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A UAV motor denoising technique to improve localization of surrounding noisy aircrafts: proof of concept for anti-collision systems

P. Marmaroli, X. Falourd and H. Lissek

Ecole Polytechnique Fédérale de Lausanne, EPFL STI IEL LEMA, 1015 Lausanne, Switzerland
patrick.marmaroli@epfl.ch

Unmanned Aerial Vehicles (UAVs) have become very affordable and small in recent years, and are increasingly used in a wide range of monitoring and surveillance applications. A major problem when operating with swarm of UAVs is the risk of mid-air collisions. Sensor technology to detect other aircrafts in order to prevent collisions currently receives a lot of attention in the research community. Therefore acoustic technologies could play an important role in anti-collision systems for small lightweight UAVs. Since most of aircrafts rely on active propulsion using propellers or jets, they emit noise which reveals their presence and position. It is therefore possible to detect the range and the bearing of other aircraft to avoid collisions without relying on active communication within the swarm. Because acoustic sensing is passive, tracking acoustic sources in air faces number of substantial challenges because of low signal to noise ratio of the surrounding aircrafts noises compared to the own propeller noise. In this context we propose a propeller noise reduction technique for on board microphone array processing.

1 Introduction

Anti-collision systems for UAV is a subject of growing interest since the last five years. Two kind of problematic can be distinguished, firstly the collisions between cooperative UAVs during swarm operations, secondly the collision between one UAV and its environment (trees, man made constructions etc.). This paper is mainly focused on the former kind of collision avoidance.

Both active and passive methods have been investigated in the robotic literature. Despite their high performances, the main drawback of active sensors like radar, sonar or laser explored in [1, 2, 3] is their energy consumption generally incompatible with long requested missions. Therefore, a large community of researchers developed algorithms based on passive video signal like stereo vision, optic flow or infrared [4, 5, 6]. Despite promising results using embedded camera and their low energy consumption, their performances are drastically reduced under bad weather conditions and/or during the night; in addition the angle of vision limits its usefulness for 3D vision.

As most aircrafts rely on noisy active propulsion using propellers or jets, the use of passive acoustic sensors is a logical complementary technique to hear and to avoid other UAVs. Promising results for tracking sonorous flying objects using acoustic pressure sensors or acoustic vector sensors deported on the ground have ever been obtained in [7, 8]. More recently, the feasibility of sound source localization using acoustic vector sensors mounted below a UAV have been demonstrated in [9]. An embedded solution is effectively the most attractive one for autonomous oriented missions. In practice, this is a quite challenging task because of the low signal to noise ratio (SNR) due to wind, vibration and own propeller noise. If appropriate equipments associated to adequate disposition of sensors help to counteract the effects of the two first, a signal processing method is necessary to attenuate the latter. We propose to take advantage of the knowledge of the engine speed to achieve such a denoising.

The remainder of this paper proceeds as follow. In Section 2, a brief discussion is given about the studied aircraft noise properties in term of spectral contents and directivity. The proposed denoising algorithm is detailed in Section 3. Proof of concept and assessment of such a denoising technique for localization and detection of surrounding sonorous flying objects are provided in Section 4. A general conclusion is given in Section 5.

2 Acoustical properties of the UAV

The presented study is based on a UAV from *SenseFly*[1] depicted by the Fig. 1. The aircraft has a wingspan of 80 cm and a total weight of about 400 g. More technical details about the embedded electronic board and available sensors can be found in [5]. In this section, some acoustical properties of such an UAV in term of spectral contents and directivity are exposed. All the presented measurements have been done under anechoical conditions.

Figure 1: UAV prototype.

2.1 Spectral analysis

One microphone is placed at one meter from a physical point of the sound source, i.e the front side of the wing. One tachometer is placed behind the aircraft in order to measure the speed of rotation of the propeller. Acoustic and tachometer signals are synchronously recorded during a rise and fall of the engine speed. Both Rotations Per Minute (RPM) and spectrogram are confronted on Fig. 2. It appears that the propeller noise is strongly harmonic and one can check that the fondamental frequency is directly proportional to the RPM. The fondamental frequency reaches about 60 dB SPL for the highest engine speed.

2.2 Directivity measurement

For the directivity measurement, the UAV is fixed on a turntable. Two microphones are located at 1 and 4 meters from the propeller respectively. The rotation speed of the engine is set to its maximum that is about 9700 RPM. A spectral analysis is performed for each azimuthal bearing - from 0° to 360° with 5° step.

