International Journal of Natural and Engineering Sciences
E-ISSN: 2146-0086 18(2): 92-107, 2024
Research Article

Surge control in centrifugal compressor using dynamic controllers

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(Received: January 4, 2024 / Accepted: July 30, 2024)

Abstract

Compressors are of particular importance due to their widespread use in various industries for compression and gas transfer. The centrifugal compressor increases the gas pressure and temperature by increasing the kinetic energy using rotating blades. Controlling the compressor's surge phenomenon is very important because it happens very quickly and will cause damage to the compressor, electric motor drive, and the production process. This phenomenon is defined as an instability during compressor workflow and usually occurs in centrifugal compressors. Controlling the surge phenomenon is causing of the expansion the operational range of the compressor operation. In this paper, the third-order Moore–Greitzer's dynamic model and the active control method are presented based on the back stepping and dynamic surface for controlling the surge phenomenon. The simulation results show that the controllers designed in both ways have the ability to control the compressor in the surge mode. Among the prominent innovations of the article, we can point out a structure for evaluating the back-stage controller in the case of constant increase in the centrifugal compressor and the dynamic level controller in the case of the constant increase in the centrifugal compressor. In Dynamic surface control system indicate that the scaled annulus-averaged flow is stable in 1 s and high accuracy is maintained.

Keywords: surge phenomena, dynamic surface control, compressor, back-stepping controller

Introduction

With the increasing expansion of industrial centres and increasing the scope of energy use, providing energy for life has become very important [1,2]. Energy plays a fundamental role in the prosperity of the industrial economy, in other words, with the availability of sufficient energy, economic development will also be possible [3,4]. Energy exists in many forms, such as heat, light, mechanical, electrical, chemical, and nuclear [5,6]. Much research has been done in the field of production, conservation, and transmission, which shows the importance of energy use [7,8].

The gas power plant is one of the power plants used in power networks, and their power is from one megawatt to 100 megawatts [9,10]. In Iran, gas power plants are responsible for more than 20 percent of electrical energy generation [11,12]. Gas power plants are suitable for peak consumption hours due to their high start-up speed [13]. The working fluid in the gas power plant is air and operates according to the Brayton cycle. According to Figure 1, it consists of three main components: compressor (compressing the air), combustion chamber (burning the fuel in the chamber), and turbine (turning the generator) [14,15]. Compressors are used in various industries to compress and transport gases [16,17]. Based on how energy is transferred from the compressor to the fluid, the compressors are divided into two groups: dynamic compressors and positive displacement compressors. In dynamic compressors, the fluid's energy transfer is permanent and is divided into centrifugal and axial groups [18,19].

The compressor in a gas power plant, like a turbine, has a rotor on which a movable blade is placed [20,21]. The air hits the stationary blades and changes the direction of the air's movement, and this air hits the moving blades again; and this cycle continues, and the air will become more compact with each operation. Compressors are a huge consumer of energy [22,23]. The inlet fluid enters the compressor and enters the combustion chamber after condensation and slightly warming. Compressed hot air acts like compressed hot steam in steam turbines. Turbines have stationary and movable blades, and compressed hot air enters the gas turbine, causing the generator to rotate [24,25].

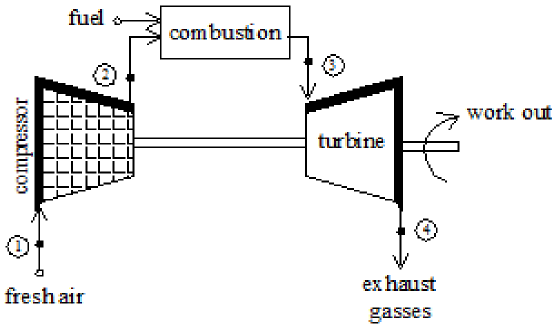

Figure 1. *Gas power plant working cycle*

The surge phenomenon is an instability of the airflow, and by limiting the operation region of the compression system, it is preventing from reaching the maximum efficiency of the compressor [26,27]. This phenomenon occurs at low air mass flow rates in the compressor and causes fluctuations with large amplitude in the pressure and mass flow rate of the compressor's output air. One of the important points in analysing the performance of a compressor is estimating its surge limit [28,29]. So far, various studies on the problems of the surge phenomenon and its control methods have been presented in axial and centrifugal compressors [30,31].

Literature survey

A feedback controller has been proposed based on the compensation method for surge control in [32]. In such a way, the input signal is used to control the surge, and the simulation results show the proper performance of this controller. In [33] is used a PID controller to control the surge of a centrifugal compressor. In [34], Moore-Greitzer's model is used for modelling, and two fuzzy PI and PID controllers are used to control the compressor surge. By examining the system's stability time with the controller, which is two and three seconds for the fuzzy PID and PI controllers, respectively, the superiority of the fuzzy PI controller over the PID controller is shown. In [35], the output static positive feedback control is presented based on the pole placement method using Moore-Greitzer's linearized model with two-mode variables for control the surge with the valve stimulator of discharge the mass flow. And ignoring changes in the compressor speed and temperature causes improving about seven percent at the mass flow of the surge point. In [36] examines a centrifugal compressor with a DC motor. A nonlinear relationship between airflow (air pressure) and motor speed is considered, and compressor surge control is performed by speed change. Also with assuming the air inlet flow is constant, it has shown that motor speed control by an intelligent controller can increase or decrease the output air pressure. A multi-level pressure system is used in [37]. The compressor is radial, and the control target is considered a closed-loop. The output pressure is according to the air inlet's adjustment valve, and whatever the inlet valve is closed, the pressure will be reduced.

