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Active Compressor Surge Control System by Using Piston Actuation: Implementation and Experimental Results ⋆

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Abstract: A novel implementation and experimental test results of a piston actuated active surge control system (PAASCS) on a laboratory scale pipeline-compressor system are presented. The experimental test is done to prove the concept of stabilizing compressor surge by dissipating the plenum energy using a piston actuation. The PAASCS's controller is applying ψ-control introduced in (Uddin and Gravdahl, 2016), which only uses feedback from pressure measurements at the compressor discharge and in the plenum. Practical aspects of implementing the PAASCS are presented including: flow measurement, generating a compressor map based on a compressor performance test, piston design, and the test setup. The experimental test results show that the PAASCS is able to stabilize surge and prove the concept of PAASCS with the advantage of ψ-control which stabilizes compressor surge by using feedback from pressure measurements only.

Keywords: Compressor, active surge control, pitot tube flow measurement, linear actuator, hardware in the loop test, experimental.

1. INTRODUCTION

A centrifugal compressor operating area is commonly shown by a compressor map, where the compressor operation at low mass flows is limited by a surge line. The operating area on the left side of the surge line is unstable and will lead to surge, while it is stable operating area on the right side of the line. Compressor surge is an aerodynamic instability in the compression system and results in an axisymmetric oscillation of the compressor mass flow and the compressor pressure. The instability is physically indicated by pressure fluctuation, reversal flow, temperature fluctuation and followed by severe vibration. Compressor surge leads to compressor damage especially at the rotating parts, for examples: compressor blades, shaft and bearing, and also pipeline and structure (Gravdahl and Egeland, 1999).

A method to stabilize surge by using a state feedback control was introduced by Epstein et al. (1986). The method is known as active surge control system (ASCS). Several actuators have been applied in the ASCS as summarized in (Willems and de Jager, 1999; Uddin and Gravdahl, 2015), for examples: movable plenum wall, close couple valve, drive torque, active magnetic bearing, and piston actuation. Based on how the actuators work to stabilize surge, the ASCS can be classified in two types: upstream energy injection and downstream energy dissipation (Uddin and Gravdahl, 2015). The upstream energy injection ASCS is stabilizing surge by increasing the upstream pressure to increase the upstream energy, while the downstream energy dissipation ASCS is stabilizing surge by flowing extra fluid out from the plenum to decrease the downstream energy. Two general state feedback control law for the both ASCS types were introduced by Uddin and Gravdahl (2016), and named ϕ-control for the upstream energy injection and ψ-control for the down stream energy dissipation. Both control laws make the closed loop system globally asymptotically stable (GAS) and the advantage of them are the minimum sensor requirement. The ϕ-control requires feedback from the compressor mass flow measurement only, while the ψ-control requires feedback from pressure measurements at the compressor discharge and in the plenum only.

Piston actuated active surge control system (PAASCS) was in introduced by Uddin and Gravdahl (2011b). It is in the class of ASCS with downstream energy dissipation. Theoretical works to improve the PAASCS performance have been done by: introducing integral action to eliminate piston drift (Uddin and Gravdahl, 2011a), and introducing a back-up system by using blow-off mechanisms (Uddin and Gravdahl, 2012b) and by using surge avoidance system (SAS) (Uddin and Gravdahl, 2012a) for fail-safe operation.

This paper presents the implementation and the experimental test results of a PAASCS on a laboratory scale pipeline-compressor system running at a constant compressor speed. An experimental test setup is built in Compressor laboratory at Departement of Engineering Cybernetics, NTNU. The PAASCS control law is applying

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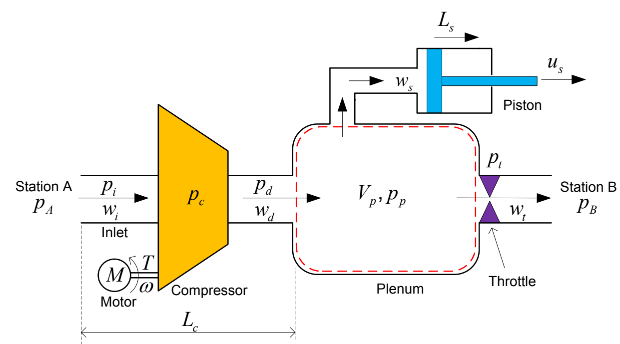

Fig. 1. Piston actuated active surge control system.

the ψ-control. The control gain is determined by using the test setup parameters and a compressor map. The compressor map is obtained through a compressor performance test. The control law algorithm is written in Matlab and Simulink and embedded in a dSpace board to build a hardware in loop simulation. The PAASCS is tested experimentally to see the performance of the system in stabilizing surge. The test is started by running the compressor at a constant speed and reducing the flow by closing an outlet valve (throttle) such that the compressor is entering surge while the PAASCS is inactive. The PAASCS is then activated after the compressor is in surge. The surge is shown by pressures oscillation sensed by pressure sensors at the compressor discharge and in the plenum. This is the first experimental confirmation of actively stabilizing compressor surge by using piston actuation.

