

Enhancing Experimental and Numerical Data Validation through Acoustic Noise Signal Demodulation for Estimating Drone Propeller Rotational Speed

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Abstract. This study addresses a novel approach for estimating the rotational speed of small-scale propellers, typically found in drones, through the analysis of their acoustic noise signal. Accurately determining the instantaneous rotational speed of propellers in anechoic wind-tunnels poses significant challenges due to inherent experimental rotational speed fluctuations. These fluctuations can distort harmonic peaks levels, or deteriorate the process of applying comparable techniques when validating constant rotational speed numerical simulations with experimental data. This can be overcome by the knowledge of the propeller instantaneous rotational speed, allowing the signal to be resampled, correcting it to a constant rotational speed. Measured tachometer data is often not available nor reliable, as the use of external devices is not always feasible due to space constraints, costs, and sensitivity to adverse environmental conditions. An alternative approach is to directly estimate the propeller rotational speed from the measured acoustic signal, which is the focus of this study. The proposed methodology is based on the signal demodulation, which is a tacholeless method that calculates the Hilbert Transform of the acoustic signal to obtain the frequency and phase related to the shaft rotation. To evaluate the technique, a synthetic propeller noise data are generated with a previous established rotational speed fluctuation, allowing a characteristic error for the algorithm predicted instantaneous rotation to be obtained. Secondly, the process is repeated for a real propeller noise signal, and the results are compared with the actual rotational speed measurement obtained with the tachometer. Finally, the obtained instantaneous rotation is employed to resample the experimental signal, allowing it to be suitable for validating numerical simulated signals. The spectra obtained from both signals are then compared, and the signal components are evaluated using a Time Synchronous Averaging (TSA) analysis. Preliminary results indicate the consistency and feasibility of the technique.

Keywords: Propeller noise, frequency estimation, signal processing, aerodynamic noise.

1. INTRODUCTION

In the ever-evolving realm of drone technology, the precise estimation of propeller rotational speed stands as a pivotal challenge. The need of knowing this information provides further analysis, such as dynamic control, precise noise sources identifications with decomposition techniques and failure prediction.

Upon scrutinizing the acoustic traits of noise produced by fully electric propulsion systems, it becomes apparent that the primary sources are the interactions between the blades and the airflow, encompassing turbulence and vortical effects. The dominant aspect of the noise spectrum comprises the tonal rendition, characterized by multiples of the blade-pass frequency (BPF), signifying a periodic signal. In contrast, the broadband feature, originating from the blade interactions, disperses energy throughout all frequency bands, exhibiting inherent stochasticity. In order to better analyze the noise sources, the features must be separated, which can express plenty difficulties, upon rotational speed fluctuations.

In this context, the Time Synchronous Averaging Method (TSA) (McFadden, 1987) finds extensive application in rotors operating at constant rotational speeds, owing to its straightforward implementation and effectiveness in isolating peaks. The method operates by averaging segments of acoustic data corresponding to a single rotation length in the time domain. However, its efficacy diminishes when applied to systems with varying speeds, as the irregular periodicity of

segments undermines its performance. Sharma and Parey (2016) proposed a tonal and broadband components TSA-based decomposition in order to calculate fault indicators in gears, which considers the rotational frequency fluctuation, therefore, this technique takes in account the tachometer signal, using n pulses per revolution. With this device it is possible to track the angular position of any shaft.

Small-scale propellers, typically found in drones, necessitate accurate measurement techniques amidst the backdrop of inherent experimental fluctuations. Traditional methods, reliant on tachometer data, often falter due to practical constraints and environmental sensitivities, prompting a quest for alternative methodologies. Peeters *et al.* (2019) presents a complete analysis on various methods that discard the need of a tacho signal.

Urbanek *et al.* (2011) investigate three major instantaneous frequency estimation techniques without any phase markers use in wind turbines speed tracking application. The spectrogram-based method proceeds with a maxima tracking due to the fact the peaks with the highest energy on the spectrogram should correspond to the value of the instantaneous frequency at each moment in time.

In another approach, Bonnardot *et al.* (2005) proposed a tacholess technique of estimating the instantaneous rotation of a shaft with limited frequency fluctuations. The method is based on the phase demodulation and utilizes the Hilbert Transform, a mathematical instrument to obtain the imaginary part of the analytic signal, which corresponds to the phase of the signal. The main achievement of this technique is that it extinguishes the need of a tachometer, the instant rotation can be calculated based on the shaft vibration data. This work analyses the merits and the feasibility of this method.

