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An improved signal envelope estimation method for analysis of acoustic signals emitted by remotely piloted helicopters

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ABSTRACT

This study presents a new signal envelope estimation method in order to improve the performance of the Empirical Mode Decomposition (EMD), especially in dealing with transient signals. An important application of this method is the analysis of signals containing spikes such as acoustic signals. For this purpose, both the spline interpolation and control point selection algorithm are adapted. To construct signal envelopes, the Catmull-Rom spline interpolation is employed due to its desired features. Also, a new algorithm is utilized in order to select control points prior to the iterative sifting process. Afterward, the proposed method is verified by some benchmark signals. Performance indices indicate that the proposed EMD outperforms the traditional one in handling transient signals. Finally, the proposed method is applied to acoustic signals gathered during some flight tests of a remotely piloted helicopter. The results demonstrate that the proposed method is able to isolate acoustic signals emitted by dissimilar sources.

1. Introduction

Among dissimilar types of unmanned aerial systems, Remotely Piloted Helicopters (RPHs) offer great potential for urban applications due to the ability to hover and maneuver in confined spaces. Nevertheless, civil uses of the RPHs are confronted with several issues. Noise emitted by the RPHs is one of the most important problems which should be carefully examined in that regard. So far, numerous studies have been conducted about acoustic signals generated by helicopters including the measurement [1,2], identification [3], modeling [4,5] and simulation [6,7] of noise, and the helicopter operation [8,9] and design [10] based on noise considerations. Focused on manned helicopters, however, the studies disregard RPHs. In the current paper, a new method appropriate for analyzing acoustic signals of both manned and unmanned helicopters is presented.

Acoustic signals generated by a helicopter are complex phenomena. On the one hand, they are emitted by several sources such as the main rotor, tail rotor, fuselage, engine, and power transmission system. On the other hand, they are generated due to several aerodynamic mechanisms including thickness noise, loading noise and impulsive noise such as high speed impulsive noise and blade-vortex interaction noise. Therefore, it has been observed that these acoustic signals are multi-component. During measurements, some components may dominate others, depending on several factors such as the position of the receiver to the source and flight conditions. Hence, for an effective investigation, components of an acoustic signal should be isolated and then individually studied in order to determine the effects of every component on the total signal.

Until now, various flight test approaches have been suggested for the measurement of helicopter acoustic signals including placement of microphones either on the helicopter itself, on an airplane moving at the same speed as the helicopter, or on the ground at certain points [11]. Ground-based tests are the most commonly used approach due to the significance of the rotorcraft acoustics during terminal phases. In this method, acoustic signals are measured during the helicopter flight over an array of microphones affixed on the ground. However, the distance and angle between the helicopter and microphones do not remain constant. Therefore, acoustic signals acquired by microphones are non-stationary. This characteristic is called the Doppler effect, and necessitates compensating the distance and angle prior to any analysis. Numerous de-Dopplerization methods are proposed in the frequency [12] and time domains [11,13]; however, the non-stationary signals still cause several difficulties for signal processing procedures.

In the physical world, signals are usually non-stationary and multi-component. Nevertheless, there are few appropriate methods for analysis of these signals. Empirical Mode Decomposition (EMD) is one of the methods recently developed for analysis of convoluted signals [14]. The EMD is an algorithm aimed to decompose a signal into its constituent mono-component modes consisting of only one mode of oscillation during every cycle. These components are called Intrinsic Mode

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Functions (IMFs). An IMF is a function with envelopes symmetrical with respect to zero. The EMD capability to analyze multi-component non-stationary signals is essentially due to its adaptive bases derived from the signal itself. Therefore, the IMFs containing dissimilar frequencies can be separated while they do not have to be in conformity with a predetermined structure. After completing the decomposition process, each IMF can be described as time-varying amplitude and frequency functions by means of the Hilbert transform. Hence, the EMD is appropriate for a variety of applications in which the time-frequency interpretation of a signal is required [15–17].

In conclusion, helicopter acoustic signals are superpositions of several components generated by different sources, and they are achieved in a non-stationary manner during ground-based acoustic tests. Furthermore, the EMD is a suitable method for analyzing multi-component, non-stationary signals. Therefore, it is proposed for the first time to employ the EMD to analyze helicopter acoustic signals. However, the traditional EMD has some drawbacks such as the handling of transient phenomena like spikes that are frequently present in acoustic signals. Hence, an improved envelope estimation method is proposed in this paper in order to adapt the EMD algorithm for the analysis of acoustic signals.

The remainder of the paper is organized as follows: Splines utilized to construct signal envelopes for the EMD algorithm are reviewed in Section 2. Then, the proposed envelope detection method including the interpolation and control point selection method are presented in Section 3. Next, IMF performance indices are presented, and the new method is verified by some benchmark signals in Section 4. Afterward, in Section 5, the proposed method is applied to the RPH acoustic signals in order to reveal its performance. Finally, the paper is concluded in Section 6.

