A COMPRESSOR SURGE CONTROL SYSTEM: COMBINATION ACTIVE SURGE CONTROL SYSTEM AND SURGE AVOIDANCE SYSTEM

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ABSTRACT

A novel method for combining active surge control system (ASCS) and surge avoidance system (SAS) for a centrifugal compressor is presented. ASCS is a promising method to improve compressor operating area by stabilizing surge. However, this method is not applied yet in industrial compressors. Safety issue is considered in implementing the ASCS. A failure in ASCS may endanger the compressor by entering deep surge as the compressor is allowed to operate in the stabilized surge area. Combination of ASCS and SAS is proposed to improve the safety by utilizing the SAS as a back-up system. SAS is a reliable method in surge control and widely applied in industrial compressors. However, the compressor operating area is reduced by applying the SAS. An ASCS by using piston actuation is used as a case study and performance evaluations of the combined system are done by simulations.

1 INTRODUCTION

Compressor operating area can be described by plotting compressor pressure rise against flow for varying compressor speed and called a compressor map. The stable compressor operating area is limited for low mass flows by the so-called surge line and for high mass flows by the stone wall or choke line. Operating the compressor at mass flows below the surge line will drive the compression system into an instability known as surge. This is an axisymmetric oscillation of mass flow and pressure rise and is followed by severe vibrations in the compression system. The vibrations may reduce the reliability of the system and large amplitude vibrations may lead to compressor damage, especially to compressor blades and bearings.

The compressor surge phenomenon can be solved by preventing the compressor operating point from entering the surge area. This solution is known as a surge avoidance system (SAS). The SAS usually works by recycling flow from downstream to upstream when the operating point reaches a surge control line (SCL). The SCL is located to the right of the surge line and becomes the minimum allowed mass flow for the compressor. Such surge avoidance schemes successfully ensure safe operation, but the introduction of the surge control line reduces the usable size of compressor map, thereby restricting the compressor operational envelope.

Another surge solution is to stabilize the surge phenomenon by using an active control system. This method is known as active surge control system (ASCS) and was proposed by Epstein et al. in [1]. Since then a number of theoretical and experimental results have been published. A number of different actuators and control methods have been applied, as summarized by [2]. Recent developments in this field include the work by [3] on hydraulic actuators as well as [4] on drive torque actuation.

Active surge control systems have mainly been implemented in laboratories and have not yet found wide spread use in industrial compression systems. To our best knowledge, an industrial compressor equipped with ASCS has not been reported yet and it is believed that concerns about safety is the main reason. Since ASCS works by stabilizing surge to enlarge the operating area, the enlarged area is open loop unstable such that a failure in the active system may cause the compressor to go unstable by entering surge. A back-up system can be a solution to improve the safe operating of the compressor with ASCS. We have introduced blow-off surge control as the back-up of a main ASCS using piston actuation [5]. The PAASCS as the main system is working by default and the back-up system is working only if the PAASCS should fail. The changing operation from the main system to the back-up system is carried out by a switch. The result shows the back-up system was able to keep the compressor in a safe operation when the ASCS is fail. The ASCS with piston actuation or known as piston actuated active surge control system (PAASCS) was proposed in [6]. A piston is applied to absorb plenum energy during compressor surge. An improvement in control design to minimize the required piston stroke was done by including integral action as presented

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TABLE 1. Dimensional and non-dimensional variables

Variable	Dim.	Non-Dim.
Pressure	p	$\psi = \frac{p}{\frac{1}{2}\rho U^2}$
Compressor pressure rise	p_c	ψ_c
Mass flow	w	$\phi = \frac{w}{\rho U A_c}$
Effective duct length	L	
Sound velocity	a_0	
Duct cross section area	A	
Piston stroke	L_s	$\lambda = \frac{L_s}{L_c}$
Piston cross section area	A_s	
Volume	V	

Subscripts

f	feed line	b	buffer	s	piston
c	compressor	d	discharge	p	plenum
1	inlet	t	throttle	r	recycle line

in [7]. Active surge control using a blow off valve was presented in [8].

Considering the application of blow-off surge control is limited and not applicable in several industrial process, for example in natural gas, petrochemical or toxic gas, then recycling surge control (SAS) should be applied. A model of a compressor equipped by SAS including the effect of the recycling flow to the upstream states was studied in [9]. It was also presented an example of PI controller for the SAS. This paper builds on the work in [5] by combining ASCS and SAS where the SAS is used as the back up of the ASCS to improve the safe operation of ASCS. Since the SAS is widely applied in industrial compressors, it also is proposed as a bridge to make the ASCS closer to the industrial implementation. A study case using piston actuated active surge control system and a failure cases due to piston saturation is presented. Stability of the switching operating of the both system is shown by the system trajectories.