2. SYSTEM DYNAMICS AND CONTROL

A model of PAASCS is shown in Figure 1. The PAASCS model is a modification of the Greitzer compressor model (Greitzer, 1976) by adding a piston. The assumptions in the Greitzer model are applied in the PAASCS model. The p_A and p_B are the ambient pressures and assumed to be equal, and fluid pressures in the system are measured relative to the ambient pressure. It is assumed that pressure drop along the ducts in the system are neglected. Therefore, the compressor discharge pressure (p_d) is equal to the compressor pressure rise (p_c), and the compressor discharge mass flow (w_d) is equal to the inlet mass flow (w_i). Dynamic equations of the PAASCS model are given as follows (Uddin and Gravdahl, 2011b):

$$\dot{w}_i = \frac{A_c}{L_c}(p_c - p_p) \tag{1}$$

$$\dot{p}_p = \frac{a_0^2}{V_p}(w_i - w_o - w_s), \tag{2}$$

where A_c is the compressor duct cross-sectional area, L_c is the effective length of the equivalent compressor duct, p_p is the plenum pressure, a_0 is the speed of sound, V_p is the plenum volume, w_o is the outlet mass flow, and w_s is the piston mass flow. The outlet mass flow is the set point of the desired compressor operating mass flow. A compressor operating point is an equilibrium point where $\dot{w}_i = 0$ and $\dot{p}_p = 0$. The piston mass flow is defined by:

$$w_s = \rho A_s \frac{dL_s}{dt}, \tag{3}$$

Table 1. Major components of test setup.

Component	Detail
Compressor	Supercharger Vortech V-1 S-Trim Race M
Pressure sensor	Druck PTX 610
Mass flow sensor	Endress+Hauser t-mass 65F80
Valve	Siemens PN 10
Pipeline	Polypropylene pipe with diameter 75mm
Plenum	Cylindrical vessel
Control board	dSpace DS1103
Piston	See Section 3.3

where ρ is the fluid density, A_s is the piston cross-sectional area, and L_s is the piston position. To simplify the surge control design, we ignore the piston dynamic and assume that the piston will generate a mass flow w_s following a reference signal. Define constants $B_1 = \frac{A_c}{L_c}$ and $B_2 = \frac{a_0^2}{V_p}$, and substitute them into (1) and (2) such that results in:

$$\dot{w}_i = B_1(p_c - p_p) \tag{4}$$

$$\dot{p}_p = B_2(w_i - w_o - w_s). \tag{5}$$

The PAASCS is in the class of downstream energy dissipation ASCS (Uddin and Gravdahl, 2011b) such that the ψ-control introduced in (Uddin and Gravdahl, 2016) is applicable.

Theorem 1. The ψ-control states that an equilibrium point of (4) and (5) is globally asymptotically stable (GAS) if $w_s = w_u$, where $w_u = -k_u(p_c - p_p)$ with $\frac{2B_1}{B_2}k_m < k_u < \frac{2B_1}{B_2}k_n$, $k_m = \left.\frac{\partial p_c}{\partial w_i}\right|_{\max}$ and $k_n = \left.\frac{\partial p_p}{\partial w_o}\right|_{\min}$.

The stability proof can be found in (Uddin and Gravdahl, 2016). The surge control requires w_s to behave as w_u, and it is the task of a piston as the actuator of PAASCS.

3. LABORATORY TEST SETUP

The concept of PAASCS is implemented and tested on a laboratory scale pipeline-compressor system at Compressor Laboratory in Department of Engineering Cybernetics, NTNU. A PAASCS test setup is built as shown in Figure 2. Major components in the setup are listed in Table 1 and most of the components have been used in an experimental work on compressor surge control using torque drive (Bøhagen, 2007). Fluid pressures in the setup are measured relative to the ambient pressure.

3.1 Mass flow measurement

The mass flow sensor used in the setup is Endress+Hauser t-mass 65F80-AE2AG1AAAAAA. It is a high performance mass flow sensor for industrial gases and compressed air. The sensor is configured to measure mass flow at a range of 0 to 0.26 kg/s. The sensor has high accuracy with measurement error 2% of the measured value (Endress+Hauser, 2015). However, the sensor response is quite slow such that it is only applicable for measuring steady flow and not for measuring unsteady flow. Because surge is unsteady flow, we measure mass flow using a pitot tube as an alternative solution. The pitot tube is installed at the compressor inlet duct and equipped with two pressure sensors to measure the total pressure (p_t) and the static pressure (p_s). The mass flow is calculated by following equation:

$$\bar{w} = A_c\sqrt{2\rho(p_t - p_s)}, \tag{6}$$