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Structural Analysis for Air Supply System of Fuel Cell

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ABSTRACT

The paper focuses on the application of structural analysis based on mathematical model of air supply system of fuel cell to realize the objective of fault detection and isolation. The model of the air supply system which is based on volumetric air compressor is transformed into structural state equations in order to simplify the procedure of structural analysis. A state of art mentioned air compression system is given. A faults tree is provided before the application of the FDI approach. The paper is concerned on how to generate analytical redundancy relations in dynamic states. The results show that all faults in specifications can be detected but not isolated.

Index Terms— air compressor, faults tree, structural analysis, analytical redundancy, detectability, isolability, monitorability, faults signature, fault detection and isolation.

1. INTRODUCTION

Air supply takes an important role in the domain of fuel cell technology. Increasing the pressure of the air improves the kinetics of the electrochemical reactions and leads to higher power density and higher stack efficiency. Therefore, it is necessary to install air supply system for pressurization and purification of air. On the other hand, the power required to compress the air to a high pressure reduces the net available power from the fuel cell system. Some of this energy can be recovered by expanding the cathode exhaust through a turbine before exhausting it to the atmosphere [1]. Generally, air supply system functions as a process for regulating the air recirculation flow. In this paper, this process is based on air compressor device. Air compressors are used, for example, as part of a gas turbine for jet and marine propulsion or power generation, in superchargers and

turbochargers for internal combustion engines, and in a wide variety of industrial processes ([2], [3]).

This paper deals with the fault detection and isolation (FDI) problem for air supply system based on volumetric compressor. FDI procedures implemented in the industrial supervision platforms consist of the comparison between the actual behaviour of a system and its reference behaviour. The methods of fault detection and diagnosis could be classified into two major groups: those which do not utilize the mathematical model of the plant and those which do based on models. In fuel cell diagnosis domain, experimental approaches are the most popular diagnostic tools [4]. Special sensors may be installed explicitly for detection and diagnosis. These may be limit sensors (measuring e.g., temperature or pressure), which perform limit checking (a fault situation indicated by thresholds) in hardware. Other special sensors may measure some deviated signals for fault-indicating physical quantity [5]. Model-based fault detection and diagnosis methods utilize an explicit mathematical model of the monitored plant. Most of the model-based fault detection and diagnosis methods rely on the concept of *analytical redundancy*. In contrast to physical redundancy which is often used as diagnostic tool in non-model FDI approaches, when measurements from parallel sensors are compared to each other, now sensory measurements are compared to analytically computed values of respective variable. Such computations use present and/or previous measurements of other variables, and the mathematical plant model describing their nominal relationship to the measured variable. The idea can be extended to the comparison of two analytically generated quantities, obtained from different sets of variables. In either case, the resulting differences, called *residuals*, are indicative of the presence of faults in the system. Another class of model-based methods relies on directly on *parameter estimation* which is not the focus of this paper. Sometimes, mathematical models can be presented graphically [6] or in the form of neural network [7] for generation and evaluation of residuals. This paper

used model-based approach for fault detection and diagnosis of air compressor through results of structural analysis. It is organized as follows:

In section 2, a general air supply system and its faults tree are presented. In section 3, the state of arts of air compression system modeling is given. In section 4, a mathematical model of air supply system is developed in structural form based on physical phenomena inside of the system. Section 5 presents a structural analysis for generation of analytical redundancy relations (ARRs). In section 6, the detectability and isolability of the air supply system is given based on the results of structural analysis.

2. FAULTS TREE OF AIR SUPPLY SYSTEM

2.1 Air supply system

The air supply system based on compressor is given in figure 1. It is combined with the cathode of fuel cell, as the source of one of the reactant gaz. Generally, there exists a humidifier as function for air humidification which is not given in the scheme. Since this paper focuses on fault detection and diagnosis for air supply system, several assumptions

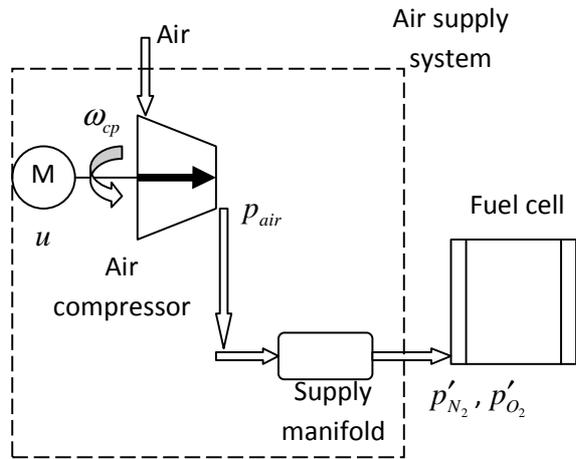


Figure 1. Air supply system

It is composed by an air compressor driven by an electric motor and a supply manifold. The air is pressurized in the compressor before entering into supply manifold. With the supply manifold, the air is distributed uniformly into the cathode of fuel cell. All variables of the system are defined as follows:

- u : input voltage,
- ω_{cp} : angular speed of the compressor,
- p_{air} : air pressure in the supply manifold,
- p'_{N_2}, p'_{O_2} : nitrogen and oxygen partial pressures in the cathode of fuel cell.

