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^{st}-order in time and space

Incompressible Flow in Turbomachinery

NASA LSCC

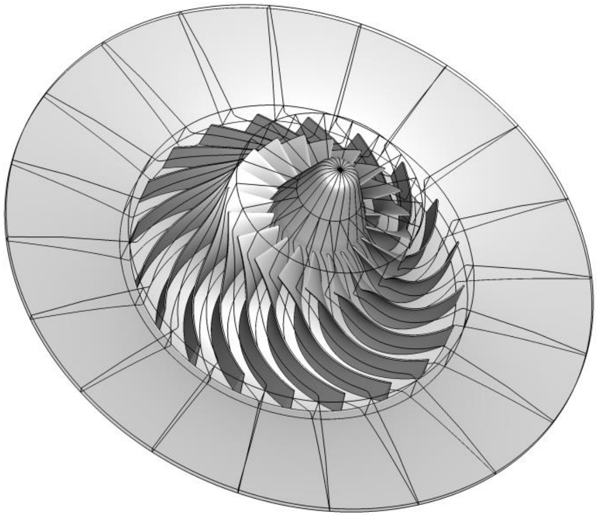
20 impeller blades at 55° backsweep with a vaneless diffuser

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.



NASA LSCC

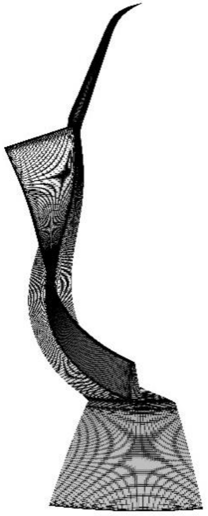
A single passageway was modeled with periodic BC in the rotational direction.

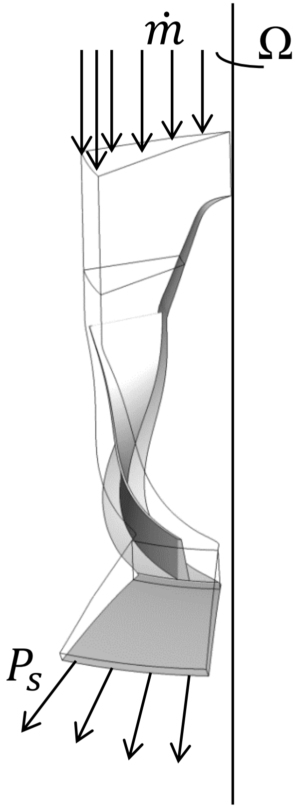
Mass flow rate was imposed on the inlet and a static pressure on the outlet.

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.





