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Energy-based visualisation of an axial-flow compressor system for the purposes of Fault Detection and Diagnosis

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Abstract: As the complexity of industrial systems increases, the necessity also increases for more reliable, robust and accurate Fault Detection and Diagnosis (FDD) techniques. This article proposes a methodology for the design of an FDD system, based on an energy visualisation of an axial-flow compressor system. This method investigates the steady state and transients of the system for residual generation. A nonlinear model is derived for this compressor system that are capable of modelling compressor instabilities such as rotating stall, surge and leaks. A power-energy analysis is done using the state variables of the system under normal and fault conditions and are visually presented. Two fault conditions are analysed in terms of power and energy. The first test case introduces a leak in the system. The second focuses on the more complex situation when the system enters an unstable operation, namely rotating stall. The results indicate that the power and energy of the system may be useful for the purposes of FDD.

Keywords: Energy-based visualisation, Axial-flow compressor, Fault detection and diagnosis, Rotating stall, Leak.

1. INTRODUCTION

As the complexity of large-scale industrial systems increases, issues such as safety, reliability, performance and cost become all the more important. Faults that occur in a system can influence all four of these factors. A properly designed FDD system can minimise the severity of the consequences of these faults.

Gertler (1998) categorised FDD systems as either model-free or model-based. Model-free methods are based on physical redundancy, where additional hardware is used to detect any deviation in the system's operation. Isermanm (1997) stated that model-based methods implement analytical redundancy by using a model of the observed system to detect abnormalities.

Model-based methods are mostly favoured over model-free methods since they do not impose penalties such as volume, mass and cost according to Bokor and Szabó (2009). Model-based methods such as observer-based, parity-space and parameter identification are well-known methods in literature.

García-Matos et.al. (2013) conducted a model-based FDD on an axial-flow compressor of a Combined-Cycle Power Plant. Their methodology is based on a hybrid approach that entails a physical model and a multilayer perceptron (MLP) model for residual generation. This was done for general fault conditions that may occur in a compressor system. Typical faults, such as leaks, blockages and fouling can occur in a compressor system according to Breese et al. (1992). Leaks are caused by corrosion and development of high pressures in components that results in an undesired discharge of pressure from the system. Instabilities are also common in axial-flow compressors. Gravdahl (1998) discussed two examples of such instabilities namely rotating stall and surge.

Faults cause abnormalities in the response of a system, which in turn result in undesired energy exchanges within the system. Advances in nonlinear energy-based FDD methods have made it possible to monitor these energy exchanges. Chen (2011) has applied this approach to the energy balances of a pendulum and robot manipulator in two test cases.

This paper aims at illustrating the potential of using an energy-based visualisation of an axial-flow compressor system for designing an FDD system. In order to illustrate this potential, a leak is introduced in the compressor system, and the effects on the energy response are analysed. A second test case is investigated, where a change in operating point causes the compressor to enter rotating stall.

In this paper, the state space model of an axial-flow compressor system is derived in Section 2. The model is extended to include the dynamic effects of a leak in the plenum. Section 3 contains the simulation and validation of the model. The validation of the model is done by comparing the model's response to the response of a Flownex$^{®}$ model. The two test cases are investigated in section 4 from an energy perspective, one case for a leak and the other for rotating stall. Section 5 concludes the paper with a discussion of the results and planned future work.

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2. STATE SPACE MODEL

A number of axial-flow compressor models can be found in literature. These models range from simplistic 1-D models of Greitzer (1976) to complex 3-D models of Takata and Nagano (1972). The set of differential equations in Greitzer (1976) is used for the state space model in this paper. The model is capable of representing the dynamics of both rotating stall and surge. Temperature effects are however not included. The model is further expanded to include the dynamics of a leak in the plenum volume.

The system considered in the derivation of the state space model is shown in Fig. 1. Three main components are identified in the system. These components include the compressor, plenum and throttle. The compressor is located in the inlet duct while the throttle is located in the outlet duct.

