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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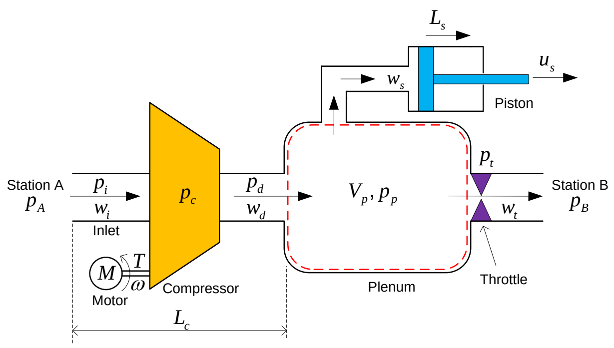

Fig. 1. Piston actuated active surge control system.

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:

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

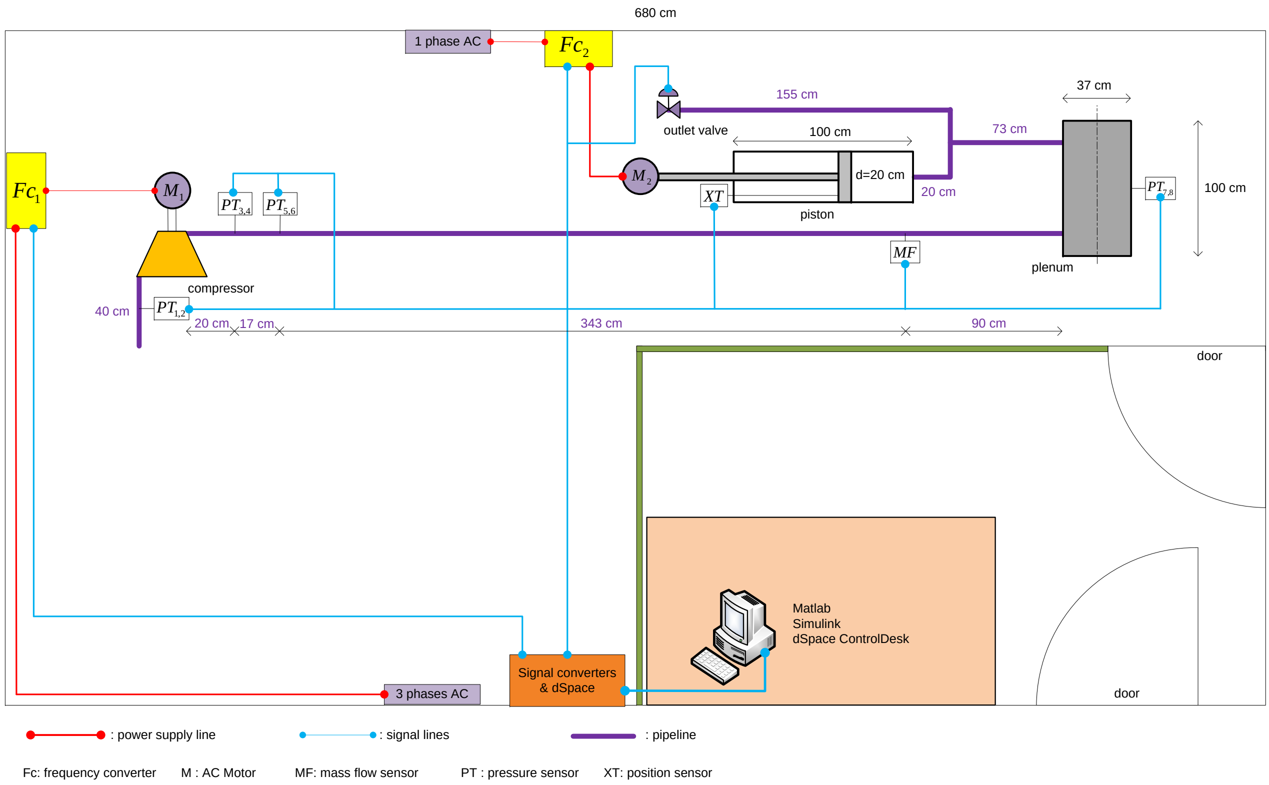

Fig. 2. Compression system with PAASCS test setup at Compressor Laboratory, Dept. of Engineering Cybernetics, NTNU.

where $\bar{w}$ is the calculated mass flow and A_c is the inlet pipe cross-sectional area. The fluid density (ρ) is assumed to be constant and equal to the ambient air density. The calculated mass flow is corrected by calibrating the mass flow measurement using pitot tube with the mass flow measurement using the mass flow sensor. The corrected mass flow is given as follows:

$$w = 0.45\bar{w} - 0.0035, \tag{7}$$

where w is the corrected mass flow. The main reasons for this correction are misalignment of pitot tube and incorrect air density. The pitot tube mass flow measurement provides a much faster response than the mass flow sensor.

