Simulation of Mild Compressor Surge using GT-POWER

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1.1 Surge Definitions

**Mild Surge** - The annulus average mass flow rate oscillates but remains in the forward direction at all times. Such oscillations are characterized by the Helmholtz frequency of the compression system (Greitzer, 1976).

\[
    f_H = \frac{a}{2\pi} \sqrt{\frac{A_c}{V_p L_c}}
\]

where

- \(a\) = speed of sound
- \(V_p\) = volume of the compression system plenum
- \(A_c\) = cross-sectional area of the equivalent compressor duct
- \(L_c\) = length of the equivalent duct.

**Deep Surge** - The mass flow oscillations are severe and the mean flow reverses its direction during part of the cycle.

![Diagram of Fink's large B compression system](image)

Figure 1: Fink's large B compression system (Fink, 1988).
1.2 Helmholtz Resonance of the System

The Helmholtz resonance frequency of mild surge oscillations is unique to the duct-plenum (cavity) coupling in terms of inertia in the duct balanced by pressure forces due to compressibility in the cavity.

The dominant frequency of oscillations is 7.0 Hz, which is close to the theoretical Helmholtz resonator frequency of 7.3 Hz.

The presence of the compressor will just be a perturbation to the behavior.
1.3 Zero-Dimensional Surge Models

- Zero-dimensional (lumped parameter) models have been developed to predict the surge behavior of both axial (Greitzer, 1976) and centrifugal (Yano and Nagata, 1971) compression systems with reasonable accuracy.

- Greitzer’s model formulated a set of nonlinear equations to estimate the system dynamics in the compression system. This analysis revealed a dimensionless number defined by

\[ B = \frac{1}{2} \frac{U}{a} \sqrt{\frac{V_p}{A_c L_c}}, \]  

where:

- \( B \) is the surge number
- \( U \) is the speed of sound
- \( a \) is the isentropic exponent
- \( V_p \) is the inlet velocity
- \( A_c \) is the cross-sectional area
- \( L_c \) is the length of the compression system

Greitzer (1976) defined:

- \( B \leq 0.8 \rightarrow \) No Surge
- \( B \geq 0.8 \rightarrow \) Surge

Benefits of predicting surge with a nonlinear 1-D time-domain solver compared to lumped models:

- Many of the simplifying assumptions of the 0-D formulation are eliminated.
- Spatially distributed wave dynamics of the compression system can be predicted.
- The methodology can be readily integrated into engine simulations.
Fink et al. (1992) presented experimental compressor characteristics taken from a small and large $B$ system at six constant rotational speeds.

- The compressor characteristics are a property of the compressor alone.
- The coupled compression system (compressor, ducting, and throttle) dictates the stable portion of the map available for use.

**Figure 3:** Fink’s small and large $B$ compressor characteristics.
The **compressor flow coefficient** $\phi_c$ represents the mass flow rate non-dimensionalized as

$$\phi_c = \frac{\dot{m}_c}{\rho A_c U},$$

where $\rho$ is the density at the compressor inlet (for forward flow).

The nondimensional **compressor isentropic head coefficient** $\psi_c$ involves the nondimensional pressure $\Pi_c$ as

$$\psi_c = \frac{\Pi_c^{(\gamma-1)/\gamma} - 1}{(\gamma - 1) Ma_{t,0}^2},$$

where

$$\Pi_c = \frac{p_{3t}}{p_0}$$

$p_{3t} = \text{total pressure at the compressor exit}$

$p_0 = \text{pressure at ambient conditions}$

$\gamma = \text{ratio of specific heats}$

$Ma_{t,0} = \frac{U}{a_0} = \text{Mach number of the impeller exit tip}$

$a_0 = \text{speed of sound at ambient conditions}$

Figure 4: Fink’s nondimensional compressor characteristics.
2.3 Compressor Map Extrapolations

**To zero mass flow rate**
Polynomials fits are applied to the individual small $B$ constant speed lines.

**To zero speed**
A speed weighted linear interpolation is performed between the nondimensional form of the lowest constant speed line (25k rpm) and zero speed, assuming zero mass flow rate, pressure rise, and efficiency when the impeller is not rotating.

**To higher speeds**
The nondimensional form of the highest speed (51k rpm) is transformed into dimensional form as higher speeds.

**To choke**
This procedure is neglected here since the range of operation for the compressor in the current study is not near that region of the map.
The MATLAB preprocessor, developed in the current study, extrapolates and interpolates the data and writes the compressor map information to a text file with the format required for the code.
The ducts of the compression system are modeled as straight pipes with circular cross-sections.

The throttle valve is modeled as a circular orifice and the diameter is adjusted to obtain the desired mass flow rate.
These comparisons demonstrate the ability of GT-Power to predict the unsteady compressor behavior during mild surge.
The dominant mild surge frequency is predicted here to be 7.3 Hz and is identical to the measured result reported by Fink.

The steepened wave forms lead to additional frequency content at harmonics of the fundamental frequency. This behavior has also been observed experimentally by Gravdahl et al. (2004).

Figure 8: Frequency domain analysis of $\phi_c$ and $\psi_p$ from mild surge simulation result.
The operating points nearly follow the characteristic while the flow is decelerating. The predictions demonstrate that during mild surge the compressor spends a significant amount of time to the left of the large \( B \) surge line.
The maximum SPL of about 160 dB occurs at the compressor inlet, corresponding to the dominant mild surge frequency of 7.3 Hz.
The temperature fluctuations are largest at the compressor exit during mild surge, but the amplitude is relatively small at 2.5 K.

Mass flow rate fluctuations are severe throughout the compression system.
5. Conclusions

- Demonstrated the ability to successfully predict compression system mild surge physics with GT-Power

- The computational results for mild surge almost exactly reproduce the amplitudes, frequency, and time averaged operating points of the experimental observations.

- The present study implemented a compressor map which was created from experimental data that was extrapolated and interpolated to cover the entire forward flow operating region.

- A detailed computational analysis of the pressure, temperature, and mass flow rate fluctuations is presented at key compression system locations during mild surge.

- The approach described here may be incorporated into turbocharged engine models to assist with the design.
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Thank You for Your Attention

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