Model predictive control methods have been suggested in various articles for surge control [38,39]. In [40], the model predictive control method is used to control the surge, such as controlling the inlet gas valve to prevent the compressor from entering the surge region. In [41], the model predictive control method is used to design the surge controller in centrifugal compressors. The system dynamics are considered nonlinear, and the controller is tested in the form of a closed-loop by numerical methods, which has yielded good results for the controller. And it works well compared to PI and PID controllers. In the above research, surge control has been designed and simulated by several different controllers.

In [42] the design of a close-couple valve (CCV)-based surge controller for centrifugal compressors is studied. The nonlinear controller model, predictive control method, is studied tested with the modelling Moore–Greitzer’s of simulation scenarios at different conditions. Its capability to reject the flow disturbances related to surge instability and stabilize the compressor system has been shown. In [43] is presented a new robust predictive controller for centrifugal compressors. The controller is designed to optimize the 'worst-case' objective function over an infinite moving horizon to show the proposed algorithm's efficiency and effectiveness; a surge phenomenon avoidance problem in centrifugal compressors is solved. The results obtained from the simulation show the efficiency and resistance of this controller

The sliding mode control method has been used in a number of references to control the surge [44]. In [45], using the second-order mode sliding method and controlling the valve close to the compressor without the need to know the compressor, and using Moore-Greitzer's model, the process of the surge in the compressor was controlled. And the validation of the proposed model using simulation in MATLABS/W has been shown.

Centrifugal air compressors are a pivotal part of the cathode air supply system, and have a central position to ensure the efficient operation of the on-board fuel cells. In [46], the predictive performance of linear-based reinforcement models has been investigated, and the multi-objective optimization of propeller structural parameters has been performed through reference vector oriented evolutionary algorithm. It is clear from the simulation results, the main compressor impeller shows a large entropy increase, insufficient gas compression, and serious energy loss, so considerable space is required for design optimization.

Main study and innovation

One of the important instabilities in the compressor's performance is the surge phenomenon, which reduces efficiency and causes damage to the compression system. Fuzzy systems for the system can be used in two ways: system control and the system's dynamic approximation. In this paper, the method of controlling the surge phenomenon and preventing its occurrence is presented. Moore-Greitzer's third-order model is used to modelling the phenomenon, and its dynamic equations are described. Fuzzy dynamics will be used to better the approximation of the close-couple valve. Because the compressor is a highly nonlinear system, back stepping control methods and dynamic surfaces have been used to control it. According to this paper's authors, for this model of centrifugal compressors, no dynamic surface controller has been used to date. The simulation results show the effect of the presented method on controlling the surge phenomenon.

The centrifugal compressor increases the gas pressure and temperature by increasing the kinetic energy using rotating blades. The gas is sucked into the chamber, and the blade forces the gas to spin at high speed. Finally, the gas with the highest speed passes through a diffuser, in which the volume of the gas increases and its speed decreases. In this process, the gas's kinetic energy at low pressure and high speed is converted to low speed and high pressure. The final pressure also increases as the blade rotates. Unlike the reciprocating compressor, in the centrifugal compressor, all processes (suction, compression and discharge in each cycle) are performed simultaneously and continuously.

The innovations of this paper are:

1. The structure of the Moore–Greitzer’s is designed to model the centrifugal compressor.

2. The structure to assess the back stepping controller concerning the constant surge in the Centrifugal compressor.

3. The structure to assess the dynamic surface controller concerning the constant surge in the Centrifugal compressor.

In this paper, surge control centrifugal compressor is investigated. A Moore–Greitzer’s is used for modelling compressors. The back stepping and dynamic surface control methods are used to control the compressor. The structure of the paper is as follows: In section 2, the surge of the compressor is briefly described. The modelling and designing of the back stepping and dynamic surface controllers are discussed in sections 3 and 4, respectively. In section 5, the results of the simulation are discussed. Finally, in section 6, the conclusion is provided.

Surge

The surge phenomenon cause is limiting the operational range of gas compressors. This phenomenon consists of a non-constructive and destructive cycle. The gas flow inside the compressor is reversed for a moment; in other words, the gas is driven from the compressor outlet to the compressor inlet. Among the causes of the surge phenomenon: (1) is high pressure at the outlet when the compressor is on the work line, (2) increasing the pressure in the compressor outlet valve due to closing the path in the lower hand, (3) reducing the inlet gas pressure to the compressor, (4) the rapid reduction in the compressor speed. Also, the characteristic of the occurrence of surge can be referred to severe pressure fluctuations, excessive compressor vibrations, rapid reversely of the compressor output current, rapid increase in the temperature of the passing gas, and the internal temperature of the compressor. Surge control methods are the use of drain valve and the use flow return pipes [47]. The compressor performance diagram consists of two horizontal and vertical axes as well as a curved handle that shows the horizontal axis, the flow rate (capacity), and the vertical axis, head, or pressure [48,49].

The compressor must change its speed to change the output flow. There are a minimum point and a maximum point of flow for each velocity, which among them, the compressor's operation is stable and predictable. The maximum capacity point is called the stonewall point, and the minimum capacity point is called the surge point. By connecting the surge points at different turns, the surge line of the compressor is formed. The surge is shown on the characteristic curve of the compressor in Figure 2 [50,51].

