Stability Improvements of Pressure-Based Compressible Solver and Validation for Industrial Turbomachinery Applications

Henrik Rusche, Wikki GmbH, Braunschweig, Germany

Hrvoje Jasak, Wikki Ltd., London, United Kingdom

Sebastian Schmitt, Honda Research Institute Europe, Offenbach, Germany

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Agenda

- Stability improvements of pressure-based compressible solver
- Unified solver for incompressible and compressible flow
- Formulation of energy equation
- Formulation and implementation of radial balance boundary condition
- Results for new tutorial
- Results for fan compressor (full-stage) and validation against NUMECA results
FOAM's steady-state pressure-based compressible solvers are not very stable
- Especially for trans-sonic flows
- Pressure and temperature waves are produced which are difficult to handle at boundaries
- Reflections blow up the simulation

Several solutions have been proposed, but the results have been lacking behind commercial competition
Derivation of pressure equation

Derivation of pressure equation in FOAM's compressible flow solvers:

1. Continuity Equation
\[ \nabla \cdot (\rho \mathbf{U}) = 0 \]

2. Substitute discretised Momentum Equation
\[ A \mathbf{U} = H(\mathbf{U}) - \nabla p \]
\[ \nabla \cdot \left( \rho \frac{H(\mathbf{U})}{A} \right) = \nabla \cdot \left( \frac{\rho}{A} \nabla p \right) \]

3. Substitute discretised Momentum Equation
\[ \rho = \frac{p}{RT} = \Psi p \]
\[ \nabla \cdot \left( \Psi \frac{H(\mathbf{U})}{A} p \right) = \nabla \cdot \left( \frac{\rho}{A} \nabla p \right) \]
Deficiencies of pressure equation

\[ \nabla \cdot \left( \Psi \frac{H(U)}{A} \rho \right) = \nabla \cdot \left( \frac{\rho}{A} \nabla p \right) \]

- Derivation is formally correct, but ...
- Equation does not assume incompressible equation in the incompressible limit – \( \Psi \rightarrow 0 \) (?)
- Incompressible limit? You substituted the ideal gas law! What do you expect?
- Shouldn't we linearise around \( p^o \)

\[ \rho = \rho^o + \frac{\partial \rho}{\partial p} \bigg|_? (p - p^o) \]
Derivation of new pressure equation

1. Continuity Equation

2. Substitute discretised Momentum Equation

\[ A\mathbf{U} = H(\mathbf{U}) - \nabla p \]

\[ \nabla \cdot \left( \rho \frac{H(\mathbf{U})}{A} \right) = \nabla \cdot \left( \frac{\rho}{A} \nabla p \right) \]

3. Substitute linearisation

\[ \rho = \rho^o + \left. \frac{\partial \rho}{\partial p} \right|_{p_0} (p - p^o) \]

\[ \nabla \cdot \left( \frac{\partial \rho}{\partial p} \right|_{p_0} \frac{H(\mathbf{U})}{A} p \bigg) + \nabla \cdot \left( \left( \rho^o - \left. \frac{\partial \rho}{\partial p} \right|_{p_0} p^o \right) \frac{H(\mathbf{U})}{A} \bigg) = \nabla \cdot \frac{\rho}{A} \nabla p \]

- In the incompressible limit, the incompressible pressure equation is obtained → That's what we wanted!
- Which compressibility should we use?
Choice of compressibility

- Assume that enthalpy is fixed during solution of the pressure equation

\[
\frac{\partial \rho}{\partial p} = \frac{\partial \rho}{\partial T} = \frac{1}{RT}
\]

- We had that and it does not work that well
- We notice that a change in pressure will change the enthalpy due to pressure work term

\[
\nabla \cdot (\rho \mathbf{U} h) + \nabla \cdot \alpha_{eff} \nabla h = \tau \nabla \mathbf{U} + \nabla \cdot (\mathbf{U} p)
\]

- Assume isentropic process instead

\[
\frac{\partial \rho}{\partial p} = \frac{1}{\gamma RT}
\]

- This works and drastically increases stability. Generalisations under-way.
- In fact, this is used in other major codes
Review of energy equations

- Implementation and validation of several formulations for the energy equation. In particular:
  - Rothalpy equation including jump conditions at moving frame boundaries (Ilaria Dedominicis, Alstom Power / GE)
  - Total energy equation including moving frame correction
Radial Equilibrium Pressure Boundary Condition

- Implementation of radial equilibrium pressure boundary condition

\[ \frac{\partial p}{\partial r} = \frac{\rho V^2}{r} \]

- Implementation requires integration along radius
- \( p_{\text{ref}} \) is either fixed or adjusted to match a given mass flow rate using a PID controller
Validation for Fan Compressor

- Full stage (rotor-stator)
- Total energy equation
- @inlet:
  Total pressure, Total temperature
- @oulet:
  Radial equilibrium pressure boundary condition with $p_{ref}$ adjusted to match specified mass flow rate
  zeroGradient on temperature
- Mixing plane at interface

- 2 two RPMs
- More than 10 flow rates per RPM
- Results compared to NUMECA
Representative Results

Static pressure on blade and absolute velocity vectors
Representative Results

Static pressure on blade and absolute velocity vectors
Representative Results

Static pressure on blade and relative velocity vectors
Compressor Maps

The diagrams show the relationship between static inlet pressure ($P_{in}$) and total inlet pressure ($P_{t_{in}}$) with respect to total flux for two full stages (rotorStator) labeled RPM1 and RPM2. The plots compare data from NUMECA and FOAM simulations.

- **Static Inlet Pressure ($P_{in}$)**: The x-axis represents the total flux, while the y-axis shows the static inlet pressure. The plots illustrate the pressure drop as the total flux increases.
- **Total Inlet Pressure ($P_{t_{in}}$)**: Similar to the static inlet pressure plot, the x-axis is the total flux, and the y-axis shows the total inlet pressure. The plots highlight the consistency in pressure across different total flux values.

The diagrams are labeled to indicate the simulation data source (NUMECA and FOAM) for each stage (RPM1 and RPM2).
Compressor Maps

![Diagram of compressor maps showing static outlet pressure ($P_{out}$) vs. total flux, with data points for NUMECA and FOAM, and RPM1 and RPM2 at different pressure ratios.](image)
$\eta_s = \frac{\frac{\bar{p}_{tot,i}}{\bar{p}_{tot,o}} \frac{\gamma - 1}{\gamma} - 1}{\frac{\bar{T}_{tot,i}}{\bar{T}_{tot,o}} - 1}$
Span-wise distributions @ rotor exit for RPM2

![Graphs showing axial velocity and total pressure distributions at rotor exit](image_url)
Span-wise distributions @ stage exit for RPM2

![Graph showing axial velocity and total pressure distributions at stage exit for full stage, rpm2, massflow = 1.16 [-]. The graphs display comparisons between NUMECA and FOAM simulations.](image-url)
Conclusions and Future Work

- Stability of compressible solver increased substantially
- Unified solver released
- Implemented many features critical for turbo-machinery applications
- Initial validation results are encouraging
- Differences are being investigated
Thank you for your attention!

Questions?

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