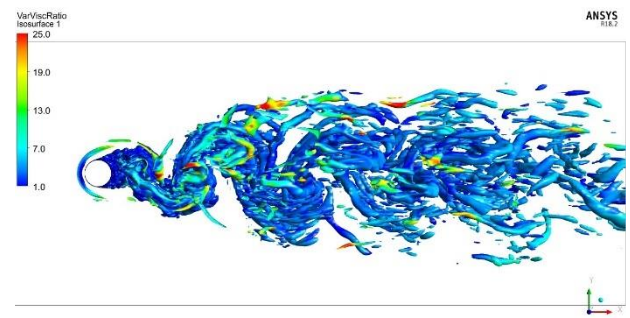




$\lambda_{2\,0}$x100

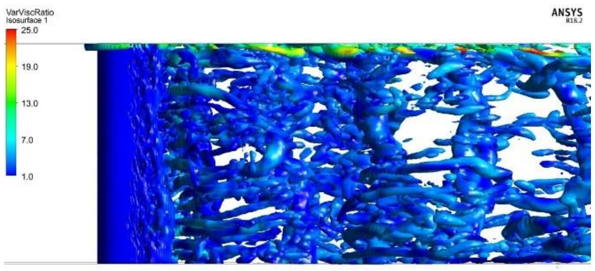
λ_2 = -500000 s^{-1}

0.06% of max



*max in absolute value

4. λ_2 criterion - Influence of value on detection

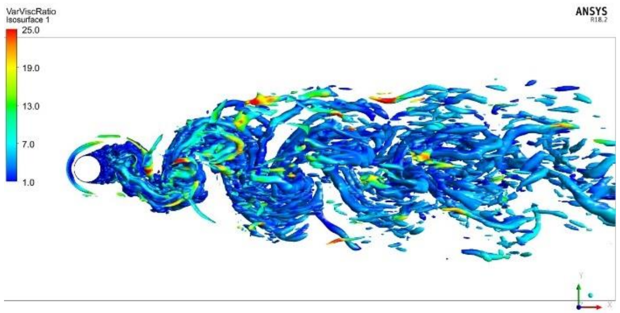


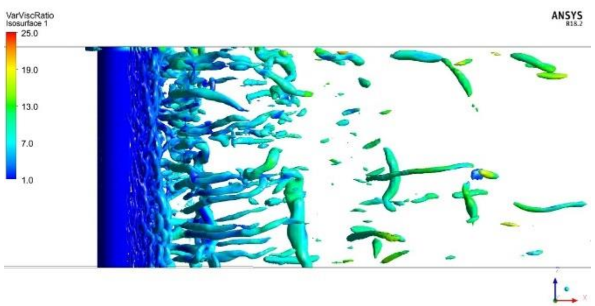
Flow direction

$\lambda_{2\ 0}$x100

λ_2 = -500000 s^{-1}

