An insect-inspired collapsible wing hinge dampens collision-induced body rotation rates in a microrobot

Andrew M. Mountcastle¹, E. Farrell Helbling² and Robert J. Wood²

¹Department of Biology, Bates College, Lewiston, ME 04240, USA
²School of Engineering and Applied Sciences and the Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, MA 02138, USA

Cite this article: Mountcastle AM, Helbling EF, Wood RJ. 2019 An insect-inspired collapsible wing hinge dampens collision-induced body rotation rates in a microrobot. J. R. Soc. Interface 16: 20180618.

Received: 14 August 2018
Accepted: 8 January 2019

Subject Category:
Life Sciences – Engineering interface

Subject Areas:
biomechanics, biomimetics

Keywords:
wing, insect, collision, robotics, flight, MAV

Author for correspondence:
Andrew M. Mountcastle
e-mail: amountca@bates.edu

Electronic supplementary material is available online at https://dx.doi.org/10.6084/m9.figshare.c.4372118.

1. Introduction

Many flying insects regularly navigate heterogeneous and dynamic three-dimensional landscapes while immersed in turbulent and unpredictable airflows. Inadvertent body collisions with obstacles are often unavoidable under these conditions, and wing collisions in particular are a common occurrence for some insects. Foraging bumblebees, which regularly weave through cluttered vegetation in search of floral resources, strike their wings against leaves and flower petals roughly once per second [1], and it is likely that many other insect pollinators experience similar rates of wing collisions. These types of collisions typically occur in bouts, with a flapping wing repeatedly striking an obstacle at high frequency until the insect moves away from it.

Repeated wing collisions with vegetation can cause cumulative and irreversible wing damage over time [1], which can in turn cause an increase in mortality [2]. In light of these significant costs, it is not surprising that at least some insects have evolved wing morphologies that help mitigate damage associated with repeated wing collisions [3]. Wasp wings feature a flexible resilin joint called a ‘costal break’ located distally along the leading edge of the wing, which allows the wingtip to crumple reversibly when it hits an obstacle. However, although the costal break readily flexes upon collision, it does not deflect appreciably under the aerodynamic and inertial loads that accompany typical flapping flight behaviour [3]. This observation suggests that the costal break is a strain-weakening flexure that is initially stiff, but eventually collapses at some torque threshold.

We hypothesized that in addition to mitigating wing wear, collapsible wing tips benefit flight performance in yet another important way: by reducing...
sudden and unpredictable body rotations during wing collisions. Upon impact with an obstacle, a wingtip experiences a nearly instantaneous deceleration that is likely to exceed both the aerodynamic and inertial forces experienced during normal wing flapping. A collapsible wingtip could function as a type of shock absorber by dampening the extreme forces caused by collisions, which would otherwise be transmitted directly to the body through a rigid wing. By reducing unpredictable and extreme body rotations upon collision, a collapsible wingtip may actually simplify flight control.

In order to perform complex flight manoeuvres and stabilize themselves after unpredictable perturbations, flying insects must be able to rapidly assess their self-motion and modulate their wing motions in response [4]. The insect world features a variety of specialized sensorimotor pathways that have evolved to accomplish this task, including those that rely on optic flow from compound eyes [5,6], visual feedback from ocelli [7], and mechanosensory feedback from assorted receptors on the head and body [4,8]. Controlled flight is not solely reliant on the active responses of neurally based systems, however; passive body dynamics can also play a role. Full & Koditschek [9] argue that while the nervous system tends to dominate the control of slow, variable-frequency locomotion, the mechanical system may be largely responsible for controlling rapid, rhythmic locomotion by passively rejecting sudden perturbations. Although their hypothesis was focused on explaining legged locomotion on land [9], it is equally plausible for insect flight locomotion. Offloading challenging control requirements from the active nervous system to the passive dynamics of the mechanical system has the potential to simplify control.

Recent technological advances have brought us closer to the realization of field-deployable insect-scale micro air vehicles (MAVs), devices that have potential to transform search-and-rescue operations, surveillance and reconnaissance [10–12]. The majority of MAVs currently in development are constructed with mostly rigid materials, which makes them fragile and prone to breaking when they collide with obstacles. Just like insects, however, these extremely small and light-weight devices will face a high risk of collision when operating near physical obstacles in real-world conditions. Even highly sophisticated micro-scale sensing and control technology is unlikely to prevent collisions in all circumstances. MAVs will therefore benefit from design innovations that help minimize structural damage and facilitate flight control when subjected to unpredictable, sudden perturbations.