[1] www.sensefly.com

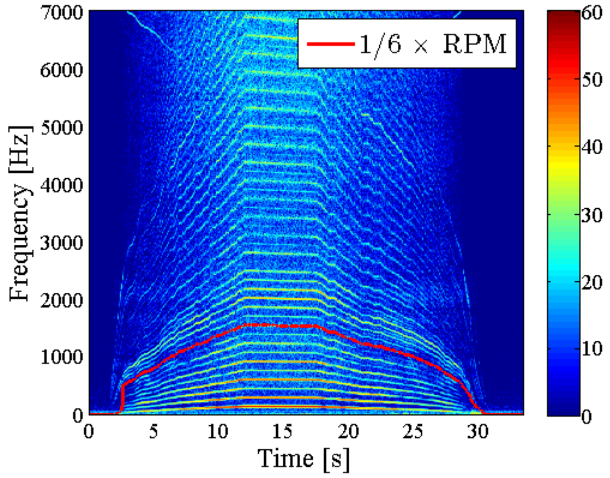


Figure 2: Spectrogram, in dB re2μPa @ 1 m of the propeller noise with associated RPM.

Fig. 3 depicts two polar graphs representing the spectral components of the UAV in function of its orientation at both distances. Frequencies from 0 Hz to 1500 Hz are readable on the radius and bearing is readable on the perimeter. The harmonics previously identified are clearly visible for any orientation except when the microphone is too close to the rear of the UAV where wind noise is dominant. Therefore, we can conclude that the detection probability of one UAV is quiet equal for any direction of arrival.

Fig. 4 depicts a third octave analysis at three specific orientations: 0°, 90° and 180°. The loss of level due to the geometric decay is close to 15 dB between both microphones. The distance, even short, is therefore a more problematic parameter than bearing in term of detection probability.

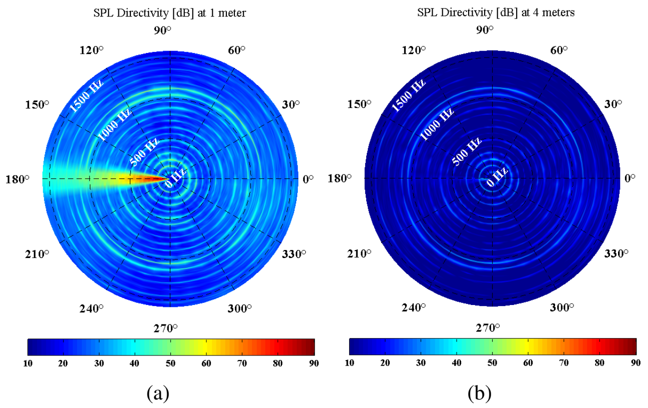


Figure 3: Spectral Sound Pressure Level Directivity. Left: 1 m, Right: 4 m.

3 Own propeller noise attenuation

Hearing the surrounding environment in flight using a microphone array mounted on the UAV is a quite challenging task because of the very low SNR due to wind, vibration and own propeller noise. In this section, we present our strategy to attenuate the latter.

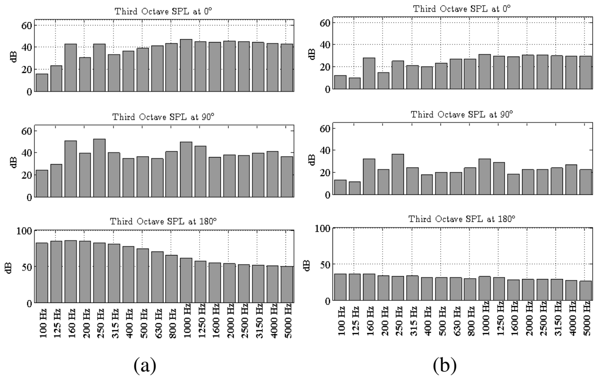


Figure 4: Third Octave Sound Pressure Level at 0°, 90° and 180° . Left: 1 m, Right: 4 m.

3.1 The order-analysis approach

Classical denoising techniques like spectral substraction [10], Wiener Filtering, McAulay [11], Ephraim and Malah [12] estimators and derived are of limited interest in such a context for following reasons:

- the strong harmonics components undermine the gaussianity assumption of the propeller noise,
- as each UAV presents roughly the same statistical properties, suppress the propeller noise of one UAV will mitigate the chances to detect other ones,
- the stationarity assumption is not valid for in flight conditions because of the rapid speed engine variation.