In this paper, only the air compressor and the supply manifold are considered in the modeling. However, partial pressures in the cathode will be used as the only connections between the air supply system and fuel cell.

2.2 Faults tree of air supply system

Figure 2 shows the scheme of faults tree of air supply system. In this paper, four major faults are considered respectively: short-circuit, stall of crank shaft, compressor efficiency decrease and controller breakdown which are correspondent to four subsystems (electrical parts, mechanical parts, hydraulic parts and controller parts). In electrical part, internal resistance of compressor motor will change caused by short-circuit. In mechanical part, compressor motor mechanical efficiency will be decreased by stall of crank shaft. In hydraulic part, compressor efficiency will decrease caused by wear and friction. In controller part, controller breakdown is the major considerable fault.

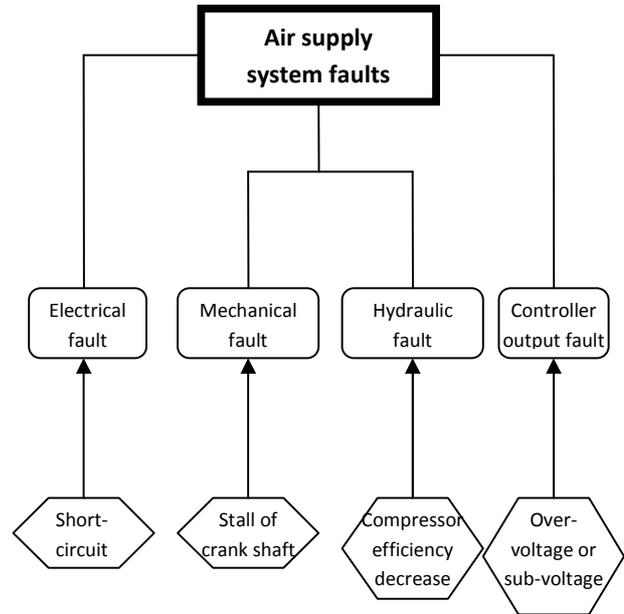


Figure 2. Faults tree of air supply system

3. LITERATURE ON AIR COMPRESSION SYSTEM MODELING

Since we take model-based FDI method for air compressor, the step of modeling is very important for structural analysis. The main requirement for a dynamic model is that it describes the phenomena of interest in the actual system with sufficient accuracy. One of the first models for the dynamic behavior of basic compression systems was derived by Emmons et al. in [8]. The authors of this paper exploited the analogy between a self-excited Helmholtz resonator and the small oscillations associated with the onset of surge to develop a linearized compression system model. The nonlinear model in the same field was developed by Greitzer in [9]. This Greitzer model for axial

compressors was the first model capable of describing the, in essence nonlinear, large amplitude oscillations during a surge cycle. The model was applied in a centrifugal compression system by Hansen et al [10]. As one of the most important advancement in this evolving field, A sophisticated two-dimensional, compressible flow model for centrifugal and axial compressors was developed by Spakovszky (2000) [11]. This low-order, analytical model describes the effect of unsteady radially swirling flows between the impeller and diffuser in centrifugal compressors and via its dedicated modular structure the possible significance of interblade row gap flow is accommodated. Besides of this modeling field, Mazzawy (1980) [12] took an entirely different approach in modeling high speed surge transients by focusing on the shock wave propagation through an axial compressor. Most of the air compressor modeling is oriented to control problem as mentioned precedent. A semi-structural model of centrifugal compressor was developed in [13] for diagnostic purpose. The model was deduced from [14] which proposed a bond graph model of centrifugal pump that can analogize to centrifugal compressor.

