Study of Rotating Stall in Centrifugal Compressor

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Introduction - Rotating Stall

Rotating stall is an instability that can occur before surge in compressors.

It can cause a decrease in performance and efficiency, along with structural damage.

It’s caused by adverse pressure gradients and secondary flow features that are prevalent in centrifugal compressors, particularly at off-design operating conditions.

Rotating stall is a global feature and requires the modelling of the full compressor to accurately capture it.
Usage of *Code_Saturne* and Problems

*Code_Saturne* is an open-source code that can solve a wide range of CFD problems.
- Good scaling on clusters
- Wide-range of turbulence models and LES
- Open-sourced
- Good results for turbomachinery flows

However, some limitations of *Code_Saturne* exist in regards to compressible flow
- The algorithm within each time iteration is ‘non-conservative’ and depends on following iteration to ensure conservativity.
- Compressible module isn’t formulated for a rotating reference frame.
- Only 1\textsuperscript{st}-order in time and space
Incompressible Flow in Turbomachinery
NASA LSCC

20 impeller blades at 55° backsweep with a vaneless diffuser

The inlet and outlet radius are 0.435 m and 0.765 m, respectively.

\( \dot{m}_d = 30 \, kg/s \) and an off-design \( \dot{m} = 23.61 \, kg/s \)

Rotational speed of 1862 rpm

Maximum Mach number is less than 0.3; incompressible flow assumption is made.
A single passageway was modeled with periodic BC in the rotational direction.

Mass flow rate was imposed on the inlet and a static pressure on the outlet.

k-ω SST model with curvature correction was used.

Mesh generated with ANSYS® ICEM
  ◦ 2.3 millions cells used
  ◦ Mean $y^+$ of 51 with max and min $y^+$ of 146 and 3.9, respectively.
Hathaway et al.

\[ J = 85 \]
\[ \left( \frac{M}{M_0} \right) = 0.149 \]

\[ J = 110 \]
\[ \left( \frac{M}{M_0} \right) = 0.396 \]

\[ J = 165 \]
\[ \left( \frac{M}{M_0} \right) = 0.941 \]
Rotating Stall in NASA LSCC

In Progress...
Modifying Compressible Algorithm
Governing Equations

Inertial Reference Frame

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\mathbf{u} \otimes \rho \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{t}
\]

\[
\frac{\partial (\rho e)}{\partial t} + \nabla \cdot \left( (\rho \mathbf{u}) \left( e + \frac{p}{\rho} \right) \right) = \tau \cdot \mathbf{u} - \nabla \cdot k \nabla T
\]

Rotating Reference Frame

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}_r) = 0
\]

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\mathbf{u} \otimes \rho \mathbf{u}_r) = -\nabla p + \nabla \cdot \mathbf{t} - \rho (\mathbf{\Omega} \times \mathbf{u})
\]

\[
\frac{\partial (\rho e)}{\partial t} + \nabla \cdot \left( (\rho \mathbf{u}_r) \left( e + \frac{p}{\rho} \right) \right) = \tau \cdot \mathbf{u} - \nabla \cdot k \nabla T - \nabla \cdot (\mathbf{\Omega} \times \mathbf{R}) p
\]
Compressible Algorithm

1.) \[ \frac{\partial P}{\partial t} + \nabla \cdot (\rho^n u^n) - \nabla \cdot (\Delta t \nabla P^*) = 0 \quad \rightarrow \text{Enforces mass conservation from } t^{n-1}, \text{ and obtain a prediction for } P \text{ and } Q \text{ at } t^n. \]

2.) \[ \frac{\partial (\rho u)}{\partial t} + \nabla \cdot (u \otimes \rho u) = -\nabla p + \nabla \cdot t \quad \rightarrow \text{Momentum prediction} \]

3.) \[ \frac{\partial (\rho e)}{\partial t} + \nabla \cdot \left( (\rho u) \left( e + \frac{p}{\rho} \right) \right) = \tau \cdot u - \nabla \cdot k \nabla T \quad \rightarrow \text{Energy Prediction} \]

