# Aerodynamic evaluation of four butterfly species for the design of flapping-gliding robotic insects

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*Abstract*— **Alternating gliding and active propulsion is a potentially energy saving strategy for small-scale flight. With the goal of finding optimal wing shapes for flapping-gliding robots we evaluate the quasi-steady aerodynamic performance of four butterfly species (Monarch *(Danaus plexippus)*, the Orange Aeroplane *(Pantoporia consimilis)*, the Glasswing *(Acraea andromacha)* and the Four-barred Swordtail *(Protographium Ieosthenes))*. We fabricate at-scale wing models based on measured wing shapes and vary the forewing angle in nine steps to account for the ability of the butterfly to change the relative orientation of its forewing and hindwing during flight. For comparison we include twelve technical planforms as performance benchmarks for the butterfly wing shapes. We then test these 48 wing models at 2m/s, 3.5m/s and 5m/s (Reynolds number between 2'597 and 12'632) in a low speed wind tunnel which allows lift and drag force measurements of centimeter-size wings. The results indicate that the forewing orientation which maximizes the wing span offers the best gliding performance and that overall the gliding ratios are highest at 3.5m/s. The wing shapes with the best gliding ratio are found in the Glasswing butterfly with a maximum of 6.26 which is very high compared to the gliding performance of similarly sized flying robots. The results from this study are important for the development of novel biologically-inspired flying micro robots as well as for biomechanics studies in biology.**

## I. INTRODUCTION

The development of flying robotic insects is one of the grand challenges in robotics research [1]–[4]. One of the main limitations of insect-scale flying robots is aerodynamically unfavorable scaling laws that result in increased cost of transport as the size is reduced. Based on observations of flying animals and mathematical modeling of their flight, it has been suggested that adapting a hybrid flapping-gliding flight mode can be a promising locomotion strategy to minimize the energetic cost of locomotion [5], [6]. In fact, many animals such as birds, dragonflies, locusts, bats and butterflies employ intermittent flight, i.e. alternate flapping and gliding flight, as their aerial locomotion mode. Although recent projects have explored gliding flight for aerial microrobots [7]–[11] very little research has addressed intermittent flight and its implications on the design of flying micro robots. Several authors describe the aerodynamical effects in air at Reynolds numbers between $10^5$ and $10^6$ [12]–[15]. However, these studies are not applicable at Reynolds numbers below $10^4$ due to the increased influence of viscous and boundary layer effects [16]. The Reynolds number regime between 1000 and 10000 is of particular interest because the smallest animals which perform intermittent flight operate in this regime. Studies in biology have correlated wing morphology of flying insects and birds to flight performance on live animals [17]–[22] and using artificial models of butterflies and dragonflies [23]–[25]. One of the main limitations of these studies using static models is that the wing shape is extracted from pictures without accounting for a potential variability of wing orientation. Of particular importance is the relative orientation of forewing and hindwing which changes the overall planform of the wing significantly. Butterflies may hold the wings in an orientation during gliding flight which may be very different from how they are pinned down in a museum collection. In fact, museums display butterfly specimens with spread wings mainly for aesthetic reasons and not to mimic the aerodynamical functionality of the wing shape.

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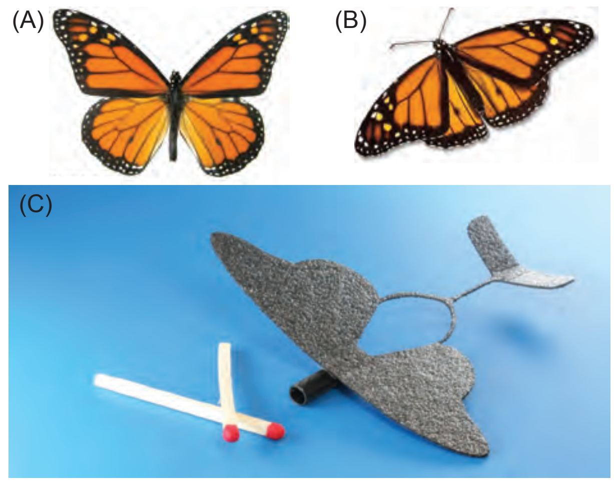


Fig. 1. The wing planform depends on the forewing orientation. A: Wing shape of a Monarch *(Danaus Plexippus)* specimen in a museum collection, B: Wing shape of a Monarch when feeding on a plant in nature (image: Wikimedia), C: Microglider prototype weighing a mere of 58mg.