As an example, Fig. 5 depicts an audio excerpt of the propeller noise in a real flight condition acquired with an embedded microphone. It is clear that the spectral shifting can be very abrupt and an effective denoising system would require a real-time tracking of the fondamental frequency, which is today hardly implementable on one embedded microcontroller because of their restrictive computing resources. Therefore, the proposed technique exploits the advantage of the knowledge of the RPM to make an Order-Analysis (OA) based denoising algorithm.

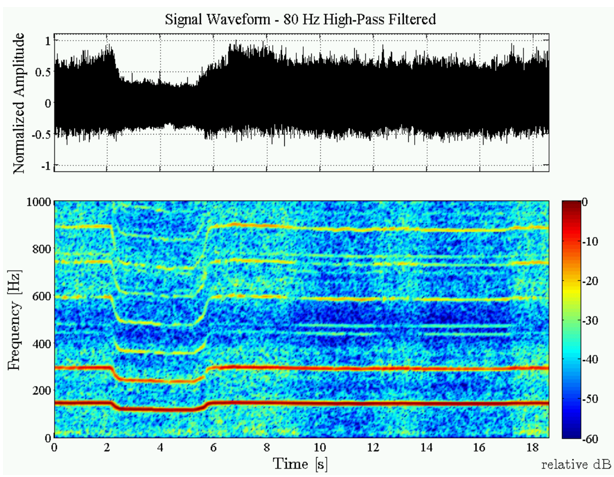


Figure 5: Temporal waveform and spectrogram of a in-flight propeller noise recording with an embedded microphone.

OA is a measurement technique generally preferred to the classical time-frequency analysis to monitor the health and behavior of rotating machinery [13]. The key procedure consists in resampling the acquired signal in order to give a new observation block with a number of samples proportional to the RPM. Such a processing altere the notion of time to keep constant each harmonics whatever their value, therefore this is called orders (from 1 to N) rather than harmonics (from f_0 to $(N-1)f_0$) and one say that the signal is processed in the Order-Revolution domain. Revolutions denotes the number of blade turns in the block observation.

Fig. 6a and 6b respectively depicts the sound produced by a rise and a fall of the UAV engine speed in the Time-Frequency plan and in the Order-Revolution plan. As expected shifting harmonics are converted into constant orders. One advantageous effect is that the signal to noise ratio is drastically improved on a slice of changing signal as depicted by Fig. 6c and Fig. 6d. In practice, working on constant and better defined orders allows the offline design of an analogical comb filter aiming at reducing desired orders.

3.2 The OA-based denoising algorithm

Let the propeller noise $\mathbf{x}$ be observed at instant k through a snapshot $\mathbf{x}[k]$ of L samples and let r_k be the measured RPM (a scalar) at same time. Regarding what have been measured and exposed in section 2.1, $\mathbf{x}[k]$ is composed of N harmonics with unknown amplitude and phase but of fondamental frequency equal to $r_k/60$. Let $N^\star$ be the cardinal of undesired harmonics (among 1 to N). The proposed technique aiming at attenuate these specific components is described by the algorithm 1.

Algorithm 1 Attenuation of $N^\star$ among N harmonics

for all $n \in N^\star$ **do**

Creation of $\mathbf{x}_o[k]$ of length L_0 by resampling $\mathbf{x}[k]$ with $L_0 \propto r_k$

Estimation of the amplitude $\hat{a}_n$ and phase $\hat{\phi}_n$ of the order n contained in $\mathbf{x}_o[k]$.

Subtraction of the order n:

$\mathbf{x}_o[k] \leftarrow \mathbf{x}_o[k] - \sqrt{2}\hat{a}_n sin(2\pi kn + \hat{\phi}_n)$

Go back in the temporal domain: creation of $\tilde{\mathbf{x}}[k]$ by re-sampling $\mathbf{x}_o[k]$ with a factor L/L_0.