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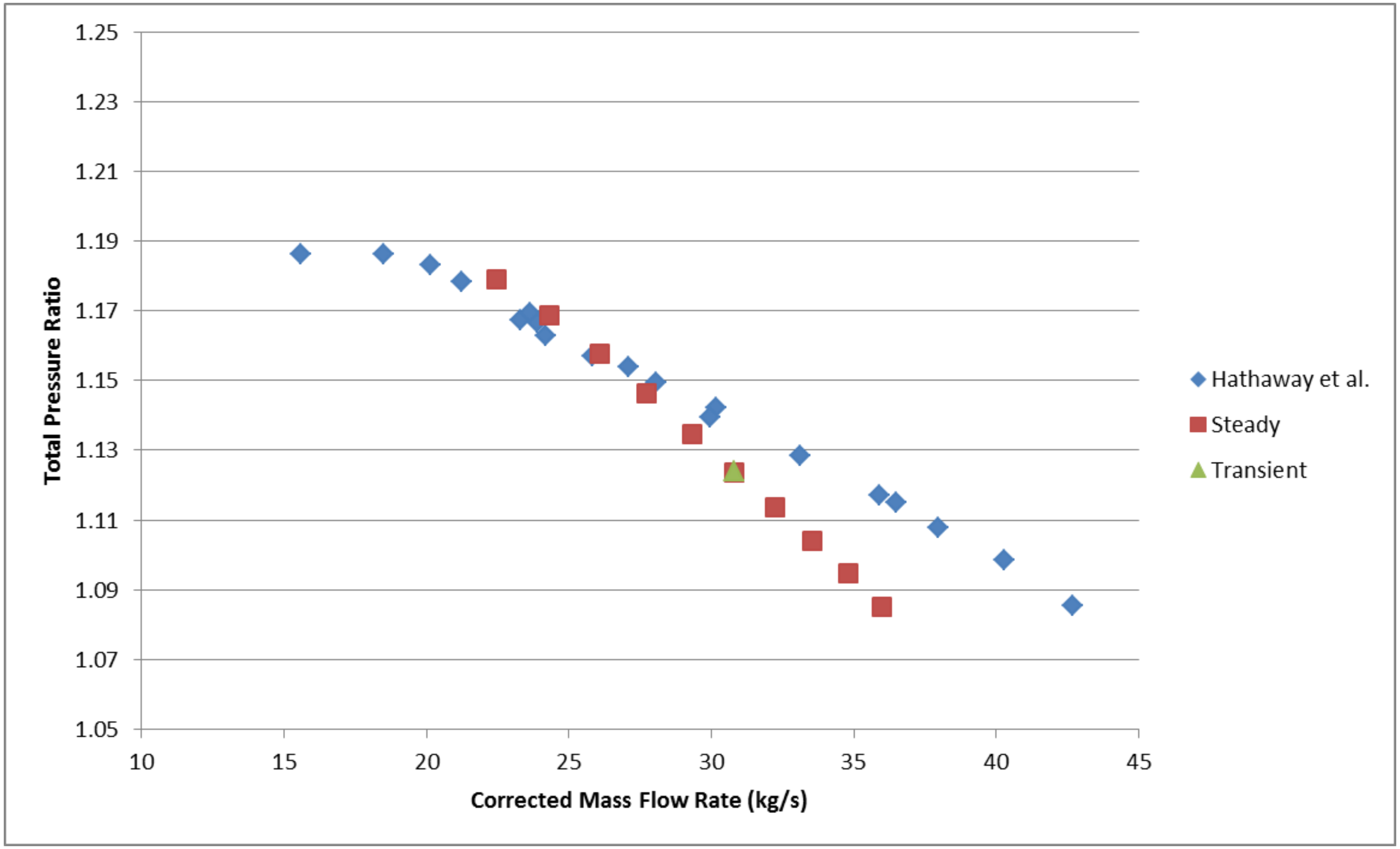
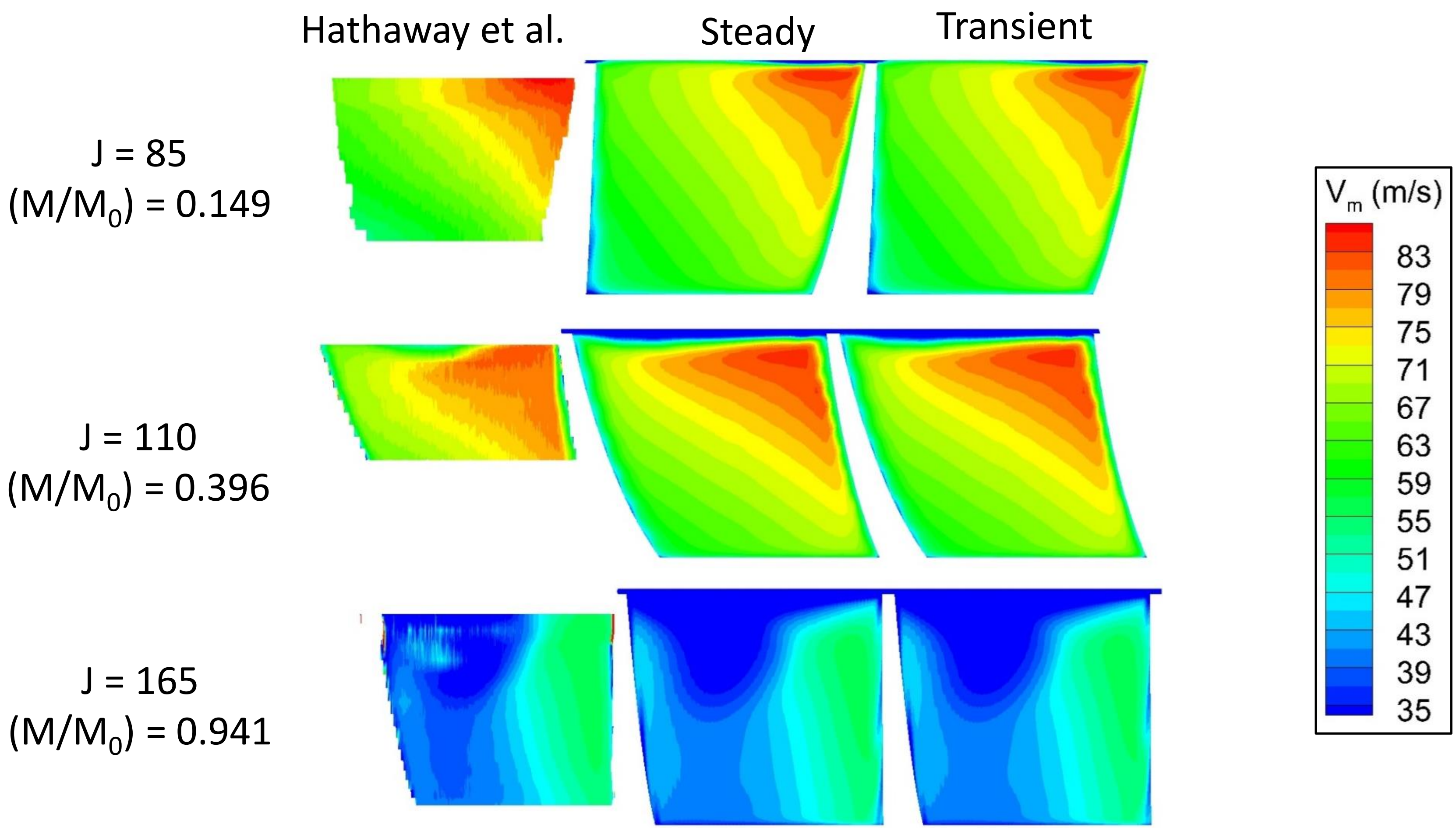


Total Pressure Ratio
1.25
1.23
1.21
1.19
1.17
1.15
1.13
1.11
1.09
1.07
1.05
10
15
20
25
30
35
40
45
Corrected Mass Flow Rate (kg/s)
Hathaway et al.
Steady
Transient

NASA LSCC


Hathaway et al.
Steady
Transient
J = 85
(M/M0) = 0.149
J = 110
(M/M0) = 0.396
J = 165
(M/M0) = 0.941
Vm (m/s)
83
79
75
71
67
63
59
55
51
47
43
39
35

Rotating Stall in NASA LSCC

In Progress…

Modifying Compressible Algorithm

Governing Equations

Inertial Reference Frame

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\boldsymbol{u} \otimes \rho \boldsymbol{u}) = -\nabla p + \nabla \cdot \boldsymbol{t}$$

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

Rotating Reference Frame

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}_r) = 0$$

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

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot \left((\rho \boldsymbol{u}_r) \left(e + \frac{p}{\rho} \right) \right) = \boldsymbol{\tau} \cdot \boldsymbol{u} - \nabla \cdot k \nabla T - \nabla \cdot (\boldsymbol{\Omega} \times \boldsymbol{R}) p$$

