Surge Control in Constant Speed Centrifugal Compressors Using Nonlinear Model Predictive Control

Masoud Taleb Ziabari[1]*, Mohammad Reza Jahed Motlagh[2],Karim Salahshoor[3],Amin Ramazani[4]

Received:2015/6/25 Accepted:2015/9/1

Abstract - Surge is one of the two destructive factors in compressors. surge is the stream instability phenomenon in compressor that imposes severe damages to the compressors. Nowadays, suppressingsurge phenomenon is one of the most important issues in oil and gas industries, especially when flow reduction or gas reflux is considered. According to Moore-Greitzer compressor model, this paper designs an active controller for surge control in constant speed centrifugal compressors. As such, the applied operator considered for surge control is Close Couple Valve (CCV) and it is designed to stabilize a centrifugal compressor system with disturbaces using nonlinear predictive controller. The proposed controller, without any information about the amount of Throttle Valve variations, could control the surge instability and reduce the distance between compressor operation point and the surge line. Finally, the compressor system with controller is simulated and the obtained results will show the efficiency of the designed nonlinear predictive controller.

Keywords: Surge, centrifugal compressors, CCV, active control, nonlinear predictive contro.

l. Introduction

Stodulla and Kirton were researchers who described surge phenomenon in 1927 and 1937, respectively. In 1946, it was observed that a duct connected to a compressor in downstream allowed the compressor to surge.

All the studies up to now on surge phenomenon have been conducted according to the fact that surge is a sinusoidal and time-dependent phenomenon that has a close relationship with Helmholtz frequency. In most works on surge, the flow is assumed to be uncompressible. It wasn't until early 90s that the signs of compressibility were also studied. In most works conducted in this field, it is assumed that the flow is unidimensional. In last years, there have been some studies on non-linear control for a two dimensional, compressible flow [1,2].

Surge is still a vague and unknown phenomenon that can induct mechanical or thermal stress in a system and cause great damages. This kind of aerodynamic instability educes the pressure on the compressor ends, and thus decreases the total efficiency of the system [3].

Surge phenomenon can be suppressed by running the system in a far point from the surge line. On the other hand, given the high ratio of pressure to efficiency near the surge line, it is better to operate the compressor as near as possible to the surge line. According to the abovementioned points, there are three viewpoints regarding surge control that are:

- Avoidance of surge
- Revealing the surge region and avoiding it
- Transferring the surge margin

The first viewpoint has been used in industry and business for a very long time. In this viewpoint, the control system does not allow the compressor to operate at the left side of the surge line because in the compressor specification curve the surge line is not specified clearly and definitely. Therefore, a zone must be introduced at the right side of the surge line as surge zone or margin in order for the control system to prevent the system from operating in those points.

In the second viewpoint, a special sensor reveals the beginning of the instabilities. This sensor is sensitive to inlet or outlet temperature and pressure. The measured data are compared to the reference values (related to surge), that exist in the computer system. This way, if the data shows a surge, then the control system is activated. The advantage of these control systems over the first type is that there exists no longer a surge zone, thus it is possible to reach a higher pressure difference (differential pressure) and a greater efficiency. A defect in this control system is the need for a high controlling force and its operation in a short time interval in order to prevent the instabilities from growing. Another defect in this

1.* Department of Electrical Engineering,Science and Research branch,Islamic Azad University,Tehran,Iran.
m.t.ziabari@gmail.com
2 . Department of Electrical and Computer ,Iran University of Science and Technology , Tehran,Iran
3 . Department of Automation and Instrumentation,Petroleum University of Technology (PUT),Iran
4 . Department of Electrical and Computer Engineering , Tarbiat Modares University , Tehran,Iran

system is its severe dependence on the controlled compressor. Since various compressors, when instability emerges, show different behaviors, so the mentioned control system application is limited to only the existing compressor.

In the third viewpoint on surge control, surge margin is transferred in order to reach a higher performance. This viewpoint is divided into two classes: inactive (passive) control and active control [4]. In both systems, active or passive control systems, the compressor specification curve is adjusted by transferring the surge line into a lower mass flow (to the left side). Transferring the surge line transfers the surge avoidance line too. In other words, a part of the compressor's instable performance zone is introduced into the stable zone. The advantage if this system and controlling viewpoint is that the performance point can be as close as possible to the maximum pressure and efficiency.

