Active Surge Control with Variable Inlet Guide Vane

Wookjin Choi* , Sangun Kim** and Sangchul Won***

*Department of Electronic and Electrical Engineering, POSTECH, Pohang-si, 790-784, Korea
(Tel: +82-54-279-5576; Fax: +82-54-279-8119; Email:{$wjchoi^*, un1214^{**}, won^{***}$}@postech.ac.kr)

Abstract: In this paper, we propose to use variable inlet guide vane as a means of active surge control to solve above problems. There is some advantage. For example, since the inlet guide vanes are already present in POSCO, no additional actuation device is required. We can collect all data easily which is related to the test and can simulate new model using our compressors. We can obtain the result that blow-off valve is opened less 5% and can operate air compressor automatically and more efficiently. Through a simulation example, the effectiveness of the proposed schemes is illustrated.

Keywords: Active surge control, compressor, Wiener model, MPC

1. Introduction

Recently centrifugal type compressors are widely used for several kinds of applications such as turbo-charging of internal combustion engines, air compression in gas turbines of oxygen or power plants and so on. As we know while centrifugal type compressors have several kinds of advantages themselves without other type compressors, there are some disadvantages such as surge and so on. Surge can cause severe damage to the compressor because it is an unstable operation mode which occurs when the operation point of the compressor is to the left of the surge line, which is the stability limit in the compressor map. And surge is highly undesired because the compressor is very expensive and takes a long time to repair or replace. POSCO in Korea which is one of the largest steel making companies in the world also has over 20 air turbo compressors of centrifugal type to produce pure oxygen and pure nitrogen gases for steel making. We also have some problems for stable operation of each compressor but the major one is as follows. We used anti-surge line to give about 10% margin against surge line in compressor map to avoid surge in each compressor but blow-off valve which is for active surge control to stabilize the compressor was usually opened about 10 15%. When blow-off valve is opened, we have to close blow-off valve fully for increasing the air compression efficiency and economizing utilities like the electric power. In that case inlet guide vane which is located in the compressor inlet can control the flow rate of suction air of compressor inlet. But sometimes the result was worse and worse. Because any actions like more open or more close of inlet guide vane caused the fluctuation of the pressure and the flow rate of suction air (differential pressure) at the compressor outlet, operating point that is made newly was also unstable position. Therefore we did not operate the compressor more efficiently and couldn't control automatically these two control loops, anti-surge and inlet guide vane, simultaneously. As the above result, we need stronger controller than existing controller for anti-surge and inlet guide vane control and new model for operating the compressor automatically and efficiently.

Wiener models are particularly useful in representing the nonlinearities of a process without introducing the complications associated with general nonlinear operators. Wiener models consist of a linear dynamic element followed in series by a static nonlinear element, while Hammerstein models contain the same elements in the reverse order. These models correspond to process with linear dynamics but a nonlinear gain, and can adequately represent many of the nonlinearities commonly encountered in industrial processes such as distillation columns, a heat exchanger and pH neutralization processes, [Norquay 1999A.B, Zhu 1999, Bloemen 2001].

There are several methods to relax the computational demand of the nonlinear optimization problem for Wiener models. Norquay et al. use the specific structure of Wiener models to relax the computational demand. This is done by inverting the static nonlinearity, thus essentially removing it from the control problem, which enables the use of linear MPC techniques for the remaining linear block. Thus the Wiener model is represented as a linear model with uncertainty, which enables the use of robust linear MPC techniques to control this kind of system. The optimization problem is given by minimization of a linear cost function subject to linear matrix inequalities (LMIs)[Boyd 1994]. By the way, every suggested Wiener model predictive control (WMPC) algorithms are considered on regulation and state feedback or state observer based form.

In this paper,we propose to use variable inlet guide vane as a means of active surge control to solve above problems. We can obtain the result that blow-off valve is opened less 5% and can operate air compressor automatically and more efficiently. The control scheme is based on the minimization of a finite horizon cost function with finite terminal weighting matrices and can easily be implemented using linear matrix inequalities optimization. We developed wiener model for air separation plant using subspace identification and applied to proposed control scheme. Through a simulation example, the effectiveness of the proposed schemes is illustrated.