0.06% of max



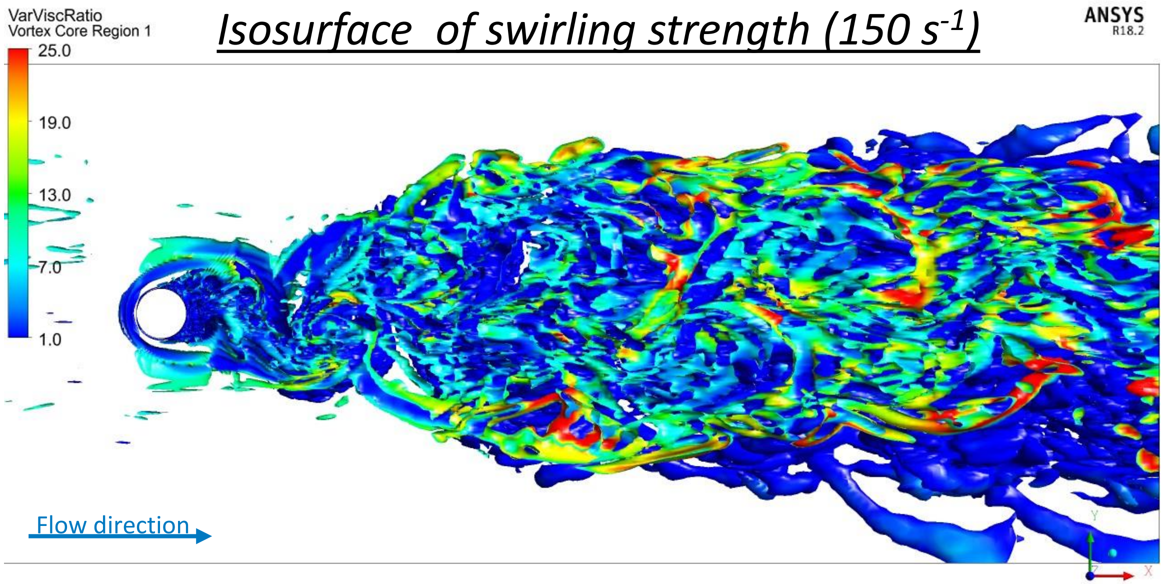


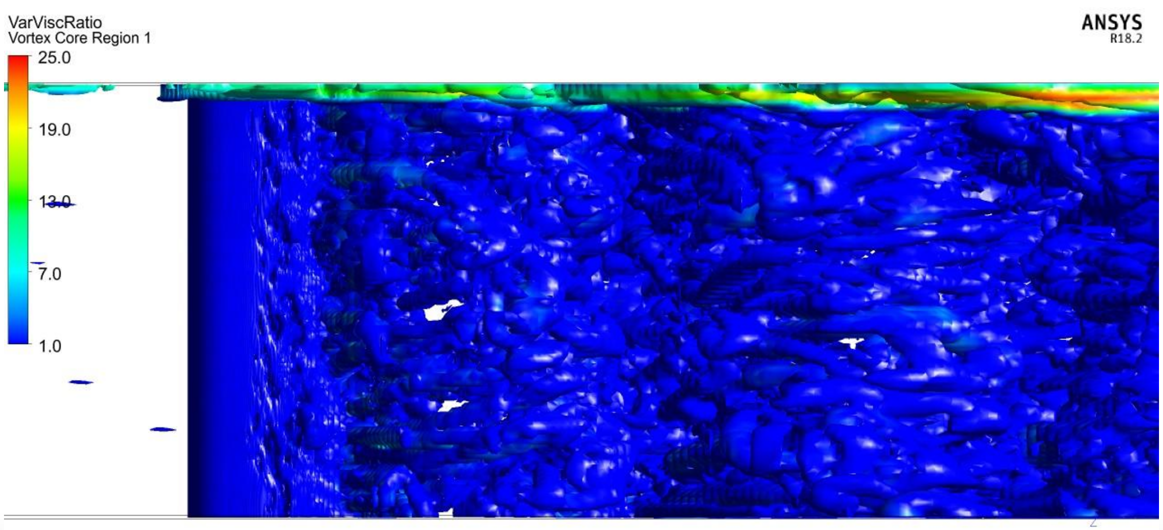
$\lambda_{2\ 0}$x1000

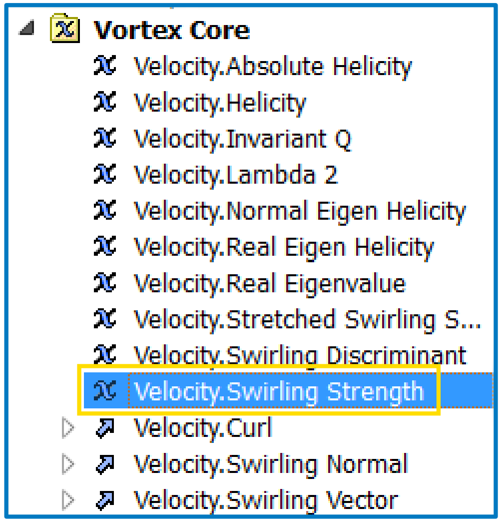
λ_2 = -5000000 s^{-1}

0.6% of max

5. Swirling strength





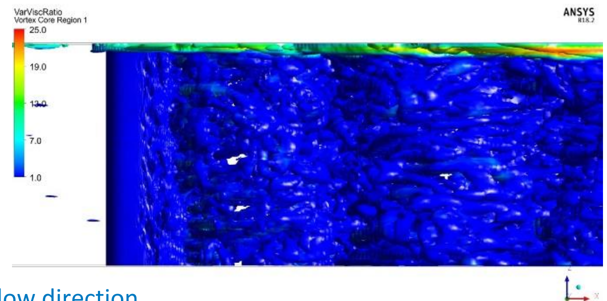


Swirling strength uses the following decomposition for the velocity gradient tensor:

