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# NOISE MEASUREMENTS OF FLAPPING WINGS WITH TENSED MEMBRANE

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Micro air vehicles with flapping wings have the potential to be both more efficient and manoeuvrable than similar-sized fixed or rotary-wing aircraft. Reducing the noise produced by flapping wings without compromising or possibly enhancing their aerodynamic performance would be crucial in surveillance and military applications. To this aim we have designed and fabricated flapping wings whose supporting stiffeners tense the membrane material to which they are bonded. The sound produced by these wings at different flapping frequencies has been recorded in an anechoic chamber simultaneously to the thrust they produce. The results are compared with those of standard wings without tensed membranes. The tensed-membrane wings have lower noise per unit thrust and their characteristics and performance are discussed.
Keywords: membrane flapping wing, noise reduction

## 1. Introduction

Micro air vehicles (MAVs) have the potential to revolutionize the sensing and information gathering capabilities in both military and civil fields. Fixed wing, rotary wing, and flapping wing (FW) [1, 2] are the three main vehicle concepts, the latter having very attractive characteristics (high manoeuvrability and high efficiency at very-low speed) for flight in confined spaces. Well known FW-MAVs are the DelFly [3] from TU Delft and the RoboBee [4] from Harvard University.

The wings of current FW-MAVs resemble those of insects and bats which can provide inspiration for optimizing their aerodynamic and acoustic characteristics. Insect wings are one of nature's lightest structures; lacking bones and muscles, these wings cannot actively change their shape since they consists of a thin panel with stiffening veins of chitin, a tough material that also composes an insect's hard outer skin. Insect wings have complex aerodynamics characterized by highly-unsteady flow in a very-low Reynolds-number range [5]. While many experimental, e.g. [6, 7], and numerical, e.g. [8, 9], studies have been conducted to understand the aerodynamics of insect wings, their sound has received less attention [10]. Bat wings are the most sophisticated of animal wings. They consist of a highly evolved and specialized arm/hand structure that allows a high degree of control of the shape and tension of the skin membrane (patagium) it supports. This allows rapid active control of the aerodynamic and acoustic performance of their wings in a wide range of flight conditions [11, 12].

Inspired by these, the current work explored two design variations of the standard wings of the FlowerFly, a FW-MAV developed by the NUS Temasek Laboratories whose wings are fabricated using Mylar sheets for their membrane and carbon-fibre rods of different diameters for their supporting stiffeners [13]. By slightly bending some of the rods, a tension can be induced in some portions of the membrane which can be used to tailor its aerodynamic and its acoustic behaviour. This in some ways emulates a bat’s wing albeit in a passive rather than active way. Simultaneous measurements of the noise and of the thrust produced by the wings were performed in an anechoic chamber to identify the wing configuration with lower noise per unit thrust. The wings were mounted on the flapping mechanism of the FlowerFly and were operating at flapping frequencies from 8 to 13 Hz which are representative of the flight conditions of this FW-MAV.

## 2. Experimental setup

The flapping-wing mechanism used in this project is detailed in [13]. It suffices here to recall that it consists of a gear box which synchronously drives four wings and creates double clap-and-fling effects during one flapping cycle. A Hall-effect sensor in the mechanism allows measuring the flapping frequency and adjusting it within ±0.5 Hz of its nominal value.

Simultaneous acoustic and thrust measurements were performed inside the anechoic chamber of the NUS Temasek Laboratories, Fig. 1, whose inner walls are covered with polyurethane-foam acoustic wedges (Illbruck SONEXsuper) with an absorption coefficient higher than 1.0 for frequencies above 500 Hz. The inner dimensions between the wedges are about 2350 × 2350 × 2350 mm. The flapping-wing model was installed at the centre of the chamber by mounting it on a post firmly fixed to the chamber's ceiling to suppress any vibration generated by the flapping motion, Fig. 1. This overhanging-mount configuration prevented the supporting post to interfere with the downward flow created by the flapping wings. Two 1/2 inch condenser microphones installed at the same height of the flapping wings and connected to a preamplifier and signal conditioner (Brüel & Kjær Models 4953, 2669, and NEXUS 2690-A, respectively) were used to record their noise, Fig. 1. The radial distance between the tips of the flapping wings and the heads of the microphones was about 500 mm. The microphones were mounted on poles rotated by a servo motor which allowed measurements at any angle around the flapping-wing model. Measurements were taken from 0° to 360° at 45°-spaced angles.