The effect of a change in forewing and hindwing orientation on the overall wing shape is illustrated in figure 1.A and figure 1.B for a Monarch butterfly. Another limitation of several previous studies is a lack of force measurements. A reason for the lack of studies focussing on force measurements on at-scale insect wings is the need for a very sensitive and controlled wind tunnel allowing for low speeds of 2m/s and a force resolution of 0.1mN. In this paper we present the development and characterization of a low speed wind tunnel which can measure complete aerodynamical polar curves of at-scale insect wings with on-line quality control to ensure precise and repeatable results.

Using this wind tunnel we present our first set of results on systematic wing shape variations in four butterfly species. For each of these four butterflies we vary the forewing orientation at increments of 10° and measure the lift to drag ratios at 42 angles of attack at 2m/s, 3.5m/s and 5m/s. Based on these experiments we compare and discuss the gliding performance of the wing shapes from these four butterfly species. Furthermore, we include twelve technical planforms which we use to study the effects of the geometry of the wing tip, the leading edge and the trailing edge. This study provides important experimental insight into the aerodynamical effects of different wing shapes for small scale flight. Furthermore, the gliding performance of these shapes can be used as design benchmark for wing optimization in robotic flying insects which use gliding flight as part of their locomotion strategy. A first generation of micro gliders is depicted in figure 1.A, weighing a mere of 58mg. Applications of such micro gliders include distributed sensor networks, search and rescue and environmental monitoring, where increasing flight range and reducing the energy consumption is of major concern.

## II. Wing shape selection

As a starting point we focus on wing shapes found in four butterfly species. We selected migrating Monarchs *(Danaus plexippus)* which use a combination of hybrid flapping and gliding flight and have been documented to glide up to 80% of their flight time [15]. In addition to the Monarch, we evaluate the wing shapes of the Orange Aeroplane *(Pantoporia consimilis)*, the Glasswing *(Acraea andromacha)* and the Four-barred Swordtail *(Protographium Ieosthenes)* (butterflies depicted in figure 2). Based on museum specimens, we extract the wing shapes and vary the forewing orientation angle systematically in increments of 10° in order to account for the ability of the butterflies to dynamically change this angle during flight. To study the effects of different wing tip, leading edge and trailing edge geometries, we include twelve technical wing shapes to the study (round, square, tips at front and tips at back). The tested wing shapes are illustrated in figure 3. To isolate the effect of the wing shape from the influence of other parameters such as wing flexibility, camber, wing corrugation or surface topologies, we fabricate the wings out of rigid flat plates. Further, the wing edge geometry can have a strong effect on the aerodynamic performance of a wing shape [26]. We therefore choose to laser cut the wings from flat steel plates with a thickness of 150$\mu$m (figure 4.A) using a Diode-pumped solid-state (DPSS) laser which ensures a very clean and repeatable cut as illustrated in the Scanning Electron Microscopy (SEM) image of the wing model edge (figure 4.B). For normalization we scale all wings to an area of 900mm$^2$.


Fig. 2. We test the wing shapes from four butterfly species: Monarch *(Danaus plexippus)*, Orange Aeroplane *(Pantoporia consimilis)*, Glasswing *(Acraea andromacha)* and Four-barred Swordtail *(Protographium Ieosthenes)* (images: Wikimedia and Picasa).

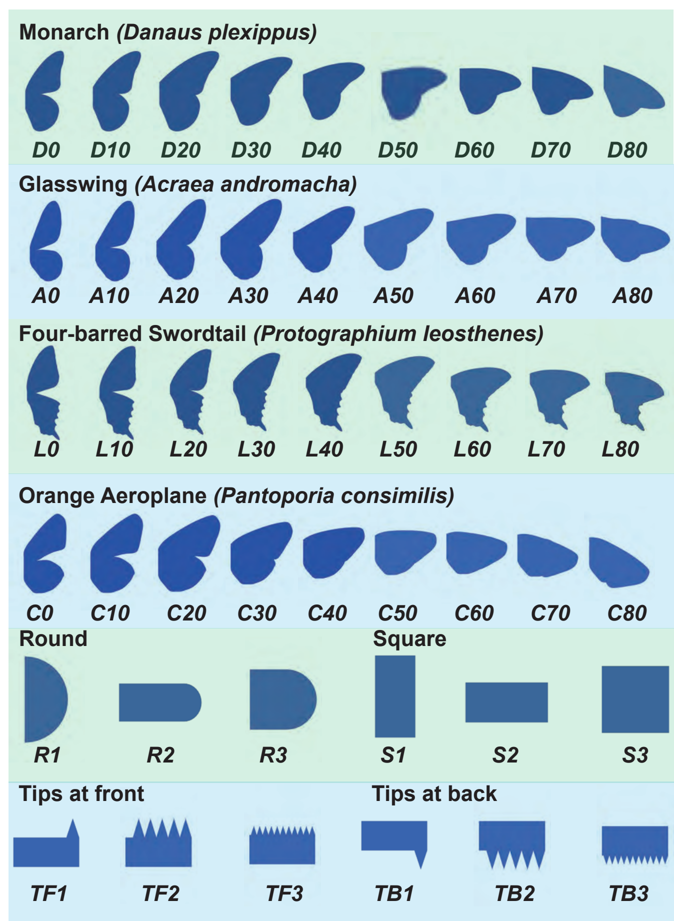


Fig. 3. Wing shape variation accounting for the capability of the butterfly to orient its forewing during flight.

