Hybrid RANS/LES simulations of a cavitating flow in Venturi

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Jean Decaix
jean.decaix@hevs.ch
University of Applied Sciences, Western Switzerland

Eric Goncalves
eric.goncalves@legi.grenoble-inp.fr
Laboratoire des Ecoulements Géophysiques et Industrielles
Study overview

Objectives

- To compute a 3D cavitation sheet on a Venturi geometry by application of Hybrid RANS/LES turbulence models

⇒ Detached Eddy Simulation and Scale Adaptive Simulation based on the Spalart-Allamras model

Motivations

- Some studies put in evidence 3D mechanisms for the cavitation cloud shedding
Cavitating flow features

Main characteristics:

- liquid/vapour mixture $\rho_{liq} = 1000 \text{ kg/m}^3$; $\rho_{vap} = 0.02 \text{ kg/m}^3$
- unsteady cavity closure
- large range of Mach number
- compressibility effects on turbulence?

\[
\frac{\partial u_k', i}{\partial x_i} = \frac{1}{\alpha_k} u_k' n_k \delta I
\]

Pressure/temperature diagram

Mixture speed of sound (Wallis 1967)
Flow modelling

Homogeneous compressible RANS approach

- One fluid compressible RANS modelling:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho \tilde{u}_l}{\partial x_l} = 0
\]

\[
\frac{\partial \rho \tilde{u}_i}{\partial t} + \frac{\partial \rho \tilde{u}_i \tilde{u}_l}{\partial x_l} = -\frac{\partial p}{\partial x_i} + \frac{\partial \sigma_{il}}{\partial x_l} - \frac{\partial \tau_{il}}{\partial x_l}
\]

\[
\frac{\partial \rho \tilde{E}}{\partial t} + \frac{\partial \rho \tilde{u}_i \tilde{H}}{\partial x_i} = \frac{\partial \sigma_{il} \tilde{u}_l}{\partial x_i} - \frac{\partial q_i}{\partial x_i} - \frac{\partial Q_i}{\partial x_i}
\]

- Turbulence model ⇔ Hybrid RANS/LES models with an eddy-viscosity assumption

- Cavitation modelled
  ⇔ barotropic equation of state
  (Delannoy & Kueny 1990)
Turbulence modelling : DES model

**DES97 formulation**

\[
\frac{\partial \rho \tilde{\nu}}{\partial t} + \frac{\partial}{\partial x_l} \left[ \rho u_l \tilde{\nu} - \frac{1}{\sigma} (\mu + \rho \tilde{\nu}) \frac{\partial \tilde{\nu}}{\partial x_l} \right] = c_{b1} (1 - f_t^2) \tilde{S} \rho \tilde{\nu} + c_{b2} \frac{\partial \rho \tilde{\nu}}{\partial x_l} \frac{\partial \tilde{v}}{\partial x_l} - \left( c_{\omega 1} f_\omega - \frac{c_{b1}}{\kappa^2} f_t^2 \right) \frac{\tilde{v}^2}{\tilde{d}^2}
\]

with:
- \( \tilde{d} = \min(d, C_{DES} \Delta) \) the new distance
- \( d \) is the distance from the nearest wall,
- \( \Delta = \max(\Delta x, \Delta y, \Delta z) \)
Turbulence modelling: a SAS formulation of the Spalart and Allmaras model

The modify $\tilde{v}$ transport equation

Substitution of the distance $d$ by The von Karman length scale $L_{v\kappa}$

$$
\frac{\partial \tilde{\rho} \tilde{v}}{\partial t} + \frac{\partial}{\partial x_l} \left[ \tilde{\rho} \tilde{u}_l \tilde{v} - \frac{1}{\sigma} (\mu + \tilde{\rho} \tilde{v}) \frac{\partial \tilde{v}}{\partial x_l} \right] = c_{b1} (1 - f_{i_2}) \tilde{S} \tilde{\rho} \tilde{v} \\
+ \frac{c_{b2}}{\sigma} \frac{\partial \tilde{\rho} \tilde{v}}{\partial x_l} \frac{\partial \tilde{v}}{\partial x_l} \\
- c_{\omega_1 f_{\omega} \tilde{\rho} \xi_{sas}} \frac{\tilde{\nu}^2}{L_{v\kappa}^2} \\
- \frac{c_{b1}}{\kappa^2 f_{i_2} \tilde{\rho}} \frac{\tilde{\nu}^2}{d^2}
$$

with a tunable parameter $\xi_{SAS} = 3$ (for cavitating flows).
Main feature of the hybrid RANS/LES model