Surge and rotating stall phenomena are two dynamic instabilities that occur in both axial and centrifugal compressors. There are different ways to remove the surge limitation in compressor systems using mathematical and aerodynamic fluid instability models, obtained in [5-22]. In surge avoidance method, we select the surge control line and design a controller to prevent the system from entering the instable zone. This method has a wide application in industry. The active surge control method, presented by Epstein [5] and addresses the surge stability issue, doesn’t have a significant application in industry, and there are only a few works with different control methods and different operators [6, 7]. In [8], using a piston and LQR a controller is presented for surge control. Paper [9] provides a model of the compressor with a surge avoidance system including flow return valves, and designs a PI controller for it.

A high variety of operators has been presented by designers in order to control surge, including Inlet Guide Vanes (IGV) [10], Throttle Control Valve (TCV) [11, 12], and Close Couple Valve (CCV) or Anti-Surge Valve[13]. Also in [14] a combination of inlet valves and TCV is presented for surge control. In addition to the operators, there are different control methods for surge suppression, summarized as follows. Several adaptive and passive controllers using CCV operators have been suggested in [13]. Also continue to investigate the compressor control by increasing the complexities of non-disturbance surge control, constant disturbance surge control, time-variable disturbance surge control, non-disturbance stall and surge control. In [15], using CCV operator and a second order sliding mode method, and has presented some controller based on active control just by measuring air flow. Paper [16] has provided two methods from robust feedback control for stabilizing surge phenomenon in compressor. In [17] a predictive model controller has been designed for surge control in centrifugal compressors. The applied MPC uses the least squares method to increase the compressor efficiency.

A high gain, adaptive controller for surge suppression in centrifugal compressors with a inlet duct and a TCV operator has been suggested by[18]. In [19], by controlling the valves (control valves) around the operating zone if a closed system, the authors has designed a new, positive feedback controller using pole-place method in order to control surge. A centrifugal compressor with constant speed and CCV and TCV valves has been studied in [20], where some controllers has been designed for it using Fuzzy, Anti-Windup PID, Gain Scheduling PID, Sliding Mode and Back-stepping methods. Thesis [21] seeks that how can the compressor performance be controlled with several compressors connected in series and parallels. In order to solve this problem the predictive controller has been used. To find an optimum control in a predictive controller Quadric Programming is used. The compressor model applied for designing the controller was linear and uncertainty and disturbance weren’t considered. The focus of [22] is on surge control using active control. The model used for the compressor system is Greitzer model, in which the system is stabilized using the positive feedback [19] and linear predictive controller. As such, after discussing robustness and disturbanceand noise avoidance, a combined predictive controller is presented that is more robustness than linear predictive controller to uncertainty, disturbance and noise. This work investigated on the active surge control problem considering a CCV as actuator. It is mainly focused on using Nonlinear Model Predictive Control (NMPC), as a setup for controlling each compressor to a fixed operating point on the characteristic with relation to mass flow and pressure. In surge avoidance method, selecting the technique and the controlling tools, as well as determining an appropriate margin between the control line and surge line, is of utmost importance because the stable operation of compressor in optimum operation zone is the most desirable target of these systems. Most of the previous works have focused on compressor stability and preventing the compressor from entering the instability area, thus, in order to have a stable performance, they should be at a distance from the surge line which decreases efficiency.

The paper is structured as follows. In section 2 is recalled the model of Moore and Greitzer. In section 3 is designed surge control using nonlinear model predictive control. The results of some computer simulations are discussed in section 4, and some concluding remarks are presented in the final section 5.