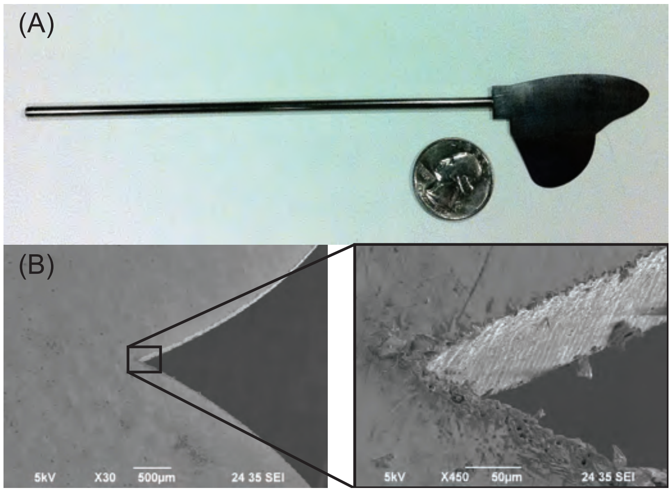


Fig. 4. The wing model is machined using a DPSS laser in order to ensure a very clean and repeatable cut of the wings.

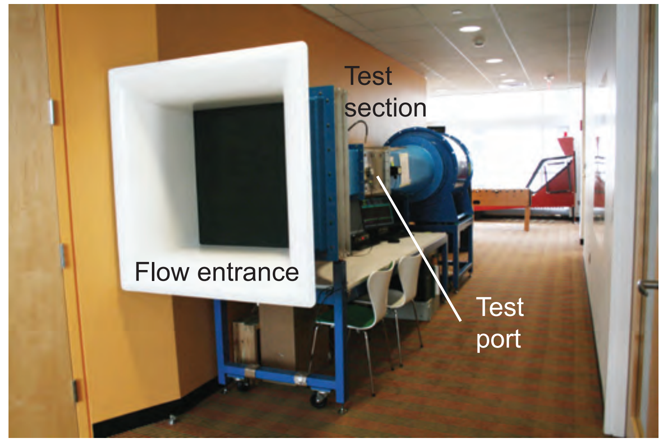


Fig. 5. Low speed wind tunnel which allows at-scale lift and drag measurements of millimeter and centimeter sized wings.

## III. Wind tunnel

The wind tunnel is an open circuit Eiffel type wind tunnel (figure 5) oriented horizontally with a contraction ratio of 6.25:1 from Engineering Laboratory Design Inc.. The square test section has a height and width of 30.5cm and a length of 61cm with two test ports integrated in the side walls with a diameter of 100mm each. The test port is outfitted with a rotation stage and a 6-axis force/torque sensor which allows the angle of attack of the wing sample to change while measuring the lift and drag forces (figure 6). The 6-axis force/torque sensor (Nano 17 from ATI, figure 6.a) has a force measurement resolution of 3mN and a torque resolution of 15mN-mm. It is affixed to a Newport PR50CC mini DC rotary stage (figure 6.b) which has an angular resolution of 0.01° for precise angular positioning of the wing samples. This stage is mounted on the the wind tunnel test section wall using a transparent Poly(methyl methacrylate) interface port (figure 6.c). The wing samples (figure 6.d) were mounted to a 31.4cm long carbon fiber lever arm (figure 6.d) which is used to amplify the forces acting on the wing. The free end of this carbon tube is positioned on the force/torque sensor with the shape held in the mid height of the test section (figure 6.f). Real time wind tunnel velocity verification was achieved using the TSI air velocity transducer (model 8455) mounted in the span wise plane of the test section 45cm downstream from the test section entrance. It has a resolution of 0.07% of the full scale selected range (0-25m/s).

### *A. Wind tunnel characterization and quality control*

The wind tunnel is controlled using a Dell Optiplex 980mt host computer with an IBM Thinkcenter acting as the target machine using the Matlab Simulink XPC computational environment. The control schematic is shown in figure 7. The hardware control of the rotational stage, the wind tunnel fan speed, and the TSI air velocity transducer are implemented using the Newport XPS-C2 2 axis controller.