Compressible Algorithm

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

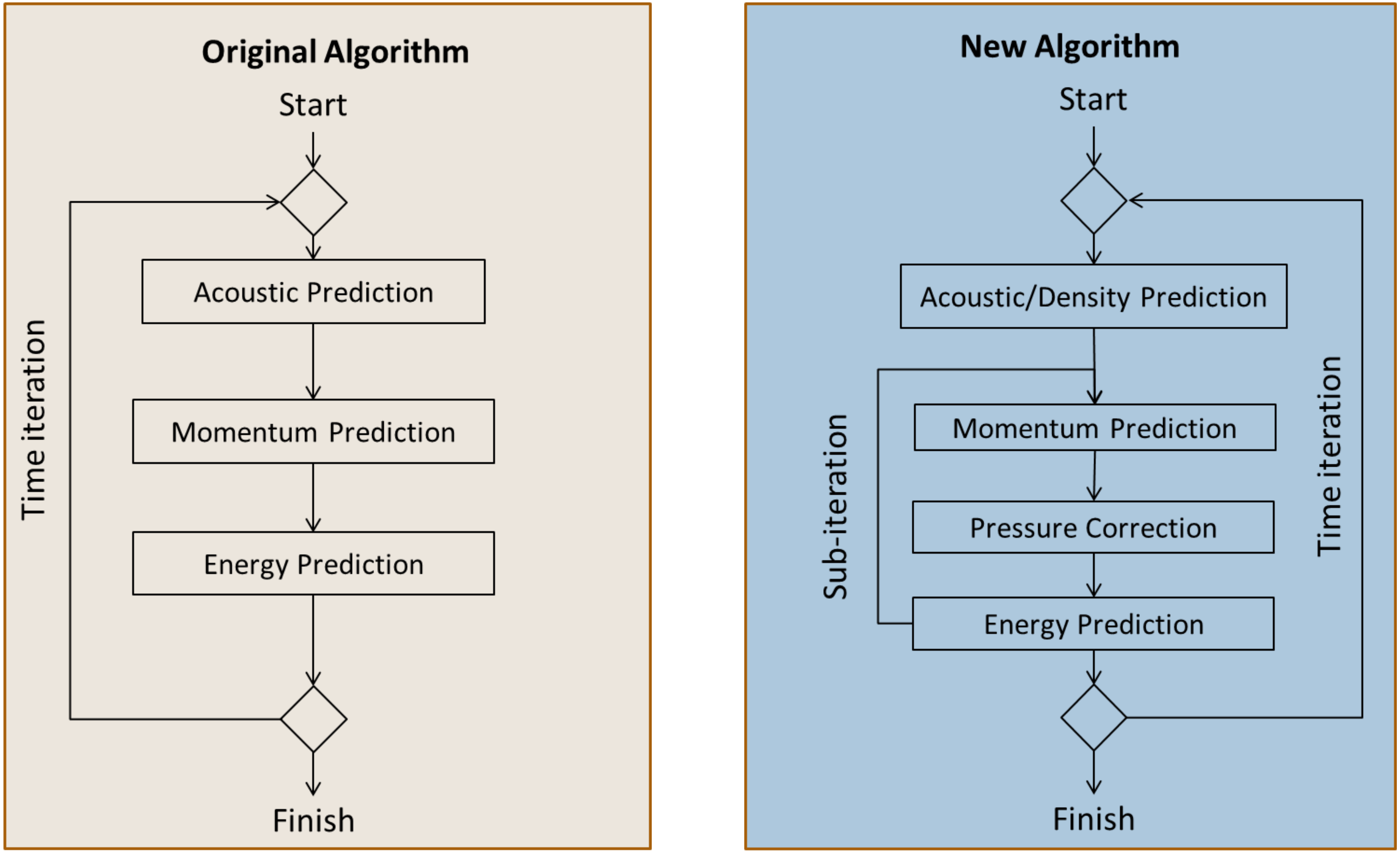
2.) $$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\boldsymbol{u} \otimes \rho \boldsymbol{u}) = -\nabla p + \nabla \cdot \boldsymbol{t}$$ ⟵ Momentum prediction

3.) $$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot \left((\rho \boldsymbol{u}) \left(e + \frac{p}{\rho} \right) \right) = \boldsymbol{\tau} \cdot \boldsymbol{u} - \nabla \cdot k \nabla T$$ ⟵ Energy Prediction

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

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

Compressible Algorithm



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 2nd-order upwind scheme is implemented with the minmod limiter.

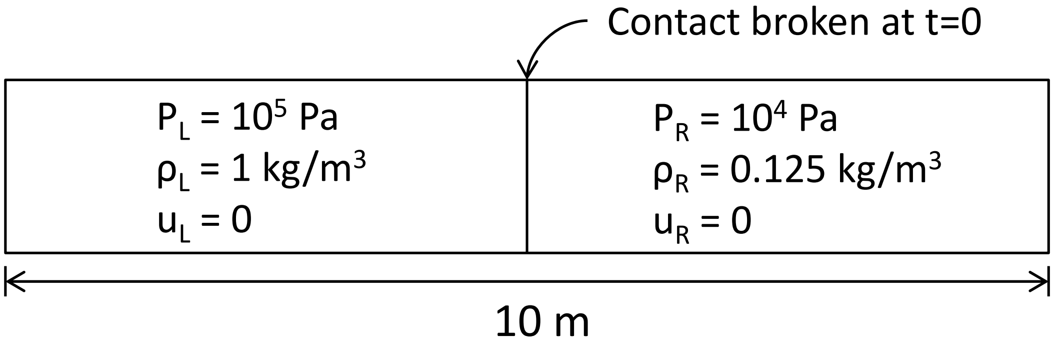
$$\phi_f = \phi_i + \varphi(r)\nabla\phi_i$$

