Chinese Journal of Aeronautics, (2014),27(3): 643–654

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Sensor selection of helicopter transmission systems based on physical model and sensitivity analysis

Lyu Kehong [a,*], Tan Xiaodong [a,b], Liu Guanjun [a], Zhao Chenxu [a]

[a] *Science and Technology on Integrated Logistics Support Laboratory, National University of Defense Technology, Changsha 410073, China*

[b] *Department of Electronic Technology, Officer's College of CAPF, Chengdu 610213, China*

Received 15 June 2013; revised 8 July 2013; accepted 22 August 2013
Available online 2 May 2014

KEYWORDS

Condition indicators;
Health indicator;
Helicopter transmission systems;
Mann–Kendall test;
Physical model;
Sensitivity analysis;
Sen slop estimator;
Sensor selection

Abstract In the helicopter transmission systems, it is important to monitor and track the tooth damage evolution using lots of sensors and detection methods. This paper develops a novel approach for sensor selection based on physical model and sensitivity analysis. Firstly, a physical model of tooth damage and mesh stiffness is built. Secondly, some effective condition indicators (CIs) are presented, and the optimal CIs set is selected by comparing their test statistics according to Mann–Kendall test. Afterwards, the selected CIs are used to generate a health indicator (HI) through sen slop estimator. Then, the sensors are selected according to the monotonic relevance and sensitivity to the damage levels. Finally, the proposed method is verified by the simulation and experimental data. The results show that the approach can provide a guide for health monitoring of helicopter transmission systems, and it is effective to reduce the test cost and improve the system's reliability.

1. Introduction

In the helicopter systems, transmission systems are the most efficient and compact devices used to transmit torque and change the angular velocity. The operating conditions of gears are very complicated, because they may encounter various problems, such as excessive applied torque, bad lubrication and manufacture or installation problems.[1] Local tooth damage (e.g., tooth crack, pitting, breakage, etc.) occurs due to excessive stress conditions.[2] As the damage level increases, the function of systems will be affected, and it will result in the final failure of the systems.

To minimize the loss that result from the interruption of production and high machine failure cost, it is necessary to monitor machine condition on-line using an effective condition monitoring system to provide timely information for condition-based maintenance (CBM) decision-making.[3] Generally, condition monitoring for CBM involves the observation of machine condition using periodically sampled dynamic response measurements through massive sensors instrumented in the system and detection methods. Obviously, data or information obtained from sensors is the basis of CBM decision-making. In this paper, the meaning of "sensor" is developed, and it represents the available condition variables in physical

* Corresponding author. Tel.: +86 731 84574329.
E-mail address: fhrlkh@163.com (K. Lyu).

Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

1000-9361
http://dx.doi.org/10.1016/j.cja.2014.04.025

model of a system (e.g., displacement, velocity, acceleration, temperature, pressure, flow rate, forces, etc.), condition monitoring techniques (e.g., vibration monitoring, acoustic emission,[4] temperature monitoring, fluid monitoring, corrosion, etc.), and accelerometers, thermocouple, oil sensor in different locations, etc.[4–8]

Recently, studies have shown that traditional ways of simply adding sensors are impractical, and it will ultimately reduce systems' reliability and increase the monitoring cost.[4–8] However, if the number of sensors is insufficient, the objective of condition monitoring cannot be achieved, and the false alarm and missed detection can be caused. Therefore, careful selection and implementation of sensors is critical to enable high fidelity system health assessment, improve the systems' reliability, and reduce the test cost on the basis of meeting the requirements of CBM.[5]

