Numerical Simulation of Fluid Flow and Solid Structure in Screw Compressors

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Screw compressor working principle
Flow and Deformation

Screw compressor performance is affected by:

- Temperature and pressure field,
- Distortion of rotors and housing,
- Reverse effects to the flow,
- Leakage through the gaps,
- Rotor wear or even seizure in extreme cases

One-Dimensional models assume that:

- Effects of pressure and temperature distortions are negligible!?

To overcome that:

3-D flow and stress calculation

CCM (Computational Continuum Mechanics) ⇒ FSI (Fluid – Solid Interaction)
Problems associated with numerical analysis and operation of Screw Machines

- Geometry ratio 300-1000
- Regions of highly turbulent flow and fully laminar flow
- Transonic velocities
- Large pressure gradients
- High temperature
- Rotor distortions
- Multi phase flow
CCM in Screw Compressors

- A commercial CCM solver(s) capable for efficient calculation
- “Expert system” for application in screw compressor

**METHOD:** Advanced Grid Generation & commercial CCM solver
- Finite volume method, block-structured hexahedral mesh
- Moving domains, sliding boundaries
- Automatic running and analysis of the results

**TOOL:** SCORG - Analytical grid generation & Pre-processor
- Multidimensional stretching Hermite transfinite interpolation,
- Boundary adaptation, smoothing, orthogonalisation and regularity check,
- Fast and reliable calculation of thermodynamic properties of real fluids
- Multiphase flow, novel boundary conditions, mesh movement
- Simultaneous generation and calculation of fluid/solid interaction
- Automatic transfer to the CCM solver, Post-processing
**Screw Compressor FSI calculations**

Conservation laws: continuity, momentum, energy, concentration and space

\[
\frac{d}{dt} \int_V \rho \phi dV + \int_S \rho \phi (\mathbf{v} - \mathbf{v}_s) \cdot dS = \int_S \Gamma_\phi \nabla \phi \cdot dS + \int_S q_{\phi S} \cdot dS + \int_V q_{\phi V} \cdot dV
\]

<table>
<thead>
<tr>
<th></th>
<th>( \phi )</th>
<th>( \Gamma_\phi )</th>
<th>( q_{\phi S} )</th>
<th>( q_{\phi V} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fluid momentum</td>
<td>( \mathbf{v}_i )</td>
<td>( \mu_{\text{eff}} )</td>
<td>( \left[ \mu_{\text{eff}} (\nabla \mathbf{v})^T - \left( \frac{2}{3} \mu_{\text{eff}} \nabla \cdot \mathbf{v} + p \right) I \right] \cdot \mathbf{i}_i )</td>
<td>( f_{b,i} )</td>
</tr>
<tr>
<td>Solid momentum</td>
<td>( \frac{\partial u_i}{\partial t} )</td>
<td>( \eta )</td>
<td>( \left[ \eta (\nabla \mathbf{u})^T + \left( \lambda \nabla \cdot \mathbf{u} - 3K \alpha \Delta T \right) I \right] \cdot \mathbf{i}_i )</td>
<td>( f_{b,i} )</td>
</tr>
<tr>
<td>Energy</td>
<td>( e )</td>
<td>( \frac{k}{\partial e/\partial T} + \frac{\mu_i}{\sigma_T} )</td>
<td>( \frac{k}{\partial e/\partial T} \frac{\partial e}{\partial p} \cdot \nabla p )</td>
<td>( T \cdot \nabla \mathbf{v} + \mathbf{h} )</td>
</tr>
<tr>
<td>Concentration</td>
<td>( c_i )</td>
<td>( \rho D_{i,\text{eff}} )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Space</td>
<td>( \frac{1}{\rho} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Turbulent kinetic energy</td>
<td>( K )</td>
<td>( \mu + \frac{\mu_i}{\sigma_k} )</td>
<td>0</td>
<td>( P - \rho \varepsilon )</td>
</tr>
<tr>
<td>Dissipation</td>
<td>( \varepsilon )</td>
<td>( \mu + \frac{\mu_i}{\sigma_\varepsilon} )</td>
<td>0</td>
<td>( C_1 \frac{\varepsilon}{k} - C_2 \rho \left( \frac{\varepsilon^2}{k} - C_3 \rho \varepsilon \right) \nabla \mathbf{v} )</td>
</tr>
</tbody>
</table>

\[ \rho = \rho(p,T), \quad e = e(p,T) \]

Constitutive relations, equation of state and turbulence model.
Pre-processing

- **Multiphase flow**
  - Oil - passive ‘species’ - exchange heat with gas
  - Liquid phase – active ‘species’ – exchange mass