$$\varphi(r) = \max(0, \min(1, r))$$

$$r_i = \frac{\emptyset_i - \emptyset_{i-1}}{\emptyset_{i+1} - \emptyset_i}$$

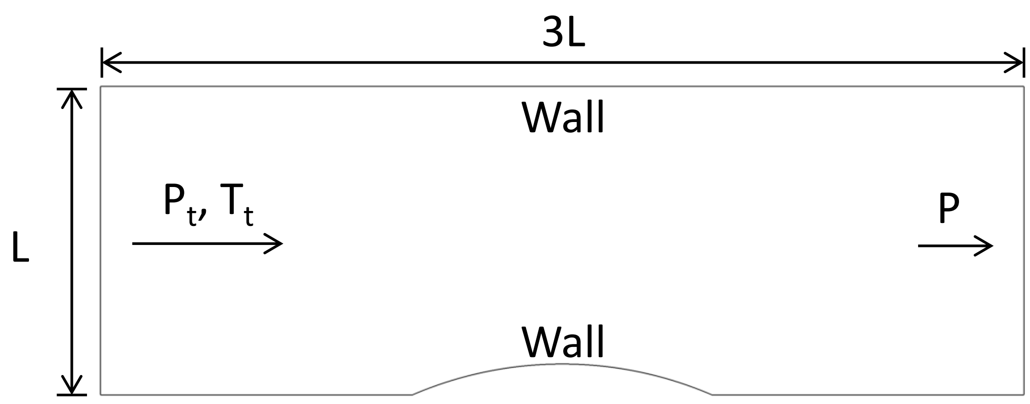
Test Cases

Sod Shock Tube



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

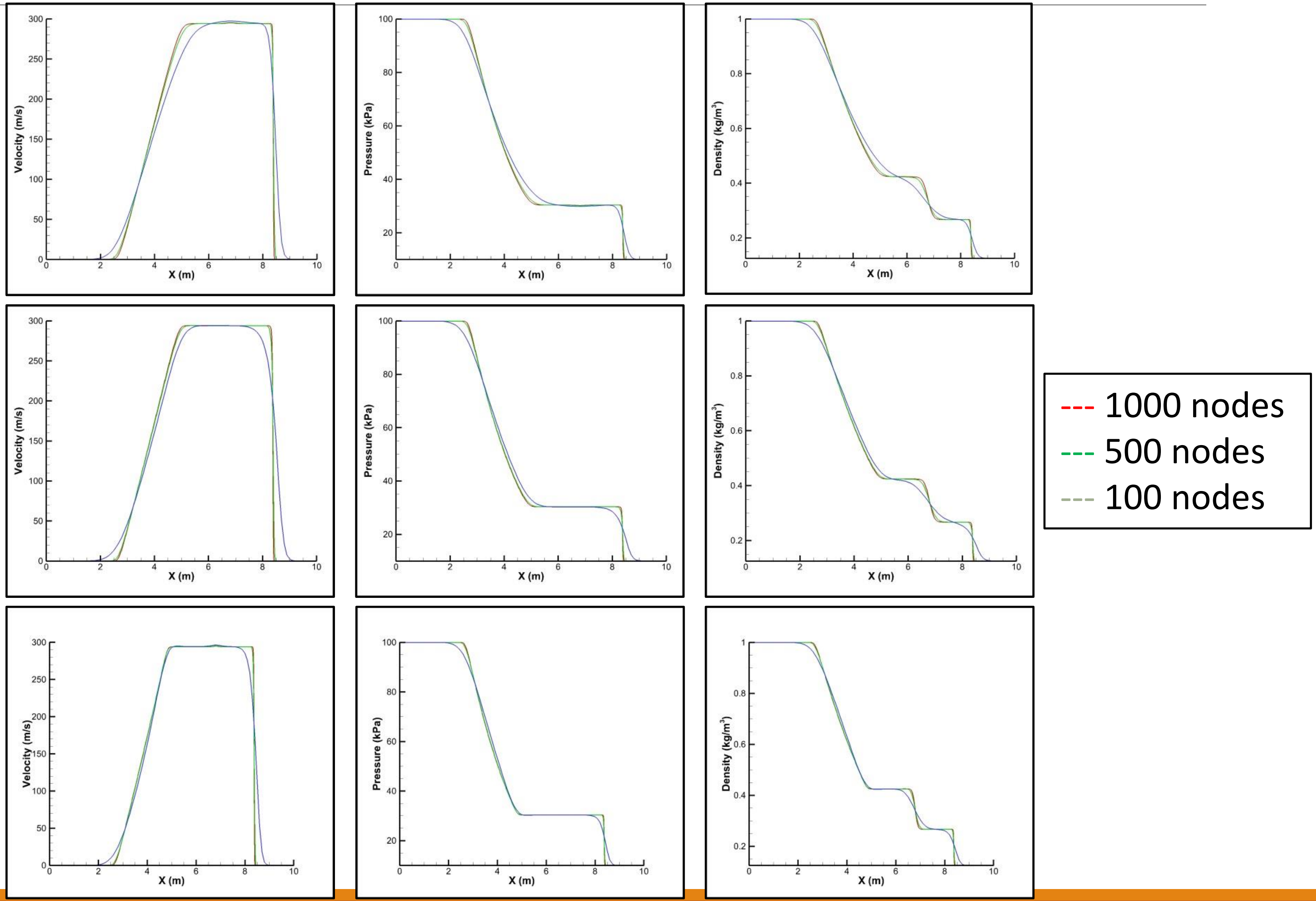


Shock Tube

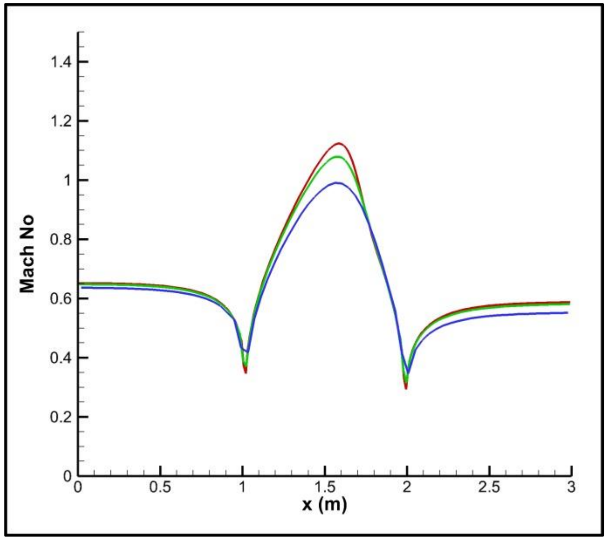
V4.0.1

Mod
(1st order)