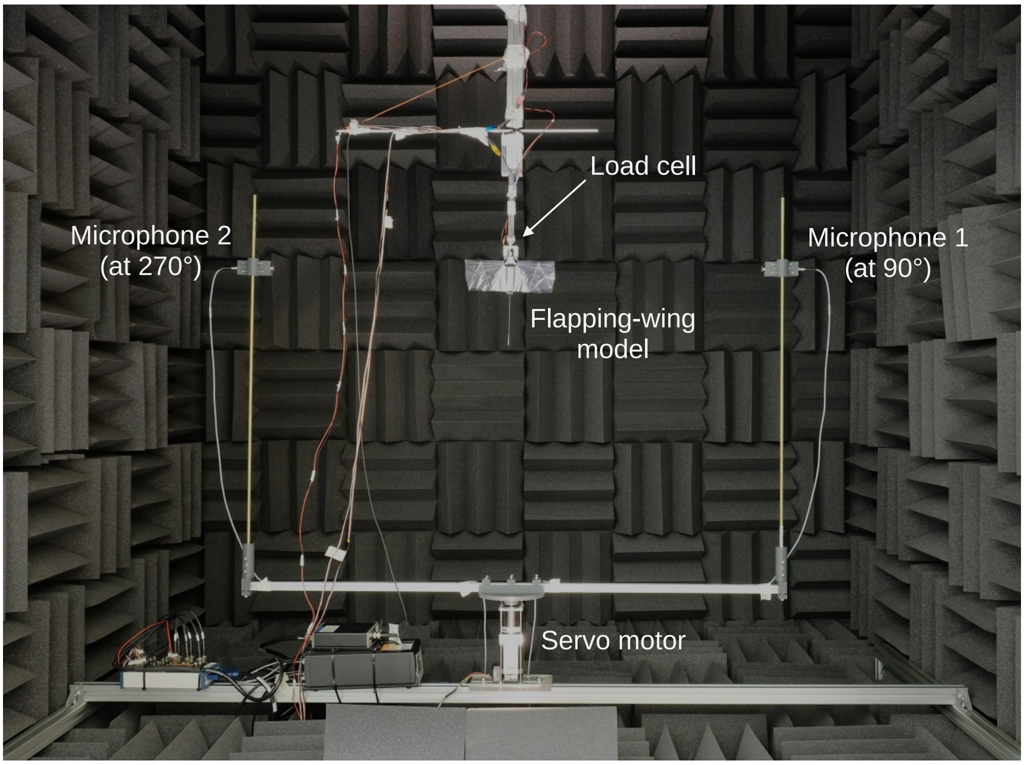


Figure1: Experimental setup inside the anechoic chamber.

The signal of each microphone consists of $5 \cdot 10^5$ samples recorded at 50 kHz. The signal was low-pass filtered at 24,949 Hz by a Butterworth filter to avoid aliasing. The narrowband power spectrogram of the microphone voltage was computed using a 2048-point short-time Fourier transform providing a spectral resolution of about 24 Hz. Using the microphone's sensitivity and accounting for the amplifier gain setting, the voltage power spectrogram was converted to the power spectrogram of $p'/p_{ref}$, where $p'$ is the pressure fluctuation and $p_{ref}$ =20 μPa is the commonly used reference pressure. Converted to decibels, this becomes the spectrogram of the sound pressure level, SPL($f$), where $f$ is the measured frequency. A-weighting correction was applied to the SPL spectrogram to account for the relative loudness perceived by the human ear. Time integration of the spectrogram values provides the corresponding SPL spectrum. The overall sound pressure level is then obtained by integrating the SPL spectrum:

$$\mathrm{OASPL} = 10\log_{10}\int_0^{f_{\mathrm{upper}}} 10^{0.1\cdot\mathrm{SPL}(f)}\,df \qquad (1)$$

where the upper integration limit is the high frequency resolved by the microphones (15 kHz).

The thrust produced by the flapping wings was measured by an ATI Nano17 Titanium load cell placed in the mount connecting the flapping-wing mechanism to its supporting post, Fig. 1. The force range (and resolution) in the thrust (vertical) direction is 28.2 (±5.15·$10^{-3}$) N. The load cell is factory calibrated and the corresponding conversion factors are stored in the acquisition unit used with it such that the obtained values of the thrust are already corrected. The load-cell signal consists of 5·$10^4$ samples recorded at 5 kHz. The signal was low-pass filtered at 2,499 Hz by a Butterworth filter to avoid aliasing.