Manufacturer testing found velocity uniformity to vary a

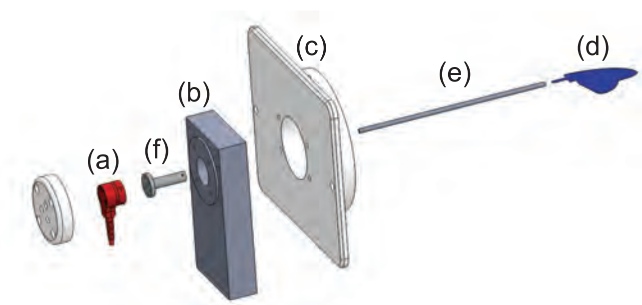


Fig. 6. Wind tunnel mount containing the Nano 17 6-axis force sensor (a), the Newport rotation stage (b), a transparent interface port (d), the wing sample (d), a carbon tube lever arm which amplifies the forces on the wing (e) and a connection piece mounting the carbon tube to the force sensor (f).

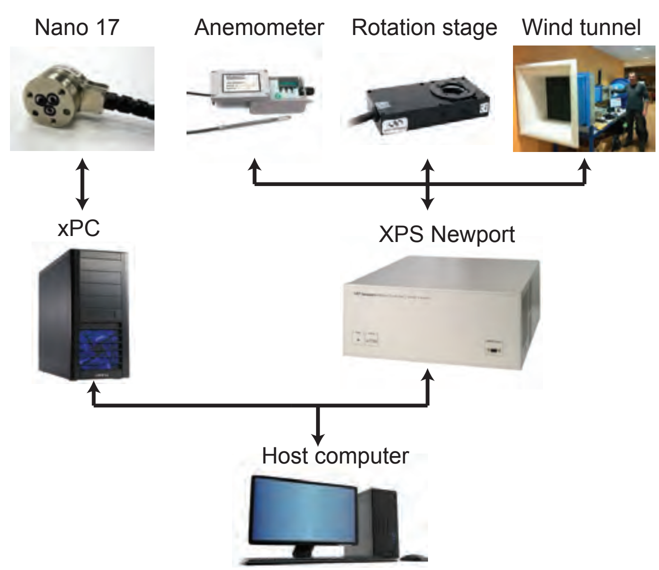


Fig. 7. The wind tunnel is controlled using a xPC environment with on-line quality control.

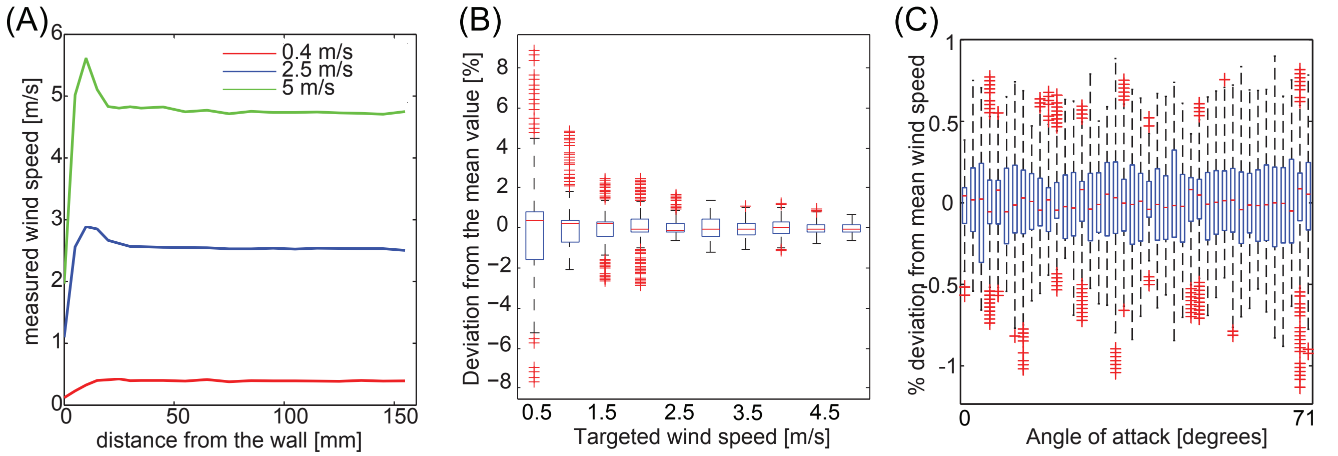


Fig. 8. The wind tunnel is capable of high quality force measurements at wind speeds of less than 1m/s. A: Measured wind speed across the test section in the wind tunnel, B: Wind speed deviation from the mean value for different target wind speeds C: Force deviation from mean value for different target wind speeds