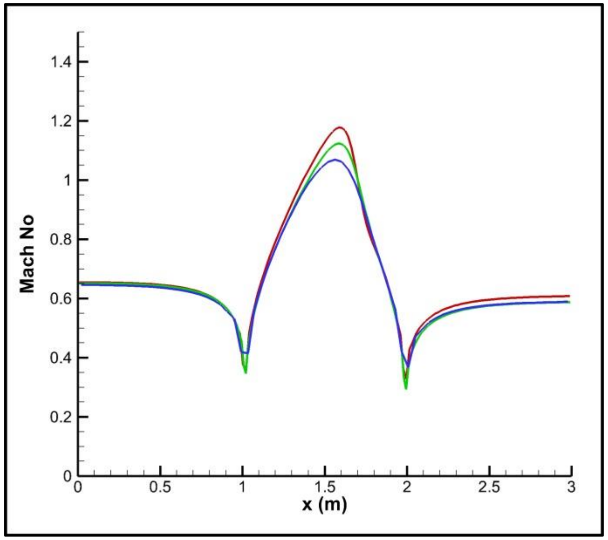
Mod
2nd order



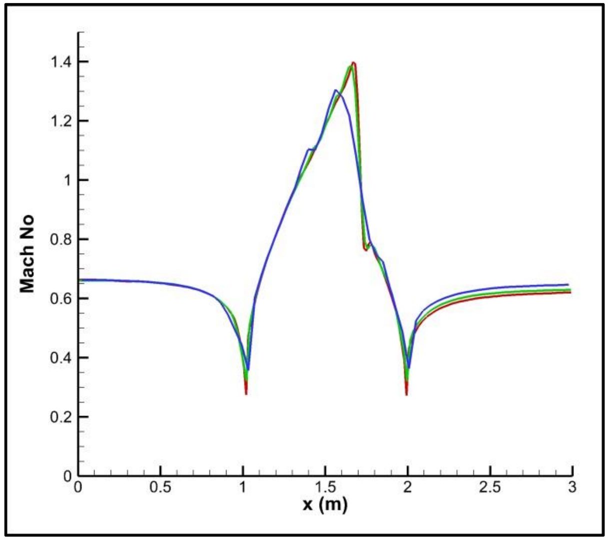
Channel Flow with Bump – M=0.675



V4.0.1



Mod – 1^{st} order



Mod – 2^{nd} order

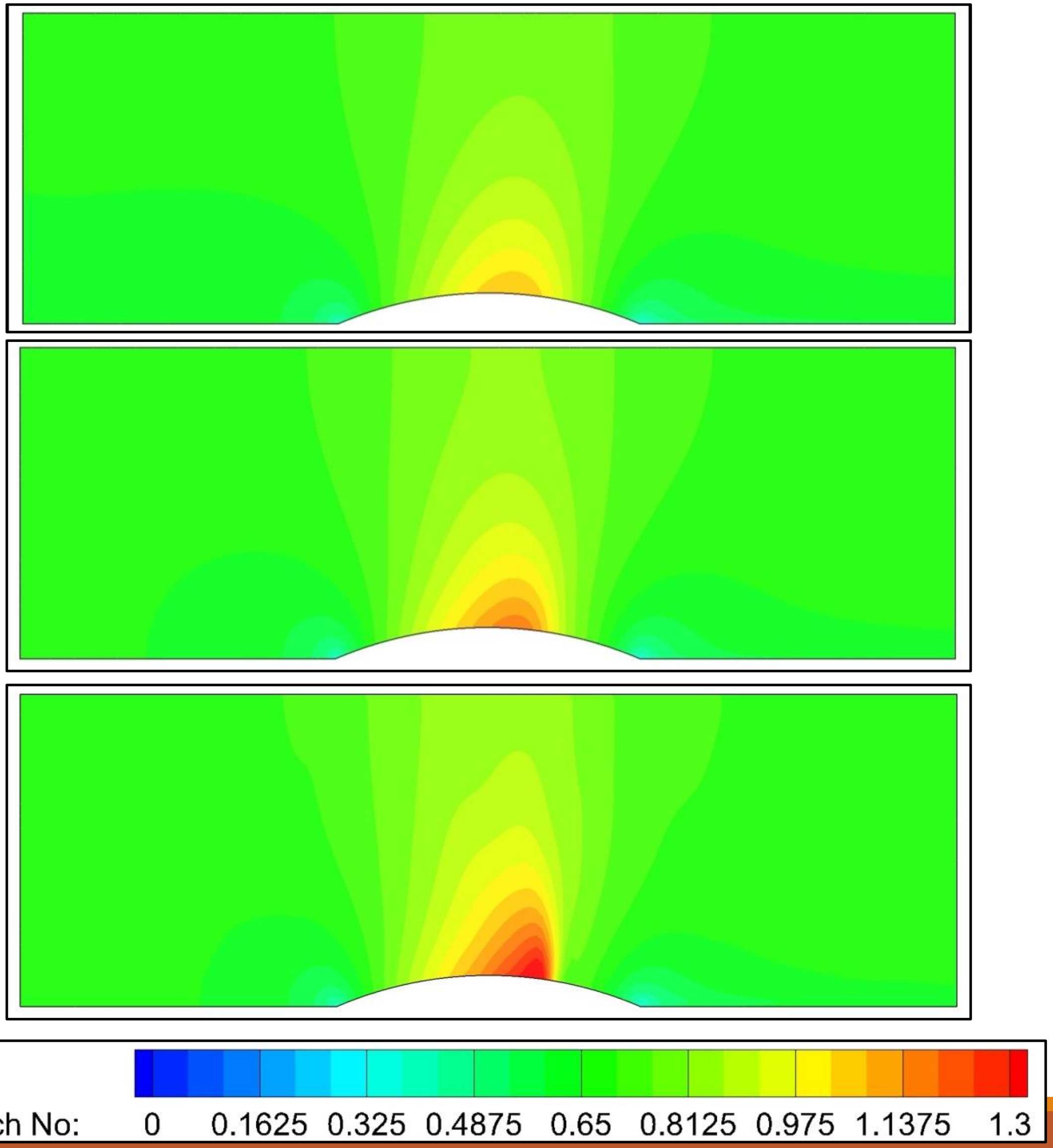
--- 225x120 --- 179x80 --- 75x40

Channel Flow with Bump – M=0.675

V4.0.1

Mod – 1st order

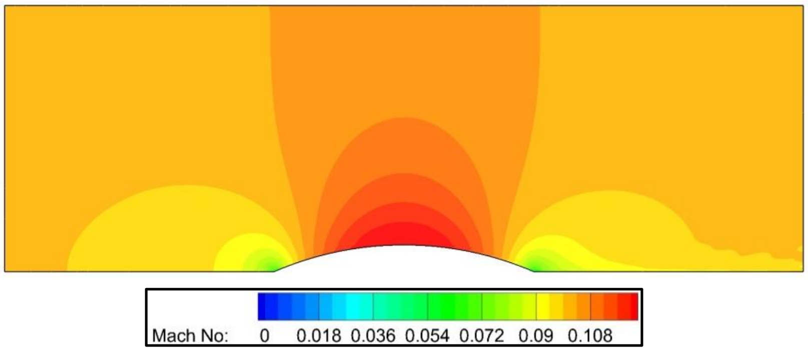
