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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 tacholess 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 dificulties, 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 considerates 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 discart the need of a tacho signal.

Urbanek *et al.* (2011) investigate three major instantaneous frequency estimation techiniques 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 matematical 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 extincts the need of a tachometer, the instant rotation can 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) techiniques. Finally, Section 5 concludes the consistency of the demodulation method.

2. TEXT FORMAT

The manuscripts should be written in English, typed in A4 size pages, using font Times New Roman, size 10, except for the title, authors affiliation, abstract and keywords, for which particular formatting instructions are indicated above. Single space between lines is to be used throughout the text.

The text block that contains the title, the authors' names and affiliation, the abstract and the keywords must be indented 0.1 cm from the left margin and marked by a leftmost black line border of width 2 1/4 pt.

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PAGES **SHOULD NOT** BE NUMBERED

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The mathematical equations must be indented by 0.5 cm from the left margin. They must be typed using Times New Roman, italic, size 10 pt. font. Arabic numerals must be used as equation numbers, enclosed between parentheses, right-aligned, as shown in the examples below. Equations should be referred to either as "Eq. (1)" in the middle of a phrase or as "Equation (1)" in the beginning of a sentence. Matrix and vector quantities can be indicated either by brackets and braces, as in Eq. (1), or in bold style, as in Eq. (2). Symbols used in the equations must be defined immediately before or after their first appearance.

One single line must be included above and below each equation.

$$[M]\{\ddot{x}\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = f(t) \tag{1}$$

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{f}(t) \tag{2}$$

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Figures and tables should be placed in the text as close as possible to the point they are first mentioned and must be numbered consecutively in arabic numerals. Figures must be referred to either as “Fig. 1” in the middle of a phrase or as “Figure 1” in the beginning of a sentence. The figures themselves as well as their captions must be centered in the breadth-wise direction. The captions of the figures should not be longer than 3 lines.

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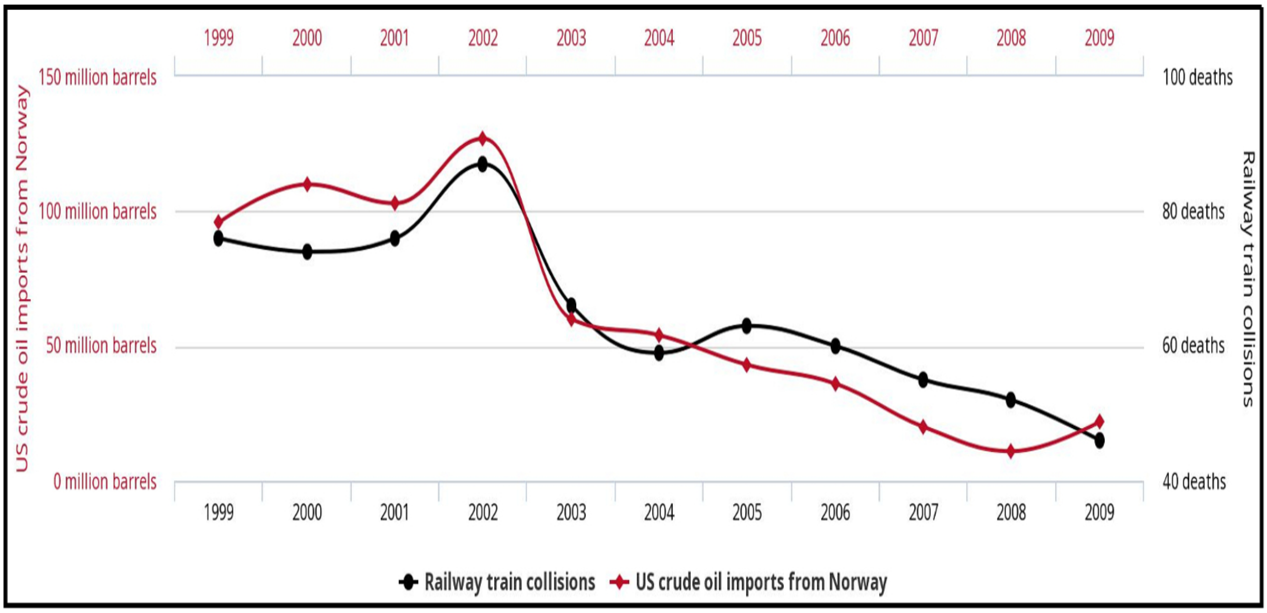