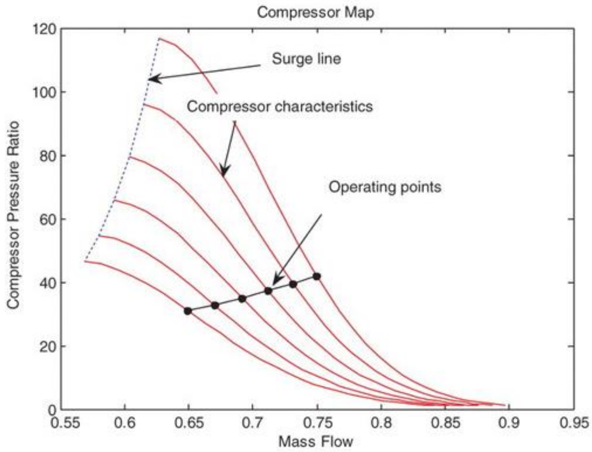

Figure 2. *Specifying the surge line in the compressor performance diagram*

If the compressor works on the right side of the surge line, it is in stable mode, and if it works on the left side of the surge line, it is in unstable or surge mode. By using the methods based on active surge control, it is possible to eliminate the instabilities leading to the surge and expand the system's stable performance region to the other side of the surge line, thus expanding the system's stable region.

Compressor dynamic model

A suitable dynamic model is required to design the controller and simulation the system. Due to the compressor structure of Figure 3, the dynamic model used for the compressor in this paper is the third-order Moore–Greitzer's model, which displays its state space is as follows [52]:

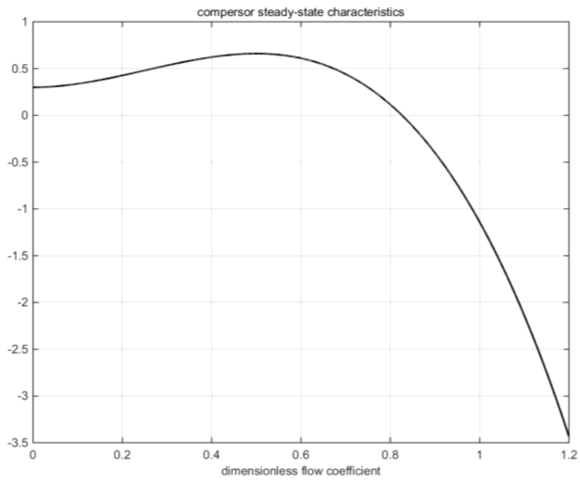

Figure 3. *Permanent-state characteristic of the compressor*

$$\frac{d\Psi}{dt}=\frac{1}{4B^2 l_c}[\Phi-\Phi_T(\Psi)] \tag{1}$$

$$\frac{d\Phi}{dt}=\frac{1}{l_c}[\Psi_c(\Phi)-\Psi-\frac{3H}{4}(\frac{\varphi}{W}-1)J] \tag{2}$$

$$\frac{dJ}{dt}=J[1-(\frac{\Phi}{W}-1)^2-\frac{J}{4}]\delta \tag{3}$$

where Φ is the average passing current, Ψ (output pressure to the compressor inlet) is dimensionless pressure rises coefficient, Φ_T is the throttle valve characteristic, Ψ_C is the characteristic of the constant state of the compressor, J is the suffocation coefficient and U is the compressor speed and the parameters δ and H are constant, W is the compressor width map, φ is the new flow rate coefficient. The Moore-Greitzer's constant (B) is also expressed as follows [53]:

$$B=\frac{U}{2L_C\,\omega_H} \tag{4}$$

The L_C is the effective length of the compressor tube. Assuming that the volume of the air collector (plenum) is equal to V_P and the cross-sectional area of the compressor passing current is A_C, which ω_H is the Helmholtz resonator frequency and is equal to

$$\omega_H=a\sqrt{\frac{A_C}{V_P L_C}} \tag{5}$$

That a is the speed of sound, in the Moore-Greitzer's model, the parameter B of the compression system is more than a critical value of B_{cr}, and the instability type of the compression system is considered as an increase. Then, parameter B is less than B_{cr}; the instability is presented as rotation, the steady-state characteristics of the compressor can be approximately according to the cube curve [54,55]. Figure 4 shows the characteristic of a permanent state of the compressor that a cubic curve can approximate.

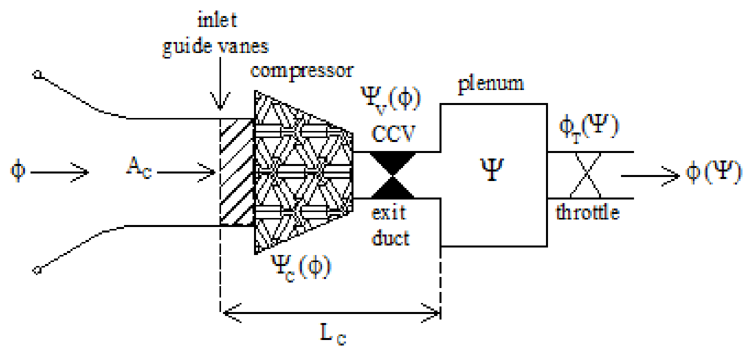

Figure 4. *The structure of system compression system with valve*

Surge control system

One of the challenges when working with a compressor is the surge phenomenon. At least, such phenomena should be prevented automatically or non-automatically. In this paper, the resistant adaptive fuzzy control method and dynamic surface control (DSC) method are used.

Back stepping control system

The back stepping method is one of the resistant control methods. Like the sliding model and other resistant methods, this controller is completely resistant to disturbances and changing parameters, as well as annoying noise. This method is widely used in various nonlinear systems. One of the reasons for this method's high efficiency is the simplicity of design and back stepping design. Also, this method relative to sliding mode in terms of no chattering is superior [56,57].