maximum of ±0.98% from the mean free stream velocity of 2m/s over the area of the test section excluding the boundary layer. In order to verify the precision of our wind tunnel and to characterize the boundary layer thickness we performed span-wise velocity measurements at a target flow velocity of 0.4m/s, 2.5m/s and 5m/s (figure 8.A). The results indicate that the flow field is uniform at a distance greater than 25mm from the wall. In order to characterize the variation of the air speed we performed a series of experiments at target velocities between 0.5m/s and 5m/s over a time interval of 20s at a sampling rate of 1000Hz (figure 8.B). It can be seen that the deviation from the target wind speed is less than 2% with an increased number of outliers at low flow velocities. Based on these two flow characterizations we choose to perform our wing shape tests at a distance of 30mm from the test section wall and at velocities of 2m/s, 3.5m/s and 5m/s. Further, we characterized the variation of the forces measured at each angle of attack (figure 8.C). It can be seen that the force variation is uniform for the different angles of attack with a range of ±0.5%. During these measurements the environment is controlled to minimize perturbations such as ground vibrations of people walking by or transient air movements. In order to ensure consistency and high quality of the force measurements even when running experiments for long periods, we implemented an on-line quality control scheme. The principle of this scheme is that at every angle of attack the wind speed is held constant and a series of force measurements are taken over a period of 20s at a sampling rate of 1000Hz. Based on this data, both the mean and the variation is recorded and evaluated. In the event that the variation of the data sequence is larger than a prefixed value, the measurement series is rejected and repeated until it meets the defined quality criteria. For the tests in this paper we define the acceptable threshold such that 97% of the measurements have to be within a variation of only ±1% of the mean value.

## IV. Results and discussion

Each wing was tested at wind speeds of 2m/s, 3.5m/s and 5m/s which corresponds to a Reynolds number range between 2’597 and 12’632. The tested angles of attack range between 0° and 72° and are evaluated during 20s at each angle with a sampling rate of 1000Hz. The final result is an average of two complete tests to account for potential variability between measurements.

The results of the measurements are represented in figure 9, figure 10 and figure 11 respectively, showing a clear difference in performance of the various butterfly species as well as the variation of the forewing orientation. The maximum gliding ratio, which is defined as the maximal value of the lift to drag polars, is achieved by the model A70, reaching a value of 6.26. It can be seen that there is a clear velocity dependence of the gliding ratio for all tested wings shapes. The average, as well as the maximal value of the gliding ratio, is highest at 3.5m/s indicating an aerodynamically beneficial velocity range for the tested butterfly wings. The gliding ratios reached by the tested wings are very high compared to the measured gliding ratios of gliding micro robots of similar size (3 in [9] and 5.6 in [11]).

Further, it can be seen that there is an optimum as well for the forewing orientation angle. The results indicate that for all tests the forewing angle which maximizes the wing span offers the best gliding performance (D60, A70, L60, C60). The only exception from this tendency is the Glasswing at 2m/s although the difference of the gliding ratio of the model with maximal wing span is relatively small (6.7%).

The round and the square technical wings perform very well compared to the butterfly wing shapes. The R2 and the S2 wing shapes are different in wing tip geometry but have very similar gliding ratios. The lower aspect ratio round and square wings vary more indicating that the wing tip geometry is of higher importance for lower aspect ratio wings and has little effect on narrow and elongated wings.