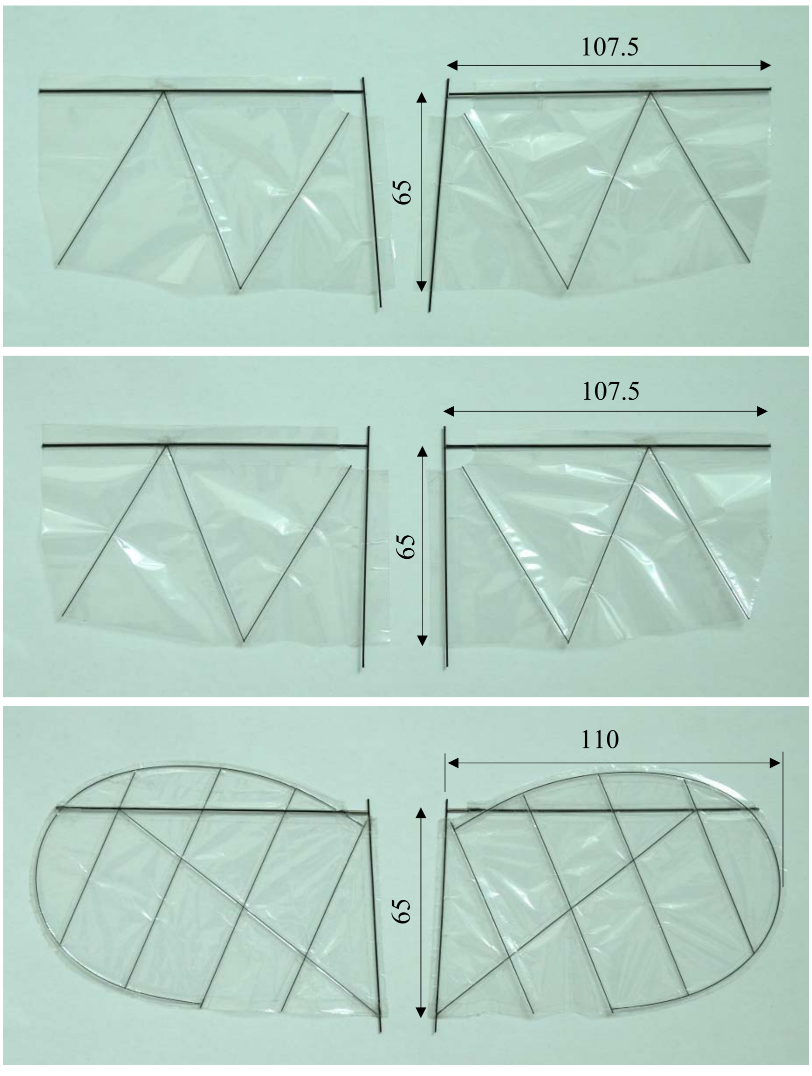


Figure 2: Tested wings: standard type A (top), type A1 (middle), and type B (bottom).

## 3. Experimental results

Figure 2 shows couples of tested wings. Two couples of each type (4 wings in total) were installed in the flapping mechanism. Wings A are the standard (reference) type used in the FlowerFly. Their membrane consists of a 10 μm-thick Mylar sheet supported by carbon-fibre rods of diameter 0.8 mm at the leading edge and 0.6 mm at the wing root. The latter rods are angled 5° inward toward the trailing edge such that once mounted straight in the flapping mechanism they create a slack of the membrane close to the wing root. This allows alternate passive tilt of the wings in the downstroke and upstroke phases of a flapping cycle. Smaller 0.3mm diameter rods are used as stiffeners of the wing membrane. The weight of a single wing A is 0.346 g.

Wings A1 are similar to the A type except that their wing-root rods are not angled. This reduces the slack of the membrane close to the wing root thus making the membrane more tensed during flapping which is thought to reduce the corresponding noise. The weight of a single wing A1 is 0.350 g. Wings B have a 5 μm-thick Mylar sheet membrane supported by carbon-fibre rods of diameter 0.7 mm at the leading edge and 0.5 mm at the wing root in the same arrangement of wing A. However the arrangement of the 0.3 mm rods is very different and comprises a curved rod that flexes around the leading edge, the tip, and part of the trailing edge. This introduces tension in most of the wing membrane except close to the wing root. This tension is hoped to further reduce the flapping noise. A diagonal stiffener is also added to reduce wing flexibility when the wing rotates. This stiffener stores energy at the start of a stroke, and releases energy at the end of the stroke to ensure faster and smaller wing fluctuation on its rotation. The weight of a single wing B is 0.406 g.