The diagram block of the back stepping control system is shown in Figure 5. In this control system, a is the virtual control law, and u is the real control law, B_{E1}, and B_{E2}, respectively, are estimated value of the unknown upper bound of pressure disturbance cycle in subsystems one and two, which as following are considered in the resistant adaptive fuzzy system for control the surge:

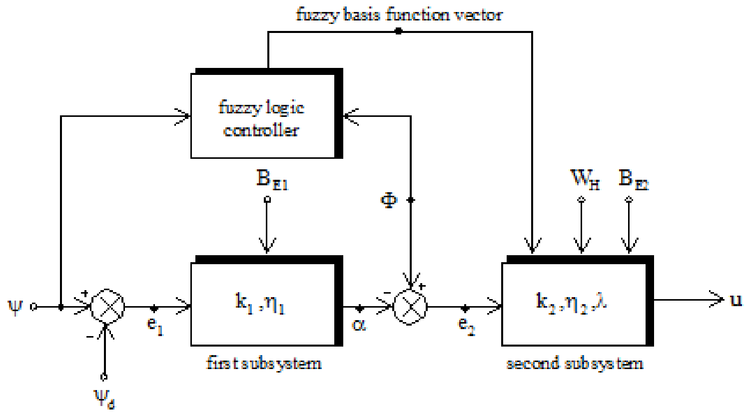

Figure 5. *Structural diagram of the back stepping surge control system*

$$\alpha = -k_1 e_1 + \Phi_T(\Psi) + 4B^2 L_C \dot{\Psi}_d + u_{r1} \tag{6}$$

$$u = k_2 e_2 + e_1 + \hat{f}_\alpha(\Psi, \Phi) - u_{r2} \tag{7}$$

$$\dot{\hat{B}}_1 = e_1 \tan(\frac{e_1}{\eta_1}) \tag{8}$$

$$\dot{\hat{B}}_2 = e_2 \tan(\frac{e_2}{\eta_2}) \tag{9}$$

where k_1 is the first sub-system, k_2 is the second sub-system, e1 and e2 are coordinate transformations, Ψ_d the given value of pressure coefficient, $\hat{f}_\alpha$ the fuzzy system, u_{r1} and u_{r2} are robustness designed for flow disturbance, η_1 and η_2 are controlled constant number. Proof of the stability of the above relationships is given in reference [58].

Dynamic surface control system

Although, control methods based on the back stepping method provide a resistant adaptive strategy for controlling the system in the presence of indeterminacy and operator saturation. But almost all of them suffer from the problem of sentence bursting, which is due to the creation of the consecutive derivatives of nonlinear functions and the limitations on the availability of all derivatives of reference paths for controlling design. A common way to overcome these limitations is to use the dynamic surface control method as an alternative to the back stepping control method to control the indefinite nonlinear systems [59,60].

Figure 6 shows the dynamic surface control method in which multiple sliding surface (MSS) and low-pass filter (LPF) constitute DSC. Also u is the control signal, φ is the new flow rate coefficient, and ψ is the pressure coefficient. ψ_{deb} is based on the state information as well as the filtered signal and ψ_{des} is calculates the forcing state values. Error coordinates for the dynamic compressor system are considered as follows:

$$\begin{cases} \psi = \Psi - \Psi_e \\ \varphi = \Phi - \Phi_e \end{cases} \tag{10}$$

Due to resolve the problem of surge control, the model is defined as follows [61,62].

$$\dot{\varphi} = \psi + \psi_c(\varphi) \tag{11}$$

$$\dot{\psi} = \frac{1}{4B^2 l_c}(\varphi + \Phi_0 + 1 - \gamma\sqrt{\Psi}) \tag{12}$$

So ψ_c is equal to:

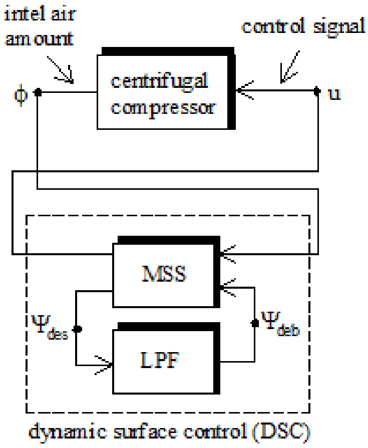

Figure 6. *Structural diagram of the dynamic surface surge control system*

$$\psi_c(\varphi) = \Psi_C(\Phi) - \Psi_C(\Phi_0) = \frac{3}{2}\varphi - \frac{1}{2}(\varphi^3 + 3\Phi_0\varphi^2 + 3\Phi_0^2\varphi) \tag{13}$$

The dynamic surface variable S_1 is defined as follows:

$$S_1 = \psi - \psi_{des}(\varphi) \tag{14}$$

As a result, equation (10) changes:

$$\dot{\varphi} = -c_1\varphi + p(\varphi)\varphi - S_1 \tag{15}$$

In the back stepping method, the design steps are step-by-step, and the derivative calculations $\psi_{des}(\varphi)$ are complex; p is the provides damping. The dynamic surface control method is used to simplify the computational processes and maintain useful nonlinearities to solve this problem. Consider the following relation.

$$\psi_{desb}(\varphi) = (c_1 + a)\varphi, c_1 \geq 0 \tag{16}$$

which in the above relations $\psi_{des}(\varphi)$ follows $\psi_{desb}(\varphi)$. That S_1 is the level between $\psi_{des}(\varphi)$ and $\psi_{desb}(\varphi)$ that will continue until the difference is zero. To solve the problem of return method, we will transfer $\psi_{desb}(\varphi)$ from a first-order filter:

$$\begin{cases} \tau_2\,\dot{\psi}_{des} + \psi_{des} = \psi_{desb} \\ \psi_{des}(0) = \psi_{desb}(0) \end{cases} \tag{17}$$

where τ_2 is a time constant, So the control signal is:

$$u = -c_2 S_1 + \dot{\psi}_{des}, c_2 \geq 0 \tag{18}$$

Finally, the control law is considered as follows:

$$\gamma = \frac{(\Phi_0 + 1) - B^2(-c_2 S_1 + \dot{\psi}_{des})}{\sqrt{\Psi}} \tag{19}$$

where c_1 and c_2 are controller parameters, γ is the control variable. The proof of the stability of the above relations is given in [63].