We were motivated to design a bioinspired wing flexure for RoboBee [10,11], an insect-scale microrobot, for two primary reasons: to test the hypothesis that a collapsible wing joint can dampen collision-induced body rotations, and to offer a bioinspired design solution for enhancing the real-world flight performance and wing durability in MAVs. We built a micro-scale buckling hinge that exhibited nonlinear strain-weakening behaviour, similar to the wasp costal break. We then integrated this hinge design into the wings of a RoboBee, and performed wing collision tests in a yaw-based magnetic tether system. We tested both flexible and stiff wings for comparison, and recorded collision trials with a high-speed camera. Videos were analysed to determine the mean yaw rate of the RoboBee airframe immediately after collision. We focused on yaw rotations for two related reasons: firstly, the dominant axis of rotation for the flapping wings coincides with RoboBee’s yaw axis, implying that any torques on the airframe resulting from wing collisions would be greatest about the yaw axis. Secondly, the RoboBee airframe has the smallest moment of inertia—and is therefore the least stable to external perturbations—about the yaw axis, suggesting that unpredictable torques about the yaw axis would pose the greatest challenge to a flight control system. We focused on analysing the airframe’s angular velocities because flight control systems, including the sensorimotor pathways responsible for insect flight control, are often tuned to sense and respond to body rotation rates.

2. Material and methods

2.1. Torque-deflection measurements

In order to inform how to construct our bioinspired flexure hinge, we first characterized the torque-deflection behaviour of a wasp costal break. A live specimen was used because insect wings are susceptible to desiccation [13]. We collected a yellowjacket wasp (Vespula maculifrons) while it foraged on the Harvard University campus, cold anesthetized it at −15°C for approximately 5 min, and placed it in a custom brace designed to immobilize its body and splay its wings orthogonally to the body axis (after [3]). A drop of cyanoacrylate adhesive was added to the base of the left forewing to fix its position relative to the brace. The brace was mounted on a belt-driven rotation stage and positioned with the long axis of the wing orthogonal to the axis of rotation of the motor, which itself was aligned with the costal break (experimentally set-up illustrated in electronic supplementary material, figure S1). We measured the torque-deflection behaviour of the costal break by rotating the wingtip onto a miniature S Beam Load Cell (LSB200; FUTEK Advanced Sensor Technology, Inc., Irvine, CA, USA), and deflecting the joint up to 35°. We used this same test stage to measure the torque-deflection behaviour of six identical bioinspired buckle hinges, performing 400 consecutive deflection trials on each hinge to investigate whether hinge stiffness changed over multiple load cycles.

2.2. Design and fabrication of micro air vehicle wings

To replicate the nonlinear strain-weakening behaviour of the costal break, we designed a buckle hinge consisting of two layers of thermoplastic elastomer (TPE) film separated by an intervening gap, and incorporated this hinge into the leading-edge spar of a RoboBee wing, the design of which has been featured in several recent studies from our group [14,15] (figure 1a–d).

A standard RoboBee wing consists of a sheet of 80 μm thick carbon fibre spars bonded to a Mylar film. We modified this design to incorporate a buckle hinge by segmenting the leading-edge spar proximal to the outer trailing spar, and laminating an additional layer of carbon fibre above and below the central layer on both sides of the cut to generate a sufficient gap between the two TPE overlays. A layer of 38 μm thick TPE film was attached to each side of the raised carbon fibre platform by manually inserting micro tenons through aligned laser-cut holes in the TPE and underlying carbon fibre laminate (figure 1c,d). Each tenon was cut from the same 80 μm thick carbon fibre stock material used for the wing, and terminated in a broad shoulder. The tenon was dipped in uncured 60 minute epoxy prior to setting into the mortise, ensuring that once cured the tenon shoulder would mechanically clamp the TPE layer to the face of the underlying carbon fibre. Four tenons were used for each hinge—two on each side of the wing—and each tenon formed an extension of a much larger tab, which served as a handle for grasping with forceps during
the assembly process. The tab was manually snapped off from the tenon shoulder once the tenon was set into the mortise.

We relied on trial-and-error approach to determine which combination of hinge geometry and TPE material properties yielded a hinge with strain-weakening characteristics suitably scaled for implementation on a RoboBee wing. Specifically, we sought a hinge with a critical buckling torque that was slightly higher than the maximum aerodynamic and inertial load applied to the hinge during a typical wing flapping cycle, so that the hinge would deflect only minimally during normal flapping flight but buckle easily upon collision with an obstacle. We tested each hinge iteration by attaching the wing to a fixed RoboBee airframe, driving it at a range of flapping frequencies, and recording the dynamic behaviour with a Phantom v710 high-speed camera at 5000 frames s⁻¹. Through visual inspection of the high-speed videos, we ultimately selected a hinge design (figure 1c) that displayed minimal deflection (less than 10°) when oscillated at roughly the same kinematics as an obstacle upon which RoboBee wings were forced to collide.