The A-weighted OASPL measured inside the anechoic chamber with all the electric and electronic components turned on but without any movement of the flapping-wing model is about 27 dBA. This level is typical of a quiet bedroom and is lower than the level inside the average home.

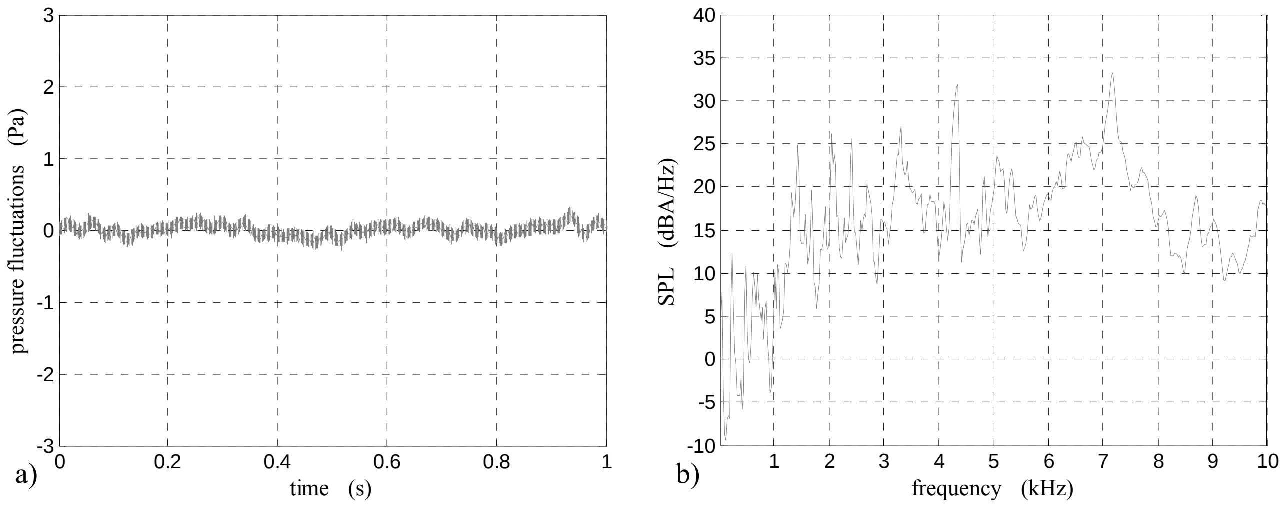


Figure 3: Noise measured at 0º of the flapping mechanism alone operating at 12 Hz: a) timetrace of the pressure fluctuations; b) A-weighted SPL spectrum.

Figure 3a) shows one second of the pressure-fluctuations timetrace produced by the flapping mechanism alone at 12 Hz, the typical flapping frequency of the FlowerFly, and measured at 0°. Figure 3b) is the corresponding A-weighted SPL spectrum which shows different audible components. Figure 4a) shows one second of the timetrace measured at 0° for wings A flapping at 12 Hz. Strong pressure fluctuations can be seen that are associated to the clap-and-fling effects. Between these are smaller fluctuations corresponding to the clap-and-fling occurring at ±90°. The corresponding SPL spectrum in Fig. 4b) shows that this type of wings has a broad, high-intensity spectral distribution from which small peaks emerge some of which (e.g. at about 4200 and 7200 Hz) appear to be related to the flapping-mechanism noise, see Fig. 3b). Figures 4c) and 4d) show that wings A1 have lower pressure fluctuations and spectral amplitude than wings A in similar conditions.