Simulation results

The compressor's ability to overcome the disturbances that may occur around its performance point is called stability in the compressor. The model obtained in the previous section has been studied by the controller designed in three scenarios without a controller, with the controller, and with a controller in the presence of environmental disturbance. The parameters of the compressor system are considered according to Table 1.

Table 1. *Compressor system parameters*

Symbol	Parameter	Amount	Unit
B	Moore–Greitzer's constant	1.8	-
L_C	Compressor pipe length	2	Meter
H	Semi-compressor height map	0.18	-
W	Compressor width map	0.25	-
ψ_C	Compressor shutdown valve factor	0.352	-
U	Average rotor speed	68	m/s
V_P	Compressor air volume	0.1	m^3
A_C	The cross-sectional area of the passing flow of the compressor	0.0038	m^2
a	Sound speed	340	m/s

No-control system

Figure 7 shows the changes in pressure coefficients and inlet flow rate in terms of time. As you can see, the compressor cannot reach the constant pressure without a controller, and the system works unstable. The result shows that compressor entered into deep surge after turning down the opening of throttle valve.

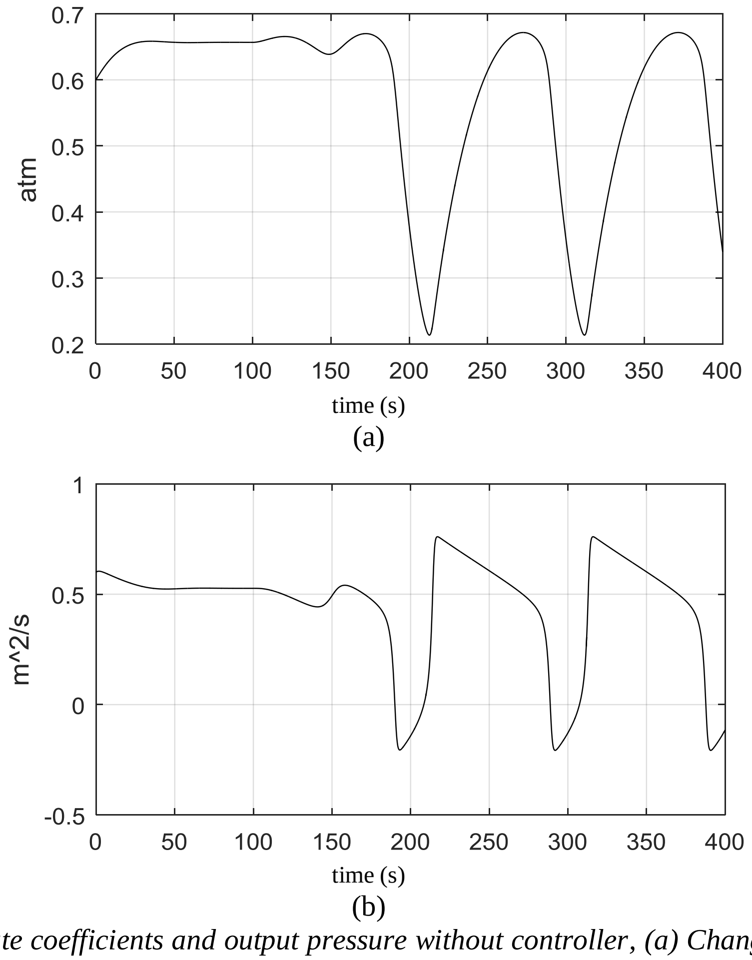

Figure 7. *Input flow rate coefficients and output pressure without controller, (a) Changes in output pressure coefficient without controller and (b) Changes in the input flow rate coefficient without controller*

Designed controller to the back stepping method

In this case, the designed controller to back stepping method enters the system, and the parameters are considered according to Table 2. Figure 8 shows the changes in pressure and inlet flow rate and control signal. As can be seen, the pressure coefficients and the inlet flow rate are fixed from the beginning, and the system will be easily controlled. And when the compressor enters the surge region, the coefficients change rapidly, and the compressor is taken out of this functional state and bring out from stability. The result shows that without disturbance, compressor was successfully stabilized in the region of low flow by the controller and did not enter into surge which demonstrated the effectiveness of the controller.

Table 2. *System parameters with controller*

Symbol	Parameter	Amount	Unit
K_1	First sub-system	0.5	-
K_2	Second sub-system	1.0	-
η_1	control constant number	0.05	-
λ	Control design parameter	2.0	-