1. Compression system

The compressor model is given by [2]:

$$\frac{d\psi}{d\xi} = \frac{1}{4B^2 l_c}\left(\phi - \phi_T(\psi)\right) \tag{1}$$
$$\frac{d\phi}{d\xi} = \frac{1}{l_c}\left(\psi_c(\phi) - \psi - \frac{3H}{4}\left(\frac{\phi}{W} - 1\right)J\right)$$
$$\frac{dJ}{d\xi} = J\left(1 - \left(\frac{\phi}{W} - 1\right)^2 - \frac{J}{4}\right)\delta$$

Where, ψ is dimensionless pressure rise coefficient, ϕ is dimensionless flowcoefficient, J is the square of the rotating stall amplitude and $\xi = \left({}^{U}/_{R}\right)t$ is dimensionless time, of which U is rotor tangential speed and R is the average radius of compressor. B, l_c and δ are constant numbers. The parameter B is defined as:

$$B = \frac{U}{2a_s}\sqrt{\frac{V_p}{A_c l_c}} \tag{2}$$

Here, a is local velocity of sound, V_p is , the volume of air collector, A_c is compressor flow area and L_c is the effective length of compressor pipe. ψ_c is the cubic characteristic of Moore and Greitzer (1986), which is defined in (3):

$$\psi_c(\phi) = \psi_{c0} + H\left(1 + \frac{3}{2}\left(\frac{\phi}{W} - 1\right) - \frac{1}{2}\left(\frac{\phi}{W} - 1\right)^3\right) \tag{3}$$

ψ_{C0} , H and W are applicable constant numbers. ϕ_T is throttle valve characteristics which is defined as:

$$\phi_T(\psi) = \gamma_T\sqrt{\psi} \tag{4}$$

In the case of pure surge, that is when $J \equiv 0$, the *model reduces to:*

$$\dot{\psi} = \frac{1}{4B^2 l_c}\left(\phi - \phi_T(\psi)\right) \tag{5}$$
$$\dot{\phi} = \frac{1}{l_c}\left(\psi_c(\phi) - \psi\right)$$

As in all types of physical systems, disturbances will occur in the compression system. This paper is complicated the model by assuming the possible presence of pressure and flow disturbances:

$$\dot{\psi} = \frac{1}{4B^2 l_c}\left(\phi - \phi_T(\psi) + d_\phi(\xi)\right) \tag{6}$$
$$\dot{\phi} = \frac{1}{l_c}\left(\psi_c(\phi) - \psi + d_\psi(\xi)\right)$$

Figure 1 is the diagram of compression system with CCV. The CCV actuator is located close to the compressor outlet duct and causes the additional adjustable pressure drop

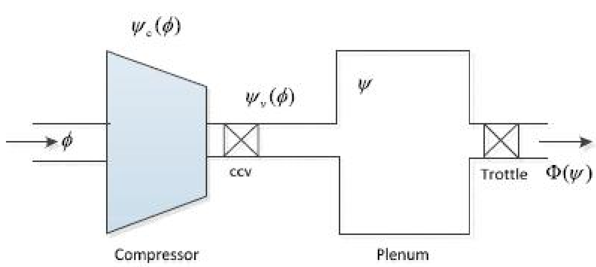

Figure 1. Diagram of compression system with CCV [23].

The system's state space model is formulated as:

$$\dot{\psi} = \frac{1}{4B^2 l_c}\left(\phi - \phi_T(\psi) + d_\phi(\xi)\right) \tag{7}$$
$$\dot{\phi} = \frac{1}{l_c}\left(\psi_c(\phi) - \psi - \psi_V(\phi) + d_\psi(\xi)\right)$$

Taking $\psi_v(\xi)$ as system control quantity, it is obtained:

$$\dot{\psi} = \frac{1}{4B^2 l_c}\left(\phi - \phi_T(\psi) + d_\phi(\xi)\right) \tag{8}$$
$$\dot{\phi} = \frac{1}{l_c}\left(\psi_c(\phi) - \psi - u + d_\psi(\xi)\right)$$

Surge is simulated by decreasing the throttle gain beyond the surge limit corresponding to a throttle gain of 0.616. When the operating point crosses the surge line, limit cycle fluctuations are observed, as shown in Figure 2.

