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Abstract

This report describes a project in nonlinear control where the results of Eyad Abed et. al. concerning surge phenomena in axial flow compressors. The problem is analyzed and simulation programs are presented.

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Verification of Anti-Surge Phenomena in Axial Flow Compressors

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1. Introduction

This report verifies the results presented by [1] concerning bifurcation analysis in axial flow compressors. The work was supervised by Karl Johan Åström who came up with the idea.

Axial flow compressors behave undesirably (see [1]) for pretty small disturbances in the throttle characteristic, for example a slight closing of the throttle. The system characteristics are given in Figure 1. The intersection of the initial characteristics is the operating point, where the system operates efficiently. At the perturbed intersection, efficiency is low and so called rotating stall behavior, that requires a restart of the compressor, occurs. But is the Rotating Stall Equilibrium (RSE) always a global attractor for the system? We examine this aspect.

2. Variation of the Lumped Compressor Parameter B

Exactly what is the system behavior for different lumped compressor parameters, B? Mathematical investigation (see [1]) gives us the reduced order system model

$$\frac{d\dot{m}_C}{dt} = B(C_{ss}(\dot{m}_C) - \Delta P) \tag{1}$$

$$\frac{d\Delta P}{dt} = \frac{1}{B}(\dot{m}_C - \frac{A_T}{A_C}(\Delta P)^{\frac{1}{2}}) \tag{2}$$

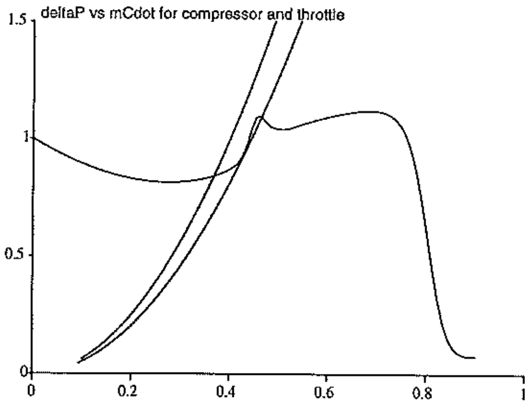

Figure 1 The compressor and throttle characteristics. The operating point is at the peak of the compressor characteristic, where it intersects the original (right) throttle characteristic. The perturbation moves the throttle characteristic left and the intersection is now the Rotating Stall Equilibrium (RSE).

Variation of the B-parameter gives completely altered system behavior, as mathematically predicted, see [1].

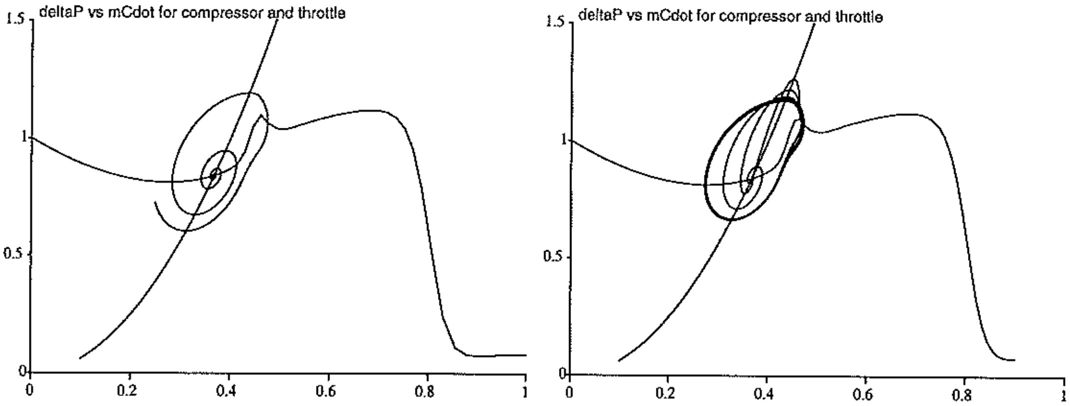

Figure 2 *Left figure:* B=0.368, starting point $\dot{m}_C = 0.25$, $\Delta P = 0.73$. The RSE is a global attractor for the system at this small B. *Right figure:* B=0.1, 0.2, 0.3, 0.405, starting at the operating point. As B increases, the convergence to RSE slows, until at $B = 0.405$ the solution becomes periodic.

For *small B* the RSE is a global attractor for the system (see Figure 2 and [2]), and consequently perturbations from the initial value of the operating point converge quickly to the RSE, see Figure 2.