Mod – 2nd order

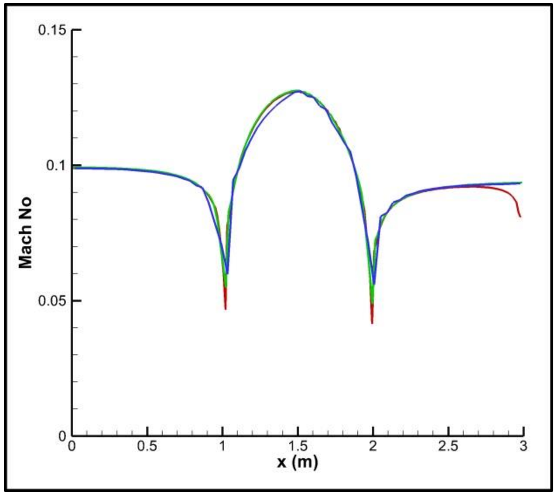


Mesh size
159x80

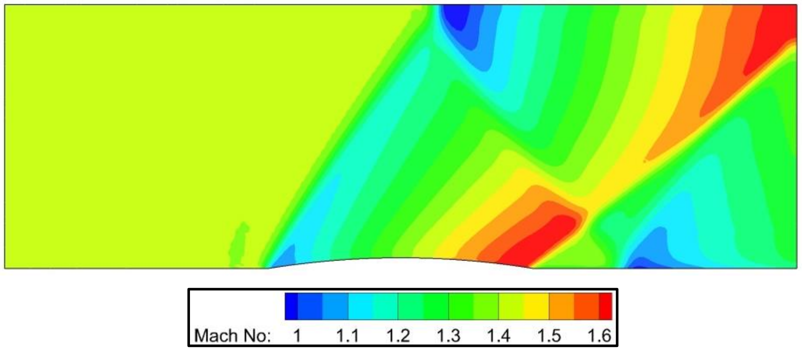
Channel Flow with Bump

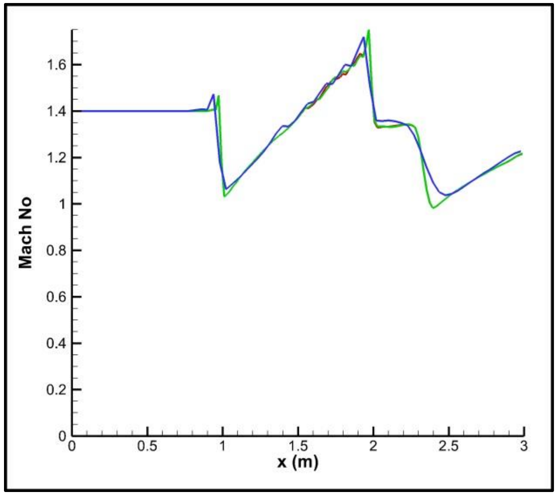
M = 0.1





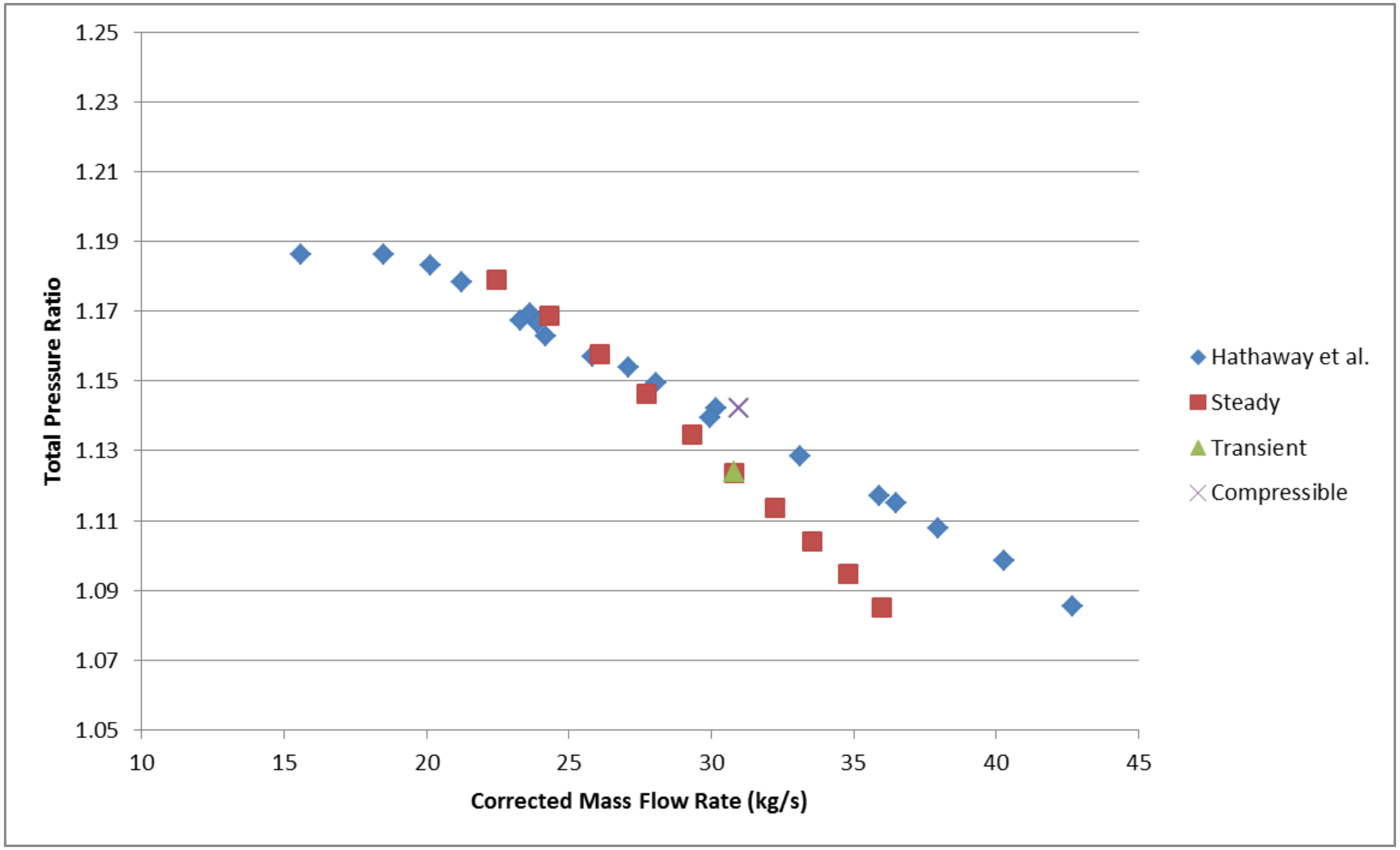
M = 1.4



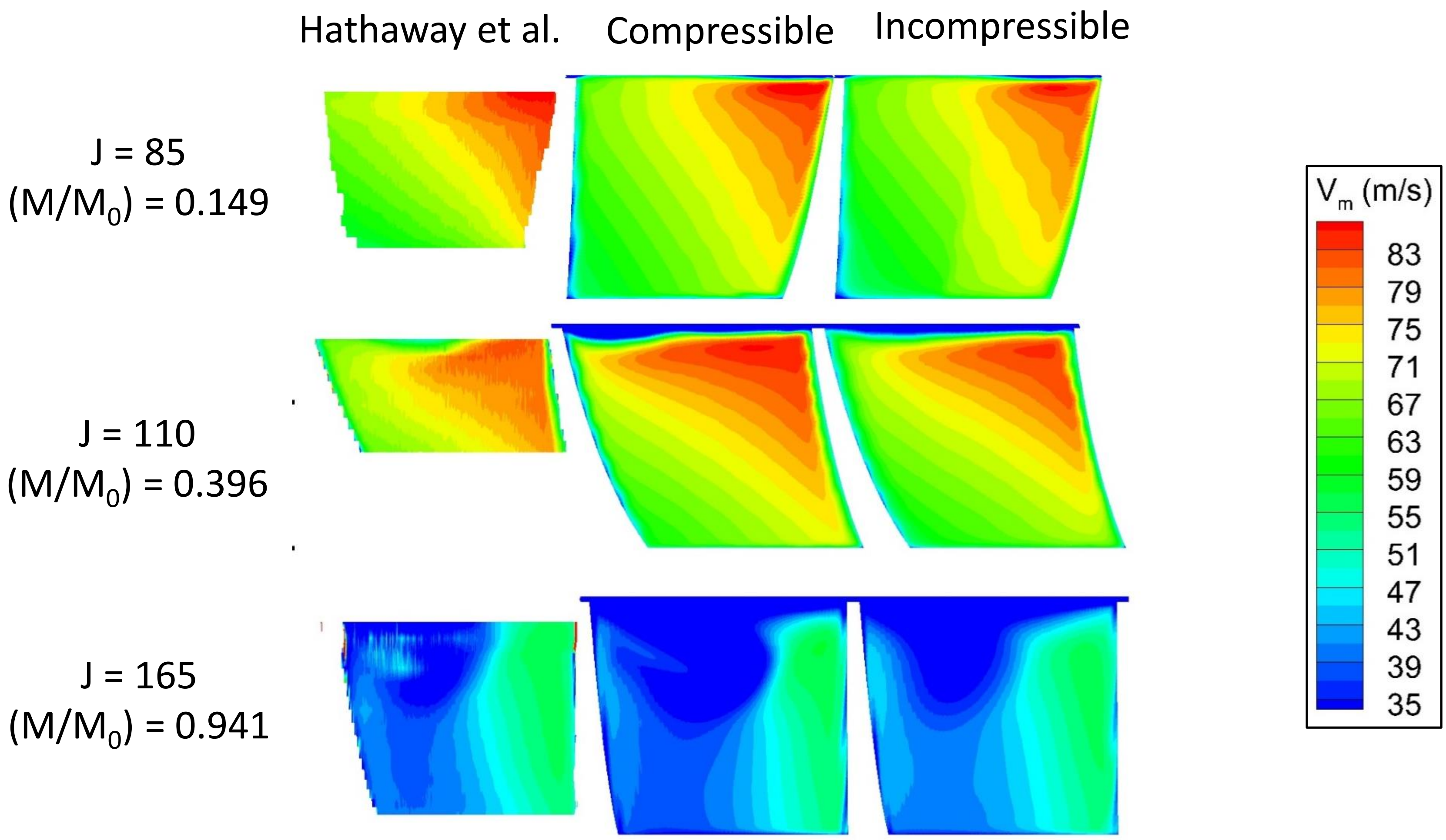


--- 225x120 --- 179x80 --- 75x40

NASA LSCC - Compressible



NASA LSCC - Compressible



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 2nd-order scheme further improves the results. However, the results was found to be oscillatory, particularly for 2nd-order, which solicits a closer look at the boundary conditions and further work to ensure that the 2nd-order scheme is TVD.