2. Problem statement

2.1. Anti-surge

2.1.1 Surge

Surge is an axisymmtrical oscillation of the ow through the compressor, and is characterized by a limit cycle in the compressor characteristic. An example of such a characteristic

This paper is supported by my funding agencies.

is shown as the S-shaped curve in Figure 1.1. The dotted segment of the curve indicates that this section usually is an approximation of the physical system, as it is difficult to measure experimentally. Surge oscillations are in most applications unwanted, and can in extreme cases even damage the compressor.

The first of these types is a phenomenon with oscillations in both pressure and flow in the compressor system, while in the second type, the oscillations in mass flow have such a large amplitude, that ow reversal occurs in the compression system. A drawing of a typical deep surge cycle is shown in Fig.1. The cycle starts at (1) where the ow becomes unstable. It then jumps to the reversed ow characteristic (2) and follows this branch of the characteristic until approximately zero ow (3), and then jumps to (4) where it follows the characteristic to (1), and the cycle repeats.

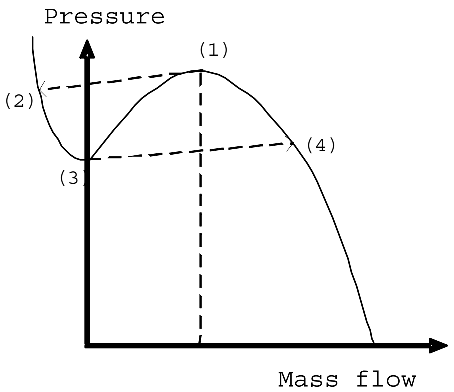

Fig. 1. Surge cycle

2.1.2 Anti-surge control loop

Figure 2 is the block diagram of the Anti-surge control loop.

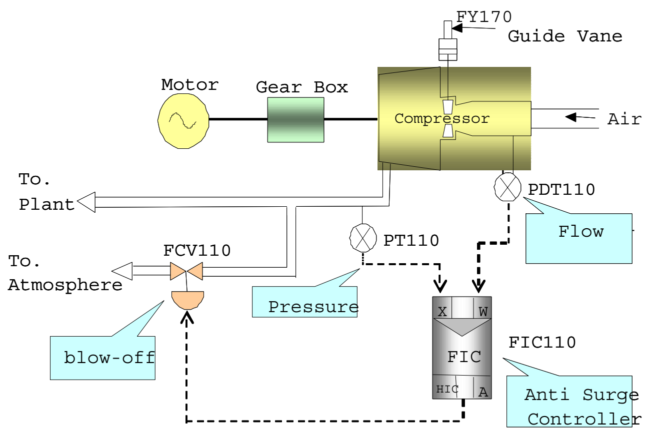

Fig. 2. Anti-surge control loop

2.2. Surge model

The wiener model consists of a linear dynamic block followed by a static nonlinear block. This model is useful in modelling several nonlinear processes in industry, for example distillation columns. Subspace identification method is recently developed in system identification, which has effectiveness in identifying dynamic state space systems. In this case, blow-off valve are selected as output variables. And input variables are shown in Table 1. The resulting sub-

PT-110	Pressure
PDT-110	Throttle flow
FY-170	Inlet guide vane control valve
FIC-110	Anti-surge control valve

Table 1. Control valve

space wiener model is described by a 4th-order deterministic system, as:

$$A = \begin{bmatrix} 0.9987 & -0.2072 & -0.0591 & 0.1726 \\ 0.0002 & 0.9909 & 0.3778 & -0.0789 \\ -0.0000 & -0.0200 & 1.0078 & -0.4573 \\ 0.0002 & -0.0009 & 0.2011 & 0.8557 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.0586 & 1.5536 & 0.0212 \\ 0.0252 & -9.8954 & 0.0369 \\ -0.0993 & -6.6561 & 0.0335 \\ -0.0105 & -6.6456 & 0.0259 \end{bmatrix}$$

$$C = \begin{bmatrix} -0.2522 & -0.3988 & 0.3140 & 0.2329 \end{bmatrix}$$

Static output nonlinearity is represent following polynomial.

$$p = [-2.021 \quad 0.0914 \quad 12.1841 \quad -5.0069]$$

Using the experimental data, we obtain the state space linear model and polynomial type static nonlinearity. Firstly, we obtain the linear model by subspace model identification algorithm and then the polynomial function is obtained by nonlinear function approximation algorithm.