We fabricated two sets of wings for our collision trials: an experimental group with collapsible wingtips (flexible wing treatment), and a control group with non-collapsible wingtips (stiff wing treatment). Each of the flexible wings were constructed with an integrated buckle hinge, as described above. The stiff wings were constructed with the same hinge architecture in order to replicate the mass distribution and shape profile of the flexible wings, except the middle layer of leading edge carbon fibre was not sectioned at the hinge so as to prevent the wingtip from flexing during collisions.

2.3. Free flight tests
To ensure our modified wings were still capable of serving their primary function of flight, we attached a pair of flexible wings to a RoboBee airframe and performed a number of controlled flights in a test arena. The controller was adapted from [16] and control gains were hand-tuned to ensure stable flight. Flights were recorded with a Phantom v710 high-speed camera filming at 1000–7500 frames s⁻¹.

2.4. Collision trials
To test the effect of wingtip flexibility on RoboBee body dynamics during wing collisions, we placed the RoboBee in a yaw-based magnetic tether based on the set-up used by [17], and forced one wingtip to collide with an obstacle at different phases of the stroke cycle (experimental set-up illustrated in electronic supplementary material, figure S2). We affixed a 25 mm steel vee jewel pivot to the anterior end of the airframe, coincident with the primary body axis. The RoboBee was inverted and the tip of the vee jewel pivot was placed onto a sapphire vee jewel bearing, which rested on top of a rare earth magnet. The magnetic field kept the jewel pivot oriented vertically but allowed the RoboBee to rotate freely about its yaw axis. By positioning the RoboBee upside down in the magnetic tether, aerodynamic forces generated during wing flapping acted to increase the downward force, thereby ensuring continuous contact with the jewel bearing.

We attached a small piece of retroreflective fabric to the end of each of three 10 mm long carbon fibre spars projecting from the posterior end of the RoboBee, which serves as a stand for the bee when it is upright. These markers were used as tracking landmarks for capturing body kinematic data.

We used a small 2.5 mm diameter × 10 mm long brass post as an obstacle upon which RoboBee wings were forced to collide. The post was affixed perpendicularly to the end of a 100 mm long lever and positioned just below the swept path of a flapping wingtip, distal to the buckling hinge. By manually depressing the other end of the lever during a trial, the post would rapidly move up into the wing path and cause the wingtip to collide. Body torques generated by a colliding wing caused the pivot to swivel in the low-friction jewel bearing.

A Phantom v710 high speed camera was positioned directly above the magnetically tethered robotic fly and we recorded wing collision trials at 11 000 frames s⁻¹. Yaw-based body kinematics were digitized by tracking the retroreflective markers on the airframe using Matlab-based tracking software [18]. We also analysed the video to determine the moment—within a margin of error equal to the frame duration of 90 ms—the wing contacted the obstacle.

We captured a total of 27 wing collision trials from the flexible wing group and 18 trials from the stiff wing group, with collisions spanning a range of wing positions within a stroke cycle, from the beginning of a half-stroke (just after the wing reversed its flapping trajectory) to the end of a half-stroke.
2.5. Data analysis

The digitized body data were processed with a fifth-order Butterworth low-pass filter with a cut-off frequency of 1500 Hz, using the zero-phase 'filtfilt' Matlab function. We calculated angular velocity by numerically differentiating the yaw position data, and found the mean airframe yaw rate within a 20 ms period after the initial wing collision for each trial. The 20 ms time window was chosen based on evidence that it takes roughly 20 ms for freely flying honeybees to sense, process and initiate a musculoskeletal response to sudden gust perturbations [19]. Thus, we inferred that the rotational velocity of the body during this sensorimotor latency period will have important implications for biologically-based flight control systems. We performed Mann–Whitney U tests to determine whether the mean post-collision yaw rates in the flexible and stiff wing treatment groups came from populations with the same or different distributions.

Finally, we also analysed post-collision yaw rates based on the wing position upon collision. Since the RoboBee’s wing kinematics were essentially the same (only reversed) between upstroke and downstroke, we pooled body collision response kinematics from both the downstroke and upstroke to represent the data simply as a function of normalized wing stroke phase, where 0 represents the beginning of a half-stroke and 1 represents the end of a half-stroke. We performed a simple linear regression on the mean yaw rate data for each treatment group to predict yaw rate based on wing stroke phase (figure 2d).

