Mechanical Systems and Signal Processing 88 (2017) 9–24

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Detection of the ice assertion on aircraft using empirical mode decomposition enhanced by multi-objective optimization

Seyed Amin Bagherzadeh[a,*], Davood Asadi[b]

[a] Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
[b] Department of Mechanical and Aerospace Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

ARTICLE INFO

Keywords:
Empirical mode decomposition
Aircraft ice assertion
Multi-objective optimization
The genetic algorithm

ABSTRACT

In search of a precise method for analyzing nonlinear and non-stationary flight data of an aircraft in the icing condition, an Empirical Mode Decomposition (EMD) algorithm enhanced by multi-objective optimization is introduced. In the proposed method, dissimilar IMF definitions are considered by the Genetic Algorithm (GA) in order to find the best decision parameters of the signal trend. To resolve disadvantages of the classical algorithm caused by the envelope concept, the signal trend is estimated directly in the proposed method. Furthermore, in order to simplify the performance and understanding of the EMD algorithm, the proposed method obviates the need for a repeated sifting process. The proposed enhanced EMD algorithm is verified by some benchmark signals. Afterwards, the enhanced algorithm is applied to simulated flight data in the icing condition in order to detect the ice assertion on the aircraft. The results demonstrate the effectiveness of the proposed EMD algorithm in aircraft ice detection by providing a figure of merit for the icing severity.

1. Introduction

While crossing through clouds containing undercooled water droplets (e.g., cumulus and stratus), aircraft commonly encounter the formation of ice on exposed surfaces. Despite aircraft being ice-protected by employing a variety of de-icing and anti-icing systems, the ice accretion on aircraft surfaces continues to occur due to several reasons. The ice formation exerts significant adverse influences on the aircraft aerodynamics, such as decreases in the total lift and effectiveness of stability and control derivatives, and a drastic increase in the drag [1]. Consequently, it reduces the aircraft performance [2–4], and adversely affects the flight dynamic characteristics such as stability, controllability and maneuverability [5,6]. Also, changes in control rules are often required to keep the aircraft in a limited flight envelope, and to maintain the aircraft performance and flying qualities in acceptable levels during icing conditions. For appropriate altering of control rules, an identification of the shape, size and location of ice on aircraft surfaces is necessary. The ice assertion is a complicated phenomenon depending on many factors, including environmental parameters (i.e., the temperature, humidity and size of water droplets), flight parameters (i.e., the speed, altitude, angle of attack and the time spent in conditions prone to the ice formation), and the surface parameters. Therefore, it is essential to provide suitable methods for the detection of ice properties based on the mentioned factors.

So far, several sensors using dissimilar technologies have been developed and employed to detect the ice formation on aircraft surfaces [7]. However, many of these sensors provide limited information about ice characteristics [8]. Therefore, relying exclusively on the sensors is not effective, and new approaches for ice detection are necessary. According to literatures, one of the best

* Corresponding author.
E-mail addresses: bagherzadeh@pmc.iaun.ac.ir, sabagherzadeh@gmail.com (S.A. Bagherzadeh).

http://dx.doi.org/10.1016/j.ymssp.2016.11.013
Received 5 January 2016; Received in revised form 17 October 2016; Accepted 12 November 2016
0888-3270/