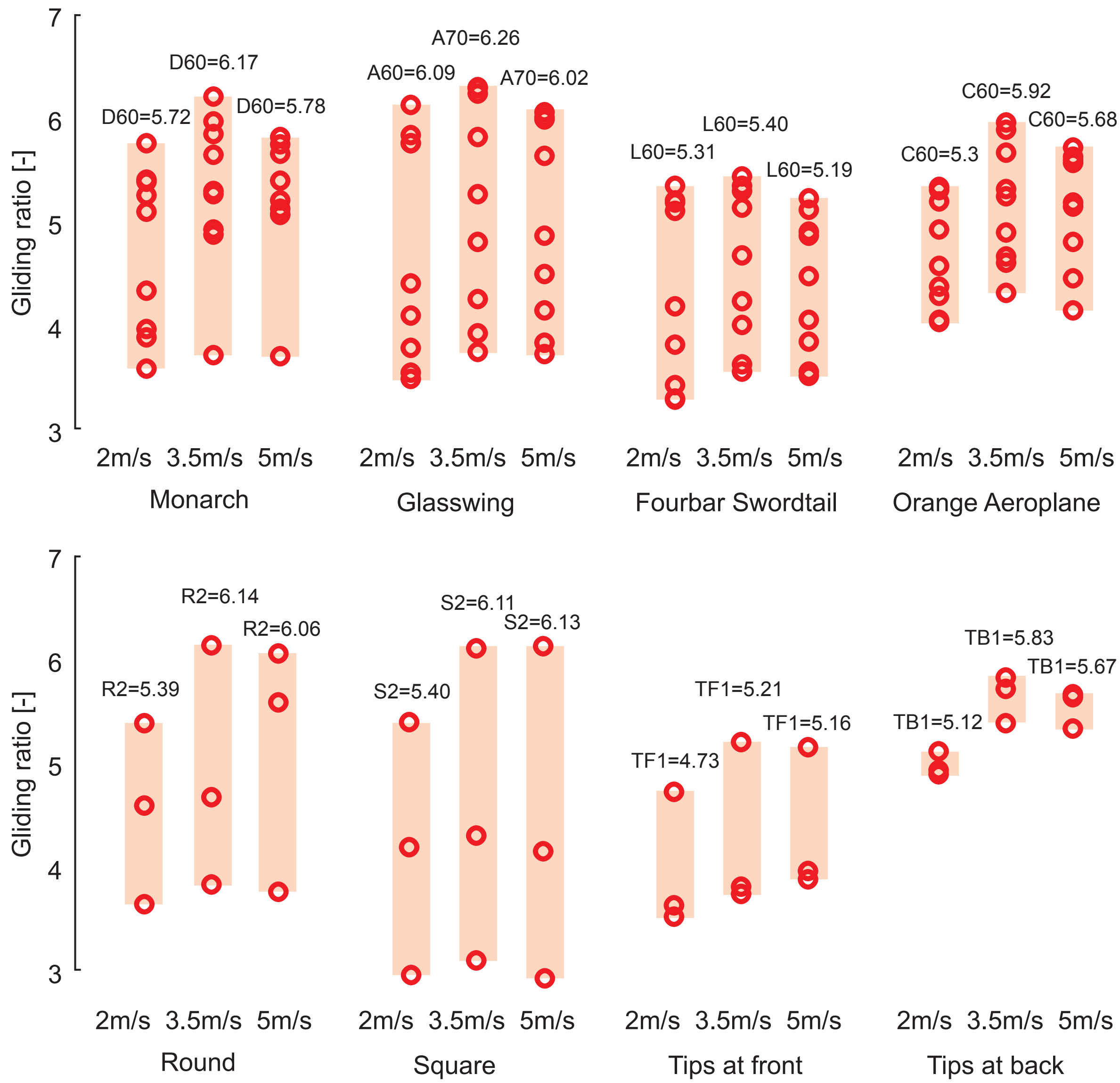


Fig. 9. The gliding ratio corresponds the maximal Lift/Drag ratio from the polar curves in figure 10 and figure 11 represented as circles. The gliding performance for all tested wings is maximal at 3.5m/s and for the butterfly wing shapes which maximize the aspect ratio, which provides important design guidelines for flying robotic insects.

The results from the leading edge and trailing edge variation indicate that changing the leading edge geometry has a stronger effect on gliding ratio than varying the trailing edge. Overall, the tips decrease the gliding ratio although other tip geometries could be more favorable than the ones tested in this study.

Averaged over the three gliding velocities the best butterfly wing shapes perform better than the technical wing shapes. In particular at 2m/s the butterfly shapes have a sustained high gliding ratio which is not the case for the round and square wings. Furthermore, the butterfly wings have a lower aspect ratio which leads to a higher mechanical robustness of the wing.

We conclude that the tested butterfly wing shapes can offer an increased flight performance at low flight velocities and a better mechanical robustness compared to the tested technical wing shapes. However, this is only the case for a wing orientation which maximizes the wing span and not for the wing shapes of butterflies typically displayed as museum specimens.

Future work will focus on a more systematic study of wing tip, aspect ratio and leading edge geometries of technical wing shapes as well as the interaction of fore and back wings if they are not hold in the same plane. We have conducted first tests on varying the hind wing orientation as an additional parameter to the forewing orientation. The first results suggest that there is a strong velocity dependance on the gliding performance with different hindwing orientations which needs further analysis using smoke flow visualization and particle imaging velocimetry to discuss the aerodynamic effects taking place.