This work is organized as follows: Section 2 presents the methodology of the phase demodulation technique, describing in details the physics behind the numerical calculation. Section 3 describes some setups of both numerical and experimental data and Section 4 compares the results with the tachometer real information, as well as evaluates the components of the resampled signal with Time Synchronous Averaging (TSA) techniques. Finally, Section 5 concludes the consistency of the demodulation method.

2. METHODOLOGY

First, a widely used mathematical tool in the field of signal analysis is presented.

2.1 The Hilbert Transform

Consider a system with an input $x(t)$ and a filter $h(t) = \frac{1}{\pi t}$. The output of the system is given by:

$$y(t) = \hat{x}(t) = h(t) * x(t) = \frac{1}{\pi t} * x(t) \quad (1)$$

This convolution operation is called a Hilbert Transform (Shin and Hammond, 2008). Note that $h(t)$ is a non-causal filter with a singularity at $t = 0$. The Hilbert transform is often referred to as a 90° phase shifter. For example, the Hilbert transform of $\cos(\omega_0 t)$ is $\sin(\omega_0 t)$, and that of $\sin(\omega_0 t)$ is $-\cos(\omega_0 t)$.

The significance of the Hilbert transform is that it is used to form the so called "analytic signal" or "pre-envelope signal". An analytic signal is a complex time signal whose real part is the original signal $x(t)$ and whose imaginary part is the Hilbert transform of $x(t)$, i.e. $\hat{x}(t)$. Thus, the analytic signal $a_x(t)$ is defined as:

$$a_x(t) = x(t) + i\hat{x}(t) = A_x(t)e^{i\phi_x(t)} \quad (2)$$

Where $A_x(t) = \sqrt{x^2(t) + \hat{x}^2(t)}$ is the instantaneous amplitude, and $\phi_x = \tan^{-1}(\hat{x}(t)/x(t))$ is the instantaneous phase.

2.2 The Demodulation Method

The primary method used for determining the instantaneous frequencies of a two-bladed propeller is the Demodulation Method (Bonnardot *et al.*, 2005), a robust and effective procedure that allows for a detailed and precise analysis of dynamic variations over time.

The technique consists in 5 steps:

2.2.1 Band Inspection and Signal Filtering

In this step, a characteristic harmonic of the signal is selected, with this study focusing on the first Blade Pass Frequency (BPF), which represents the harmonic with the highest energy. Subsequently, through a detailed visual analysis of the spectrum, a band-pass filter is applied to precisely isolate the region corresponding to the shaft rotation harmonic, along with its controlled frequency variations. This approach ensures a focused and accurate examination of the relevant dynamic behaviors.

It is important to add that the band of interest choice is primarily empirical, which results in testing band percentages and assess the performance of the ones who fit the problem the most. In this study we manage to compare multiple band percentages with the experimental instantaneous rotational frequency of the propeller.

2.2.2 Analytic Signal Estimation

The analytic signal is estimated according to 2.

2.2.3 Phase Normalization

After the analytic signal is estimated, we shall extract the phase from one $\phi_x(t) = \tan^{-1}(\hat{x}(t)/x(t))$. The phase is then normalized by dividing the phase by the order m of the harmonic chosen in the first step.

$$\phi_{x,m}(t) = \frac{\phi_x(t)}{m} \quad (3)$$

After this normalization, the angular position of the propeller in radians is determined. In order to facilitate later mathematical manipulations, the phase is transformed into a first degree function to ensure the proportionality of the angular signal obtained. This can be done easily with a Numpy build-in function.

2.2.4 Phase Markers

The phase markers are defined to identify the moment where the propeller completes one rotation, which is when the index corresponds to 2π radians. This is achieved through a linear interpolation between time and phase. From these markers, it is possible to establish a list that records the complete rotations, thus allowing the rotation period to be determined.

2.2.5 Rotational Speed Profile

Finally, the speed profile can be traced based on the propeller rotation period, since:

$$f = \frac{1}{T} = \frac{1}{t_{i+1} - t_i} \quad (4)$$

Where the notation t_i is the time instant t where the phase marker i is generated.

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