4. MATHEMATICAL MODEL OF AIR SUPPLY SYSTEM

Dynamic states of air pressure take an important position in air supply system modeling [15]. According to physical phenomena occurring in the system, the derivations of oxygen and nitrogen partial pressures inside the cathode volume are described as follows:

$$\frac{dp'_{O_2}}{dt} = \frac{\bar{R}T_{st}}{M_{O_2}V_{ca}} (W_{O_2,in} - W_{O_2,out} - W_{O_2,rcf}) \quad (1)$$

$$\frac{dp'_{N_2}}{dt} = \frac{\bar{R}T_{st}}{M_{N_2}V_{ca}} (W_{N_2,in} - W_{N_2,out}) \quad (2)$$

where V_{ca} is the lumped volume of cathode, \bar{R} is the universal gas constant, and M_{O_2} with M_{N_2} are the molar mass of oxygen and nitrogen, respectively. The compressor motor state is associated with the rotational dynamics of the motor through thermodynamic equations. A lumped rotational inertia is used to describe the compressor with the angular speed ω_{cp} .

$$\frac{d\omega_{cp}}{dt} = \frac{1}{J_{cp}} (\tau_{cm} - \tau_{cp}) \quad (3)$$

where τ_{cm} is the compressor motor torque and τ_{cp} is the load torque of the compressor. Assuming a simplified DC motor model with a static

electromechanical relation of applied motor input voltage v_{cm} and back electromotive force, τ_{cm} can be written as follow:

$$\tau_{cm} = \eta_{cm} \frac{k_t}{R_{cm}} (v_{cm} - k_v \omega_{cp}) \quad (4)$$

where k_t and k_v are motor constants, while R_{cm} is the motor resistance. The parameter η_{cm} represents compressor motor mechanical efficiency. The torque consumed by the compressor is calculated from the thermodynamic equation

$$\tau_{cp} = \frac{C_p}{\omega_{cp}} \frac{T_{atm}}{\eta_{cp}} \left[\left(\frac{p_{air}}{p_{atm}} \right)^\gamma - 1 \right] W_{cp} \quad (5)$$

where C_p and γ correspond to the constant pressure and the ratio of the specific heat capacities of the air. p_{atm} and T_{atm} represent the atmospheric pressure and temperature, respectively. W_{cp} is the mass flow rate from the compressor to supply manifold.

The rate of change of air pressure in the supply manifold that connects the compressor with the fuel cell (Fig. 1) depends on the compressor flow into the supply manifold W_{cp} , the flow out of the supply manifold into the cathode $W_{ca,in}$ and the compressor flow temperature T_{cp} .

$$\frac{dp_{air}}{dt} = \frac{\bar{R}T_{cp}}{M_{a,atm}V_{sm}} (W_{cp} - W_{ca,in}) \quad (6)$$

where V_{sm} is the supply manifold volume and $M_{a,atm}$ is the molar mass of atmospheric air.

The mathematical model of air supply system based on volumetric compressor given in [16] has been transformed into structural state equations which are oriented to fault detection and isolation through generation of analytical redundancy relations (ARRs).

$$\frac{dx_1}{dt} = f_1(x_1, x_2, x_4, \eta_{cm}, R_{cm}, u) \quad (7)$$

$$\frac{dx_2}{dt} = f_2(x_1, x_2, x_4, \eta_{cm}, R_{cm}, u) \quad (8)$$

$$\frac{dx_3}{dt} = f_3(x_3, x_4, \eta_{cm}, \eta_{cp}, R_{cm}, u) \quad (9)$$

$$\frac{dx_4}{dt} = f_4(x_1, x_2, x_3, x_4, \eta_{cm}, \eta_{cp}, R_{cm}, u) \quad (10)$$

with the state space vector $x = [x_1, x_2, x_3, x_4]^T$, where x_1 and x_2 are the oxygen and nitrogen partial pressures in the cathode of fuel cell, respectively, x_3 is the angular speed ω_{cp} of the compressor and x_4 is the air pressure in the supply manifold and the variable u represents the compressor motor voltage which is the control input. Considering the complexity of the model, we suppose all parameters constant except four ones which are useful for FDI analysis. Measure equations of the model are:

$$y_1 = h_1(x_1, x_2) \quad (11)$$

$$y_2 = x_4 \quad (12)$$

$$y_3 = h_3(x_3, x_4) \quad (13)$$

where y_1 is the fuel cell voltage (also known as polarization characteristic) and y_3 is the compressor flow map. All of the output variables at the left of equations are supposed measurable. For the description of $h_1(x_1, x_2)$ and $h_3(x_3, x_4)$, see [17], [18].

5. ARRS GENERATION BY STRUCTURAL ANALYSIS

The state equations model defining the trajectory of a set of variables can describe the behavior of system. Structural analysis only deals with the structural information contained in the model, i.e. which variables appear in which equation. This is a completely qualitative model, which does not consider the numerical form of the equations. The purpose of this section is to present an algorithm for ARRs generation by means of structural analysis. An analytical redundancy is a relation where all variables are known and can be written under following form:

$$f(K) = 0 \quad (14)$$

where K is the set of known variables including all inputs u , outputs y and parameters θ . In this paper, the expression of the ARR equation can be written as:

$$ARR : f(u, y, \theta) = 0 \quad (15)$$

The residual which represents the indicator of faults is then:

$$r = f(u, y, \theta) \quad (16)$$

It will be remembered that the system is no faulty if the residual is zero or below a certain threshold. In this

work, it is assumed in ideal case, so the residual will be zero if fault is missing.