At $B = B_1$, two initially identical periodic solution are born, as in Figure 3. The operating point is inside the envelope, and perturbation thus still results in RSE.

As B is increased, the periodic solution *splits* into one stable periodic solution (called *surge*) and one unstable (*antisurge*), see Figure 4. All solutions with initial values outside the surge or between the surge and antisurge envelope converge to the surge oscillation. Inside the antisurge, solutions still converge to

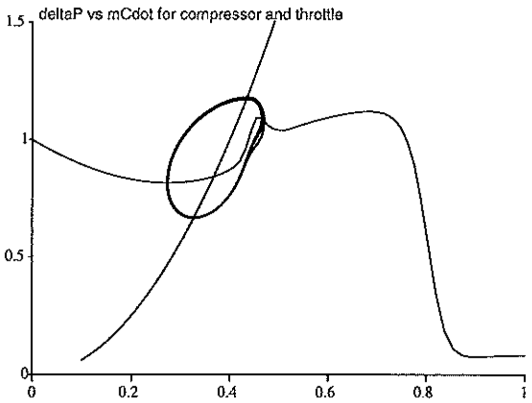

Figure 3 $B = 0.405$ The RSE is no longer a global attractor. All solutions with initial values inside the periodic solution converge to the RSE, and initial values outside give convergence to the periodic solution.

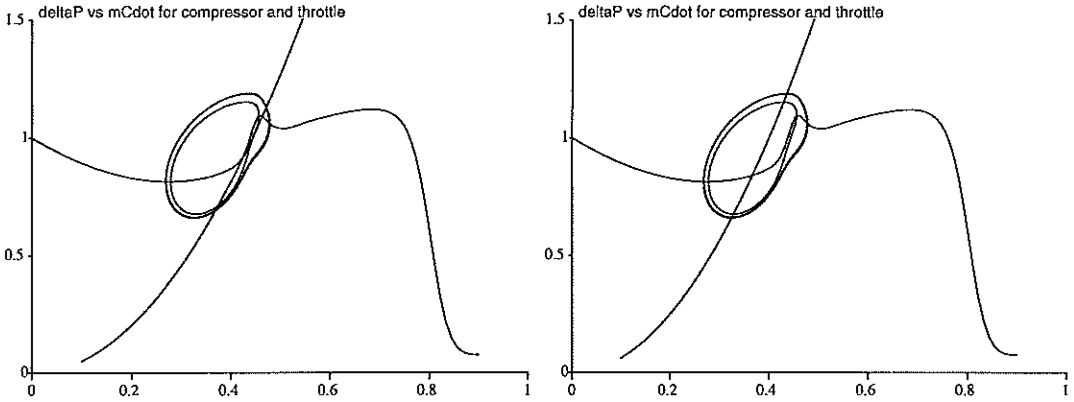

Figure 4 *Left figure:* $B = 0.41$ Unperturbed compressor characteristic. The operating point is now in the area of attraction of the surge oscillation. *Right figure:* $B = 0.41$ Perturbed compressor characteristic.

the RSE. The point of interest, the operating point, is when $B = B_2$ *between* the envelopes and the system experiences surge instead of rotating stall.

As B increases further, the stable solution expands and the unstable one shrinks. Figure 5 clearly shows the attraction areas. Finally, at $B = B_3$ the antisurge area collapses into a point (see Figure 6), the RSE in fact. This is a mathematically predicted Hopf bifurcation, see [1]. The RSE is now an unstable equilibrium point, and the stable solution is a global attractor of the system, see Figure 6.

For very large B, the surge limit cycle turns into a relaxation oscillation, characterized by having two different time scales. The oscillation follows the compressor characteristic slowly, and jumps between the branches quickly, see Figure 7.