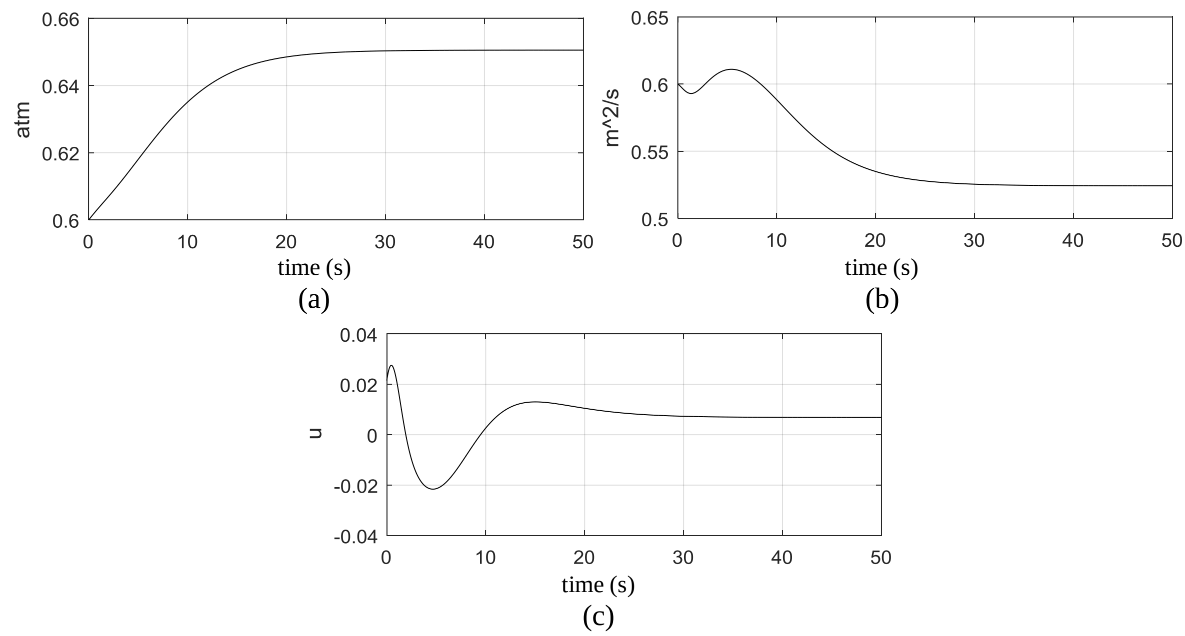

Figure 8. *Input flow rate coefficients, output pressure and control signal with designed controller to back stepping method, (a) Changes in the output pressure coefficient, (b) Changes in the input flow rate coefficient and (c) Control signal*

Designed controller by dynamic surface controller method

In this case, the designed controller is considered by the dynamic surface method. Figure 9 shows the changes in pressure coefficients, input flow rate, and control signal, which have reached stability in one second, indicating rapid adaptation.

Comparison of two controller design methods

The simulation results of the two controller methods for comparison are shown in Figure 10. As can be seen, stability with the dynamic surface controller happened less time than the back stepping controller. To make clearer the control signal and the input flow rate coefficient, the desired pressure level is considered to be 0.65 atmospheres for the back stepping controller and 2.4 atmospheres for the dynamic surface controller.

Comparison of two controller design methods with environmental disturbance

The simulation results of two controller methods with environmental disturbance are shown in Figures 11 and 12, which show the good performance of the dynamic surface controller with the presence of environmental disturbance. While the back stepping controller does not act well compared to the dynamic surface controller and has fluctuations.

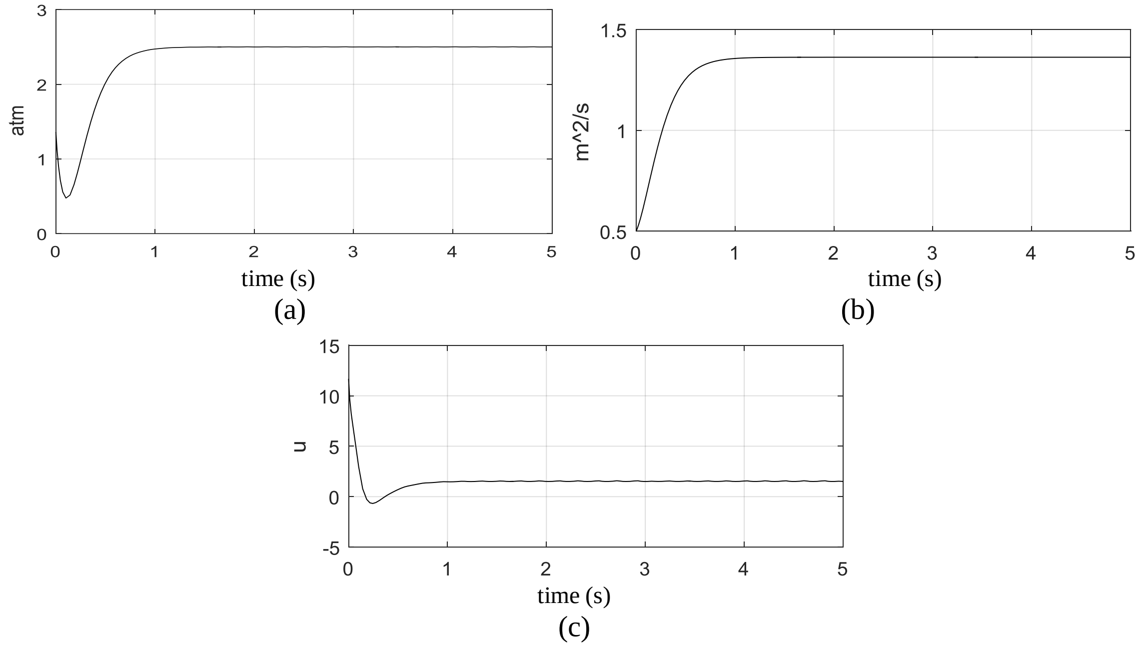

Figure 9. *Input flow rate coefficients, output pressure and control signal with designed controller to dynamic surface method, (a) Changes in the output pressure coefficient, (b) Changes in the input flow rate coefficient and (c) Control signal*

