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PROOF OF CONCEPT OF ENERGY HARVESTING FROM AERO ACOUSTIC NOISE

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Abstract: This paper reports the testing of a new mechanism converting energy radiated from an acoustic source, i.e. a small cavity created on an aircraft outside skin and inducing high frequency oscillations of airflow passing over it. This acoustic noise is then converted into electrical energy. We have submitted in a wind tunnel a set of cavities to an airflow varying the Mach number, creating high sound levels. In a second set of experiments, we have submitted passive microphones to high acoustic levels and stored in capacitors the electrical energy collected at the microphone output. Finally, directions for future work are identified.

Keywords: aero acoustic, microphone, energy harvesting

INTRODUCTION

In recent years, Wireless Sensor Networks (WSN) have been considered for various aeronautical applications, among others Structural Health Monitoring, and flight tests [1]. Each network node would perform sensing, data processing and wireless transmission of information. Thus WSN would permit (often new) functions without the need of adding extra wiring to an already large burden.

However, these nodes need to be self-powered, many of the advantages of wireless sensor networking being lost if external (i.e. wired) power sources are used. Unfortunately, such issues as environmental concerns together with safety and economical issues often prohibit the use of electrochemical batteries. Luckily, environmental energy harvesting provides a solution for long term, deploy and forget, WSN. Environmental energies such as mechanical vibrations, solar or artificial light, and thermal gradients are already being investigated. However, vibration levels may be too small and too difficult to capture, solar light is only available outside the aircraft in daylight, artificial lighting is weak, and thermal gradients are far from being available everywhere.

The purpose of the work presented in this paper is to demonstrate the feasibility of converting, during a flight, the energy associated to noise emission of aerodynamic origin. Being based on aircraft movement only, the basic benefit of this method is to be able to power devices close to a cavity acting as an aero acoustic source, itself located on the external aircraft structure, thus providing an alternative to the above-mentioned methods.

BASICS OF CAVITY NOISE

Physics

The phenomenon of cavity noise is linked to self-sustained coherent oscillations in the shear layer developing above a cavity in the presence of grazing flow. A complex feedback process can lead to important radiated noise, with both discrete and broadband components [2]. Cavity noise is one of the most important airframe noises [3]. During landing, they mainly occur from open wheel wells after the undercarriage has been lowered. During cruise, they originate from any gap in the aircraft structure.

In the following we will consider rectangular cavities (see Fig. 1).

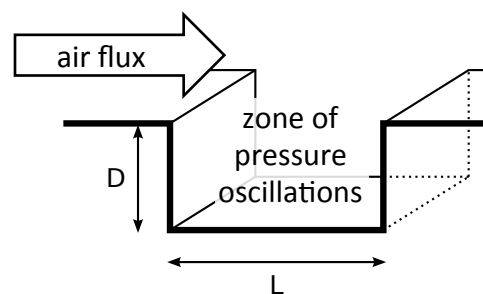


Fig. 1: Schematic of a rectangular cavity of length L and depth D .

Empirical formula

Peaks in the oscillation spectrum can be empirically forecasted using Rossiter's formula [3]:

$$f_n = \frac{U_\infty \cdot (n - \alpha)}{L \cdot \left(M + \frac{1}{\kappa} \right)} \quad (1)$$

where U_∞ is the free-stream flow velocity, L is the cavity length, α and κ are empirical constants depending on the cavity aspect ratio (i.e. ratio between length L and depth D), and M is the free-stream Mach number, i.e. the ratio between the free-stream flow velocity and the speed of sound. n is the index of Rossiter's mode.

For deep cavities (aspect ratio < 1), East [5] showed that the Rossiter's mode whose frequency coincides with that of the depthwise cavity resonance is often the most excited. On the contrary, for shallow cavities (aspect ratio > 1), the preferred excited modes are close to the longitudinal cavity resonances. In particular, the dominant frequency is the closest to the "quarter-wave" frequency proposed by East:

$$f_{1/4} = \frac{c_0}{4D(1 + 0.65(\frac{L}{D})^{0.75})} \quad (2)$$

where c_0 is the speed of sound.

Unfortunately, the Rossiter's formula provides the resonance frequency, but the amplitude and direction of the radiated noise must be determined numerically or experimentally only.

EXPERIMENTAL SETUP AND RESULTS

Aero acoustic noise

Experiments have been performed in the aeroacoustic test bench at ONERA Toulouse. This 4 m long stainless steel tube of cross-section 50 mm x 50 mm is equipped with a quasi-anechoic outlet, to limit the amplitude of reflected acoustic waves.

Cavities of various geometries have been flush-mounted to the tube and submitted to a grazing flow up to a bulk Mach number of 0.6, at ambient temperature. The boundary layer is turbulent and fully developed. A flush-mounted 1/4" microphone (B&K 4938A) was implemented to measure the sound pressure level at the cavity bottom, in the frequency range 100-12000Hz (see Fig. 2 and 3).