The paper consists of five sections as started by introduction in section I. Section II is describing compressor dynamics including surge phenomenon. Section III is presenting compressor surge and control. Active surge control using piston actuation and surge avoidance system are described. Section IV presents an active surge control with a back-up system by combining PAASCS and SAS.

2 Compressor Dynamics

A model of a compression system was introduced by Greitzer in [11] and shown in Fig. 1. It is assumed that the pressure at station A and B are same at a constant value and

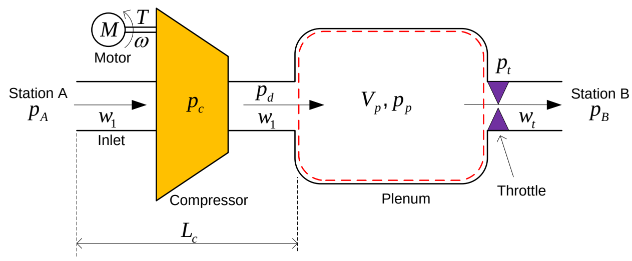

FIGURE 1. Model of basic compression system.

all pressures in the system are measured relative to the pressure at the both stations. Dynamics of the compression system are given as follows:

$$\dot{w}_1 = \frac{A_c}{L_c}[p_c - p_p] \tag{1}$$

$$\dot{p}_p = \frac{a_0^2}{V_p}[w_1 - w_t] \tag{2}$$

and the non-dimensional form are:

$$\dot{\phi}_1 = B(\psi_c - \psi_p) \tag{3}$$

$$\dot{\psi}_p = \frac{1}{B}(\phi_1 - \phi_t). \tag{4}$$

where B is the Greitzer parameter defined by $B = \frac{U}{2\omega_H L_c}$ and ω_H is Helmholtz frequency defined by $\omega_H = a_0\sqrt{\frac{A_c}{V_p L_c}}$. The time derivative is done using non-dimensional time defined by $\tau = t\omega_H$.

The compressor pressure rise is given as a function of mass flow and compressor rotational speed $p_c(w_1, \omega)$ and usually presented in a compressor map provided by the compressor manufacturer. The function can also be obtained in experiments by performing engine test to collect data and approximated by a function. Moore and Greitzer introduced a cubic function to approximate compressor pressure rise for a constant rotational speed [12]:

$$\psi_c(\phi_1) = \psi_{c_0} + H\left[1 + \frac{3}{2}\left(\frac{\phi_1}{W} - 1\right) - \frac{1}{2}\left(\frac{\phi_1}{W} - 1\right)^3\right] \tag{5}$$

where ψ_{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-hight of the cubic axisymetric compressor characteristic, consult [12] for more detailed definition.

Non-dimensional throttle mass flow is defined by:

$$\phi_t = \gamma_t\sqrt{\psi_p} \tag{6}$$

where γ_T is a function of the throttle setting.

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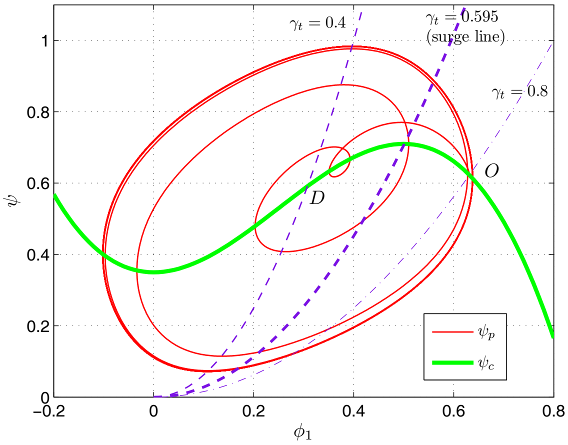

FIGURE 2. System trajectory during surge.

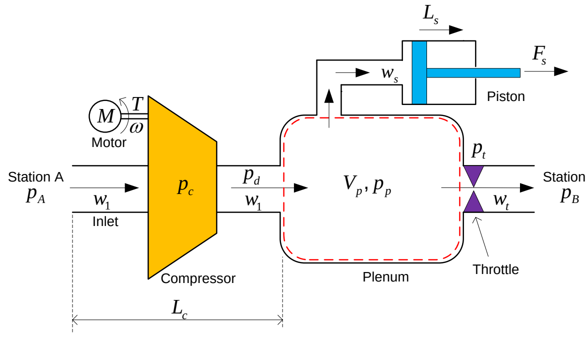

FIGURE 3. Compression system equipped with combined active surge control system and surge avoidance system.