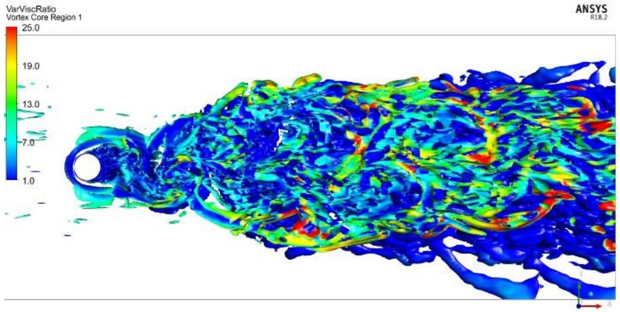
$$\nabla u = [d_ij] = [\bar{\nu_r}\ \bar{\nu_{cr}}\ \bar{\nu_{ci}}] \begin{bmatrix} \lambda_r & 0 & 0 \\ 0 & \lambda_{cr} & \lambda_{ci} \\ 0 & -\lambda_{ci} & \lambda_{cr} \end{bmatrix} [\bar{\nu_r}\ \bar{\nu_{cr}}\ \bar{\nu_{ci}}]^T$$

When using the three eigen vectors to track the local streamlines, local flow is either stretched or compressed along v_r and swirled when modified along the basis (v_{cr}, v_{ci}). The intensity of this swirling motion is quantified through the eigenvalue λ_{ci}. Such quantity is called the local swirling strength of the vortex and is > 0.

5. Swirling strength - Influence of value on detection

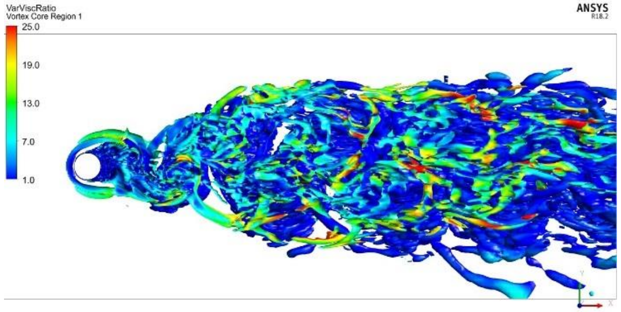


Flow direction



Swirl$_0$ = 150 s^{-1}

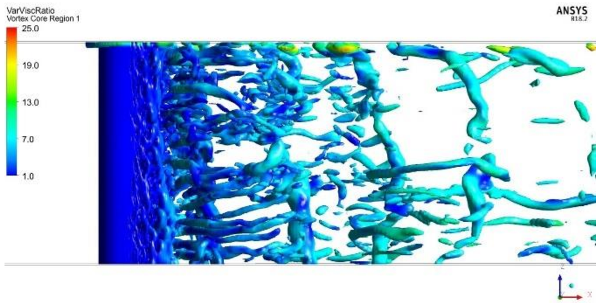
0.5% of max

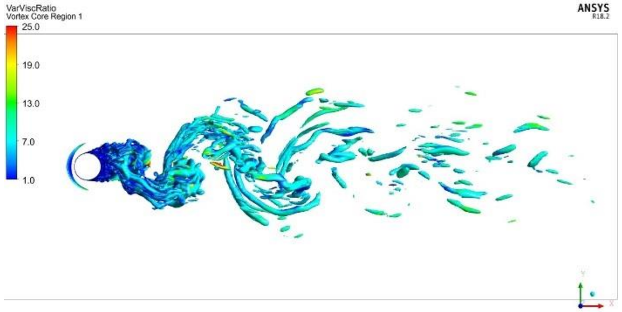


Swirl$_0$x2

Swirl = 300 s^{-1}

1% of max





Swirl$_0$x10

Swirl = 1500 s^{-1}

5% of max

Summary

Solution 2052121 gave additional elements on eddy detection tools available in ANSYS CFD-Post 18.2.

Main points observed on this test case are the following:

- ***Vorticity*** (and in a lesser way ***helicity***) cannot distinguish shear stress from rotation rate. Thus, ***vorticity*** detects wall shear stress. As a consequence, important values of ***vorticity*** are observed near walls.
- ***Vorticity***, ***helicity*** and ***swirling strength*** show stronger variations on isosurface when changing criterion value compared to other tools. That is, multiplying by 10 the ***vorticity*** has a stronger effect on observed eddies than for Q and λ_2 criteria.
- Q and λ_2 criteria detect close vortex structures for comparable absolute values. Best values for eddy detection were assessed between 0.05% and 0.5% of maximum* for this test case.

*maximum in absolute value

References

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More references on the topic of vortex detection are available in CFD-Post user's guide (section 11.1.8 Vortex Core Region).