3. Controller Design

Consider following Wiener model

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \\ z(k) &= h_p(y(k)) \\ &= H(k)y(k) \\ H(k) &= \left(\frac{\partial h(y)}{\partial y} \bigg|_{y=h^{-1}(z_r(k))} \right) \end{aligned} \qquad (1)$$

and a output feedback controller

$$u(k) = F(k)z(k) \qquad (2)$$

In which A, B, C are the system matrices of the linear dynamic block, $x(k) \in \mathbf{R}^{\mathbf{nx}}$ is the states of the plant, $u(k) \in \mathbf{R}^{\mathbf{nu}}$is the control input, $y(k) \in \mathbf{R}^{\mathbf{ny}}$ is the output of the linear block respectively, h_p is the nonlinear mapping from $y(k)$ to $z(k)$ and is the output of the nonlinear block. The numbers of linear block output $y(k)$ and nonlinear output $z(k)$ equal to p, and $i = 0, 1, \cdots, N-1$. The static nonlinear function $h(\cdot)$ is assumed to be known and invertible.

A performance index to be minimized is given by the following cost

$$J(k,k+N,x(k)) = \sum_{i=0}^{N-1}[x(k+i|k)^T Q x(k+i|k) \tag{3}$$
$$+u(k+i|k)^T R u(k+i|k)] + x(k+N|k)^T Q_f x(k+N|k)$$

Now we change system and performance index. The system (1)is changed into:

$$x(k+1) = A_{cl}(k)x(k) \tag{4}$$

where $A_{cl}(k) = A + BF(k)H(k)C$.
The performance index (3) is changed into:

$$J(k,k+N,x(k)) = \sum_{i=0}^{N-1}[x(k)^T \bar{Q}(k)x(k)]$$
$$+x(k+N)^T Q_f(k)x(k+N) \tag{5}$$

where

$$\bar{Q}(k) = Q + \bar{F}^T(k)R\bar{F}(k), \qquad \bar{F}(k) = F(k)H(k)C$$

The closed loop stability of the MPC is proven using monotonicity of the optimal cost under the terminal inequality conditions.
Lemma Assume that Q_f in (5) satisfies the following inequality

$$Q_f \geq Q + F^T RF + (A-BF)^T Q_f (A-BF) \tag{6}$$

The optimal cost $J^*(k,k+N,x(k))$ then satisfies the following relation

$$J^*(k,+kN+1,x(k)) \leq J^*(k,k+N,x(k)), \quad k \geq N \tag{7}$$

By the Lemma, we can obtain the following inequality if we choose proper Q_f

$$\begin{aligned}
&\Delta J(k,k+N,x(k)) \\
&= \sum_{i=k}^{N-1}[x^1(i)^T(i)\bar{Q}x^1(i)] + J^*(k,k+N,x^1(k)) \\
&- \sum_{i=k}^{N-1}[x^2(i)^T\bar{Q}x^2(i)] - x^2(N)^T Q_f x^2(N) \\
&\leq J(N,N+1,x^2(N)) - x^2(N)^T Q_f x^2(N) \\
&= x^2(N)^T[\bar{Q} + A_{cl}^T Q_f A_{cl} - Q_f]x^2(N) \leq 0
\end{aligned} \tag{8}$$

(8) is equivalent to the LMI

$$\begin{bmatrix} \bar{Q} - Q_f & * \\ A_{cl} & -Q_f^{-1} \end{bmatrix} \leq 0 \tag{9}$$

We define the augmented variables $X(i)$, $U(i)$ and $X_i(0)$.
$X(i) = [x^T(i)x^T(i+1),...,x^T(i+N-1)]$,
$U(i) = [u^T(i)u^T(i+1),...,u^T(i+N-1)]$,
$X_0(i) = [x^T(i),0,...,0]^T$.
Then we have

$$\begin{aligned}
X(i) &= \hat{A}X(i) + \hat{B}U(i) + X_0(i) \\
&= \bar{W}(i)U(i) + \bar{V}_0(i)
\end{aligned} \tag{10}$$