According the structural properties of this model, the set of unknown variables is $X = [x_1, x_2, x_3, x_4]$.

Equations from (7) to (13) are structural constraints, which can be defined as from C_1 to C_7 , for generation of ARRs.

Since that the cardinality of constraints is bigger than which of unknown variables, the model is over-determined. Therefore, it is structurally monitorable. Analytical redundancy relations can be deduced through the elimination of unknown variables. The incidence matrix is given in table 1. It is the matrix whose rows and columns represent the set of constraints and variables, respectively. If the variable appears in the constraint, a value 1 is set in the table, if not 0.

To eliminate x_3 and x_4 , we substitute (12) into (13).

Then with the help of (7) and (8), we eliminate x_1 and x_2 .

Since we used the structural model for analysis, x_3 can be

written as $h_3^{-1}(y_2, y_3)$ while x_1 and x_2 can be written respectively as $g_1(y_2, \eta_{cm}, R_{cm}, u)$ and $g_2(y_2, \eta_{cm}, R_{cm}, u)$.

By substituting the known expressions of x_3 and x_4 into (9), we obtain the first ARR which is sensitive to all four faults (Fig.2).

$$ARR1 : \frac{d}{dt} [h_3^{-1}(y_2, y_3)] - f_3 \left[h_3^{-1}(y_2, y_3), y_2, \eta_{cm}, \eta_{cp}, R_{cm}, u \right] = 0 \quad (17)$$

By substituting the known expressions of x_1 , x_2 and x_4 into (8), we obtain the second ARR which is also sensitive to all four faults (Fig.1).

$$ARR2 : \frac{d}{dt} y_2 - f_4 \left[g_1(y_2, \eta_{cm}, R_{cm}, u), g_2(y_2, \eta_{cm}, R_{cm}, u), h_3^{-1}(y_3, y_2), \eta_{cm}, \eta_{cp}, R_{cm}, u \right] = 0 \quad (18)$$

To obtain the third ARR, we substitute the known expressions of x_1 , x_2 into (11). The ARR3 is sensitive to all faults except hydraulic one.

$$ARR3 : y_1 - h_1 \left[g_1(y_2, \eta_{cm}, R_{cm}, u), g_2(y_2, \eta_{cm}, R_{cm}, u) \right] = 0 \quad (19)$$

Table 1. Incidence matrix

Constraints	Unknowns				Knows			
	x_1	x_2	x_3	x_4	u	y_1	y_2	y_3
C_1	1	1	0	1	1	0	0	0
C_2	1	1	0	1	1	0	0	0
C_3	0	0	1	1	1	0	0	0
C_4	1	1	1	1	1	0	0	0
C_5	1	1	0	0	0	1	0	0
C_6	0	0	0	1	0	0	1	0
C_7	0	0	1	1	0	0	0	1

6. MONITORABILITY

Each fault of the air supply system can be indicated by the combination of residuals. According to the sensibility between faults and residuals, we obtain the results of detectability and isolability (monitorability) for the compressor (Tab. 2). The set of residuals generates a binary sequence where “0” represents a null residual and “1” a non-null residual. Those binary sequences are called signatures.

The columns of Db and Ib respectively represent the detectability and isolability of faults. A value of 1 appears in the table, if it is detected or isolated. From this table, we can constant that all faults are detected but not isolated because of the correlation between residuals and physical parameters. Only hydraulic fault i.e., compressor efficiency decrease can be isolated since its different combination of residuals from other faults. To increase the monitorability of the whole system, it is necessary to add certain sensors for example voltage or current. With addition of sensors, more residuals could be generated to provide more information of faults localization.

Table 2. Faults signature

Faults	Db	Ib	r1	r2	r3
Short-circuit	1	0	1	1	1
Stall of crank shaft	1	0	1	1	1
Compressor efficiency decrease	1	1	1	1	0
Over-voltage or sub-voltage	1	0	1	1	1

7. CONCLUSIONS

A methodology of structural analysis based on mathematical model of air supply system has been presented in this paper. A faults tree with two levels was given as specifications of fault detection and isolation. The model of air supply system based on volumetric compressor was transformed into structural state equations which are oriented to diagnose. Based on this

structural model which is over-determined, we deduced 3 analytical redundancy relations and correspondent residuals by eliminating all unknown variables. An incidence matrix is provided to describe the relations between structural constraints and variables. Based on the combination of these residuals, the result of diagnosability was given. All faults in specifications are detectable but only the compressor efficiency decrease is isolable. As perspectives, it is possible to add certain sensors (for example voltage or current) for isolation of other faults.

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