- **Boundary conditions**
  - Suction, discharge, oil port receivers
  - Walls close the system
  - Mass is added to retain constant pressure

- **Properties of real fluids**
  - Based on the reality factor
  - Calculate compressibility factor
  - 2% error, fast calculation

- **User subroutines:** mesh movement, initial conditions, source terms
- **Control parameters** for CCM solver
Performance

- Volume flow (inlet and outlet)

- Mass flow (inlet, outlet, oil)

- Boundary forces

- Restraint Forces and Torque

- Compressor shaft power

- Specific power

- Efficiency

Volumetric and adiabatic

\[
\dot{V} = 60 \cdot \sum_{t=t_{\text{start}}}^{t_{\text{end}}} \dot{V}_{f}^{(i)} \left[ \frac{m^3}{\text{min}} \right], \quad \dot{V}_{f}^{(i)} = \sum_{i=1}^{I} v_{fi} S_{fi}
\]

\[
\dot{m} = \sum_{t=t_{\text{start}}}^{t_{\text{end}}} \dot{V}_{f}^{(i)} \cdot \overline{\rho}^{(i)} \left[ \frac{\text{kg}}{\text{sec}} \right]
\]

\[
F_x = p_b \cdot A_{xb}; \quad F_y = p_b \cdot A_{yb}; \quad F_z = p_b \cdot A_{zb}
\]

\[
F_{rS} = \sum_{i=1}^{I} F_{rS}(i), [N]; \quad F_{rD} = \sum_{i=1}^{I} F_{rD}(i), [N]
\]

\[
F_a = \sum_{i=1}^{I} F_a(i), [N]; \quad T = \sum_{i=1}^{I} T(i), [Nm]
\]

\[
P = 2 \cdot \pi \cdot n \cdot (T_M + T_F) \quad [\text{W}]
\]

\[
P_{\text{spec}} = \frac{P}{\dot{V}} \cdot 1000 \left[ \frac{\text{kW}}{m^3 \text{min}} \right]
\]

\[
\eta_v = \frac{\dot{V}}{V_d}; \quad \eta_i = \frac{P_{ad}}{P}
\]
Grid generation

Block structured mesh for solid (rotors) and fluid passages

- Rack generating procedure
- Basic geometrical parameters
- Discretisation on boundaries
- Multiparameter adaptation

- Transfinite interpolation
- Hermite blending functions
- Multidimensional stretching functions
- Orthogonalization
- Smoothing
- Regularity check
Cross sectional view of numerical meshes

Rotors: 189,144
Entire mesh: 353,084

Rotors: 322,560
Entire mesh: 448,830

Rotors: 515,520
Entire mesh: 637,790
Moving mesh generated by SCORG
<table>
<thead>
<tr>
<th>SCORG</th>
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</thead>
<tbody>
<tr>
<td>Screw COmpressor Rotor Geometry grid generator</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Rot</strong> <em>(nang, nast, naen, irot)</em></td>
</tr>
<tr>
<td><strong>Transf</strong> <em>(imin, imax, jmin, jmax, ntr)</em></td>
</tr>
<tr>
<td><strong>Rack</strong> <em>(nang, nada)</em></td>
</tr>
<tr>
<td><strong>Simple</strong> <em>(imin, imax, jmin, jmax, ntr)</em></td>
</tr>
<tr>
<td><strong>Distr</strong> <em>(irot, ka, idi, ma)</em></td>
</tr>
<tr>
<td><strong>Ortho</strong> <em>(imin, imax, jmin, jmax)</em></td>
</tr>
<tr>
<td><strong>Mesh</strong> <em>(nang, nada, irot, ntr, imesh)</em></td>
</tr>
<tr>
<td><strong>Gridsm</strong> <em>(imin, imax, jmin, jmax, ir)</em></td>
</tr>
<tr>
<td><strong>Inlet</strong> <em>(irot, fi1c, radd, nn1, nn2, irax, imesh, nang)</em></td>
</tr>
<tr>
<td><strong>Grireg</strong> <em>(imin, imax, jmin, jmax, ir)</em></td>
</tr>
<tr>
<td><strong>Outlet</strong> <em>(irot, fi1c)</em></td>
</tr>
<tr>
<td><strong>Smooth</strong> <em>(ra, ar, fip, fik, dfi, ns, nsp)</em></td>
</tr>
<tr>
<td><strong>Prep</strong> <em>(radd, nd, om1, pinl, pout, nang, irax)</em></td>
</tr>
<tr>
<td><strong>Names</strong> <em>(iang)</em></td>
</tr>
<tr>
<td><strong>Check</strong> <em>(npos, jro, ynew)</em></td>
</tr>
<tr>
<td><strong>Circ</strong> <em>(r, nt, a, fip, fik, dfi, jhoce)</em></td>
</tr>
<tr>
<td><strong>Equal</strong> <em>(mp, m, np, n, j)</em></td>
</tr>
<tr>
<td><strong>Celreg</strong> <em>(i, j)</em></td>
</tr>
</tbody>
</table>
FSI for screw compressor