Figure 1. United States crude oil imports from Norway versus number of drivers killed in collision with railway train. Available from: http://tylervigen.com/spurious-correlations

Color figures and high-quality photographs can be included in the paper. To reduce the file size and preserve the graphic resolution, figures must be saved into GIF (figures with less than 16 colors) or JPEG (for higher color density) files before being inserted in the manuscript.

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The style of table borders is left free. An example is given in Tab. 1.

Table 1. Experimental results for flexural properties of CFRC-4HS and CFRC-TWILL composites. Span/depth ratio = 35:1. Average results of 7 specimens.

Composite Properties	CFRC-TWILL	CFRC-4HS
Flexural Strength (MPa)$^{(1)}$	209$\pm$ 10	180 $\pm$ 15
Flexural Modulus (GPa)$^{(1)}$	57.0 $\pm$ 2.8	18.0 $\pm$ 1.3
Mid-span deflection at the failure stress (mm)	2.15 $\pm$ 1.90	6.40 $\pm$ 0.25

$^{(1)}$ measured at 25^{o}C

3. ACKNOWLEDGEMENTS

This optional section must be placed before the list of references.

4. REFERENCES

The list of references must be introduced as a new section, located at the end of the paper. The first line of each reference must be aligned at left. All the other lines must be indented by 0.5 cm from the left margin. All references included in the reference list must have been mentioned in the text.

References must be listed in alphabetical order, according to the last name of the first author. See the following examples:

Bonnardot, F., El Badaoui, M., Randall, R., Danière, J. and Guillet, F., 2005. "Use of the acceleration signal of a gearbox in order to perform angular resampling (with limited speed fluctuation)". *Mechanical Systems and Signal Processing*, Vol. 19, No. 4, pp. 766–785. ISSN 0888-3270. doi:https://doi.org/10.1016/j.ymssp.2004.05.001. URL `https://www.sciencedirect.com/science/article/pii/S0888327004000664`.

McFadden, P., 1987. "Examination of a technique for the early detection of failure in gears by signal processing of the time domain average of the meshing vibration". *Mechanical Systems and Signal Processing*, Vol. 1, No. 2, pp. 173–183. ISSN 0888-3270. doi:https://doi.org/10.1016/0888-3270(87)90069-0. URL `https://www.sciencedirect.com/science/article/pii/0888327087900690`.

Peeters, C., Leclère, Q., Lindahl, P., Donnal, J., Leeb, S. and Helsen, J., 2019. "Review and comparison of tacholess instantaneous speed estimation methods on experimental vibration data". *Mechanical Systems and Signal Processing*, Vol. 129, pp. 407–436. doi:10.1016/j.ymssp.2019.02.031.

Sharma, V. and Parey, A., 2016. "Gear crack detection using modified tsa and proposed fault indicators for fluctuating speed conditions". *Measurement*, Vol. 90, pp. 560–575. ISSN 0263-2241. doi:https://doi.org/10.1016/j.measurement.2016.04.076. URL `https://www.sciencedirect.com/science/article/pii/S0263224116301567`.

Urbanek, J., Barszcz, T., Sawalhi, N. and Randall, R.B., 2011. "Comparison of amplitude-based and phase-based methods for speed tracking in application to wind turbines". *Metrology and Measurement Systems*, Vol. 18, pp. 295–304. URL `https://api.semanticscholar.org/CorpusID:54750614`.

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