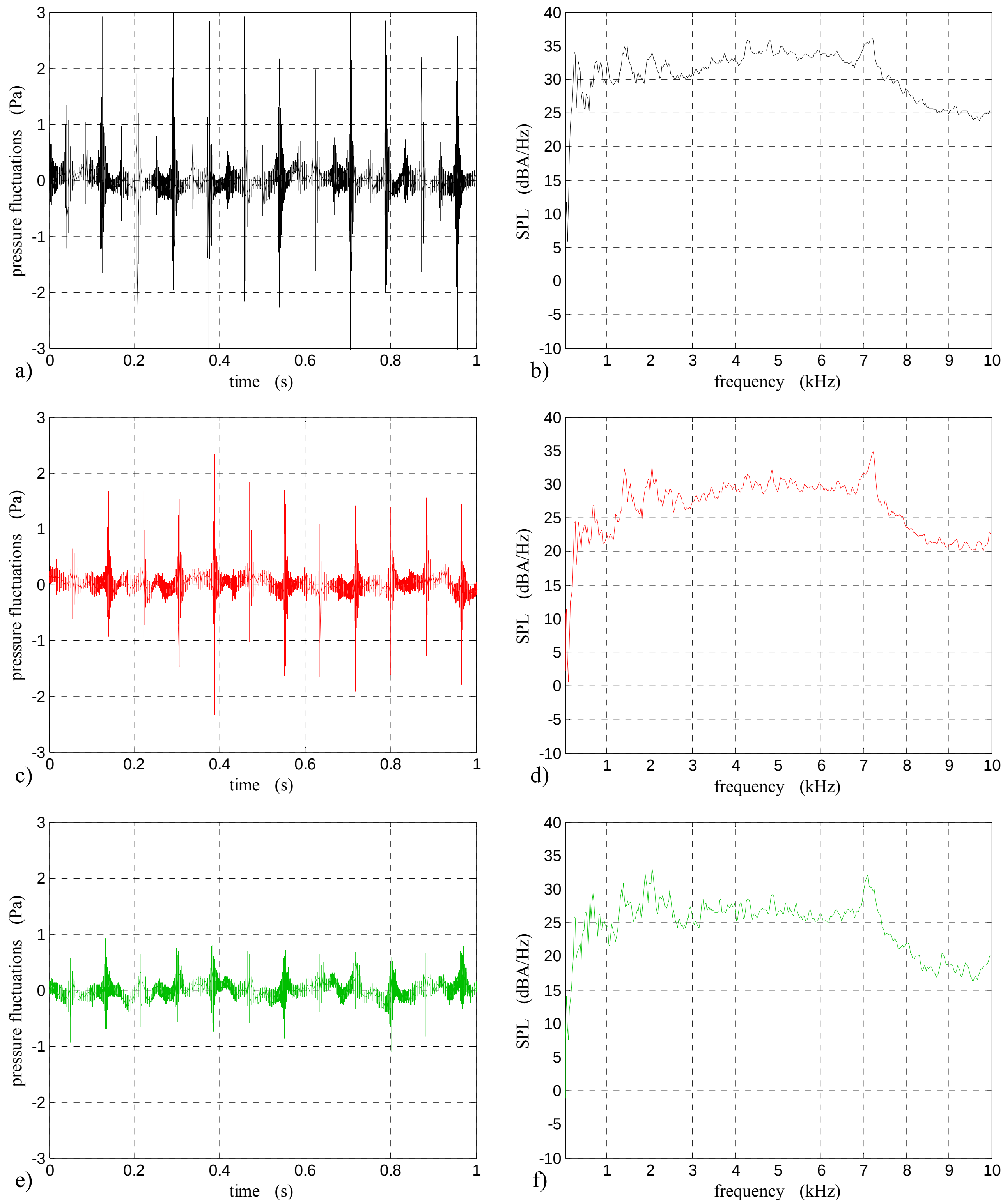


Figure 4: Noise measured at 0º of wings flapping at 12 Hz: timetrace of the pressure fluctuations (left) and A-weighted SPL spectrum (right) of: a) and b) wings A; c) and d) wings A1; e) and f) wings B.

Compared to wings A and A1, the pressure fluctuations generated by wings B flapping at 12 Hz are much reduced as visible in Fig. 4e). Accordingly, the SPL spectrum in Fig. 4f) shows an amplitude reduction across most frequencies. Some spectral peaks in Fig. 4f), which appear related to the noise of the flapping mechanism, emerge more prominently from the otherwise lower noise signature of these wings. Similar spectral characteristics have been obtained for the cases above at other angles around the flapping-wing model. The corresponding OASPL values are presented in Fig. 5

and are connected with solid lines whereas analogous values obtained at the flapping frequencies of 10 and 8 Hz are connected by dashed and dotted lines, respectively.