3 Surge and Control

3.1 Surge

Compressor operating point is defined as the intersection between compressor characteristic curve and the load (throttle) characteristic curve. Two operating points O and D are shown in Fig. 2. The operating point O is a stable operating point as located in the right side of surge line, but the operating point D is unstable operating point (in the surge area) as located in the left side of the surge line. Figure 2 is showing the system trajectory when the compressor operating point moves from O to D by reducing the throttle setting from $\gamma_t = 0.8$ to $\gamma_t = 0.4$. Surge as defined by an axisymmetric oscillation of mass flow and pressure rise is shown by a limit cycle in that figure.

Compressor surge can be stabilized either by increasing upstream energy or decreasing downstream energy [9]. Flowing out fluid from the plenum will decrease the downstream energy such that can be applied in surge control. Compressor dynamics including surge control by plenum flow-out is given by:

$$\dot{\phi}_1 = B(\psi_c - \psi_p) \tag{7}$$

$$\dot{\psi}_p = \frac{1}{B}(\phi_1 - \phi_t - \phi_u) \tag{8}$$

where ϕ_u is plenum flow-out as the control flow. Surge avoidance system (SAS) and piston-actuated active surge control (PAASCS) are the examples of surge control based on the plenum flow-out control. PAASCS is not only able to remove fluid from the plenum, but also to inject fluid back into the plenum such that the value of ϕ_u can be positive and/or negative.

3.2 Piston Actuated Active Surge Control System

A model of a compression system equipped with piston for active surge control is shown in Fig. 3 and the non-dimensional dynamics equations are given as follows [6]:

$$\dot{\phi}_1 = B\left[\psi_c - \psi_p\right] \tag{9}$$

$$\dot{\psi}_p = \frac{1}{B}\left[\phi_1 - \phi_t - \frac{k_a}{2B}\dot{\lambda}\right] \tag{10}$$

$$\ddot{\lambda} = \frac{2B^2}{M_s}(k_a\psi_p + u_s) \tag{11}$$

The control flow in PAASCS is a function of the piston velocity as given by $\phi_s = \frac{k_a}{2B}\dot{\lambda}$. The control force to drive the piston can be designed by using the available control methods. An example design by using linear quadratic control including integral action was presented in [7] and the control law was given as follows:

$$u_s = \tilde{u}_s - k_a\psi_{pO} \tag{12}$$

where $k_a = \frac{A_s}{A_c}$, $\tilde{u}_s = -K_1\tilde{x}_1$ and $\tilde{x}_1$ is states deviation from operating point O given by $\tilde{x}_1 = [(\phi_1 - \phi_{1_O}), (\psi_p - \psi_{pO}), \dot{\lambda}, \lambda, \int \lambda dt]^T$. It is assumed that the piston is idle at zero position at operating point O. A control design using the method results in $K_1 = \left[5867.2\ -476.4\ 260.9\ 1328.8\ 316.2\right]$ and the closed loop eigenvalues at $s_{1,2} = -4.9292 \pm 5.5060i$, $s_3 = -6.7789$ and $s_{4,5} = -0.2117 \pm 0.2037i$. All eigenvalues are located in the left half plane (LHP) such that the system locally asymptotically stable. Figure 4 shows the system trajectory of compressor equipped by PAASCS. It is shown the system is stable even though the operating point moves in the left side of surge control line. Figure 5 shows the piston displacement during the surge stabilization.

An alternative control law using feedback from plenum pressure and piston displacement only can be found in [6].

3.3 Surge Avoidance System

A compression system equipped with SAS is shown Fig. 6. The effect of the recycling flow to the inlet flow is shown by a control volume in the inlet called buffer. The

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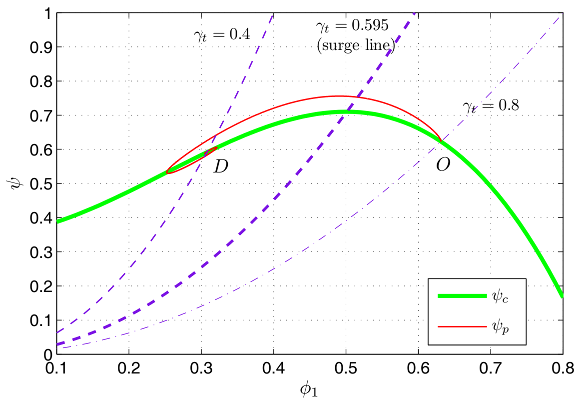

FIGURE 4. Close loop trajectory of compressor equipped with PAASCS during surge.

