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Fault Detection and Isolation of automotive Air Conditioning systems using first principle models

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ABSTRACT

Although model-based Fault Detection and Isolation (FDI) has become a common design tool in automotive fields, its application to automotive Air Conditioning (A/C) systems based upon vapor compression cycles is limited due to the lack of control-oriented models characterizing the refrigerant phase change. The emergence of Moving Boundary Method (MBM) illuminates a promising way of assisting FDI scheme development, because common faults in automotive A/C systems, such as compressor fault, pressure transducer fault and fouling fault, can be easily incorporated by the control-oriented model developed. Out of various observed-based FDI methods, the H_∞ filter technique, due to its robustness to model uncertainties and external disturbances, is chosen for designing FDI scheme over actuator/sensor/parameter faults. The model and the filter are connected closed-loop by an H_∞ controller gain-scheduled to meet different cooling loads. From the closed-loop analysis results, the H_∞ filter is capable of detecting and isolating actuator/sensor faults, as well as estimating parameter faults, even if external disturbances imposed on the air side of the evaporator exist.

1. Introduction

Timely detection and isolation of underlying faults is crucial for meeting stringent safety requirements in industry. Compared to hardware redundancy technique, model-based FDI method leads to significant cost savings. Various approaches have been applied to the residual generation problem, e.g. parity equation methods, observer-based methods or frequency domain methods (Ding, 2008; Frank, 1990; Isermann, 2005, 2006). In observer-based FDI methods (Frank & Ding, 1997; Patton & Chen, 1997), actuator commands and sensor measurements are exploited to design filters for generating residuals that are compared to thresholds. In particular, H_∞ filters attract more interests due to their robustness to model uncertainties and external disturbances. An optimization problem is formulated to minimize the influences of measurement noises, external disturbances and model uncertainties on the residuals and to maximize the effects of the faults on the residuals. A standard framework for the problem formulation and solution was proposed in Mangoubi (1998) and Stoustrup and Niemann (2002), with applications to aircraft longitudinal motion (Marcos & Balas, 2005; Marcos, Ganguli, & Balas, 2005).

Model-based FDI method has widespread applications in automotive engines, especially air path systems and fuel path systems (Kimmich, Schwarte, & Isermann, 2005; Nyberg & Stutte, 2004). In contrast, its application to auxiliary loads, such as A/C systems, has not been addressed, with limited publications available. However, Vapor Compression Cycle (VCC), the thermodynamic process obeyed by automotive A/C system, is widely applied in many industry fields, such as refrigerators, air conditioners, heat pumps and chillers. Early works on VCC fault diagnosis heavily relied on simplified models, resulting into intense calibration efforts and poor performances during transient (Keir & Alleyne, 2006). For instance, a simplified physical model of a small heat pump system was used to generate predictions, whose differences from monitored observations were transformed into useful statistical quantities to be compared with predetermined thresholds (Wagner & Shoureshi, 1992). A statistical rule-based fault detection and diagnostic method for A/C equipment was developed in Rossi (1995), and demonstrated in limited testing with a roof-top air conditioner in Rossi and Braun (1997) together with a fault evaluation method. Steady-state data representing normal operations were used to develop seven polynomial models characterizing the A/C performance and determine the statistical thresholds for fault detection, while transient data with faults were used to evaluate fault diagnosis performance (Breuker & Braun, 1998). However, since they lack control-oriented models describing the thermofluid dynamics of the phase-changing refrigerant in heat exchangers, it is difficult to achieve balances between physical

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Nomenclature

TP	two phase
SH	superheated
SC	subcooled
N	compressor speed
T	temperature
a	air
c	condenser
cmp	compressor
e	evaporator
g	gas
h	enthalpy
l	liquid
p	pressure
v	valve
$\dot{m}$	mass flow rate
$\dot{Q}$	heat transfer rate
α	valve position
γ	void fraction
δ	uncertainty
ρ	density
ζ	normalized phase region length
μ	structured singular value

accuracy and computation time of the designed FDI algorithms (Katipamula & Brambley, 2005a, 2005b).

A lumped-parameter modeling approach named MBM method of developing control-oriented models for heat exchangers with phase change changing fluid was proposed in He, Liu, and Asada (1997), He, Liu, Asada, and Itoh (1998), and Li and Alleyne (2010), where the refrigerant is lumped according to its phase status, namely pure vapor, pure liquid and mixture of vapor and liquid. Differential equations describing the mass and energy balances of the phase change process were developed. The MBM A/C model offers the advantage of capturing the transient behavior of the system, and reducing the simulation time without sacrificing physical accuracy.