For each Mach number / cavity geometry combination, the noise spectrum has been computed by running a Fast Fourier Transform algorithm. Results are given in Fig. 4 for a 27 mm x 27 mm cavity (aspect ratio $L/D=1$), and for three Mach numbers. Various spectrum peaks can be identified, the most energetic being around 2.2 kHz whatever the Mach number.

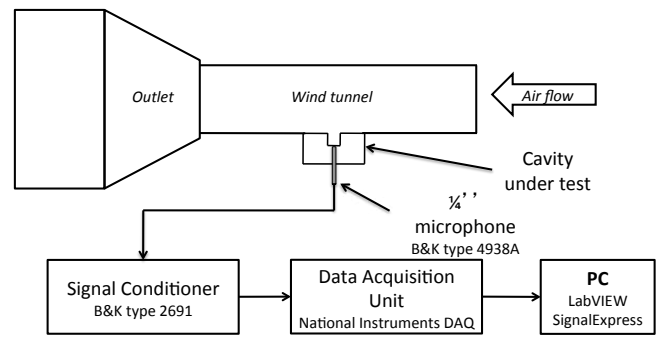


Fig. 2: Schematic of experimental arrangement for aero acoustic noise generation.

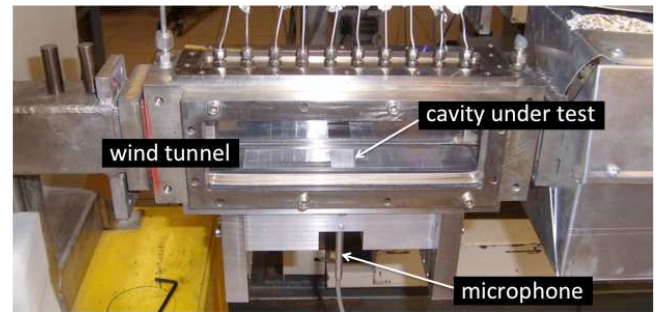


Fig. 3: View of wind tunnel central part and associated devices.

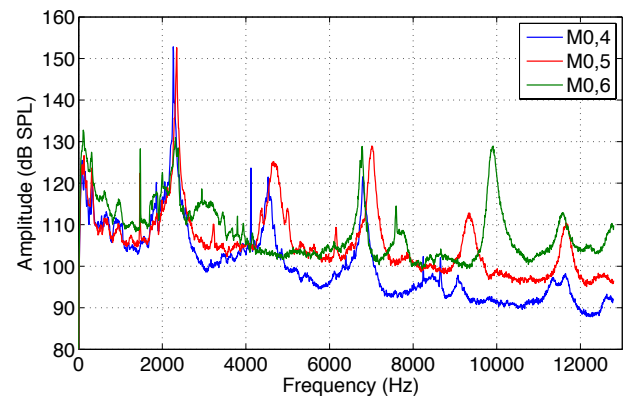


Fig. 4: Aero acoustic noise spectrum.

In Fig. 5 the first four Rossiter modes are plotted (Eq. 1) with $\alpha = 0,25$ and $\kappa = 0,61$. The East frequency (Eq. 2) is also shown. The circles represent experimental data for the 27 mm x 27 mm cavity (aspect ratio $L/D=1$). This comparison between theory and experiment allows validating that the acoustic noise analyzed in Fig. 4 actually originates from cavity noise and is not created by another interfering mechanism. Fig. 5 shows indeed that experimental data fits fairly well with the predicted frequencies.

Moreover, it confirms the dominance of the first Rossiter mode exhibited in Fig. 4: the five experimental values are all very close to the predicted

East frequency (roughly 2000 Hz) for the above cavity geometry.

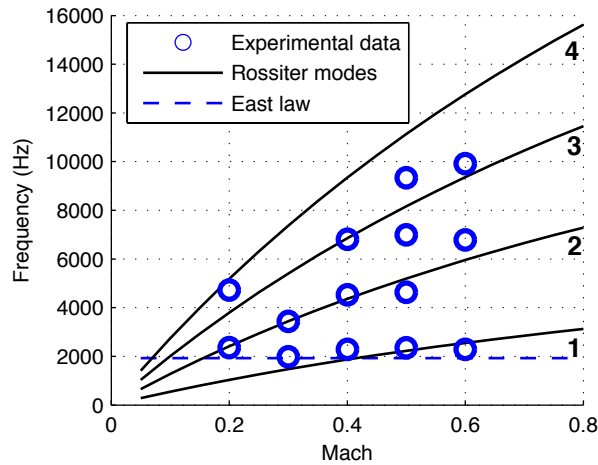


Fig. 5: Experimental data vs. Rossiter modes (1 to 4) and East frequency.

Energy conversion

Practical considerations have prevented us from using the same microphone as in the wind tunnel, and the two experiments (generation of aero acoustic noise and energy conversion) have been conducted separately. Consequently, acoustic energy conversion tests have been done at a different frequency range.