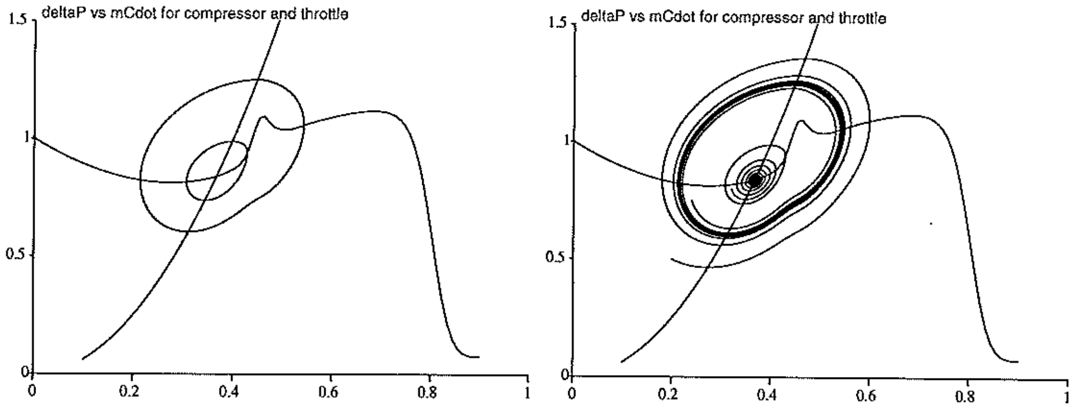

Figure 5 *Left figure:* $B = 0.5$ Surge and antisurge. *Right figure:* $B = 0.5$ Attractor regions for different initial values.

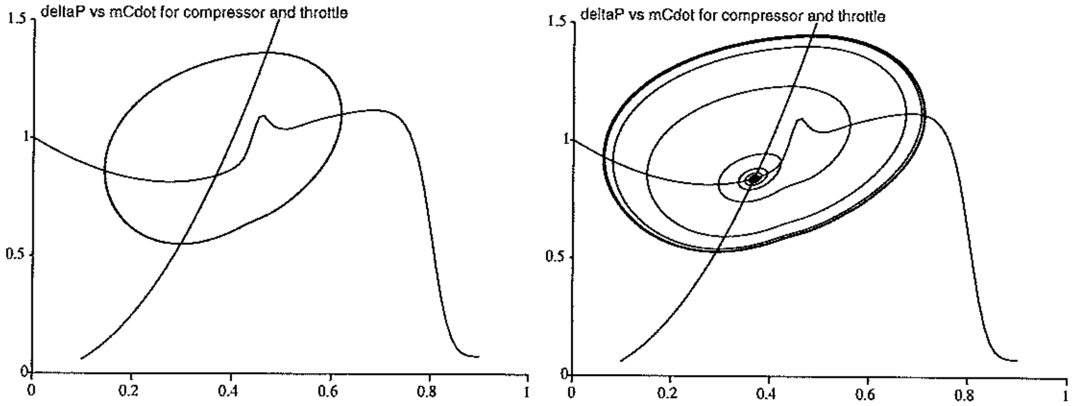

Figure 6 *Left figure:* $B = 0.58$. The antisurge oscillation has become the RSE. Solutions starting at RSE stay there, all others converge to surge. *Right figure:* $B = 0.7$, starting at RSE. RSE is now an unstable equilibrium point, and surge oscillation is a global attractor.

3. Conclusions

The compressor model used differs from that of [1] thus giving different critical values of B, but the general effects of varying B are the same.

For a small throttle perturbation, small B give quick convergence to RSE. As B increases, the speed of convergence decreases until two initially identical periodic solutions are born, one stable and one unstable (surge and antisurge). The surge amplitude increases and the antisurge amplitude decreases. Starting values outside the surge and between the surge and antisurge converge to surge and inside the antisurge converge to RSE.

As the antisurge oscillation passes the operating point, the perturbed system goes from rotating stall to surge. The oscillation amplitudes keep on changing, and finally the antisurge collapses into the RSE which turns into an unstable equilibrium point. Surge is now a global attractor.

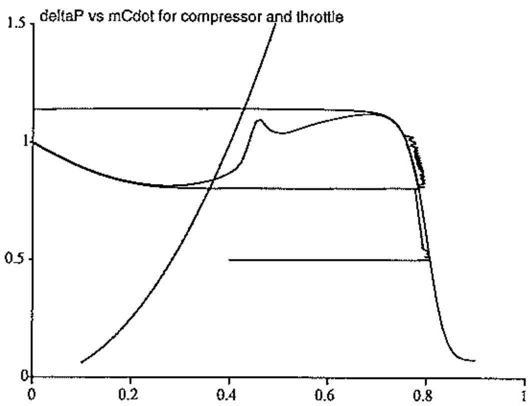

Figure 7 *Left figure:* $B = 10$. The surge oscillation has turned into a relaxation oscillation with two very different time scales. The oscillation follows the compressor characteristic slowly, and jumps between the branches quickly.

Very large B turn the surge limit cycle into a relaxation oscillation, characterized by having two different time scales: a slow time scale that follows the compressor characteristic and a fast one that jumps between two branches of the compressor characteristic.

4. Bibliography

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[2] Jean-Jaques E. Slotine and Wieping Li. *Applied Nonlinear Control* 1991 Prentice Hall