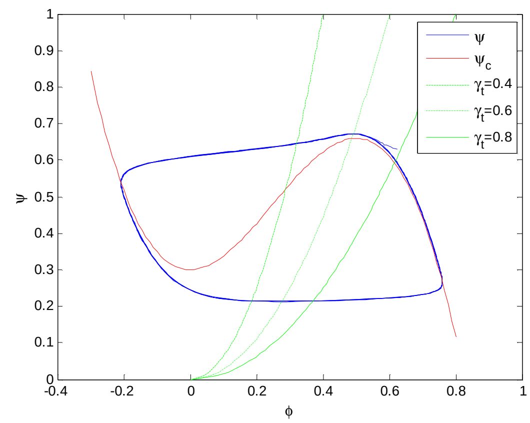

Figure 2. Surge simulation.

2. Surge Controller

In this section, we design the nonlinear predictive controller for surge control in compressors. In this line, we first define the controller inputs and outputs, as it is shown in Figure 3, where pressure and flow are defined as the controller inputs, and the output is CCV opening.

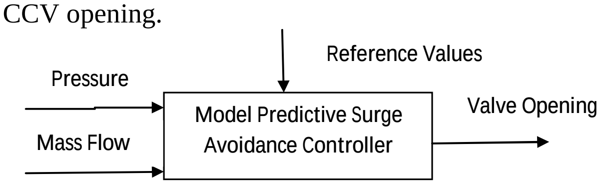

Figure 3. Inputs and output of NMPC.

Next, the cost function is selected as follows in order to optimize the system.

$$J = \frac{1}{2}\sum_{k=0}^{n-1}\left\{\left(x_k - x_k^d\right)^T Q_k\left(x_k - x_k^d\right) + \left(u_k - u_k^d\right)^T R_k\left(u_k - u_k^d\right)\right\} + \frac{1}{2}\left(x_n - x_n^d\right)^T S\left(x_n - x_n^d\right) \tag{9}$$

Where

$$Q \geq 0, R > 0, S > 0 \tag{10}$$

Although, it should be noted that, the controller output is CCV. So, the first limitation is defined as follows.

$$u(t) > 0 \tag{11}$$

The amounts of flow and pressure, which are the system modes, have also some limitations, which are selected so that the system cannot enter the surge zone.

$$\varphi_{min} < \varphi(t) < \varphi_{max} \tag{12}$$
$$\psi_{min} < \psi(t) < \psi_{max}$$

Ultimately, the optimization problem is defined as follows.

$$\begin{aligned} &Min_{u(t)} \;\; J \\ &s.t \;\; (8),(11),(12) \end{aligned} \tag{13}$$

3. Simulation

After applying the controller to the compressor system, it has been simulated. Parameters are as follows [23].

$$B = 1.8, l_c = 2, H = 0.18, W = 0.25, \psi_{c0} = 0.3 \tag{14}$$

In the first simulation, the values of d_φ and $d_\psi$equal 0 and it is assumed that there is no disturbance on the system. As such, from the beginning to 130s the throttle valve portion is considered to be 0.65, in which system is located at the right side of the surge line. After that, this amount is decreased to 0.6 and the system enters an instable zone at the left side of the surge line. The flow and pressure of the compressor systemare shown in Figure4. The controller has managed to reach the system to its operational zone. Given the fact than the controlling signal should be between 0 and 1, it can be seen that this limitation is observed strictly in nonlinear predictive controller, as it is shown in Figure 5.

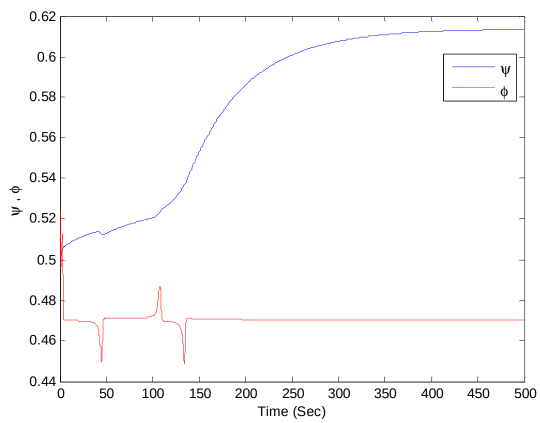

Figure 4. Flow and Pressure of compressor.