Configuration 5/6

\[ d_1 = 126.7 \text{ mm}, \quad d_2 = 101.4 \text{ mm}, \quad a = 90 \text{ mm} \]
\[ l = 212 \text{ mm}, \quad l/d = 1.66, \quad \text{wrap angle} = 320 \text{ deg} \]

Nominal clearance 65 mm

n = 5000 rpm

442 130 cells, 25 time steps/cycle
FSI for screw compressor

Examples:

Case 1: Oil injected air screw compressor
\( P_{\text{inl}} = 1 \) bar, \( P_{\text{out}} = 6, 7, 8, 9 \) bar
\( t_{\text{inl}} = 20 \) degC, \( t_{\text{out}} = 40 \) degC

Case 2: Dry air screw compressor
\( P_{\text{inl}} = 1 \) bar, \( P_{\text{out}} = 3 \) bar
\( t_{\text{inl}} = 20 \) degC, \( t_{\text{out}} = 150 \) degC

Case 3: High pressure oil injected screw compressor
\( P_{\text{inl}} = 30 \) bar, \( P_{\text{out}} = 90 \) bar
\( t_{\text{inl}} = 0 \) degC, \( t_{\text{out}} = 40 \) degC
Oil injected – Pressure/Velocity

'N' rotors 5/6
Velocity
Pressure

-1.000e+04
5.600e+04
1.220e+05
1.880e+05
2.540e+05
3.200e+05
3.860e+05
4.520e+05
5.180e+05
5.840e+05
6.500e+05
Oil injected - Pressure 3D view
Oil injected - Oil concentration
Oil injected - Oil distribution 3D view
Experimental verification

- Test rig enables oil flooded and dry air compressors to be measured. Limits:
  - Power \( \leq 100 \text{ kW} \)
  - Delivery \( \leq 16 \text{ m}^3/\text{min} \)
- High accuracy test equipment
- \( p-\alpha \) diagram – piezoelectric transducers
- Computerized data logger
- Real time calculation and presentation

- Meets Pneurop/Cagi standards
- Compressor tested to ISO 1706
- Flow measurements BS 5600
- Certified by Lloyd’s of London
P-α diagram

P-α diagram for the Screw Compressor
'N' profile, 6/6, 128mm, 5000rpm

Pressure [bar]

Angle of rotation [deg]
Integral parameters – Power, Delivery

Screw compressor integral parameters
‘N’ Profile, 5/6, 128 mm, 5000 rpm
Oil injected

$P_{inl} = 1 \text{ b} \quad P_{out} = 7 \text{ b} \quad n = 5000 \text{ rpm}$

$t_{inl} = 20 \degree \text{C} \quad t_{out} = 40 \degree \text{C} \quad \text{mag} = 20,000 \times$
Oil free

\[ P_{\text{in}} = 1 \text{ b} \quad P_{\text{out}} = 3 \text{ b} \quad n = 5000 \text{ rpm} \]

\[ t_{\text{in}} = 20 \degree \text{C} \quad t_{\text{out}} = 150 \degree \text{C} \quad \text{mag} = 1,000 \times \]
High pressure oil injected

$P_{inl}=30\, \text{b}$  $P_{out}=90\, \text{b}$  $n=5000\, \text{rpm}$

$t_{inl}=0\, ^\circ\text{C}$  $t_{out}=40\, ^\circ\text{C}$  $mag=2,000\times$
FSI integral parameters

Power-Flow diagram

Screw compressor integral parameters
"N" Profile, 5/6, 128 mm, 5000 rpm
FSI integral parameters

Screw compressor integral parameters
"N" Profile, 5/6, 128 mm, 500 rpm

Specific Power [kW/m³/min] vs Flow [m³/min] diagram

- $P = 7$ bar
- $P = 6$ bar

City University London
CONCLUSIONS

- Compressor rotors deform. Due to that, clearances change. That influence internal leakage, and deteriorate compressor performance.

- Computational continuum mechanics is employed to analyse interaction between fluid and solid,

- **SCORG** - A stand alone program is developed to transfer screw compressor geometry and parameters to CCM solver automatically;

- **COMET GMBH** ICCM was used for CCM calculation;

- Calculation results for oil injected compressor are compared with measurements

- Method is used to estimate influence of rotor deflection on overall screw compressor parameters.