2b.) \[ \frac{1}{\psi^n} \frac{\partial (\delta P)}{\partial t} + \nabla \cdot \left( \frac{1}{\psi^n} u^* \delta P \right) - \nabla \cdot (\Delta t \nabla \delta P) = -\nabla \cdot (\rho^* u^*) - \frac{\partial}{\partial t} (\rho^* - \rho^n) \]

Following the PISO scheme, a pressure correction equation is solved after momentum prediction to ensure conservativity.
Compressible Algorithm

Original Algorithm

Start

\[ \xrightarrow{\text{Acoustic Prediction}} \]

Momentum Prediction

\[ \xrightarrow{\text{Energy Prediction}} \]

Finish

New Algorithm

Start

\[ \xrightarrow{\text{Acoustic/Density Prediction}} \]

Momentum Prediction

Pressure Correction

\[ \xrightarrow{\text{Energy Prediction}} \]

Finish
New Compressible Algorithm

Mass flux and convective pressure term are interpolated with the AUSM$^+$-up flux splitting scheme

- Gives good results for all Mach regimes (subsonic to hypersonic flows)
- Good alternative to standard Rhie and Chow scheme

A 2$^{nd}$-order upwind scheme is implemented with the minmod limiter.

\[ \phi_f = \phi_i + \varphi(r) \nabla \phi_i \]

\[ \varphi(r) = \max(0, \min(1, r)) \]

\[ r_i = \frac{\emptyset_i - \emptyset_{i-1}}{\emptyset_{i+1} - \emptyset_i} \]
Test Cases

Sod Shock Tube

<table>
<thead>
<tr>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_L = 10^5$ Pa</td>
<td>$P_R = 10^4$ Pa</td>
</tr>
<tr>
<td>$\rho_L = 1$ kg/m$^3$</td>
<td>$\rho_R = 0.125$ kg/m$^3$</td>
</tr>
<tr>
<td>$u_L = 0$</td>
<td>$u_R = 0$</td>
</tr>
</tbody>
</table>

Contact broken at $t=0$

10 m

Channel Flow with a Bump

- Three mesh sizes- 225x120, 179x80, 75x40
- Tested for Mach numbers of 0.1, 0.675, 1.4
- Bump height is 0.1L for subsonic flow and 0.04L for supersonic flow
Shock Tube

V4.0.1

Mod (1st order)

Mod 2nd order

01/04/2016
Channel Flow with Bump – M=0.675

V4.0.1

Mod – 1\textsuperscript{st} order

Mod – 2\textsuperscript{nd} order

[Graphs showing Mach number vs. x (m) for different models and resolutions: 225x120, 179x80, 75x40]
Channel Flow with Bump – M=0.675

V4.0.1

Mod – 1\textsuperscript{st} order

Mod – 2\textsuperscript{nd} order

Mesh size 159x80

Mach No: 0 0.1625 0.325 0.4875 0.65 0.8125 0.975 1.1375 1.3
Channel Flow with Bump

M = 0.1

M = 1.4

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225x120  --  179x80  ---  75x40
NASA LSCC - Compressible
J = 85
(M/M₀) = 0.149

J = 110
(M/M₀) = 0.396

J = 165
(M/M₀) = 0.941
Conclusion

*Code_Saturne* predicts the flow in a centrifugal compressor accurately, however the global prediction of the pressure curve is off.

- Mediocre pressure curve is due to compressibility effects.
- Preliminary results with modified compressible algorithm are promising.

Modifying the compressible algorithm into a PISO-like scheme gives better prediction for the two test cases shown, and introducing a 2\textsuperscript{nd}-order scheme further improves the results. However, the results was found to be oscillatory, particularly for 2\textsuperscript{nd}-order, which solicits a closer look at the boundary conditions and further work to ensure that the 2\textsuperscript{nd}-order scheme is TVD.
Future Work

Test with rotating mesh

Extend the presented algorithm to 2nd order in time.

Test and study the NASA CC3, a transonic centrifugal compressor.

Implement non-reflecting boundary conditions for inlet and outlet
Acoustic Step

Momentum Step

Energy Step

Acoustic Step

Momentum Step

Energy Step

Mass Conservation