In this paper, a control-oriented model derived from first principles is used to design an FDI scheme on an automotive A/C system. A brief literature review is given in Section 2. Exemplary actuator/sensor/parameter faults are modeled and merged into the MBM A/C model in Section 3. The closed-loop system composed of the control-oriented model, the output-tracking controller and the FDI filter is presented in Section 4. The closed-loop performances are evaluated over model uncertainties and external disturbances in Section 5, with both abrupt and incipient faults considered. A conclusion is given in Section 6.

2. Recent development of VCC fault diagnosis

According to a comprehensive literature in Katipamula and Brambley (2005a, 2005b), FDI method can be generally classified into two approaches, namely data-driven approaches and model-based approaches (quantitative or qualitative). Data-driven approaches need a large amount of training data representing both normal and faulty operation, as well as a thorough understanding of the system and expertise in statistics. The resulted models are specific to the system for which they are trained and cannot be extrapolate beyond the range of the tracing data. In contrast, strengths of FDI schemes based on quantitative models allow us to model both normal and faulty operation based on first principles, such that the transient behavior of the systems is captured more precisely than any other modeling technique. In other words, they are particularly important for capturing faults during transient operation. Model-based approaches range from empirical models, simplified models and physics-based models. Following the above classification criterion, recent developments of FDI schemes on VCC applications during last decade are presented in the order of model complexity.

Empirical models are simplest, even sometimes static. In Cheung and Braun (2013a, 2013b), a gray box modeling approach is adopted to capture the influence of both operating conditions and faults on system performance. The steady-state heat exchangers are divided into regions according to the refrigerant phase, and each region is modeled with $\epsilon-NTU$ methods under a crossflow configuration. The static model describing the input–output relationship is useful for diagnosing multiple-simultaneous faults in VCC equipment with decoupling feature exploited and virtual sensor developed (Li & Braun, 2007).

Simplified models neglect some dynamics under certain assumptions. A four-state nonlinear model of a supermarket refrigeration system is built using a lumped-parameter approach in Larsen, Izadi-Zamanabadi, and Wisniewski (2007). A bank of Extended Kalman Filters (EKFs) is constructed for isolating two temperature sensor faults in the types of drift, offset, freeze and hard-over, and a multi-model adaptive estimation method is employed to handle parametric fault caused by freeze-over or dirty built up in Yang, Rasmussen, Kieu, and Izadi-Zamanabadi (2011a). However, the isolation between sensor faults and parametric faults cannot be handled by the current scheme, and is compensated by a bank of Unknown Input Observers (UIOs) constructed in Yang, Rasmussen, Kieu, and Izadi-Zamanabadi (2011b), where one state variable is treated as a system unknown input. Unfortunately, the control-oriented model introduced (Larsen et al., 2007) oversimplified the heat transfer process between the refrigerant and the air, as the refrigerant loop excluding the evaporator is not modeled and assumed as known boundary conditions.

The dynamic response of a chiller to the change of working conditions captured using a lumped-parameter model is built in Wang, Wang, and Burnett (2000), in which four first-order differential equations are built to represent the dynamics of thermal storages at the inlet and outlet of the condenser and evaporator. A new semi-physical subcooling model is adopted to represent the condensing region and subcooling region in the heat exchanger (Zhao, Wang, Xiao, & Ma, 2013). By analyzing the changing trends of two proposed performance indexes, namely the normalized heat transfer coefficient and the fictitious subcooling temperature, the pattern in fault conditions can be obtained. Similarly, a strategy, in which six physical performance indices are used to describe the health conditions and thus indicate chiller faults, is validated against field data from a centrifugal chiller in a real building (Wang & Cui, 2006). Although the model presents the effects of working conation changes on compressor load, it cannot describe the dynamic performance of chiller operation.

Physics-based models have been recently used for analyzing fault effects. In Keir and Alleyne (2006), the possibility of using more complex moving-boundary models for FDI in subcritical VCC equipment is explored. A linearized form of the model is used to explore the sensitivity of each output to fault conditions of evaporator frosting, refrigerant and valve leakages; however, no practical FDI algorithm is implemented. The static component based fault detection method is also tested for a transcritical