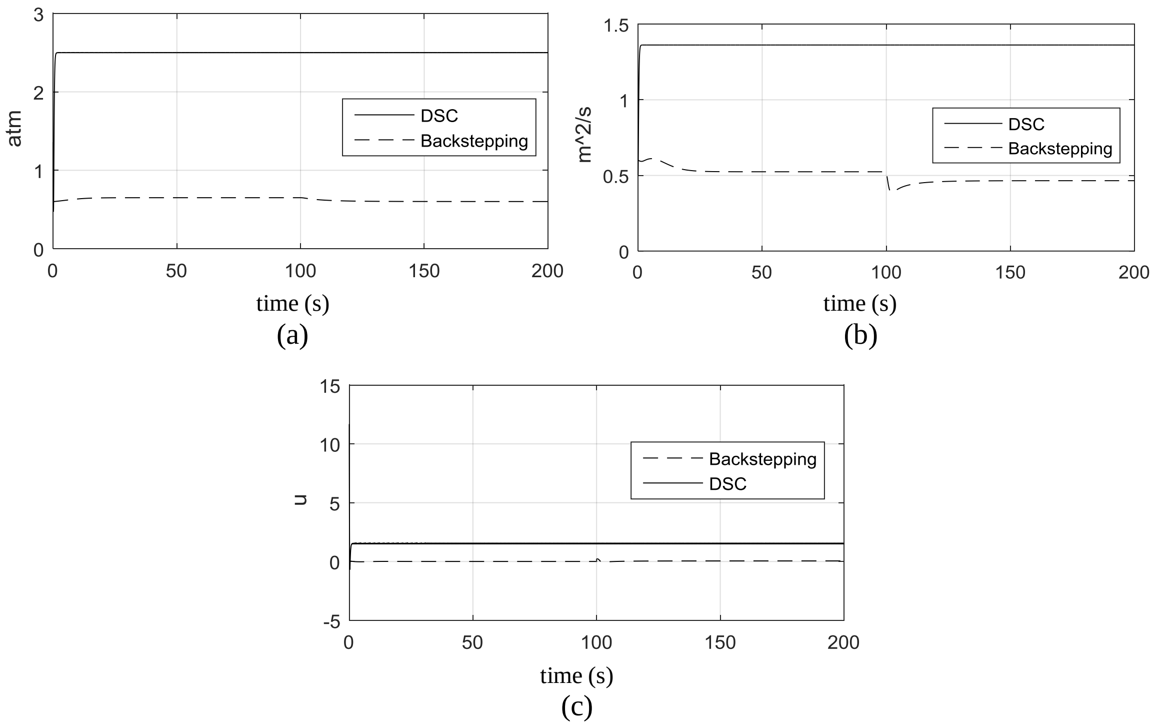

Figure 10. *Comparison of input flow rate coefficients, output pressure and control signal in design with two control methods, a) Changes in the output pressure coefficient, b) Changes in the input flow rate coefficient and c) Control signal*

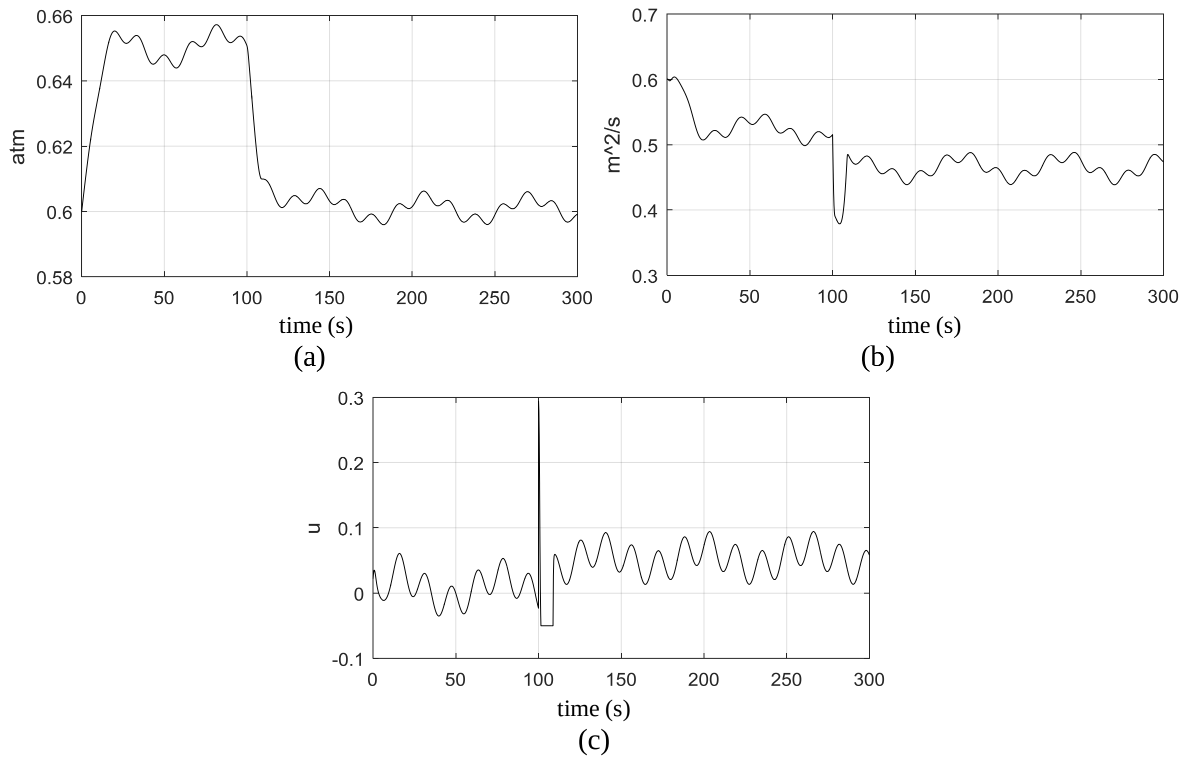

Figure 11. *Input flow rate coefficients, output pressure and control signal with designed controller to back stepping method with environmental disturbance, a) Changes in the output pressure coefficient, b) Changes in the input flow rate coefficient and c) Control signal*