$X(i)$ of (3) is represented as

$$\begin{aligned}
&J(i,i+N) = [X^T(i)\hat{Q}X(i) + U^T(i)\hat{R}U(i)] \\
&+[\Phi_{i+N,i}(A)x(i) + \bar{B}U(i)]^T Q_f[\Phi_{i+N,i}(A)x(i) + \bar{B}U(i)] \\
&= [U^T(i)W(i)U(i) + W_0(i)U(i) + V_0(i)] \\
&+[\Phi_{i+N,i}(A)x(i) + \bar{B}U(i)]^T Q_f[\Phi_{i+N,i}(A)x(i) + \bar{B}U(i)] \\
&\leq \gamma
\end{aligned} \tag{11}$$

where

$$\hat{A} = \begin{bmatrix} 0 & \dots & \dots & 0 \\ A & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \dots & A & 0 \end{bmatrix}, \hat{B} = \begin{bmatrix} 0 & \dots & \dots & 0 \\ B & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \dots & B & 0 \end{bmatrix}$$

$W_0(i) = 2\bar{V}_0^T(i)\hat{Q}\bar{W}(i), \quad V_0(i) = \bar{W}_0^T(i)\hat{Q}\bar{V}(i)$
$W(i) = \bar{W}^T(i)\hat{Q}(i)\bar{W}^T(i) + \hat{R}(i), \quad \bar{W}(i) = [I - \hat{A}(i)]^{-1}\bar{B}$,
$\bar{V}_0(i) = [I - \hat{A}(i)]^{-1}X_0(i)$
$\bar{B} = [\Phi_{i+N,i+1}(A)B, \Phi_{i+N,i+2}(A)B, \dots, B]$
$\Phi_{i+N,i}(A) = A(N-1)A(N-2)\dots A(i)$

$$\min_{u(k+i|k),i\geq 0} J(k,k+N,x(k)) \tag{12}$$

where

$$J(k,k+N,x(k)) \leq V(x(k)) \leq \gamma$$

Considering the constraints given in (12), the optimization problem for constrained case is given by

$$\min_{U(i),S,Y(i),\gamma} \gamma \tag{13}$$

subject to

$$\begin{bmatrix} \gamma - W_0(i)U(i) - V_0(i) & * & * \\ W^{\frac{1}{2}}(i)U(i) & I & * \\ \Phi_{i+N,i}(A)x(i) + \bar{B}U(i) & 0 & S \end{bmatrix} \tag{14}$$

and

$$\begin{bmatrix} -S & * & * & * \\ AS + BY(i) & -S & * & * \\ Q^{\frac{1}{2}}S & 0 & I & * \\ R^{\frac{1}{2}}Y(i) & 0 & 0 & I \end{bmatrix} \geq 0 \tag{15}$$

where $S = P_f^{-1}$, $Y(i) = F(i)H(i)CS$.
Once a solution to (13) is obtained, the controller is given by $F = Y[H(i)CS]^{-1}$.

4. Simulation

Using the experimental data, we obtain the state space linear model and polynomial type static nonlinearity. Firstly, we obtain the linear model by subspace model identification algorithm and then the polynomial function is obtained by nonlinear function approximation algorithm.
The control gain is obtained for the model (1) with the performance index (13) using LMI toolbox. Fig. 3, 4 shows the simulation results.