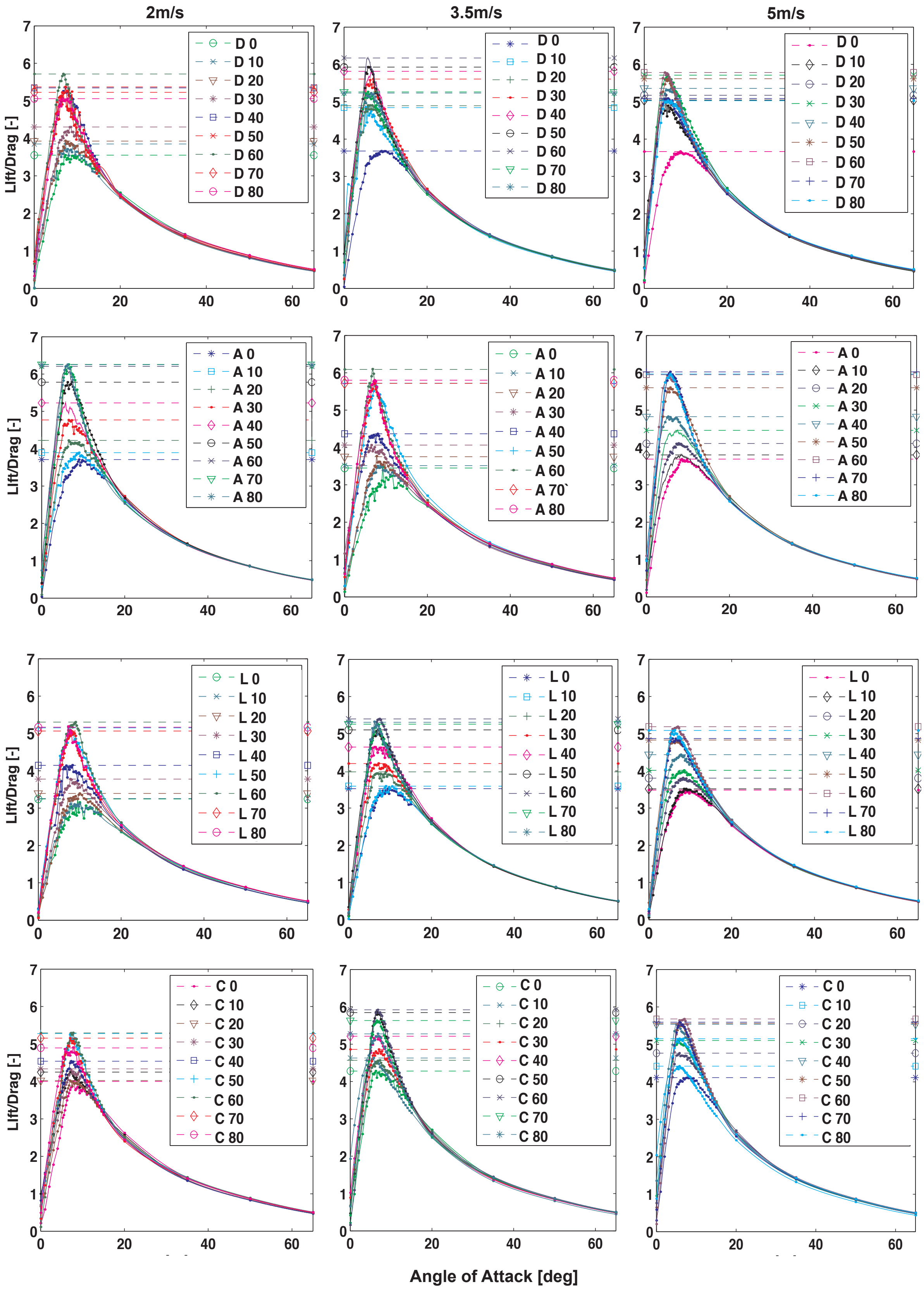


Fig. 10. Lift/drag polar curves for the 36 tested butterfly wing shapes. The gliding performance varies for the different butterfly species and wing orientations.

