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Active surge control for variable speed axial compressors

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ABSTRACT

This paper discusses active surge control in variable speed axial compressors. A compression system equipped with a variable area throttle is investigated. Based on a given compressor model, a fuzzy logic controller is designed for surge control and a proportional speed controller is used for speed control. The fuzzy controller uses measurements of the change of pressure rise as well as the change of mass flow to determine the throttle opening. The presented approach does not require the knowledge of system equilibrium or the surge line. Numerical simulations show promising results. The proposed fuzzy logic controller performs better than a backstepping controller and is capable to suppress surge at different operating points.

1. Introduction

Compressors have been widely used in modern applications and are vital to the operation of key industrial sectors. There have been continual efforts by the academic and industrial communities to improve the reliability and performance of compressors as new technology becomes available [1].

The operation range of compressors is limited by the onset of large-amplitude fluctuations in mass flow and pressure rise known as surge [2]. Surge may cause structural damage to compressors especially to blades and bearings [3]. Therefore surge control techniques have been extensively explored over the past decades. Surge avoidance is the most common technique in industry. By setting a surge margin, the flow range of the compressor is limited to the stable region. However, the surge margin prevents the compressor from operating at a high-pressure region, thus limiting the performance of the compressor system.

Active surge control is an alternative approach to surge avoidance, in which feedback is used to stabilize the instability region of the compressor map. The approach was first introduced in literature by Epstein et al. [4] using a linearized method. Williams and Huang [5] first built up experimental setups to test and verify the applicability of active surge control. Pinsley et al. [6] and Gysling et al. [7] demonstrated active stabilization experimentally for centrifugal compressors using plenum exit throttle controller and tailored structure respectively. In 1993, Simon et al. quantified the performance of several actuator/sensor configurations with the conclusion that the most promising methods were to use mass flow measurement with either a close-coupled valve (CCV) or an injector for actuation [8]. Many more sophisticated techniques for the compressors surge control have been developed since then [9]. On one hand, linear and non-linear controllers have been used including the Lyapunov approach [10,11], adaptive control [12], backstepping [13,14], bifurcation control [15], sliding mode control [16] and fuzzy logic control [17,18]. On the other hand, the selection of actuators and sensors has been studied [19]. Some novel methods have been proposed recently, like the use of drive torque [20], tip clearance [21] and piston [22].

Most of the literatures on active surge control are based on the Greitzer model [23,24] and the Moor and Greitzer model [25] (MG model). The MG model is capable of simulating surge oscillations and describing transients associated with both surge and rotating stall. The non-linear model has been deeply exploited for active surge control design and analysis in both axial and centrifugal compressors. One shortcoming of the MG model, however, lies in its constant compressor speed assumption [26]. Until 1998, a model for axial compressors considering the B-parameter as a state was derived by Gravdahl and Egeland. The qualitative behavior of Gravdahl and Egeland's non-constant speed model was first investigated by Sari et al. in 2011 [27]. Still there is a lack of detailed studies concerning model behavior and surge control for variable speed axial compressors [26].

In this work, we study active surge control in variable speed axial compressors. To suppress surge, a plenum throttle is used as the actuator. Two controllers including a proportional controller and a fuzzy logic controller are used for speed control and surge control, respectively. The fuzzy controller is well designed to suit the variable speed condition. A backstepping [28,29] controller is

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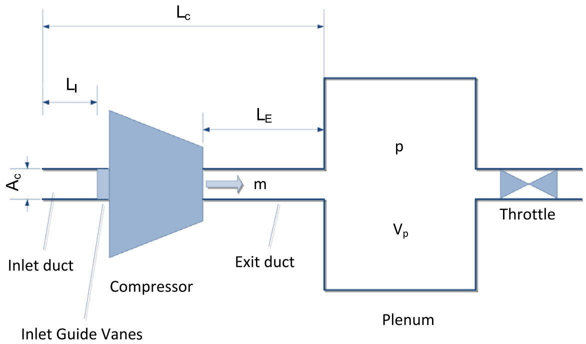

Fig. 1. The compression system.

also designed for comparison. Our aim is to suppress compressor surge under different operating conditions with its stable range extended.

2. Model description

The compression system discussed here consists of inlet guide vanes (IGV), an axial compressor, a plenum, a varying area throttle valve and connecting ducts (Fig. 1).

Based on the MG model, Gravdahl and Egeland developed a model for variable speed axial compressor systems in the form [2]

$$z = f(z) \tag{1}$$

where $z=(\phi,\psi,J_i,B)^T \in \mathbb{R}^q$. ϕ is the circumferentially averaged flow coefficient, ψ is the pressure rise coefficient, J_i is the squared amplitude of angular variation and B is the Greitzer's parameter.