3.2 Compressor Performance Test

A compressor map of the test setup is obtained through a compressor performance test. The performance test is done by running the compressor at a constant speed for several operating points and recording data of the compressor mass flow and the compressor discharged pressure for each operating points. The compressor mass flow is measured using the pitot tube and calculated using (7). The operating point is changed by adjusting the throttle opening.

A test was done by running the compressor at 23978 RPM for eight operating points. The initial operating point is at throttle opening 40% and reduced gradually at 5% for the other seven operating points. The operating points are labelled sequentially by alphabet A to H. The test results show that the compressor is operating stable at the operating points A to G (throttle opening 40% to 10%), but not at the operating point H (throttle opening 5%). Figure 3 shows the compressor states for operating points A to G. The compressor entered surge at operating point H as shown in Figure 4. The compressor surge is shown by oscillations of the compressor mass flow, the compressor discharge pressure, and the plenum pressure. The mass flow measurement is not accurate because reversal flows (negative flows) were physically observed during surge in the performance test, but the measurement output is not negative. The surge phenomenon is therefore presented by pressure oscillations in this study. A further study on flow measurement during surge using a pitot tube is suggested.

A compressor map for stable compressor operating points are obtained by approximating the compressor states of the seven operating points (A to G) by a cubic function as shown by "*Approximation 1*" in the Figure 3. The peak point of curve "Approximation 1" is the surge point. The compressor map for unstable compressor operating points are estimated by a cubical function introduced in (Moore and Greitzer, 1986) and given as follows:

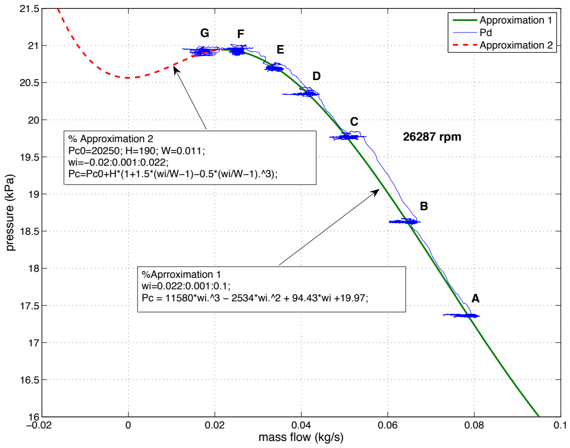

Fig. 3. Compressor map obtained by a performance test.

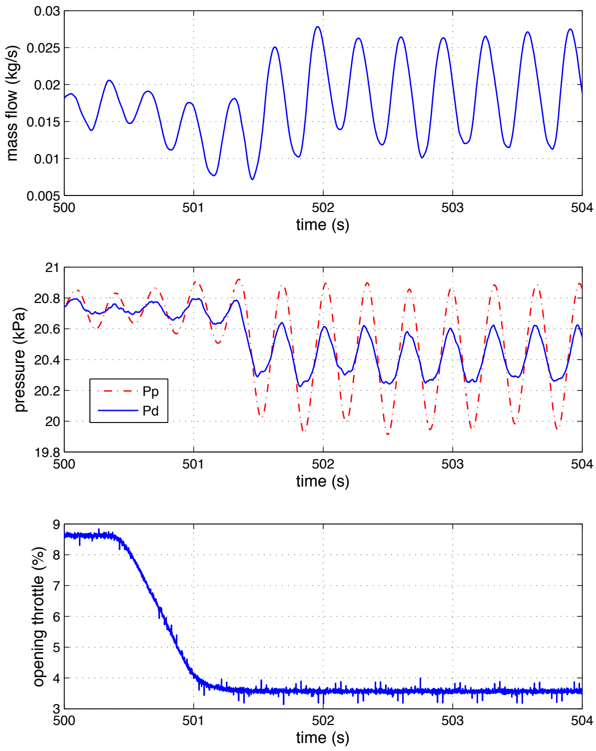

Fig. 4. Compressor is surge at operating point H with throttle setting 5%.