2. Review of splines utilized in the EMD algorithm

The main task of the EMD is to find the overall pattern of the signal called the signal trend, and eliminate it from the signal in order to find a mono-component, narrow-band IMF. There are two general approaches for the EMD. Firstly, the direct approach attempts to extract the signal trend directly in either a one-step or an iterative process [18–20]. Secondly, the envelope approach obtains upper and lower curves that entirely encompasses the signal called envelopes, and finds the signal trend by averaging the envelopes. The basic version of the EMD was based on the latter [14]; therefore, subsequent studies have been frequently developed based on it. Despite differences between the two approaches, there is a common issue for both, namely interpolation methods. Among interpolation methods, splines are the most common because of the following characteristics:

- Splines are piecewise-smooth, low-order polynomials; thus, they are easier and faster in comparison with high-order polynomials.
- Splines are smooth, i.e. usually continuously differentiable to some degree.
- Splines have local control, i.e. change of control points affects only a limited portion of the curve.
- Splines are affine invariant. In other words, changing the coordinate system does not change the relative geometry of control points.
- Splines prevent Runge's phenomenon, instabilities in boundaries caused by high-degree polynomial fits.

Because of these characteristics, a variety of splines have been employed to create the upper and lower envelopes required by the EMD:

- Natural cubic splines are used in the basic version of the EMD [14]. The main disadvantage of the cubic spline is that it causes unrealistic extrema due to the occurrence of overshoots and undershoots in the upper and lower envelopes. Therefore, finding a suitable replacement for natural cubic splines has always been a concern. Even Ref. [14], the original study presenting EMD, attempted to slightly improve results by altering the spline tension via taut splines.
- Rational splines are also used to construct envelopes [21,22]. These studies show that increasing the spline tension can restrict the range of the orthogonality criterion and reduce the effects of overshoots. As a result, the appropriate selection of the tension parameter reduces the number of sifting process, and preserves the orthogonality.
- Linear combinations of B-splines such as the cubic and quadratic moving mean average splines are used for the interpolation between all extrema in order to simplify the mathematical representation of the EMD [23]. The results show that this method produces better results in comparison with the traditional EMD in terms of the energy conservation and orthogonality criteria. It has also been observed that low-order B-splines preserve local characteristics of the signal and follow data more closely, while high-order B-splines provide more orthogonal mean signals.
- The Akima spline is studied and compared with the natural cubic spline [24]. The study indicates that the Akima spline is neither smooth nor flexible enough for the EMD. Therefore, to achieve a method with desired specifications, a new spline for the envelop estimation is presented. This interpolation is similar to the parabolic parameter spline interpolation except that the segment power function is employed to create and connect two single-valued first-order continuous curves.
- The piecewise cubic Hermite interpolation has been widely used to construct signal envelopes. The piecewise cubic Hermite interpolation is more flexible than the cubic spline [25]. Also, it ensures a resultant continuous and smooth curved, and minimizes overshoots. However, investigations show that the piecewise cubic Hermite interpolation cannot adaptively preserve the signal shape. To satisfy this indispensable property, it is suggested to incorporate shape control parameters into the envelope estimation methods [26].
- Non-polynomial splines are also utilized to achieve the envelopes [27,28]. In this method, extrema and pseudo-extrema are connected by non-polynomial cubic spline interpolation, and the envelopes are obtained by solving a differential equation. The results show that this method can reduce the mode mixing problem.
- It should be noted that methods used for the EMD envelope extraction are not limited to spline interpolations; nevertheless, due to the aforementioned advantages, splines are more prevalent for this purpose.

These investigations indicate that the EMD performance is extremely dependent upon the designated interpolation method. Dissimilar desired characteristics are expected from an interpolation method such as the flexibility and continuity. Generally, flexibility causes the curve to be close to control points; nevertheless, too high flexibility can lead to break points and too low flexibility can intensify overshoots. Also, the continuity usually causes round and fair curves; nevertheless, too high or low continuity can result in inverted or box corners, respectively. It is evident that in many cases, the desired characteristics are contradictory. For example, the shape preserving characteristics is an essential specification for the analysis of nonlinear and non-stationary signals; however, it is in contrast to the curve smoothness. Furthermore, it is essential that the curve lies between two non-intersecting envelopes; however, it is in contrast to the curve continuity. Hence, a compromise should be made between desired characteristics. In order to control interpolations, some references suggest shape parameters that generate a family of curves [26–28]. In search of an interpolation method that can provide a suitable family of curves, the Catmull-Rom spline is investigated in this paper.