Considering the simple case of pure surge, J_i is set to zero, and we are left with the model

$$\frac{d\phi}{d\xi} = \frac{H}{l_c(B)}\left(-\frac{\psi-\psi_{c0}}{H}+1+\frac{3}{2}\left(\frac{\phi}{W}-1\right)-\frac{1}{2}\left(\frac{\phi}{W}-1\right)^3-\frac{l_E U_d \Gamma \Lambda_1}{bH}\right) \tag{2}$$

$$\frac{d\psi}{d\xi} = \frac{\Lambda_2}{B}(\phi-\phi_t)-2\Lambda_1 \Gamma B \psi \tag{3}$$

$$\frac{dB}{d\xi} = \Lambda_1 \Gamma B^2 \tag{4}$$

where

$$l_c(B) = l_I + l_E\frac{U_d}{U}+\frac{1}{a}, \; B=\frac{U}{2a_s}\sqrt{\frac{V_p}{A_c L_c}}, \; b=\frac{U}{B}, \tag{5}$$

$$\Gamma = \Gamma_t - \Gamma_c = \frac{\tau_t-\tau_c}{\rho A_c R U^2}, \; \Lambda_1 = \frac{\rho R^3 A_c}{I U_d} b, \; \Lambda_2 = \frac{R}{L_c U_d} b \cdot \tag{6}$$

The circumferentially averaged mass flow coefficient, the pressure rise coefficient, the time and the distances are nondimensionalized as follows

$$\phi = \frac{m}{\rho A_c U}, \; \psi = \frac{\Delta P}{\rho U^2}, \; \xi = \frac{U_d}{R} t, \; l_I = \frac{L_I}{R}, \; l_E = \frac{L_E}{R} \cdot \tag{7}$$

The throttle mass flow ϕ_t is considered as

$$\phi_t = (k_t + \Delta k_t)\sqrt{\psi} \tag{8}$$

where

$$\Delta k_t = c_c u_t \tag{9}$$

Here $(k_t+\Delta k_t)$ represents the total gain of the throttle control valve, k_t represents the gain set at steady state, Δk_t represents the change of the throttle gain which can be either positive or negative, c_t is a coefficient and u_t is the control signal.

The behavior of the compressor, also known as the compressor map or compressor characteristic, describes the relation between pressure rise and mass flow. The compressor characteristic is usually provided by the compressor manufacturer and can also be obtained in laboratory. The cubic Eq. [25] widely used in literatures is expressed by the follow

$$\psi_c = \psi_{c0} + H\left(1+\frac{3}{2}\left(\frac{\phi}{W}-1\right)-\frac{1}{2}\left(\frac{\phi}{W}-1\right)^3\right) \tag{10}$$

3. Controller design

3.1. Fuzzy logic control

Two controllers are used here for compressor speed control and surge control, as depicted in Fig. 2.

For speed control, a proportional controller of the form

$$\Gamma_t = k_p(U_d - U) \tag{11}$$

is used to regulate the rotor speed [2]. k_p is the proportional gain and higher k_p indicts shorter regulating time.

For surge control, a fuzzy control is proposed due to its simple design and good performance. The controller is a Mamdani-type fuzzy logic controller, consisting of two input variables and one output variable. The change of mass flow and the change of pressure rise are selected as the input variables. It is of significance to choose these two variables as both of them are closely connected to surge. According to Mawali [17], the pressure imbalance between the compressor and the plenum is behind the surge phenomenon and can be detected by monitoring the change of mass flow rate signal. The change of pressure rise signal is added to the input because the only signal of the change of mass flow cannot provide enough information for the controller to operate properly. Scaling factors have been chosen for both of the input variables as well as the output variable. k_{d1} and k_{d1} are used to transfer the input variables to the fuzzy set and k_u is used to transfer the fuzzy control quantity obtained by fuzzy reasoning to the accurate control quantity. In addition, the scaling factors have a great effect on the performance of the controller. The tuning of scaling factors is based on experience and trial and error [30].

Fig. 3 describes the membership functions of the fuzzy controller. The first input variable, the change of mass flow, is divided into three sections using a Z-shaped membership function, a triangular function and an S-shaped function respectively. The second input variable, the change of pressure rise, is divided likewise. The output variable is divided into three sections, N for

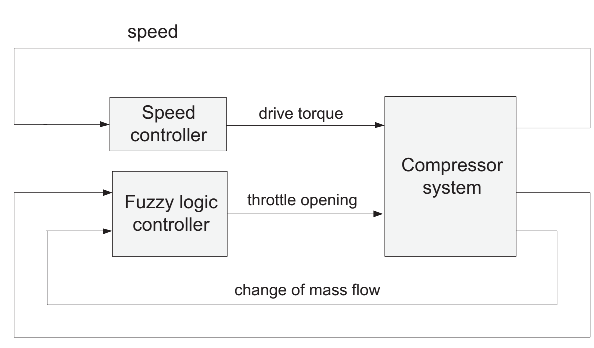

Fig. 2. The compressor system with two controllers.