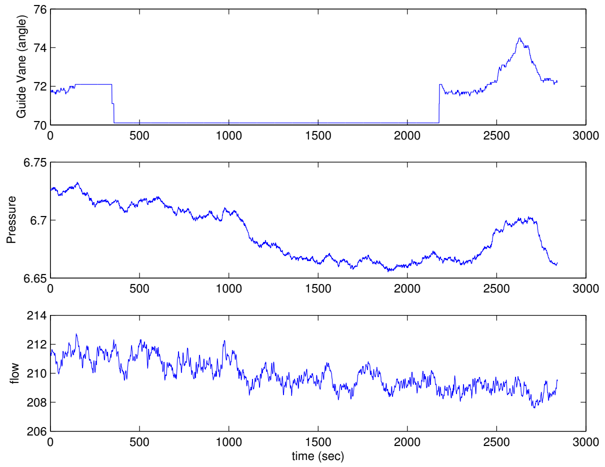

Fig. 3. Input control valve

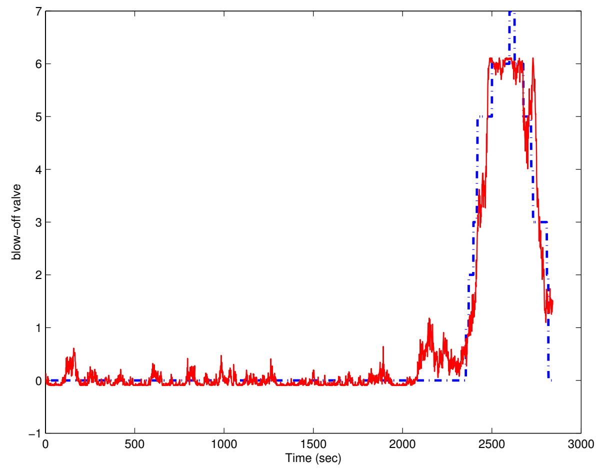

Fig. 4. Anti-surge control(blow-off valve)

5. Conclusion

In this paper, we propose to use variable inlet guide vane as a means of active surge control to solve above problems. we propose output feedback model predictive control for wiener models and adopt the Wiener model predictive control algorithms for static output nonlinearity of the wiener model. The control scheme is based on the minimization of a finite horizon cost function with finite terminal weighting matrices and can easily be implemented using linear matrix inequalities optimization. we developed wiener model for anti surge control loop using subspace identification methods and applied to proposed control scheme.

References

[1] Franco Blanchini, *Adaptive control of compressor surge instability*, Automatica, 2002(38).

[2] Jan Tommy Gravdal, *Compressor surge and rotating stall*, Springer, 1999.

[3] Jan Tommy Gravdal, *Active surge control of centrifugal compressors using drive torque*, IEEE Conference on Decision and Control, Orlando, USA, 2001.

[4] Badmus, O. O, *Nonlinear control of surge in axial compression systems*, Automatica, 32(1), 1996.

[5] Blanchini, F, *Experimental evaluation of a high-gain control for compressor surge instability*, ASMEconference on gas turbine and aeroengine congress, 2001.

[6] Willems, F, *Modeling and control of compressor ;ow instabilities*, IEEE Control Systems, 19(5), 1999.

[7] S.J. Qin, T.A. Badgwell, *An overview of industrial model predictive control technology*, Chemical Process Control(V) and AIChe Symposium Series, Vol.93, New York, USA, 1997

[8] M. V. Kothare, V. Balakrishnan, and M. Morari, *Robust constrained model predictive control using linear matrix inequalities*, Automatica, vol. 32, pp.1361 - 1379, 1996.

[9] W. H. Kwon and D. G. Byun, Receding horizon tracking control as a predictive control and its stability properties, Int. J. Control, vol. 50, no. 5, pp.1807 - 1824, 1989.

[10] J. B. Rawlings and K. R. Muske, *The stability of constrained receding horizon control*, IEEE Trans. Automat. Contr., vol. 38, no. 10, pp.1512 - 1516, 1993.

[11] K. B. Kim, *Generalized receding horizon control scheme for constrained linear discrete time systems*, Proc. Of 15st IFAC World Congress on Automatic Control, (Barcelona, Spain), 2002.

[12] S. J. Norquay, A. Palazoglu, and J. A. Romagnoli, *Model predictive control based on Wiener models*, Chemical Engineering Science, 53, 75-84, 1998.

[13] S. J. Norquay, A. Palazoglu, and J. A. Romagnoli, *Application of Wiener model predictive control (WMPC) to a pH neutralization experiment*, IEEE Transacions on Control Systems Technology, 7, 437-445, 1999.

[14] H. J. J. Bloemen, and T. J. J. Van Den Boom, *MPC for Wiener systems*, Proceedings of the 38th IEEE Conference on Decision and Control, Sydney, Australia, December, 4963-4968, 1999.

[15] H. J. J. Bloemen, T. J. J. Van Den Boom, and H. B. Verbruggen, *Model-based predictive control for Hammerstein-Wiener systems*, International Journal of Control, vol. 74, no. 5, pp. 482-495, 2001.

[16] S. Boyd, L. El. Ghaoui, E. Feron and V. Balakrishnan, *Linear Matrix Inequalities in System and Control Theory*, SIAM, Philadelphia, 1994.