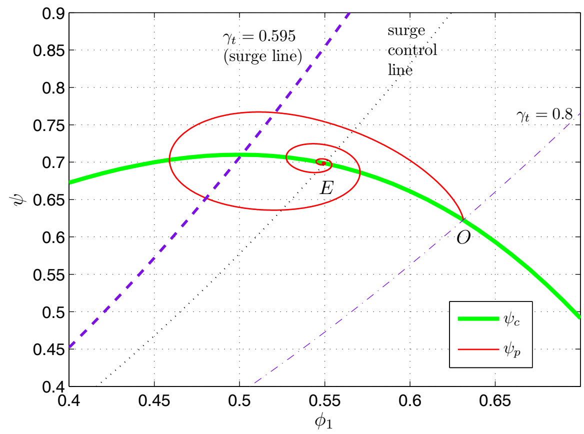

FIGURE 7. Close loop trajectory of compressor equipped with SAS during surge.

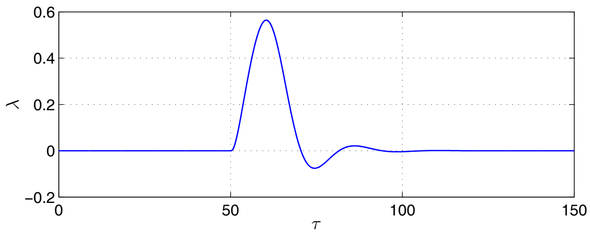

FIGURE 5. Piston displacement during the surge stabilization.

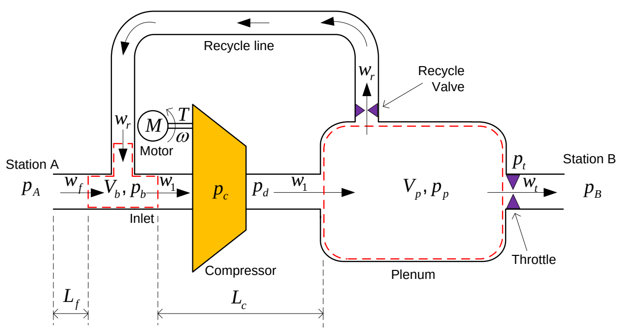

FIGURE 6. Compression system with recycle line.

non-dimensional dynamic equations are given as follows [9]:

$$\dot{\phi}_f = -B_I \psi_b \tag{13}$$

$$\dot{\psi}_b = \frac{1}{B_C}\left[\phi_f + \phi_r - \phi_1\right] \tag{14}$$

$$\dot{\phi}_1 = B\left[\psi_b + \psi_c - \psi_p\right] \tag{15}$$

$$\dot{\psi}_p = \frac{1}{B}\left[\phi_1 - \phi_t - \phi_r\right] \tag{16}$$

where $B_I = \frac{A_f L_c}{A_c L_f} B$, $B_C = \frac{V_b}{V_p} B$ and ϕ_r is recycled mass flow as the plenum flow-out control. The recycled mass flow is a function of plenum pressure as described by:

$$\phi_r = k_{\gamma_r} u_r \sqrt{(\psi_p - \psi_b)} \tag{17}$$

where k_{v_r} is recycle-valve constant and u_r is the valve control signal signal. The range value of u_r is from 0 to 100 %.

A control design using proportional and integral (PI) control was presented in [9] as follows:

$$u_r = K_p \phi_e + K_i \int \phi_e dt \tag{18}$$

where K_p is proportional gain, K_i is integrator gain, and ϕ_e is mass flow error defined by:

$$\phi_e = \phi_{SCL} - \phi_1 \tag{19}$$

where ϕ_{SCL} is mass flow at the surge control line. Only the non-negative mass flow error is used to generate the valve control signal, such that:

$$\phi_e = \begin{cases} \phi_e & \text{for } \phi_e \geq 0 \\ 0 & \text{for } \phi_e < 0. \end{cases} \tag{20}$$

We choose $\psi_{SCL} = 0.55$ in the study case. Figure 7 shows the system trajectory of a compressor equipped by SAS when the operating point moves from O to D. It shows the operating point is not able to reach the point D and goes to point E located at the SCL.