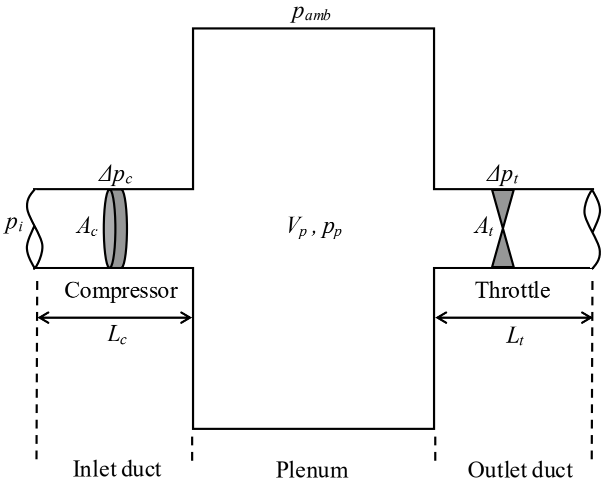

Fig. 1. Compressor system.

The set of first order differential equations is given in section 2.2. These equations govern the dynamics of the system and include the characteristics of the compressor and throttle components. In section 2.3, a fault condition is implemented within the governing equation of the plenum. In the latter part of this section, the complete model, including the fault condition, is presented in state space format.

2.1 Model parameters

The model parameters and values for the compressor system considered in this paper are given in Table 1.

Table 1. Model parameters

Symbol	Parameter	Value	Unit
a	Speed of sound	340	m/s
U	Compressor mean rotor speed	48	
A_c	Compressor duct area	0.01	m^2
A_t	Throttle duct area	0.01	
L_c	Compressor duct length	3	m
L_t	Throttle duct length	0.8	m
R	Rotor mean radius	0.1	
V_p	Plenum volume	1.5	m^3
ρ	Density	1.15	$\mathrm{kg/m}^3$
C_o	Shut off value of compressor characteristic	0.3	-
H	Comp. characteristic semi-height	0.18	
W	Comp. characteristic semi-width	0.25	
N	Rotor speed	4583	r/min

2.2 Compressor system governing equations

The set of first-order differential equations that describe the dynamics of the compressor system is derived from the conservation of mass and momentum balances for the compressor system. The set of equations is given by

$$\frac{d\dot{m}_c}{dt} = \frac{A_c}{L_c}\left(\Delta p_c - \Delta p_i\right), \tag{1}$$

$$\frac{d\dot{m}_t}{dt} = \frac{A_t}{L_t}\left(\Delta p_o - \Delta p_{t,ss}\right), \tag{2}$$

$$\frac{dp_p}{dt} = \frac{a^2}{V_p}\left(\dot{m}_c - \dot{m}_t\right), \tag{3}$$

$$\frac{d\Delta p_c}{dt} = \frac{1}{\tau}\left(\Delta p_{c,ss} - \Delta p_c\right), \tag{4}$$

with p_p the plenum pressure, Δp_c the pressure rise across the compressor, Δp_i the pressure difference between the plenum and inlet and Δp_o the pressure difference between the plenum and outlet. The compressor time lag τ found in (4) is given by

$$\tau = \frac{2\pi R N_{stall}}{U}, \tag{5}$$

where N_{stall} is the number of rotor revolutions required to develop a stall cell and is selected as 2, as in Greitzer (1976).

The characteristic that describes the pressure rise across the compressor is modelled by a third-order polynomial function. This function relates the mass flow rate through the compressor $\dot{m}_c$ [kg/s] to the steady state pressure rise across the compressor $\Delta p_{c,ss}$ [Pa], and is given by

$$\Delta p_{c.ss} = \frac{C_0\rho(NR\pi)^2}{900} - H\left(\frac{15\ \dot{m}_c^3}{\pi RN(\rho A_c W)^2} - \frac{3\dot{m}_c^2}{2\rho(A_c W)^2}\right). \tag{6}$$

The throttle characteristic is defined by a second-order polynomial function. The function relates the mass flow rate through the throttle $\dot{m}_t$ [kg/s] to the pressure drop across the throttle Δp_t [Pa] and is given by

$$\Delta p_{t,ss} = \frac{\dot{m}_t^2}{2u_t\rho A_t^2}\,. \tag{7}$$

2.3 Fault dynamics

A leak in the plenum is one type of fault that may occur in a compressor system. The result of this fault is a decrease in the performance of the system. Certain effects may be observed when the fault occurs.