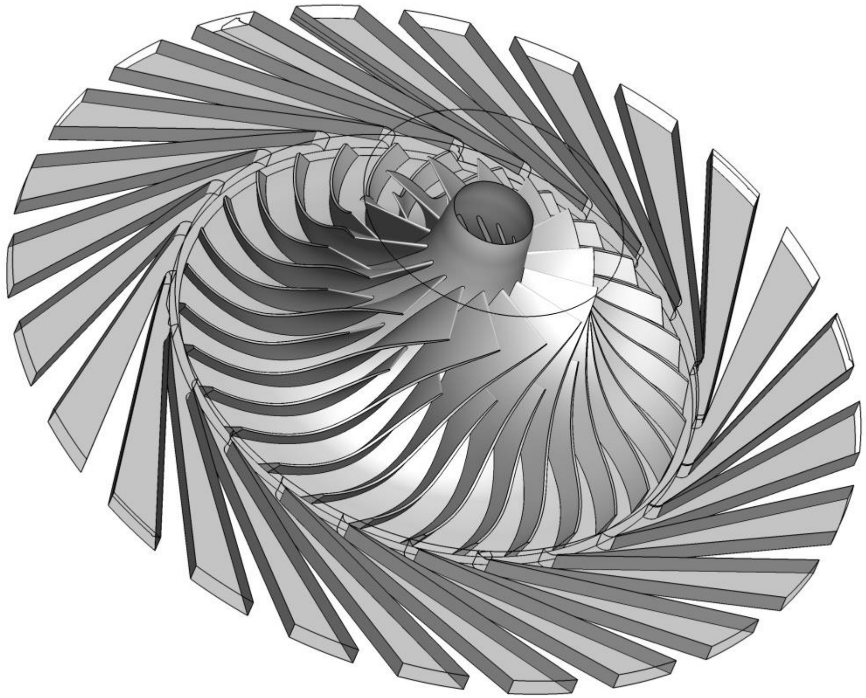
Future Work

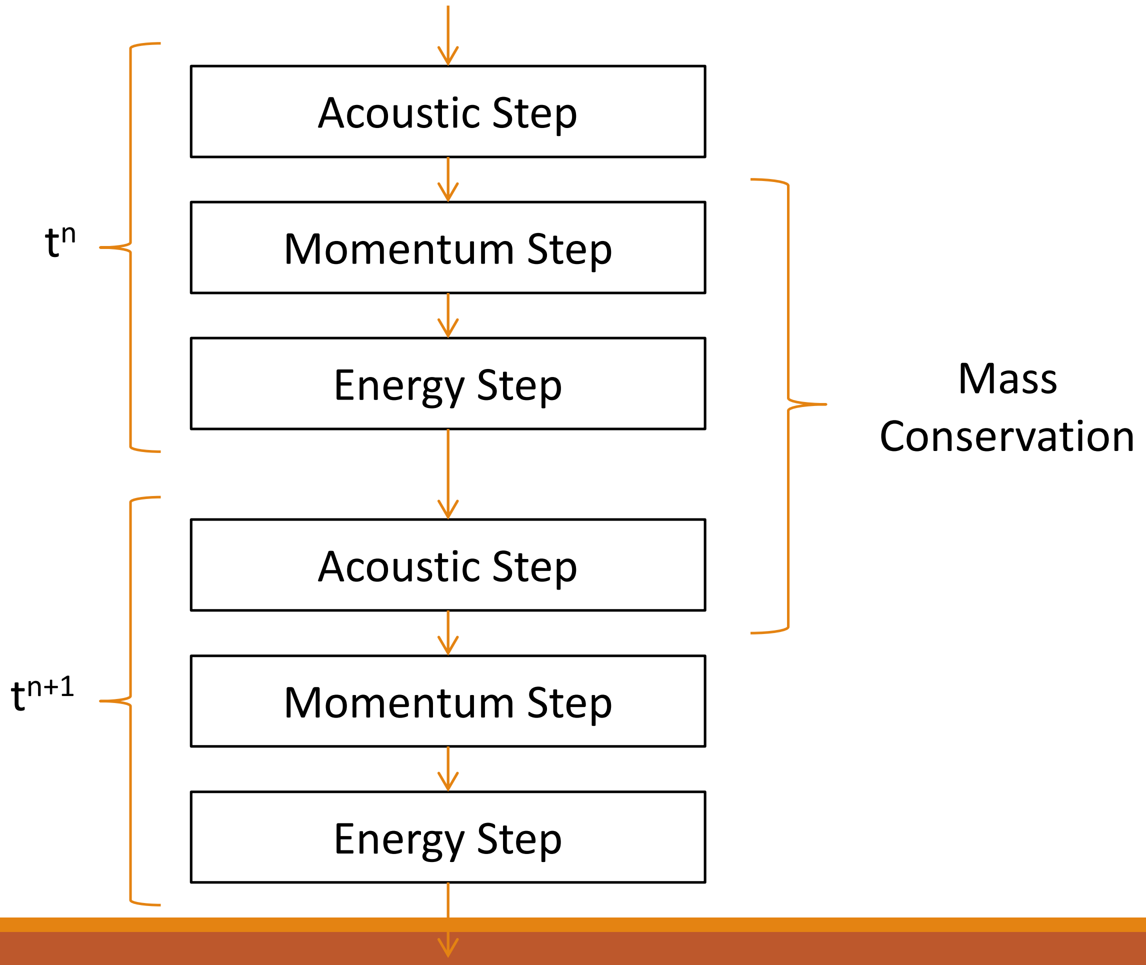
Test with rotating mesh

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
t^n
t^{n+1}
Mass Conservation

Compressible Algorithm