4 Active Surge Control with a Back-up System

4.1 Combining PAASCS and SAS

It has been shown that both PAASCS and SAS are able to maintain the stable compressor operation. However, it should

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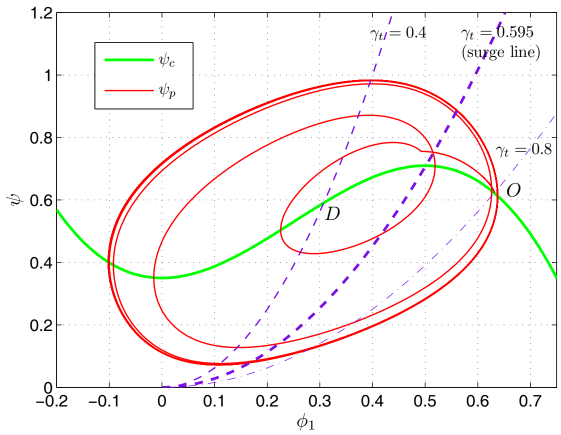

FIGURE 8. System trajectory of compressor with PAASCS when the piston saturated.

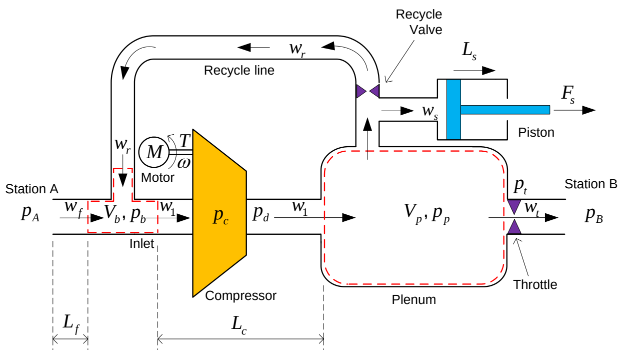

FIGURE 9. PAASCS with SAS as the back-up.

be noted that PAASCS is stabilizing surge by moving the piston such that the surge control performance depends on the piston performance. The piston performance has some limitations and one is the maximum stroke. In a condition when the required stroke is more than the maximum stroke then the piston is saturated. It has been shown in Fig. 5 that the system stabilization for the changing operation from point O to D requires piston stroke up to 0.56. In the case the available piston has maximum stroke ± 0.40, the piston will be saturated during the stabilizing surge. Figure 8 shows the system trajectory of surge stabilization by using a piston with maximum stroke ± 0.40. The piston saturation makes the PAASCS fail to stabilize the system and the compressor entering surge.

A back-up system is then necessary for the active surge control system to recovery the compressor when the active system should fail. For that purpose, we use SAS as the back-up of PAASCS as shown in Fig. 9. A switch is used to change the operation from the PAASCS to SAS and works only if the PAASCS should fail. We only consider the failures of the PAASCS due to piston saturation. Those failures are detected by observing the piston velocity $\dot{\lambda}$ and the piston control law output $\tilde{u}_s$. Since both PAASCS and SAS use plenum flow-

TABLE 2. SIMULATION PARAMETERS

Variable	Value	Variable	Value	Variable	Value
$\frac{V_b}{V_p}$	0.005	$\frac{L_f}{L_c}$	0.1	$\frac{A_f}{A_c}$	1
$\frac{A_s}{A_c}$	1	ψ_{c0}	0.352	W	0.25
ϕ_{fO}	0.6312	ϕ_{SCL}	0.55	K_i	15
ϕ_{1O}	0.6312	H	0.18	ψ_{bO}	0
ψ_{pO}	0.6226	K_p	20	k_{γ_r}	0.05
M_s	21.85	k_a	1	B	0.8

out (ϕ_u) for surge control then switching algorithm can be defined as follows:

$$\phi_u = \begin{cases} \phi_s \\ \phi_r & \text{for } \tilde{u}_s \neq 0 \wedge \dot{\lambda} = 0 \end{cases} \tag{21}$$

where $\wedge$ is AND logic operator. The switching is only one-way from the main system to the back-up system and not in the reverse way. Figure 10 shows the control loop of PAASCS including SAS as the back-up system.

Figure 11 shows the trajectories of the compressor system with PAASCS and SAS as the back-up. The SAS recoveries the compressor system from entering surge by moving the operating point to point E when the piston is fail. The system trajectories shows the switching system is locally asymptotic stable.