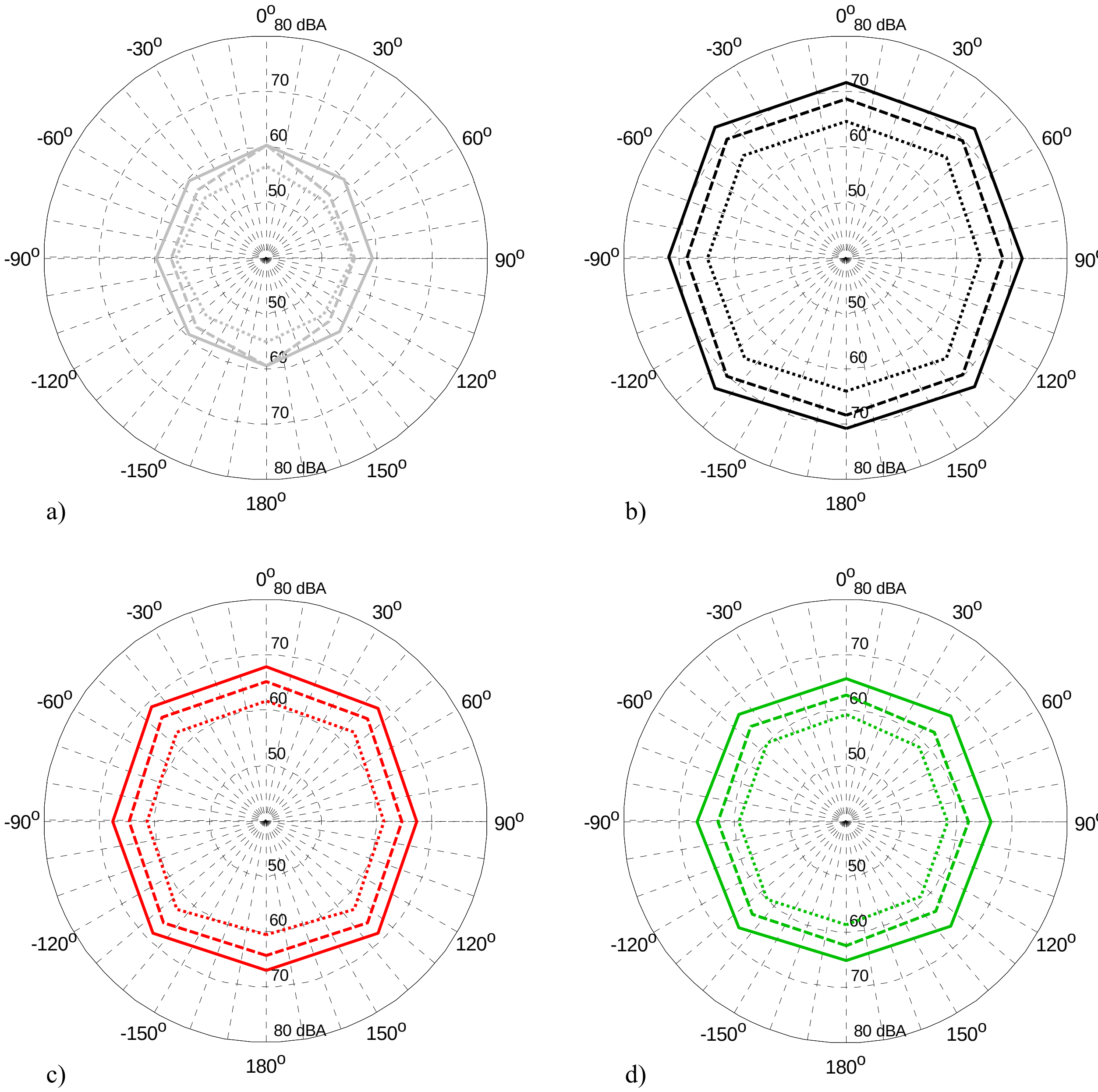


Figure 5: A-weighted OASPL values measured around the wings flapping at 12 Hz (solid line), 10 Hz (dashed line), and 8 Hz (dotted line): a) flapping mechanism alone; b) wings A; c) wings A1; d) wings B.

The OASPL values obtained at other flapping frequencies are not presented to avoid the overlapping of closely-spaced lines. As expected, the flapping wings are noisier than the mechanism alone and in all cases the overall noise increases with the flapping frequency, consistent with [14]. Also, the noise in all the cases is quite uniform around the flapping-wing model, a finding consistent with what could be experienced by a listener. For the flapping wings this is also consistent with their double clap-and-fling which creates similar noise sources every 90°. Wings B are clearly quieter than wings A1 which in turn are quieter than the standard wings A. This seems to support that flapping noise can be reduced by tensing the Mylar membranes of the wings.

The average value of the thrust produced by the wings at each flapping frequency is plotted in Fig. 6a). In all cases the thrust increases with the flapping frequency, as expected [13]. Wings B have larger thrust than wings A1 which in turn have larger thrust than the standard wings A. This thrust increase may be related to the increased tension of the membrane of wings A1 and, especially, wings B. The latter also have slightly larger wing surface which can also contribute to the thrust increase.