In the context of energy harvesting, intermediate energy storage between harvester and load is required for two reasons: first to accommodate for transient power surges from the load exceeding the mean electrical harvested power, and then to maintain the energetic autonomy is the case of an intermittent environmental source. Electrochemical storage being avoided in a lot of applications, electrostatic storage using ultra-capacitors is the alternative, with the advantage of providing an almost infinite lifetime, being safe and environment friendly. Unfortunately, similarly to batteries, ultra-capacitors are also affected by extreme ambient temperature. Moreover, the output voltage of a capacitor varies according to its electrical charge. A DC/DC regulator is therefore needed between storage and load.

To demonstrate the possibility of converting acoustical energy into electrical energy, we have submitted a pre-polarized 1/2" GRAS Type 40 AD microphone to various noise levels generated in a cylindrical acoustical impedance tube which covers the 100-5500Hz frequency range (see Fig. 6). The sensor of this microphone is an electret capacitor, which does not require energy input from a bias circuit. This microphone is usually utilized with a pre-amplifier, which was by-passed in the following experiment.

The output of the electret capacitor was thus directly connected to a Graetz bridge rectifier realized with 1N4148 diodes, itself connected to a 1 μ F storage capacitor.

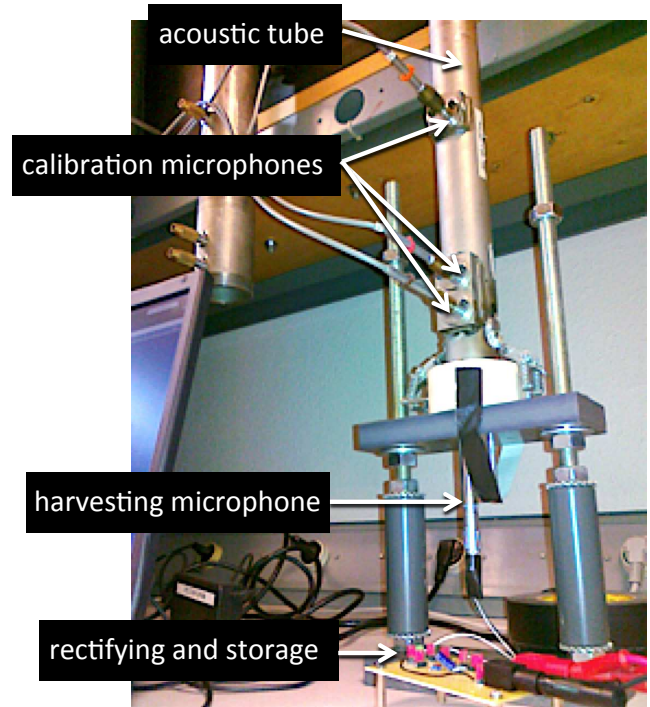


Fig. 6: Experimental arrangement for energy conversion.

The microphone was then submitted to monochromatic acoustic noise at various frequencies and pressure levels. The storage capacitor voltage was then recorded vs. time. Some results are presented in Fig. 7 at a frequency of 304 Hz.

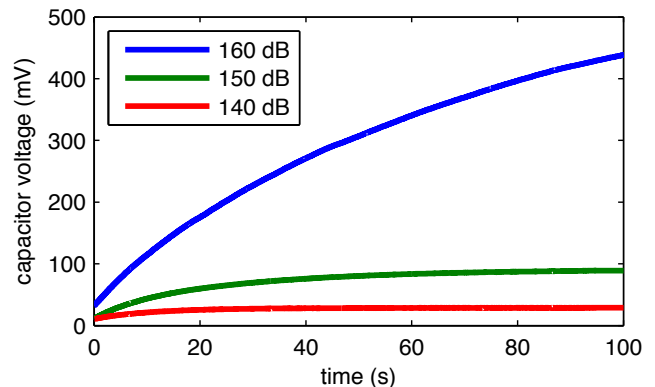


Fig. 7: Storage capacitor voltage vs. time for various noise pressure levels at 304 Hz.

Lower frequencies have been tested, but they induced lower powers. More precisely, harvested power was found to monotonously increase with frequency, which allows expecting much better performances at

the peak frequencies previously found in the aero acoustic noise experiment.

The harvested power is still modest, but ways to improve it do exist, such as devising a more efficient electrical circuit for the charge of the storage capacitor, and/or enlarging the microphone area. The high frequencies delivered by the cavity are also favorable.

Of course, fully convincing results will be only obtained with a harvesting system connected to a microphone fitted in the cavity itself.

CONCLUSION

This paper demonstrates the feasibility of harvesting energy from acoustic noise created on purpose by specifically manufacturing the outer skin of an aircraft on a limited scale. The major advantages of the method lie in the fact that the basic parameter is the aircraft speed, to be compared with other possible competitors like structural vibrations or thermal gradients, which are more specific of a given aircraft design and of the location of the components of the WSN.

However, more work is needed to precisely assess the performance of the method and the acceptability of the aero acoustic cavities.

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