Figure 12 shows the SAS is recycling the flow when the piston saturates for recovery the compressor from entering surge. The compressor mass flow and plenum pressure during the recovery are shown in Fig. 13. The compressor is recovered and operates steady at mass flow 0.55 which is value of the chosen ϕ_{SCL}.

5 Conclusions

An active surge control system using piston actuation combined with SAS as the back-up system was presented. The back-up system is only used to recovery the compressor system from entering surge when the active system should fail. The simulation result showed the capability of the SAS in performing the recovery.

6 Future Works

The work will be continued to give an analytic proof of the switching stability in the switching operation from PAASCS to SAS and the case study will be extended to the failure due to jamming piston. The proposed method in combining PAASCS and SAS will be tested in a laboratory scale at Department of Engineering Cybernetics, NTNU.

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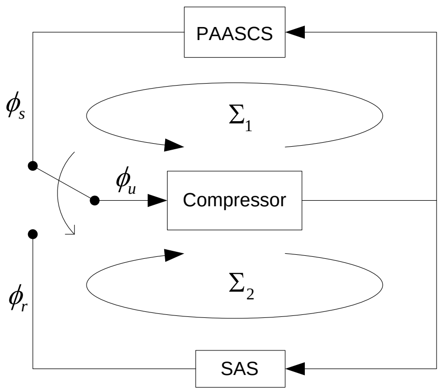

FIGURE 10. Control loop of PAASCS with SAS as the back-up .

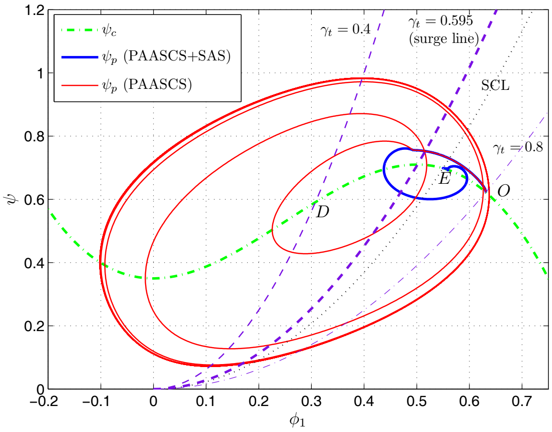

FIGURE 11. Close loop trajectory of compressor equipped with PAASC and SAS as the back-up when the PAASC is fail.

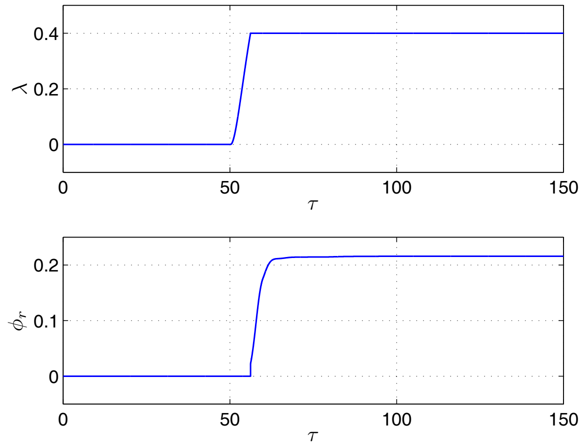

FIGURE 12. SAS is recycling flow when the piston saturates.

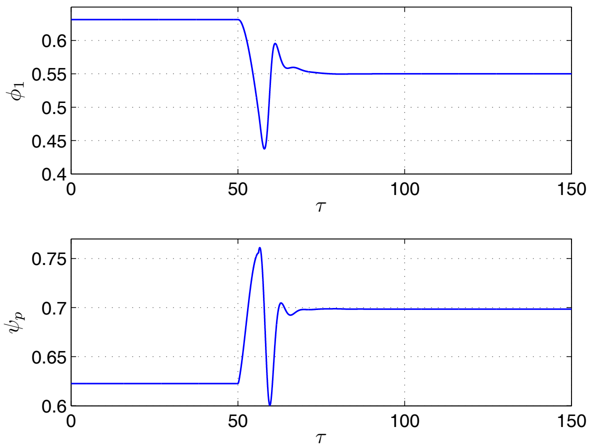

FIGURE 13. Compressor mass flow and plenum pressure of compressor equipped with PAASC and SAS as the back-upwhen the PAASC is fail.

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