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Identification method for helicopter flight dynamics modeling with rotor degrees of freedom

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Abstract A comprehensive method based on system identification theory for helicopter flight dynamics modeling with rotor degrees of freedom is developed. A fully parameterized rotor flapping equation for identification purpose is derived without using any theoretical model, so the confidence of the identified model is increased, and then the 6 degrees of freedom rigid body model is extended to 9 degrees of freedom high-order model. Bode sensitivity function is derived to increase the accuracy of frequency spectra calculation which influences the accuracy of model parameter identification. Then a frequency domain identification algorithm is established. Acceleration technique is developed furthermore to increase calculation efficiency, and the total identification time is reduced by more than 50% using this technique. A comprehensive two-step method is established for helicopter high-order flight dynamics model identification which increases the numerical stability of model identification compared with single step algorithm. Application of the developed method to identify the flight dynamics model of BO 105 helicopter based on flight test data is implemented. A comparative study between the high-order model and rigid body model is performed at last. The results show that the developed method can be used for helicopter high-order flight dynamics model identification with high accuracy as well as efficiency, and the advantage of identified high-order model is very obvious compared with low-order model.

1. Introduction

The helicopter is a very complex system and it is difficult to build helicopter flight dynamics model with high accuracy. This is because the aerodynamic phenomenon of a helicopter is very complicated. There is aerodynamic interference between main rotor, fuselage, tail rotor, vertical tail and horizontal tail. Besides, each degrees of freedom of a helicopter is highly coupled. Conventional theoretical modeling techniques build a helicopter flight dynamics model based on various physical laws. But in order to apply these physical laws to model a complex system such as helicopter, it always needs to make a lot of assumptions.[1] Therefore, the accuracy of helicopter flight dynamics model built by theoretical methods is still not satisfactory yet. Although it is necessary to continue improving conventional techniques, other modeling methods based on

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modern techniques such as system identification are also need to be developed.

The system identification is a modeling technique based on experimental data, and it only need make very few assumptions to construct mathematical models, so the accuracy and confidence of a model constructed using system identification are higher than conventional theoretical modeling techniques.[2] When applying system identification technique to build a helicopter flight dynamics model, the modeling problem becomes the extraction of a dynamic model based on input–output data from flight test database.[3,4] Since the helicopter is unstable and highly coupled, the identification problem for helicopter flight dynamics model is much more difficult than fixed wing aircraft. So when simply applying the identification methods used in fixed wing aircraft to helicopter flight dynamics modeling, the identification accuracy is not satisfactory.[4] For the past several decades, there are a lot of researches aimed to solve the specific problems in identifying helicopter flight dynamics model, and plenty of papers have summarized these works well. There are different identification methods defined for helicopter flight dynamics modeling problem and there are also different identification models from simple model such as transfer function model to complicated model which is described as a set of differential equations. For many applications such as handling quality assessment, flight control system design etc., a linear model is sufficient. The linear flight dynamics model can be expressed as transfer function or state space equations. However, the identification problem of state space equation formed flight dynamics model is quite complicated even for a rigid body model or decoupled model. There are lots of papers concerning the solution of this problems well,[4–11] and the identification accuracy of these methods is satisfactory when applying to low-order and especially decoupled models. In order to increase the identification accuracy and robustness, new techniques are also developed and have already been applied to identifying fully coupled rigid body models.[12,13]

However, the helicopter is a typical high-order system. For some applications such as simulation model validation, high bandwidth control system design etc., a high-order model is required. The identification of high-order flight dynamics model of a helicopter is much more difficult than low-order case. The key problems include how to establish a parameterized high-order model for identification purpose and how to identify so many parameters that have large differences in sensitivity. The study of high-order flight dynamics model identification problem was started as early as the 1980s, and there are also plenty of papers summing up their achievements in this area. Some of these papers established rotor models from experiment data[14–16] that can predict rotor responses well. However, the identification models used in these papers are mostly derived from theoretical models. Therefore, the confidence of these models is decreased. Some researchers developed the high-order identification model for unmanned aerial vehicles (UAVs)[17–19], and these models have very simple structure that has very few parameters to be identified. The advantage of this kind of model is it increases the model accuracy especially at high frequency compared with low-order model while it can still be identified easily (since it has simple structure). However, the simple high-order model is not suitable for manned helicopters. This is because the amplitude of high frequency responses of manned helicopter is much larger than UAV, and the damping of manned helicopter is also larger than UAV. So a simplified rotor model cannot predict high frequency rotor responses of a large helicopter with high accuracy. The most accurate as well as the most complicated high-order models that contain complete rigid body and rotor derivatives are also developed by some researchers[20,21] and these models have already been used for high bandwidth control system design.[22] It has already been proved that the fully parameterized high-order model has the highest accuracy. However, it is also the most difficult one to identify. The most difficult part in the identification of this kind of model is model structure determination which is still not solved very well in almost all of the published papers. Just as many authors mentioned,[21,23] the high-order flight dynamics model identification of a helicopter is still a very difficult problem, and a more reasonable high-order identification model structure as well as more powerful identification algorithm need further investigation.

The aim of this paper is to establish a high-order helicopter flight dynamics model without using any theoretical models in order to let the identified model have the highest confidence. In order to do this, a fully parameterized rotor flapping model is derived at first, and then the low-order rigid body model is extended to 9 degrees of freedom (DOFs) 14th order model. Then a fast frequency domain identification algorithm which has both high accuracy and efficiency is developed for identification of dynamic system. A two-step identification strategy is established for identifying the high-order flight dynamics model. The application of the developed methods to BO 105 helicopter is implemented based on its flight test data. A comparative study between low-order model and high-order model is performed finally to show the advantage of using high-order flight dynamics model.

2. Flight test database

In this paper, the flight test data of BO 105 helicopter is used for identification. The flight test was conducted in the 1980s by the Deutschen Zentrums für Luft- und Raumfahrt (DLR)[4] for identification purpose. The flight test was started from trim condition at a density altitude of 914 m in calm air environment, then the pilot used 3-2-1-1 band optimized excitation signal to excite the helicopter in order to obtain its dynamic characteristics. In this paper, there are totally two groups of test data used for the research. One group of data was excited by longitudinal stick input and the other group was excited by lateral stick input, so both longitudinal and lateral dynamic modes were sufficiently excited which is very important for fully coupled model identification. In each group of data, there are several repeated test runs, so in this paper different test data are used for model identification and verification. An example input signal for one test run in the flight test data is shown in Fig. 1.

The original flight test data contain high frequency noise and measurement errors, so a data processing procedure is required before identification. In this paper, the standard data processing technique including wild value elimination, low pass filtering, data compatibility examination and reconstruction is used to remove any unexpected terms in the test data. Finally, all refined data are put into a standard flight test database for further use in the identification.