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FULL LENGTH ARTICLE

Fault diagnosis of an intelligent hydraulic pump based on a nonlinear unknown input observer

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Abstract Hydraulic piston pumps are commonly used in aircraft. In order to improve the viability of aircraft and energy efficiency, intelligent variable pressure pump systems have been used in aircraft hydraulic systems more and more widely. Efficient fault diagnosis plays an important role in improving the reliability and performance of hydraulic systems. In this paper, a fault diagnosis method of an intelligent hydraulic pump system (IHPS) based on a nonlinear unknown input observer (NUIO) is proposed. Different from factors of a full-order Luenberger-type unknown input observer, nonlinear factors of the IHPS are considered in the NUIO. Firstly, a new type of intelligent pump is presented, the mathematical model of which is established to describe the IHPS. Taking into account the real-time requirements of the IHPS and the special structure of the pump, the mechanism of the intelligent pump and failure modes are analyzed and two typical failure modes are obtained. Furthermore, a NUIO of the IHPS is performed based on the output pressure and swashplate angle signals. With the residual error signals produced by the NUIO, online intelligent pump failure occurring in real-time can be detected. Lastly, through analysis and simulation, it is confirmed that this diagnostic method could accurately diagnose and isolate those typical failure modes of the nonlinear IHPS. The method proposed in this paper is of great significance in improving the reliability of the IHPS.

1. Introduction

A hydraulic pump is the key component in an aircraft hydraulic system, on whose operating performance the quality of the pump has an important impact. In order to meet those requirements of modern aircraft, such as high speed, high mobility, low weight, and high load capacity, the intelligent hydraulic pump system (IHPS) has been paid more and more attention to for improving the efficiency of an aircraft hydraulic system. An aircraft hydraulic system with an IHPS has become an important future development direction,[1–3] and

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the requirements for reliability and security also grow significantly,[4] which implies that an efficient fault diagnosis will improve the reliability of the IHPS significantly.

An IHPS is generally defined as a kind of pump source system whose output can be easily controlled by the virtue of an intelligent controller to meet those requirements of an actual aircraft hydraulic system. To realize feedback control of the output, necessary sensors are installed on an IHPS, including pressure sensors, displacement sensors, and temperature sensors.[5] Based on an IHPS's state parameters and its actual operating condition, the controller adjusts the displacement of the pump in accordance with the pressure signal, and then achieves optimal matching with the load. The advantage of an IHPS is that, under the conditions of different aircraft flight statuses and commands from the flight control computer, the output of the IHPS can match the load reasonably. Thereby, an IHPS can reduce the invalid power and heat of an aircraft hydraulic system to improve the aircraft's work efficiency.[6] Up to now, a lot of research on the structure design of an IHPS has been done.[7–9] Ma et al. proposed a new type of axial piston variable displacement pump,[7] which was an improvement on the basis of an A4V pump and used a servo valve to control the variable mechanism directly. This improved pump can sense the load correctly and timely based on the output pressure command of the intelligent pump controller, and can provide necessary information for monitoring the pump operating condition and fault diagnosis.[8] However, this intelligent pump is more complex than a traditional hydraulic pump in structure. Comparing to a traditional hydraulic pump, an IHPS installs many additional sensors to attain pump state signals.[10] Furthermore, an IHPS integrates a servo valve to control the pump variable mechanism, so as to realize servo control.[9] The complex structure has made the structure design and signal processing of the IHPS a tough job,[11,12] and the failure probability of the IHPS also increases with a dynamic change of the operating condition. Some previous studies have been mainly focused on the fault diagnosis of a common piston pump. Lu et al. presented a fault diagnosis method of piston pumps using a pump discharge pressure signal.[13] Wang and Hu proposed a vibration-signals-based fault diagnosis method using the fuzzy technique.[14] Some artificial neural network (ANN) models have also been widely applied to pump fault diagnosis considering their nonlinearity, adaptability, and robustness.[15] Lu et al. presented a diagnosis method for hydraulic pumps based on the chaotic parallel radial basis function (RBF) network.[16]

These above methods have been proven to be effective for piston-pump fault diagnosis to a certain extent. However, many limitations still exist obviously in these methods, which becomes pretty severe especially when we apply these methods to IHPS fault diagnose. Due to structural complexity and flexible operation conditions, the mechanism of IHPS failure is more complicated, and the fault detection and diagnosis for an IHPS is more difficult. Comparing to common variable pumps, the working modes of an IHPS switch more frequently. According to a real aircraft flight profile, an IHPS would switch its operation within four kinds of different working modes, that is, constant pressure mode, constant flow mode, constant power mode, and load sensitive mode.[17] The outputs of flow and pressure in each mode are totally different, which will obviously increase the fatigue and aging of the reset spring, as well as the wear of the variable cylinder of the pump. In such situations, the swashplate angle cannot be adjusted with a command signal, and a flow regulation of the IHPS cannot be performed. Furthermore, the leakage due to the wear of three friction pairs (swashplate and slipper, valve plate and cylinder block, and piston and cylinder bore) becomes more complex, in which the aging of sealing elements and the failure of the connection between the shaft and the roller bearing should be considered.[18] When it comes to the two aforementioned common faults of an IHPS, traditional fault diagnosis methods are not feasible for the analysis of intelligent pumps.[8,19] On one hand, due to long life cycles and actual complex flight conditions, it is difficult to obtain a large quantity of faulty pump samples and fault data. Therefore, the expert knowledge of pump failure is not perfect, and it brings difficulties to an accurate fault diagnosis based on artificial intelligence which needs long-term practical experience and a large quantity of fault information.[20–22] On the other hand, because of its severe working environment, the slowly varying fault value of leakage and aging may be overwhelmed by environmental noise and cannot be separated from the environmental interference. The dynamic change of various conditions leads to complex fault characteristic signals, which are difficult to analyze with a signal-based diagnosis method using a fixed threshold.[23–25] Therefore, it is urgent to find an effective fault diagnosis method which is suitable for the complex technical characteristics of an IHPS to ensure its reliable operation.

In this paper, to achieve higher reliability and security and improve the performance of an IHPS, a fault diagnosis method based on a nonlinear unknown input observer (NUIO) is proposed to realize IHPS fault detection. Different from factors of a full-order Luenberger-type unknown input observer presented by Chen et al. and Duan et al.[26,27] nonlinear factors of the IHPS are considered. By comparing the measured signals of the object to be diagnosed and the prior information of the system expressed by a model, a residual error is generated by utilizing a NUIO, and then the residual error is analyzed and processed to realize fault diagnosis.[28] Based on analysis of IHPS working mechanism and typical failure modes, an accurate nonlinear mathematical model of the IHPS is established. Then, a dynamic fault diagnosis method based on dynamic characteristics and variability of the signals is proposed.[29,30] Finally, based on the MATLAB simulation platform, the simulation analysis of two typical failure modes of the IHPS is carried out, and the results verify the validity and accuracy of this fault diagnosis method.

The remaining part of this paper is organized as follows. In Section 2, a mathematical model of an IHPS is established considering the working mechanism and failure modes. Section 3 presents the IHPS NUIO on the basis of output pressure and swashplate angle signals. Section 4 carries out model-based fault diagnose based on the NUIO for typical failure modes of the intelligent pump according to detailed parameters. Section 5 gives conclusions.

2. Mechanism analysis of an intelligent pump

2.1. Structure and operational mechanism of an intelligent pump

A conventional axial piston pump, as shown in Fig. 1, is widely used to provide constant high-pressure oil to manipulate an outside load, which leads to power dissipation under a small-