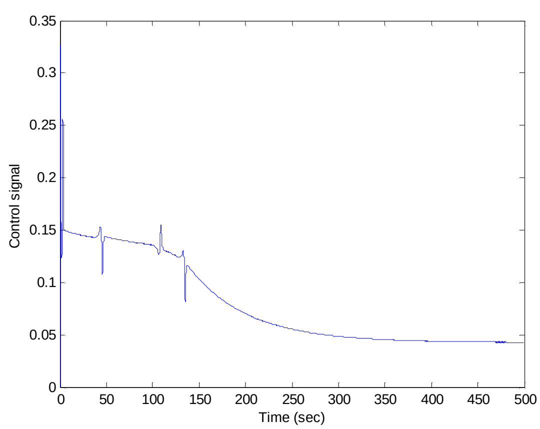

Figure 5. Control signal.

In the second simulation, it is assumed that the system contains some disturbances as follows.

$$\begin{aligned} &d_\phi(\xi) = 0.15e^{-0.015\xi}\,cos(0.2\xi) \\ &d_\psi(\xi) = 0.1e^{-0.005\xi}\,sin(0.3\xi) \end{aligned} \tag{15}$$

Once again, the same strategy is used for simulation. It is observed that, despite the system disturbance, the controller can stabilize the system and draw it toward the right side of the surge line. Figure 6 show the equilibrium point of the compressor flow and pressure. In Figure 7, the direction of compressor system stabilization can be seen with the controller signal, which is between 0 and 1.

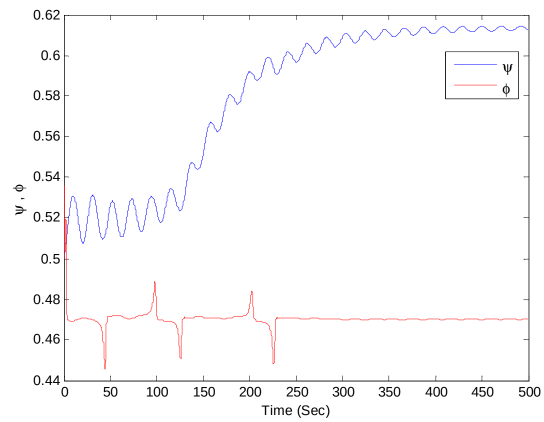

Figure 6. Flow and Pressure of compressor.

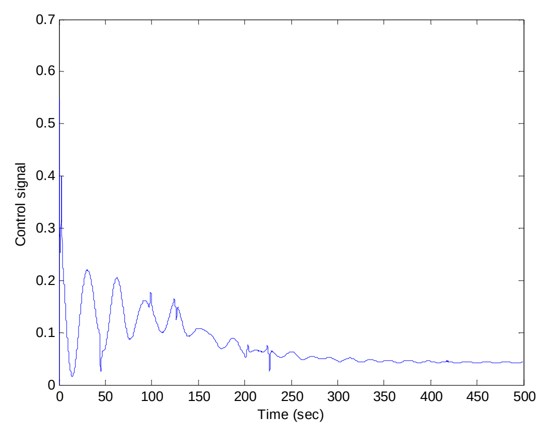

Figure 7. Control signal.

4. Conclusions

1. The predictive non-linear controller presented in this paper shows that the system stability, despite the existence of chaos in it, has been preserved completely. As such, the proposed controller, without any information about the amount of TCV variations, could control the surge instability and reduce the distance between compressor operation point and the surge line, thereby improve the compressor efficiency.

2. Referencef

[1] J. T. Gravdahl, O. Egeland, S. O. Vatland, “Drive torque actuation surge control of

centrifugal compressor," Automatica, Volume 38, Issue 11, November 2002, pp. 1881–1893.

[2] F. K. Moor, E. M. Greitzer, "A theory of post stall transients in a axial compressor system, part 1-development of Equation," Journal of Engineering for gas turbine and power 108, 1986, pp. 68-76.

[3] M. Schobeiri, "Turbomachinery Flow Physics and Dynamic Performance," Springer Verlag, 2005, ISBN: 978-3-540-22368-9.

[4] B. Bohagen, J. T. Gravdahl, "Active Surge control of compressor system using drive torque," Automatica, 44, 2008, pp. 1135-1140.

[5] A. H. Epstein, J. E. F. Williams, E. M. Greitzer, "Active suppression of aerodynamics instability in turbo machines," Journal Propulsion and Power, 5, 1989, pp. 204-211.