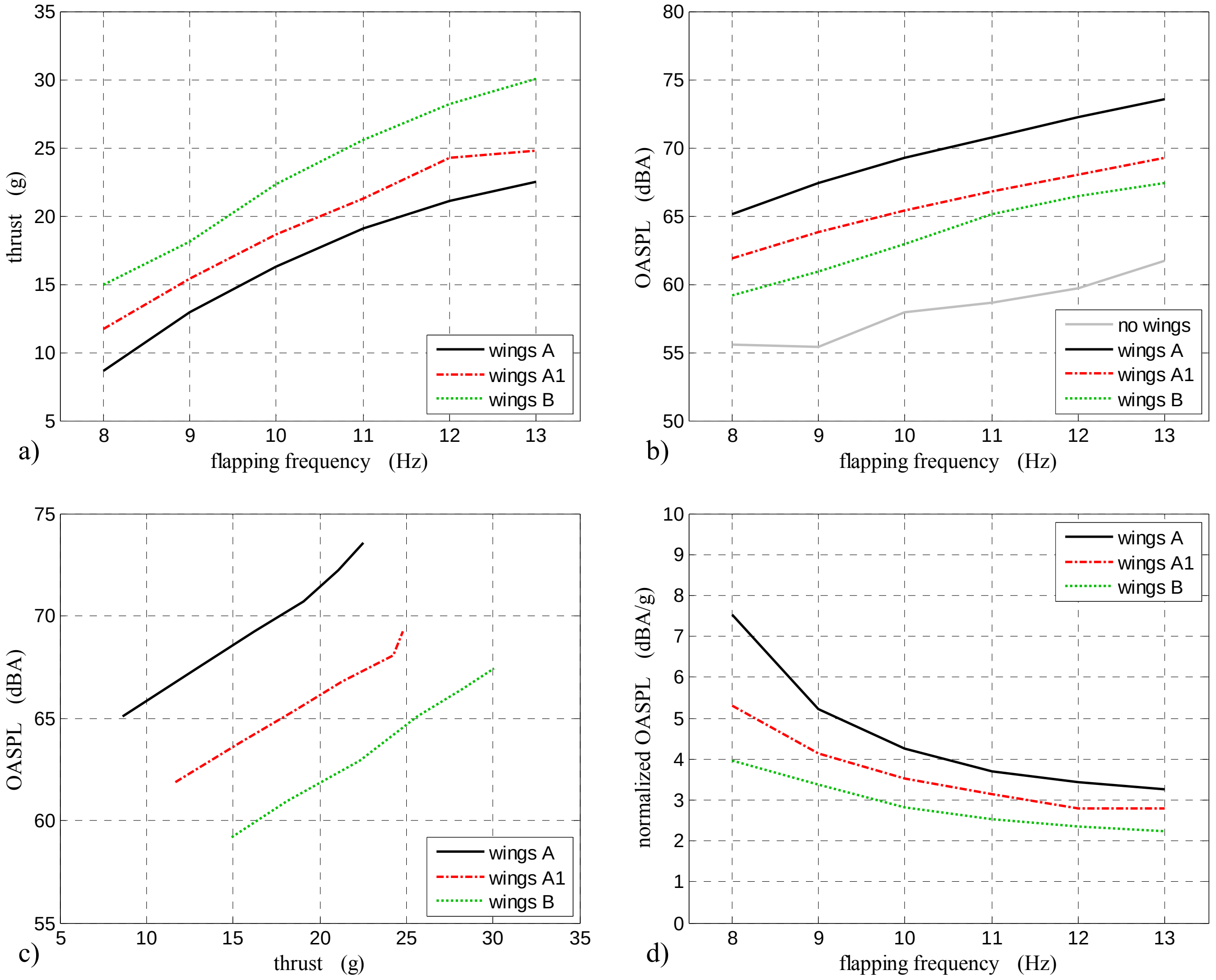


Figure 6: Characteristics of the flapping wings: a) thrust as a function of the flapping frequency; b) A-weighted OASPL values as a function of the flapping frequency; c) A-weighted OASPL values as a function of the thrust; d) A-weighted OASPL values per unit thrust as a function of the flapping frequency.

Since the OASPL values around the flapping wings are quite uniform, Fig. 5, their average can be used as the reference OASPL at each flapping frequency which is plotted in Fig. 6b). This figure also shows the values of the flapping mechanism alone (no wings) and synthesizes the results of Fig. 5, i.e. that the noise increases with the flapping frequency and that wings B are quieter than wings A1 themselves quieter than wings A. Figure 6c) plots the OASPL values as a function of the corresponding thrust. Considering that the FlowerFly weights about 20 g, replacing the standard wings A with wings B could reduce its noise by 9 dBA. Figure 6d) presents the values of OASPL per unit thrust produced by the wings flapping at different frequencies and clearly shows that wings B are the best performers. The noise per unit thrust decreases with increasing the flapping frequency, consistent with [14]. Thus, from a noise-reduction point of view, it is better to obtain the thrust required by a FW-MAV by designing wings and mechanisms that flap at higher frequency.