$$p_c\left(w_i\right) = p_{c_0} + H\left[1 + \frac{3}{2}\left(\frac{w_i}{W} - 1\right) - \frac{1}{2}\left(\frac{w_i}{W} - 1\right)^3\right] \quad (8)$$

where p_{c_0} is the shut-off value of the axisymmetric characteristic, W is the semi-width of the cubic axisymetric compressor characteristic, and H is the semi-height of the cubic axisymetric compressor characteristic; consult (Moore and Greitzer, 1986) for more detailed definitions. The value of H is approximated by the amplitude of the compressor discharged pressure oscillation during compressor surge as shown in Figure 4. The mass flow of the surge point is equal to $2W$. The value of p_{c_0} is approximated by subtracting $2H$ from the pressure of the surge point. The estimated compressor performance curve at unstable operating area is shown by "Approximation 2" in Figure 3.

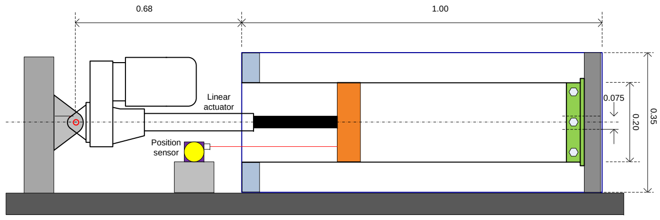

Fig. 5. Piston design.

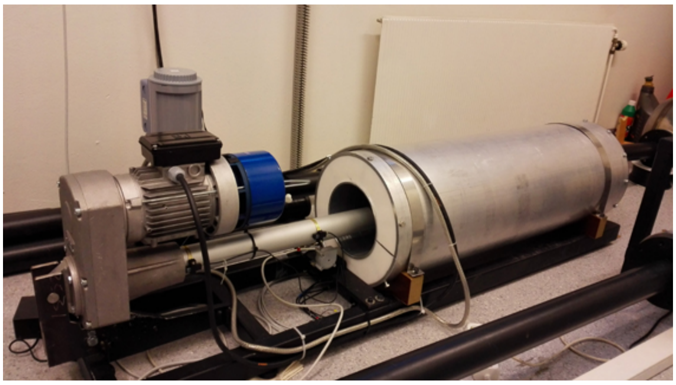

Fig. 6. Piston unit.

3.3 Piston

A piston as the actuator of PAASCS is required to have sufficient power and speed to generate mass flow w_s to stabilize compressor surge. Based on the compressor map, the piston must be able to work at pressure 21 kPa. The piston mass flow is determined by the piston cross-sectional area and the piston speed. To minimize the length of the piston, the piston should have a larger cross-sectional area. By considering further applications of the piston, we decided to have a piston with diameter 0.2 m. The piston was designed as shown in Figure 5. The piston is driven by a linear actuator Servomech UAL4RV2C500 which has maximum speed 0.44 m/s, maximum displacement 0.5 m, and maximum force 1700 N (Servomech, 2015). The piston displacement is sensed by a spring loaded potentiometer Multicomp SP1-50 Transducer. The piston displacement is set up in the range of ± 0.25 m. The piston was manufactured by the workshop staff at Engineering Cybernetics, NTNU as shown in Figure 6.