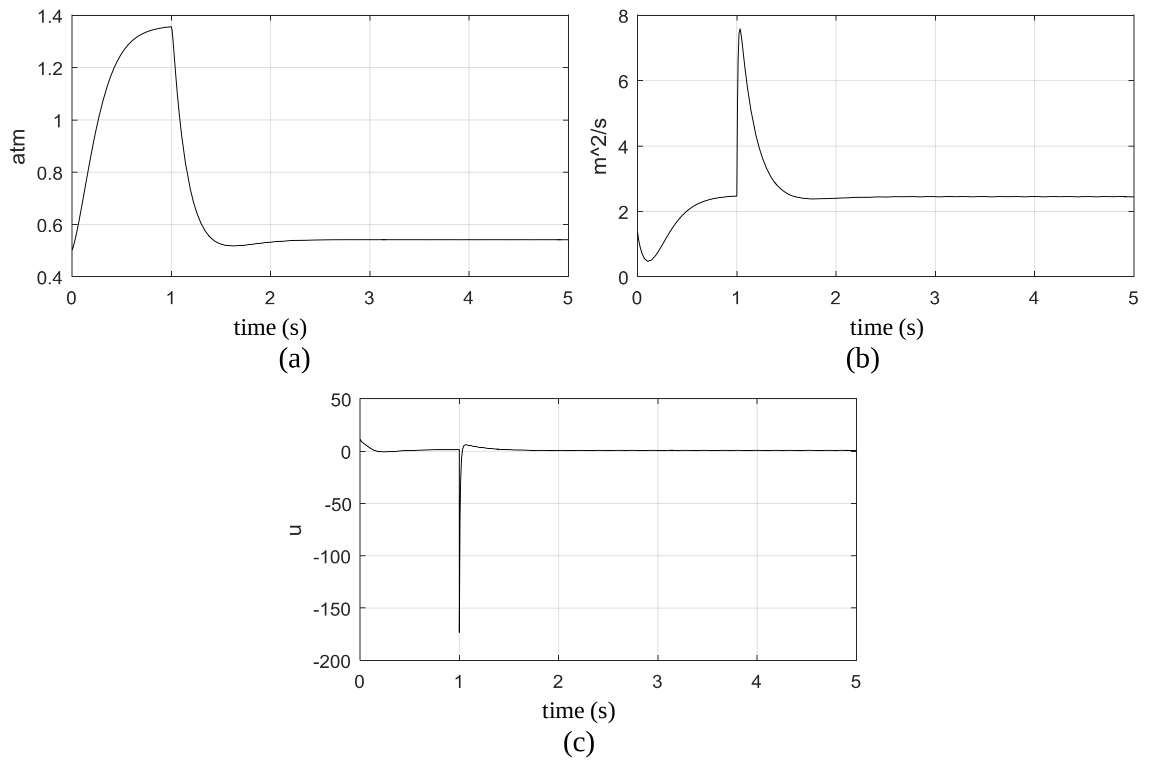

Figure 12. *Input flow rate coefficients, output pressure and control signal with designed controller to dynamic surface method with environmental disturbance, a) Changes in the output pressure coefficient, b) Changes in the input flow rate coefficient and c) Control signal*

Discussion

The controlled object with two state variables of (ϕ,ψ) is described, which have an equilibrium state of (0,0). The control objective is to design a control signal γ to guarantee that the variables of (ϕ, ψ) converge to the equilibrium state (0, 0), which indicates that (Φ,Ψ) will converge to (1, 2.72). Our steps are as follows. First, we formulate a virtual controlled law ψdesðϕÞ according to (16), where c_1=5. Then, we design the dynamic surface variable S_1. We select the dynamic surface filter according to (17), τ_2 = 0.01. Finally, we adjust the throttle opening signal γ according to (19) with c_2=5. To compare with the backstepping scheme, we also realize the corresponding backstepping project in the scenario described in [65] with the same controller parameter of c_1 and c_2. The simulation in this study focuses on these two methods with Matlab/Simulink under the same scenario. Figs show the simulationresults and also indicate that the scaled annulus-averaged flow is stable in 1 s and high accuracy is maintained. The signals (Φ,Ψ) also show an excellent transient performance, which indicates that the compressor exited the surge state successfully.

To verify the control algorithm Back stepping control system, we build active surge control platform of compressor inMATLAB Simulinkwhich mainly includes throttle valve module, controller module, and compressor module and so on. Controller module and compressor module are realized by S-function. Without close-loop control in compressor, throttle vale module is transitioned from the balanced state to the surge state by decreasing the opening of throttle valve γ_T; compressor model is second-order compressor surge model with CCV; controller is robust adaptive fuzzy controller. To verify the effect of the controller designed in this paper, simulation was taken on the above-mentioned active surge control platform of compressor by MATLAB. The result shows that with disturbance of flow and pressure, controller could still be stabilized in the region of low flow by the controller and did not enter into surge which demonstrated the strong robustness of the controller. At the beginning of controller being brought in, there is a momentary jump, which is caused by fuzzy system not adapted to adjustment at first. Controlling quantity would have continuous output after fuzzy system adapted andwas ready. It can be seen from simulation results that fuzzy system took a very short time to adapt. In Test III, controller output was seen with negative values for a little while, while pressure drop with CCV cannot be negative. To enable CCV to achieve bidirectional adjustment, need to preset an initial offset to CCV.

Conclusion

Entering the surge phenomenon affects the compressor system's working region and reduces its efficiency, ultimately causing serious damage to the entire system. This phenomenon occurs as an instability in the flow of dynamic compressors, which results from the compressor impeller's inability to generate the energy required of the system. Therefore, in this paper, to control the compressor, the back stepping and dynamic surface controllers are used to prevent it from entering the surge region, and Moore–Greitzer’s model is used for modeling. To test the designed controller, Simulink $\text{MATLAB}_{S/W}$ was used, which shows the results obtained by simulating the excellent performance of back stepping and dynamic surface controllers at the compressor exit from the surge area in the presence of environmental disturbance and without ecological disturbance. It is better to implement the above results by PLC and computer in the future

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