[6] F. Willems, B. de Jager, "Modeling and control of compressor flow instabilities," Control System Magazine, 19, 1999, pp. 8-18.

[7] G. L. Arnulfi, P. Giannattasio, D. Micheli, P. Pinamonti, "An innovative device for passive control of surge in industrial compression system," Journal Turbomachinery, 123, 2001, pp. 473-782.

[8] N. Uddin, J. T. Gravdahl, "Piston-Actuated Active Surge Control of Centrifugal Compressor Including Integral Action," 11th International Conference on Control, Automation and Systems, Oct. 26-29, 2011, pp. 991-996.

[9] N. Uddin, J. T. Gravdahl, "Bond graph modeling of centrifugal compressor system," 10th International Conference on Bond Graph Modeling and Simulation (ICBGM), 2012, pp. 177-184.

[10] K. Nakagawa, M. Fujiwara, T. Nishioka, S. Tanaykaand, Y. Kashiwabara, "Experimental and numerical analysisof active suppression of centrifugal compressor surge bysuction-side valve control," JSME International Journalof, Series B, Fluids and thermal engineering 37(4), 1994, pp. 878-885.

[11] J. E. Pinsley, G. R. Guanette, A. H. Epstein, E. M. Greitzer, "Active stabilization of centrifugal compressorsurge," Journal of Turbomachinery 113, 1991, pp. 723-732.

[12] F. Blanchini, P. Giannatasio, P. Pinamonti, D. Micheli, "Experimental Evaluation of a High–Gain Control forCompressor Surge Suppression," ASME Journal of Turbomachinery 124, 1, 2002, pp. 27-35.

[13] J. T. Gravdahl, O. Egeland, "Compressor Surge and Rotating Stall: Modeling and Control," London: Springer Verlag, 1999, ISBN-13: 978-1-4471-1211-2.

[14] Simon, S. Jonathan, "Feedback stabilization of compression systems," Phd thesis, MIT press, Massachusetts Institute of Technology, Department of Mechanical Engineering, 1993.

[15] G. Bartolini, A. Muntoni, A. Pisano, E. Usai, "Compressor Surge Suppression by Second-Order Sliding Mode ControlTechnique," 17th World Congress, The International Federation of Automatic Control, July 6-11, 2008, pp. 6238-6244.

[16] A. S. Shiriaev, R. Johansson, A. Robertsson, L. B. Freidovich, "Criteria for Global Stability of Coupled Systems with Application to RobustOutput Feedback Design for Active Surge Control," 18th IEEE International Conference on Control Applications, Part of 2009 IEEE Multi-conference on Systems and Control, July 8-10, 2009, pp. 1021-1026.

[17] C. Wang, C. Shao, Y. Han, "Centrifugal Compressor Surge Control Using Nonlinear Model Predictive Control Based on LS-SVM," 3rd International Symposium on Systems and Control in Aeronautics and Astronautics (ISSCAA), 2010, pp. 466-470.

[18] F. Blanchini, P. Giannattasio, "Adaptive control of compressor surge instability," Automatica 38, 2002, pp. 1373 – 1380.

[19] F. Willems, W. P. M. H. Heemels, B. de Jager, A. A. Stoorvogel, "Positive feedback stabilization of centrifugal compressor surge," Automatica 38, 2002, pp. 311–318.

[20] R. S. Shehata, H. A. Abdullah, F. F. G. Areed, "Variable structure surge control for constant speed centrifugal compressors," Control Engineering Practice 17, 2009, pp. 815–833.

[21] T. F. Overvag, "Centrifugal Compressor Load Sharing with the use of MPC," Master Thesis, Norwegian University of Science and Technology,Department of Engineering Cybernetics, March, 2013.

[22] P. J. H. Zillinger Molenaar, "Model Predictive Compressor Surge Control," Master thesis, Technical University Eindhoven,Department Mechanical Engineering, Dynamics and Control Technology Group, August, 2007.

[23] H. Sheng, W. Huang, T. Zhang, X. Huang, "Robust Adaptive Fuzzy Control of Compressor Surge Using Backstepping," Arab J SciEng 39, 2014, pp. 9301–9308.