In recent years, many researchers have paid more attention to sensor selection problems.[5–13] National Aeronautics and Space Administration (NASA) has studied sensor optimization configuration technology for engine health management since 2005, and proposed a famous system sensor selection strategy (S4),[5] and the researchers also studied some experimental validation and verification for health monitoring and management of some aerospace systems such as turbo engine, RS-68 rocket engine.[6,7] Cheng et al. studied sensor selection optimization for prognostics and health management (PHM) systematically, and proposed the state-of-art sensor systems for PHM and further discussed the emerging trends in technologies of sensor systems.[8] Xu et al. proposed a fault tolerant sensor architecture and realized the architecture through the design of dual mode humidity/pressure micro electro mechanical system (MEMS) sensors with an integrated temperature function for health and usage monitoring.[9] Novis and Powrie analyzed the characteristics of sensor systems used in real PHM environment in order to improve system diagnostic capability.[10] Baer and Lally constructed an open standard smart sensor structure, and designed a sensor system for PHM.[11] Cheng et al. introduce a novel radio-frequency-based wireless sensor system for PHM, and it includes a radio frequency identification sensor tag, a wireless reader, and diagnostic-prognostic software.[12] Yang et al. proposed a sensor selection model by considering the impacts of sensor actual attributes on fault detectability.[13]

The main purposes of above sensor selection methods are to provide data for fault diagnosis, detection or isolation. However, with the development of PHM theory and technique, besides meeting the above requirements, the information obtained from sensors must also provide useful data support for fault prognostics and health state assessment. There are many types of performance measures in fault prognostics and health state assessment, for example health monitoring performance (eg., the monitoring performance for fault growth, time to monitoring, etc.). To better improve those performance levels of fault prognostics and health state assessment, we should select sensors, which maximize sensitivity for crack evolution process, i.e., crack growth in different components should, as soon as possible, be able to be tracked or monitored effectively, and it means that the crack evolution trends described by sensors have a better monotonic characteristic. Previous works have demonstrated that constructing a physical model including damage levels and selecting the better sensitive sensors to damage growth so as to track the damage evolution are essential to improve the performance of PHM.[7,8] So, a physical model of crack tooth needs to be build to better analyze the effect of different crack levels on those variables in the model, thus we can obtain the crack evolution process, which is described by those variables that can be monitoring by using corrective sensors. Hence, this paper proposes a sensor selection technique based on physical model and sensitivity analysis. We take the tooth crack as an example, and the relation between the crack levels and the reduction of mesh stiffness is built. Some condition indicators (CIs) are presented to describe the crack evolution trend, and some optimal CIs having better monotonic trend with damage levels are selected using Mann–Kendall test method. The selected CIs can generate a health indicator (HI) indicating the damage level and the HI trend of sensors with damage growth will be derived. The sen slop estimator is used to calculate the sensitivity of each sensor to damage evolution, and then the optimal sensors can be selected.

The rest of this paper is organized as follows. In Section 2, the physical model of tooth crack is developed. In Section 3, the sensitivity of sensors to damage growth is developed to assist in selecting the optimal sensors. In Section 4, a simulation data of a one-stage gearbox and experimental data provided by mechanical diagnosis test bed (MDTB) of Applied Research Laboratory (ARL) at Pennsylvania State University are used to verify the effectiveness of the method proposed in this paper. Finally, this paper concludes with a summary and future research direction in Section 5.

2. Physical model of crack tooth

The stiffness of crack tooth is found to be decreased proportionally to the severity of the crack.[2] In order to build the mesh stiffness models of crack tooth, many researches have been carried out. Finite elements method (FEM) is the most popular tool applied to this.[14] In FEM, the higher solution accuracy of FEM relies on more mesh refinement, but the FEM model including more mesh refinements is computationally expensive and is very difficult to build in certain applications. Moreover, The FEM does not give precise details about when the stiffness reduction occurs and how much the various damage levels are correlated to the stiffness reduction, while such information is very important to correctly construct the model of damage dynamics of various damage levels. Choy et al. developed an analytical model that the effect of surface pitting and wear of the gear tooth were simulated by phase and magnitude changes in the gear mesh stiffness.[15] Liu et al. developed a quasi-static nonlinear mesh gear model that included effects associated with gear tooth damage.[1] Wu et al. studied the effects of tooth crack on the vibration response of a one-stage gearbox with spur gears, and a lumped parameter model was used to simulate the vibration response of the pair of meshing gears.[16] Chaari et al. developed an analytical approach to quantify the gear mesh stiffness reduction of spalling or tooth breakage.[2] The above research results show that the analytical methods offer satisfying results, good agreements and less computational time than FEM. So, through combining the advantages of the analytical approach, we take the tooth crack as an example and introduce an analytical approach to construct its physical models.