Nomenclature

a_j, b_j, c_j, d_j	The coefficients of the jth polynomial which construct the trend signal [dimensionless]
b	Aircraft wing span ft
c_i	The ith IMF [dimensionless]
$\bar{c}$	Aircraft mean aerodynamic chord ft
C_{clean}	An stability and control derivative in the clean condition [dimensionless]
C_{iced}	An stability and control derivative in the icing condition [dimensionless]
E	Energy of a signal [dimensionless]
EI	The energy index [dimensionless]
$f_{degradation}$	The effectiveness reduction of every stability and control derivative in the icing condition [dimensionless]
$f_{severity}$	The ice severity [dimensionless]
h	Flight altitude ft
$h_{i,j}$	The weak-IMF of the jth iteration for the ith IMF [dimensionless]
I	The total cost function [dimensionless]
II	The integral index [dimensionless]
I_{xx}, I_{yy}, I_{zz}, I_{xz}	Aircraft moments of inertia $slug.ft^2$
J	The number of extrema [dimensionless]
$l_{i,j}$	The lower envelope of the jth iteration for the ith IMF [dimensionless]
$m_{i,j}$	The trend of the jth iteration for the ith IMF [dimensionless]
OI	The orthogonality index [dimensionless]
PI	The mono-component penalty index [dimensionless]
r_i	The ith reminder [dimensionless]
S	The aircraft reference area ft^2
t	Time instant [dimensionless]
$u_{i,j}$	The upper envelope of the jth iteration for the ith IMF [dimensionless]
V	Total velocity kt
W	Aircraft weight lb
x	The investigated signal [dimensionless]
$\overline{X}_{CG}$	Position of center of gravity as a fraction of $\bar{c}$ [dimensionless]
α	The angle of attack deg
δE	The elevator command deg

approaches for the aircraft ice detection is the aircraft system identification [8]. It provides not only sufficient information about type, shape, size and location of ice, but also supplementary information about the impact of ice on the aircraft performance and flight dynamics for altering control rules and limiting the flight envelope. For this purpose, signal analysis methods suitable for nonlinear and non-stationary flight data are required. Hence, one may utilize the Hilbert-Huang Transform (HHT).

The HHT is a tool for analyzing physical processes in the time-frequency domain [9]. The HHT is an empirical method that can express nonlinear and non-stationary data as instantaneous characteristics, in an adaptive manner. The HHT contains two main processes: decomposing the investigated signal by the Empirical Mode Decomposition (EMD) into its fundamental mono-component narrow-band oscillatory components called the Intrinsic Mode Functions (IMFs), and the implementation of the Hilbert Transform (HT) to achieve the instantaneous amplitudes and frequencies of the IMFs. Hence, the aim of the EMD is to extract the IMFs which are prepared for the implementation of the HT.

The EMD has already been applied effectively in several fields of research. Among these applications, the main focus of attention in this paper is two fields: firstly the failure detection of systems, and secondly the analysis of flight data. Both fields have similar requirements, including the nonlinear and non-stationary signal analysis, the adaptive signal decomposition and feature extraction, and the achievement of physically meaningful results in terms of instantaneous characteristics. Therefore, the EMD appears a perfect choice for them. Literatures indicate successful applications of the EMD in both fields. The EMD is capable of detecting faults and failures, and providing required data for the damage identification and health monitoring of systems [10–13]. Also, the HHT is able to analyze flight data; for example the estimation of flight modes [14,15] and the nonlinear aerodynamic model identification [16]. The overlap of the mentioned fields is to employ the EMD for the damage identification and health monitoring of aircraft. Few researches conducted in this area lead to significant results [17]; hence, it may be studied further in the future. This paper is dedicated to one of the applications of the new field, namely utilizing the EMD for detection of the ice assertion on aircraft.

Notwithstanding the numerous advantages and applications, the EMD does not have a rigorous mathematical formulation. This weakness can be clearly observed in several aspects of the EMD, including the presentation in the form of an iterative algorithm, the absence of a comprehensive definition for the IMF and the lack of appropriate stopping criteria. As a result, the EMD is faced with several disadvantages that undermine its performance in applications requiring high accuracies (see Section 2). Thus, in order to utilize the EMD to detect the ice formation on aircraft surfaces, providing an enhanced high-accuracy version of the EMD is inevitable.

This paper is organized as follows: the EMD algorithm, its drawbacks and some studies conducted to improve the EMD are reviewed in Section 2. Next, Section 3 proposes multi-objective optimization for the EMD enhancement. Then, the proposed algorithm is verified by some benchmark problems in Section 4. Afterwards, Section 5 presents implementation of the enhanced EMD for aircraft ice detection. Finally, the paper is concluded in Section 6.

2. The EMD

2.1. Review of the classical algorithm

The EMD is an iterative algorithm containing two loops. The inner loop, sifting process expresses the investigated signal in terms of a high frequency detail component and a low frequency signal trend. The classical EMD algorithm estimates the signal trend by