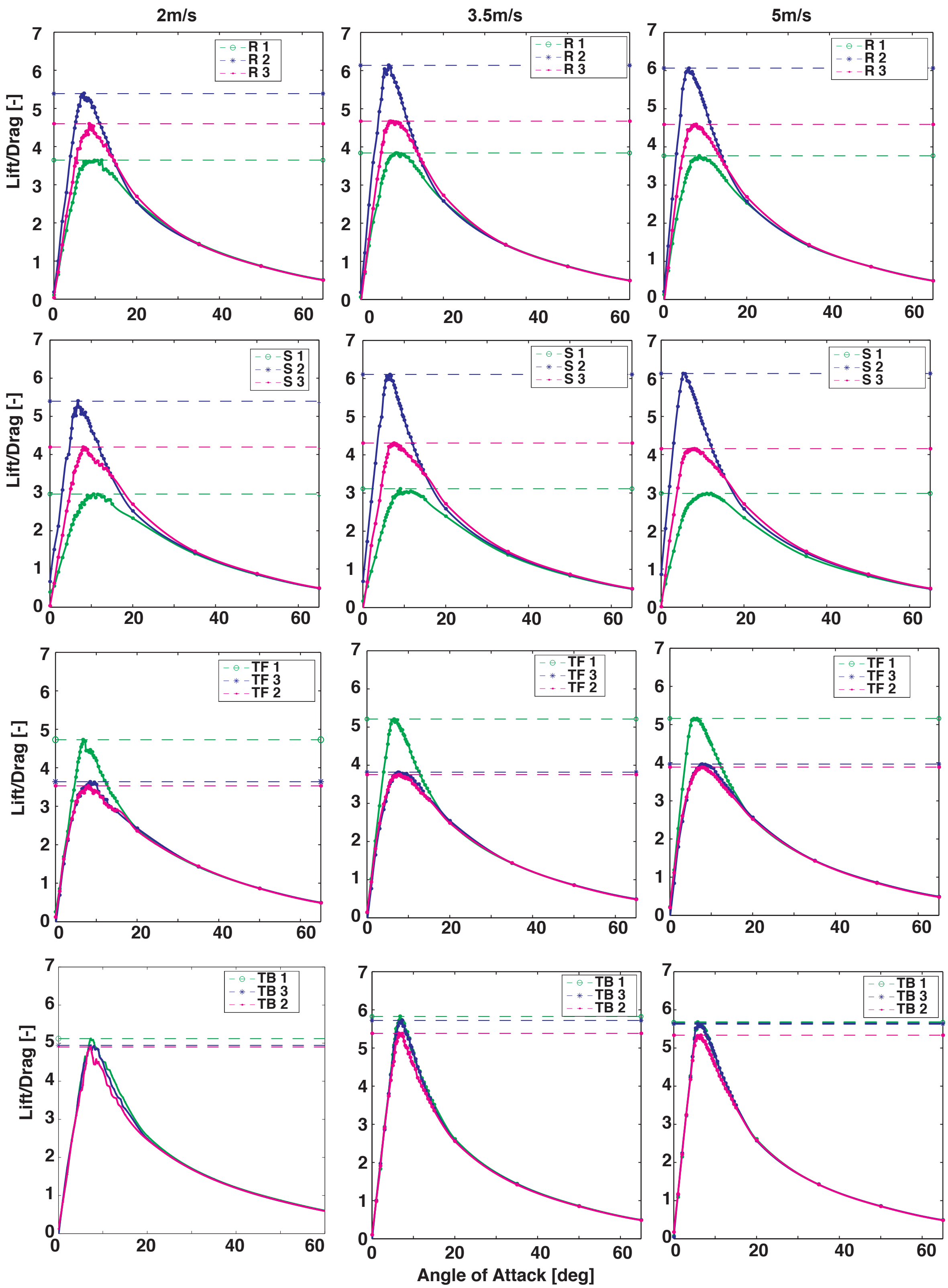


Fig. 11. Lift/drag polar curves for all the 12 tested technical wing shapes. The gliding ratio is defined as the maximal value of the Lift/Drag polar curve.

## V. Conclusion and future work

In this paper we presented a new low speed wind tunnel and control architecture which allows at-scale lift and drag force measurements of millimeter and centimeter size wings. As a first step towards the next generation of flapping and gliding micro robots, we evaluated four butterfly species with nine wing configurations each and twelve technical wing shapes at wind speeds of 2m/s, 3.5m/s and 5m/s, which corresponds to a Reynolds number range between 2'597 and 12'632. Overall, the Glasswing butterfly offers the best gliding performance with gliding ratios of up to 6.26 which is very high compared to micro air vehicles of similar size. The results indicate that the wing configuration which maximizes the wing span is the most favorable configuration with regards to increasing the gliding ratio. Further, we measure that the gliding ratio is maximal at 3.5m/s indicating the maximal range velocity for gliding flight for the wings tested in this study. This velocity optimum is an important design parameter in the development of high performance flying micro robots. From the study of the technical wing shapes we conclude that the tip geometry is of higher importance to low aspect ratio wings and that changing the leading edge geometry has a higher effect than changing the trailing edge geometry. Comparing the butterfly wings to the technical wing shapes suggests that the butterfly wings are sustain their high gliding performance at low flight velocities where the performance decreases dramatically for the technical wings. Future work will focus on a more detailed analysis of the aerodynamic effects on the wings using flow visualization techniques. Moreover, the findings in this publications can give valuable insight into the biomechanics of the four butterfly species and could be compared to in flight measurements of live insects.

## VI. Acknowledgments

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