Actualisation:

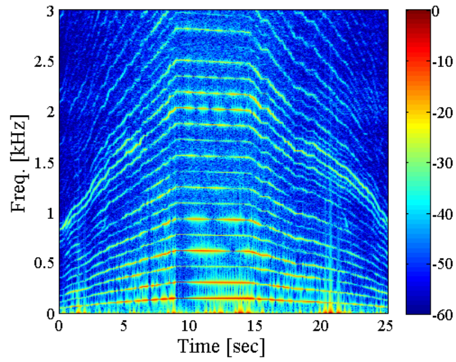
$\mathbf{x}[k] \leftarrow \tilde{\mathbf{x}}[k]$

end for

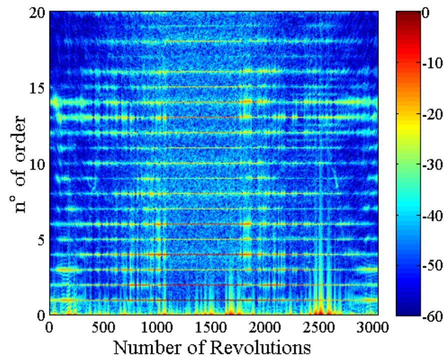
4 Simulations and in-lab tests

4.1 Proof of concept

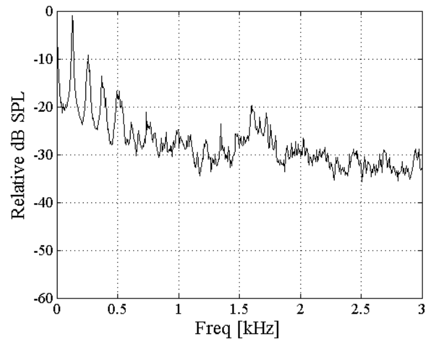
The algorithm 1 has been applied on a simulated record of 5 seconds composed of one chirp linearly increasing from 30 Hz to 200 Hz and one chirp linearly decreasing from 200 Hz to 30 Hz. Two harmonics have been associated to each of them. In this experiment, the increasing chirps play the role of the noise propeller to suppress and the decreasing chirps play the role of the target propeller to detect. Therefore, the



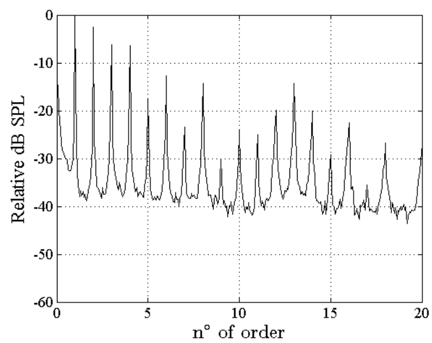
(a) Time vs. Frequency



(b) Orders vs. Revolutions



(c) Spectrum between second 5 and 7 seconds

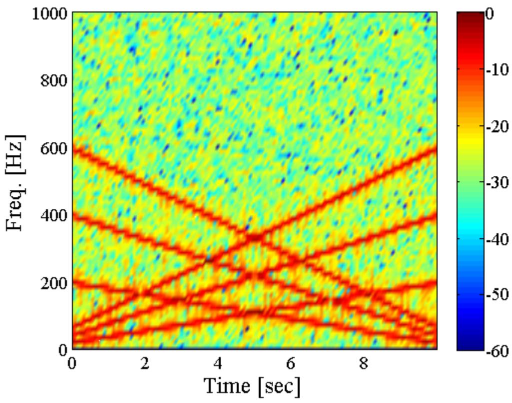


(d) Order spectrum between 5 and 7 seconds

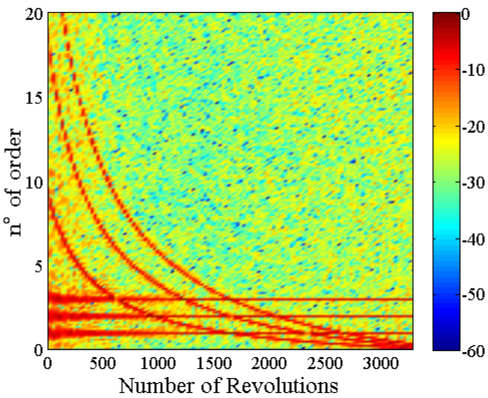
Figure 6: Representation of a propeller noise in the spectral domain and in the order domain.

fondamental frequency of the increasing chirp is known at each time step since it is related to the requested value of the RPM.

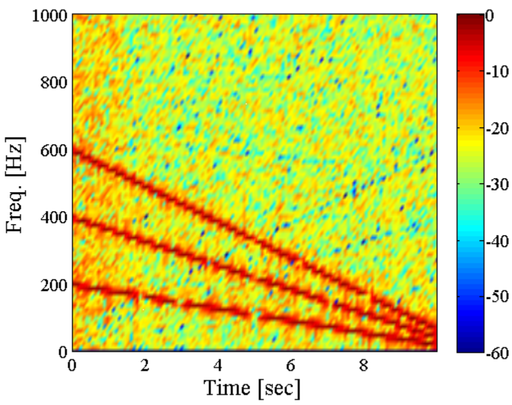
Fig. 7a depicts the raw mixed signal in the Time-Frequency plan, both target and noise have been synthesized with comparable signal to noise ratio. Fig. 7b depicts the raw signal in the Order-Revolution plan, the signal to attenuate is now composed of three constant orders. Fig. 7b shows another advantageous effect of OA in the sense that the presence of any non constant order can directly be associated to the presence of an external target. Fig. 7c depicts the mixture after processing: the noise is drastically attenuated, the energy of the target is remained.