The piston dynamics is obtained through a closed loop system identification using the data of the piston displacement and the input signal. Figure 7 shows a block diagram of the closed loop system identification where $L_{s_{ref}}$ is the position input as the reference signal, L_s is the piston displacement, k_{s_1} is a proportional control gain, k_{s_2} is the position sensor gain which is a conversion factor from meter to volt, and G_s is the piston transfer function. An initial test by exciting the piston using a step function reference signal showed that the piston movement is very

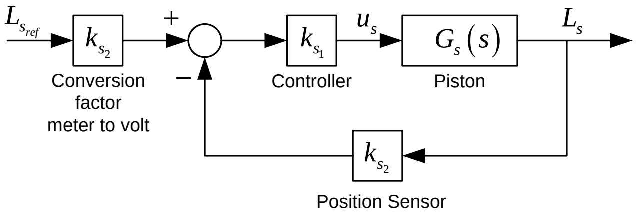

Fig. 7. Block diagram of piston system identification.

slow. Therefore, a proportional controller, $k_{s_1} = 10$, is applied to get a faster response. The value of k_{s_2} is 6.17 volt/m, which was obtained through a calibration of the piston position sensor. Processing the data of the piston input and the piston displacement using Matlab Toolbox for System Identification results in a model with transfer function:

$$G_s(s) = \frac{L_s(s)}{u_s(s)} = \frac{0.251}{s(s+5.405)} \tag{9}$$

where L_s is the piston displacement in meters and u_s is the piston input voltage in volts.

4. PAASCS IMPLEMENTATION

Figure 8 shows block diagram of PAASCS implementation and the values of parameters in the test setup are given in Table 2. The algorithms in the block diagram are

Table 2. PAASCS Test Setup Parameters

Parameter	Value	Unit	Parameter	Value	Unit
a_0	340	m/s	V_p	0.12	m^3
L_c	0.8	m	A_c	0.0038	m^2
ρ	1.2041	kg/m^3	A_s	0.0314	m^2

implemented in a Simulink model and embedded into a dSpace board DS1103 to build a hardware in the loop (HIL) simulation. The dSpace board has a 20-channels digital to analog converter (DAC) and an 8-channels analog to digital converter (ADC) as the interfaces to connect with actuators and sensors, respectively.

The surge control gain k_u is calculated by using Theorem 1 where $\frac{2B_1}{B_2}k_m < k_u < \frac{2B_1}{B_2}k_n$. By using (8), compressor map in Figure 3, and the test setup parameters, it can be obtained $k_m = \frac{3H}{2W} = 2.5909 \times 10^4$ Pa.s/kg, $k_n = \left.\frac{2p_p}{w_o}\right|_{\min} = 3.3684 \times 10^5$ Pa.s/kg, $B_1 = 0.0047$, and $B_2 = 963330$. The calculation results in $2.555 \times 10^{-4} < k_u < 3.3 \times 10^{-3}$. We choose $k_u = 4 \times 10^{-4}$ for the experimental test. The output of the surge controller is w_u which is a reference mass flow for the piston. Since we only have a position sensor in the piston, the reference mass flow is converted to velocity with a conversion factor $\frac{1}{\rho A_s}$. The velocity is a reference velocity for the piston. An inner closed loop with a piston controller is required to assure that the piston movement follows the reference velocity. The piston controller is a PID controller with $k_p = 120$, $k_i = 5$, and $k_d = 1$. The Filter 1 is a first-order low-pass Butterworth filter with passband frequency 20π rad/s and the Filter 2 is a first-order low-pass Butterworth filter with passband frequency 60π rad/s.

5. EXPERIMENTAL RESULTS

An experimental test is performed to test the PAASCS performance. The compressor is running at 24335 RPM and the throttle opening is reduced to 5% such that the compressor enters surge as shown by the pressure oscillations since $t = 475$ seconds in Figure 9. The PAASCS controller is then turned on at $t = 482$ seconds and is suppressing the pressure oscillations. It results in stabilizing the compressor surge. The PAASCS controller is then turned off at $t = 513$ seconds and as can be seen the compressor is driven back to surge.

The experimental results in Figure 9 show that the piston velocity is not following the reference signal given by the surge controller. An investigation of the piston using the closed loop system identification data shows that piston bandwidth is about 1.2 Hz. The piston bandwidth is quite low compared to the surge frequency which is 3.5 Hz. This indicates that the piston response is quite slow to follow the reference signal.

The piston was also experience with some drift. Integral control was recommended by (Uddin and Gravdahl, 2011a) to eliminate the piston drift. It has been applied in this experimental test but it does not give to much improvement in this experiment. The slow response of the piston is the main reason of it.

It is expected that a faster linear actuator for the piston would lead to better performance. Nevertheless, surge was stabilized with the current actuator.