To Provide an adaptive turbulence length scale

For the Spalart and Allmaras SAS model, equilibrium assumption gives:

$$\tilde{\nu} = L_{vk}^2 \tilde{S}$$

For the DES model:

$$\tilde{\nu} = \left(C_{DES}\Delta \right)^2 \tilde{S}$$

The von Karman length scale

$L_{vk}$ gives an information on the heterogeneity of the flow.

$$L_{vk} = \kappa \left| \frac{U'}{U''} \right| ; \quad |U'| = S \quad ; \quad |U''| = \sqrt{\frac{\partial^2 U_i}{\partial x_k^2} \frac{\partial^2 U_i}{\partial x_j^2}}$$
Numerical code

Main features

- An in house unsteady compressible RANS code
- Cell-center finite-volume formulation for structured meshes

Spatial discretisation:
- Space-centered Jameson scheme for convective flux of the mean flow
- Upwind Roe scheme for the convective flux of the turbulent flow

Temporal discretisation:
- Time integration performed with a low storage method coupled with a dual time stepping approach
- A pre-conditioning strategy is applied in incompressible regions
### Experimental conditions

**Operating point**
- $U_{\text{inlet}} = 10.8 \text{ m/s}$
- $\sigma_{\text{inlet}} = \frac{P_{\text{inlet}} - P_{\text{vap}}}{0.5 \rho U_{\text{inlet}}^2} \approx 0.55$

**Observations**
- A quasi stable cavitation sheet of 0.70 to 0.85 m length
- An unsteady closure region with vapour cloud shedding and a liquid re-entrant jet

**Available quantities**
Five stations of measurement equipped with double optical probes provide
- longitudinal velocity
- void fraction

Pressure and $p'_{\text{rms}}$ profiles at the wall
Numerical conditions

Meshes

- 3D numerical computation with a mesh composed of $250 \times 62 \times 62$ nodes

Boundary conditions

- inlet velocity
- outlet non-reflective condition
- no slip condition at the wall
- farfield value of turbulence quantities

Time integration

- dual time approach with 100 sub-iterations
- dimensional time step: $\Delta t = 1 \times 10^{-4} \text{s}$
### Computations

#### 2 computations performed

<table>
<thead>
<tr>
<th>Model</th>
<th>cavitation number</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA SAS</td>
<td>$\sigma_{inlet} = 0.6$</td>
<td>Unsteady cavitation sheet with a liquid re-entrant jet; low frequency around 6 Hz</td>
</tr>
<tr>
<td>SA DES</td>
<td>$\sigma_{inlet} = 0.6$</td>
<td>U-shape cavitation sheet with a liquid re-entrant jet; low frequency around 6 Hz</td>
</tr>
<tr>
<td>Experiment</td>
<td>$\sigma_{inlet} = 0.55$</td>
<td>Unsteady cavitation sheet with a liquid re-entrant jet; No 3D visualisation; No particular frequency</td>
</tr>
</tbody>
</table>
**Station 3 and 4: void fraction and longitudinal velocity**

**Comments**

- Satisfactory agreement between experiment and models
- Models overestimate void fraction at the wall and the re-circulation thickness

![Graphs showing void fraction and longitudinal velocity comparisons between experiment (EXPE) and models (SA-SAS, SA-DES) for Station 3 and 4.](image-url)
Mean pressure and RMS pressure fluctuations at the bottom wall

Comments

- DES underestimates pressure downstream the cavity
- 3D computations overestimates the $p'_{rms}$ downstream the cavity
Dynamic behaviour of cavitation sheet: SA-SAS computation

Density gradient visualization
Transversal instability: SA-SAS computation

Void fraction contour and velocity vector

![Graphs showing void fraction contour and velocity vector](image-url)
Fourier transform analysis

Cavitation sheet frequency

FFT of the vapour volume

Time evolution of the re-entrant jet thickness on each side

⇒ low frequency ≈ 6 Hz.
Experiment \(^1\) vs Computation

**Bifurcation**

- For \(\frac{\sigma}{2i} < \approx 4\), shedding is conducted by a shock \(\Rightarrow\) spanwise structures and low frequency \(\approx 8\) Hz
- For \(\frac{\sigma}{2i} > \approx 4\), shedding is conducted by a re-entrant jet \(\Rightarrow\) no low frequency, no spanwise structures

**Present test case:**

\[
\frac{\sigma}{2i} \approx 4.3
\]

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Conclusion

Main results

- Velocity and void fraction profiles agree well with the experiment in the mid-span
- $p_{rms}'$ overestimated downstream the cavity in the mid-span
- A transversal instability characterized by a re-entrant jet oscillation (6 Hz) and a transversal flow

Limitations

Results have to be analysed with caution as:

- No measurements are available in the transversal direction to validate the computation,
- Only one experiment put in evidence the existence of a transversal mode