## 4. Conclusions

The main goal of this research was to explore if the noise of the flapping wings of a MAV can be reduced by increasing the tension of their Mylar membrane. The reference wings are the standard type used in the FlowerFly MAV developed by the NUS Temasek Laboratories. These wings are quite similar to those used in the DelFly MAV develop by the MAVLab of TU Delft. Increasing the tension of the wings' membrane seems to both increase the thrust and decrease the noise produced by their flapping. The noise generated by such flapping wings increases with the flapping frequency albeit at a lower rate than their thrust. Thus the noise per unit thrust decreases with increasing the flapping frequency. So, from a noise-reduction point of view, it is desirable to achieve a specified thrust by designing wings and mechanisms that flap at higher frequency. Wings with curved stiffeners for tensing most of their membrane create lower noise per unit thrust than standard wings and could provide a 9 dBA noise reduction if applied to a flapping-wing MAV. The noise produced by the double clap-and-fling of the tested flapping wings is very uniform around the wings, irrespective of the wing type or flapping frequency.

## REFERENCES


1 Pines, D. J. and Bohorquez, F. Challenges Facing Future Micro-Air-Vehicle Development, *Journal of Aircraft*, **43** (2), 290-305, (2006).

2 Floreano, D., Zufferey, J.-C., Srinivasan, M. V. and Ellington, C. Ed., *Flying Insects and Robots*, Springer-Verlag, Berlin, Heidelberg, Germany (2009).

3 de Croon G. C. H. E., Percin M., Remes B. D. W., Ruijsink R. and De Wagter C., *The DelFly: Design, Aerodynamics, and Artificial Intelligence of a Flapping Wing Robot*, Springer, Dordrecht, Netherlands(2016).

4 Wood, R., Nagpal, R. and Wei, G.-Y. Flight of the Robobees, *Scientific American*, **308**, 60-65, (2013).

5 Sane, S. P. The aerodynamics of insect flight, *The Journal of Experimental Biology*, **206**, 4191-4208, (2003).

6 Ellington, C. P. The Aerodynamics of Hovering Insect Flight. I-VI, *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, **305**, 1-181, (1984).

7 Ansari, S. A., Phillips, N., Stabler, G., Wilkins, P. C., Żibkowski, R. and Knowles, K. Experimental investigation of some aspects of insect-like flapping wing aerodynamics for application to micro air vehicles, *Experiment in Fluids*, **46**, 777-798, (2009).

8 Miller, L. A. and Peskin, C. S. A computational fluid dynamics of 'clap and fling' in the smallest insects, *The Journal of Experimental Biology*, **208**, 195-212, (2005).

9 Aono, H., Liang, F. and Liu, H. Near- and far-field aerodynamics in insect hovering flight: an integrated computational study, *The Journal of Experimental Biology*, **211**, 239-257, (2008).

10 Sueur, J., Tuck, E. J. and Robert, D. Sound radiation around a flying fly, *Journal of the Acoustic Society of America*, **118** (1), 530-538, (2005).

11 Swartz, S. M., Groves, M. S., Kim, H. D. and Walsh, W. R. Mechanical properties of bat wing membrane skin, *Journal of Zoology*, **239** (2), 357–378, (1996).

12 Swartz, S. M., Bishop, K. and Aguirre, M.-F. I. Dynamic Complexity of Wing Form in Bats: Implications for Flight Performance, *Functional and Evolutionary Ecology of Bats*, Oxford University Press, Oxford, United Kingdom, 110-130, (2006).

13 Nguyen, Q. V., Chan, W. L. and Debiasi, M. Experimental Investigation of Wing Flexibility on Force Generation of a Hovering Flapping Wing Micro Air Vehicle with Double Wing Clap-and-Fling Effects, *Proceedings of the 2016 International Micro Air Vehicles Conference and Flight Competition*, Beijing, China, 17-21 October, (2016).

14 Lu, Z., Debiasi, M., Nguyen, Q. V. and Chan, W. L. An experimental investigation on the acoustic performance of a flapping wing Micro-Air-Vehicle, *Proceedings of the 43rd International Congress on Noise Control Engineering (Inter.Noise 2014)*, Melbourne, Australia, 16-19 November, (2014).