6. CONCLUSION AND FURTHER WORKS

An implementation and experimental test of PAASCS were done and the results were presented. The PAASCS is able to stabilize compressor surge and prove the concept of PAASCS. The PAASCS by using ψ-control makes the implementation simple as only requiring feedback from pressure measurements.

Recommendation of further works to improve the PAASSC are given as follows. The performance of PAASCS can be improved by using a better linear actuator with higher bandwidth. The measurement of piston velocity can be improved by using velocity sensor instead of using the time derivative of the position sensor output. The mass flow measurement by using pitot tube can be improved by considering that the air density is varying instead of assuming it as a constant. The air density can be approximated as a function of temperature. Another solution for the mass flow measurement is by using an observer as introduced in (Bøhagen and Gravdahl, 2002).

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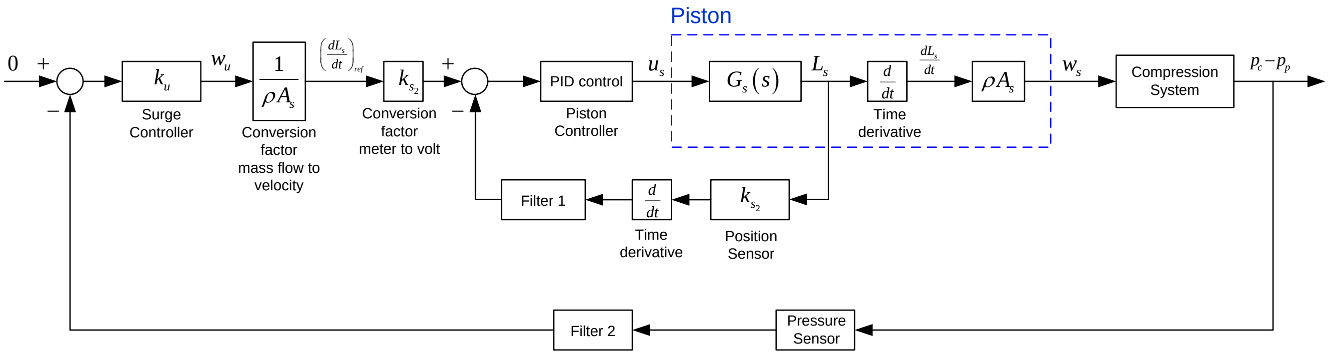

Fig. 8. PAASCS block diagram.

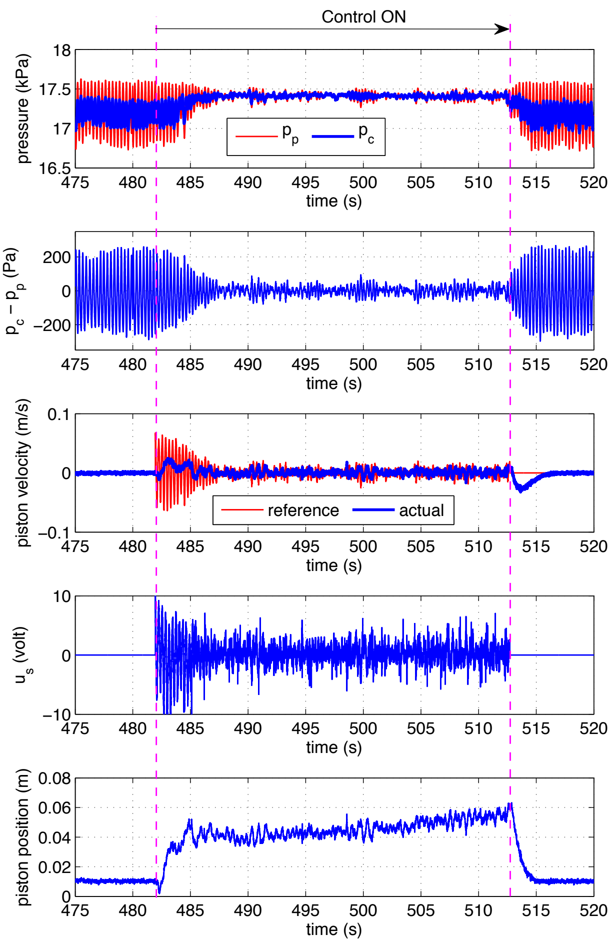

Fig. 9. Experimental result of PAASCS.

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