(a) Raw signal: Time vs. Frequency



(b) Raw signal: Order vs. Revolutions



(c) Cleaned Signal: Time vs. Frequency

Figure 7: Typical result of OA-based denoising algorithm.

4.2 Assessment for detection and localization

In this section, we focus on the performance of the proposed algorithm in term of broadband sound source detection. In particular, we are interested in seeing benefits of the order analysis for localization using a microphone array in non reverberant environment and under very low SNR. In this experiment, a synthetic white noise have been added to an excerpt of 3 seconds from the propeller noise presented in Section 2.1 (between 4 and 7 seconds). The white noise was spatialized to simulate a semi-circular movement from 0° to 180° ahead an array of two microphones rather than the propeller noise was set equal for both sensors in order to act like if it was fixed and equidistant. The amplitude of the moving target was adjusted to respect different SNR: -20, -15, and 0 dB SPL.

As broadband sound source localization is commonly achieved by estimating time difference of arrival between pairs of sensors, we computed cross-correlation on short windows (80 ms) before and after the denoising process. The latter consists in denoising the first thirty harmonics of the propeller noise according to the algorithm 1. For each SNR, we obtain a raw and an improved correlogram traducing the ability of a basic microphone array based system to localize the moving target.

Results are depicted on Fig. 8. Left and right column respectively depicts the raw and the improved correlograms. The target differs from the motor engine by a varying delay over time. Without any processing, the target is virtually no detected from -10 dB SPL and below. We observe a good improvement in term of detectability and localization for SNR going from 0 to -15 dB SPL. At -20 dB of SNR, the obtained denoising is not sufficient to observe the target again. This score can be drastically improved using more than two microphones and coherently combine time delay of each available pair.

5 Conclusion

The motor noise of a UAV makes tricky the realization of an embedded passive and acoustic anti-collision system in term of distant targets detection. Because of the strong harmonicity of the sound radiating by the propellers, the order analysis theory was explored to design a denoising algorithm dedicated to rotating machinery. The proposed algorithm was evaluated through simulations based on real anechoic measurements. A significant improvement of target detectability have been observed even under low SNR (-10, -15 dB SPL). Forthcoming works will consist in testing the presented algorithm in real flight conditions in order to assess the effect of wind and vibration.

6 Aknowledgments

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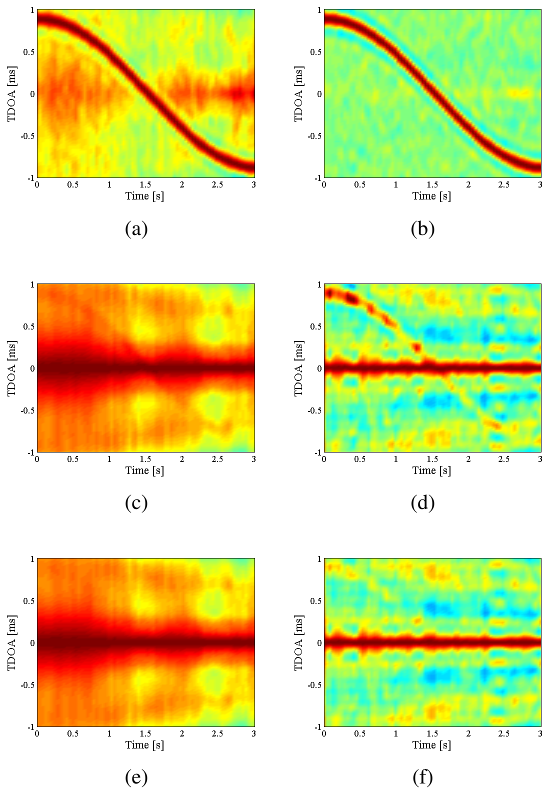

Figure 8: Correlogram before and after use of the OA-based denoising algorithm. The SNR is of 0, -15 and -20 dB SPL from up to down.

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