3. Results

3.1. Torque-deflection measurements

Both the wasp wing costal break and our bioinspired buckle hinge exhibited strain-weakening behaviour, characterized by
initially high stiffness at low deflection angles, followed by a torque plateau at approximately 10° deflection, and a subsequent decline in stiffness as deflection further increased (figure 1c). Whereas the costal break stiffness remained relatively low at high deflections up to the maximum limit of the test (35°), the buckle hinge stiffness began to sharply increase around 30° deflection. This was due to the outer layers of carbon fibre on opposite sides of the hinge contacting one another, and represented the operable limit of our buckle hinge (figure 1c).

The wing torque–deflection data reported in this study are qualitatively similar to preliminary data we collected from several other individuals using a more rudimentary set-up involving a linear actuator and a less sensitive strain gauge. Although the preliminary data did not have the same level of accuracy as the data presented here, the torque–deflection curves in every wasp tested exhibited clear strain-weakening behaviour.

The buckle hinges also exhibited an initial break-in period before their torque–deflection curves stabilized. Hinge stiffness and torque plateau magnitudes initially declined during roughly the first 150 load cycles, but levelled off thereafter, and the torque–deflection behaviour of the 400th load cycle was nearly identical to that of the 150th cycle for all six buckle hinges tested.

### 3.2. Free flight tests

RoboBee was able to achieve stable hovering flight with the integrated buckle hinge, though the additional mass of the hinge reduced RoboBee’s wingbeat frequency by roughly 15%, from the typical 165 Hz to 140 Hz. Visual inspection of the free flight high-speed videos did not reveal any noticeable hinge deflections during wing flapping (see electronic supplementary material, movie S1), but these recordings did not offer a particularly close-up view of the wing kinematics either. By comparison, the overhead views of flapping sequences in the magnetic tether prior to wing collisions, in which the wings were flapped at the same frequency and amplitude as during flight, did show some moderate out-of-plane deflection of the wing tip at the buckle hinge (see electronic supplementary material, movies S4 and S5). However, these deflections did not exceed 10°, and therefore presumably did not reach the critical buckling torque, beyond which the hinge stiffness declines appreciably (figure 1f). Whether or not the hinge exhibited some degree of moderate deflection during free flight, we confirmed that the wings could still reliably produce flight, which was the main question motivating these tests.

### 3.3. Collision trials

Collisions in the stiff wing group—regardless of where in the stroke cycle they occurred—typically involved the entire wing coming to a complete stop, immediately followed by the airframe displaying some degree of counter-rotational acceleration about its yaw axis due to Newton’s Third Law of motion (electronic supplementary material, movies S2 and S3). In contrast, collisions in the flexible wing group caused the wing to buckle at the hinge, and the proximal section of the wing to continue its forward motion while the wingtip was progressively deflected by the obstacle. In flexible wing collisions that occurred in the early to mid-wing stroke phase, the deflected wingtip would eventually swing clear of the obstacle as the proximal section of the wing passed by, and the hinge would rebound to its un-deflected state as the wing continued its motion (electronic supplementary material, movie S4). This physical interaction would sometimes repeat for multiple consecutive strokes as the wing continued flapping and the collapsible wingtip collided with the obstacle on every downstroke and upstroke. In flexible wing collisions that occurred towards the end of the wing stroke phase, the deflected wingtip would not completely pass by the obstacle because the proximal section of the wing would shortly undergo a stroke reversal and begin moving in the opposite direction for its next half-stroke, eventually allowing the wingtip to straighten out again as the wing moved away from the obstacle in the same direction from which it approached (electronic supplementary material, movie S5). Flexible wing collisions were typically accompanied by counter-rotational accelerations of the airframe that were less pronounced than those observed during stiff wing collisions.

Consistent with the observations above, we found that the distribution of mean RoboBee yaw rates within 20 ms after wing collision was approximately 40% less for the flexible wing group (median = 1205° s⁻¹) than for the stiff wing group (median = 2001° s⁻¹) across all phases of the wing stroke, and this difference was significant (Mann–Whitney U test, \( U = 67, \quad n_1 = 27, \quad n_2 = 18, \quad p < 0.001; \) figure 2c). We found that wing stroke phase significantly predicted mean yaw rate for the stiff wing group (\( F_{1,138} = 138.95, \quad p < 0.001 \)), with an \( R^2 \) of 0.897, but did not significantly predict mean yaw rate for the flexible wing group (\( F_{1,24} = 0.035, \quad p = 0.85 \)), with an \( R^2 \) of 0.001 (figure 2d). Thus, the buckle hinge had a greater effect on yaw rates for collisions that occurred early in the stroke cycle compared to those that occurred late in the stroke cycle. For collisions that occurred during the first half of the stroke (0–0.5 wing stroke phase), we found that the distribution of mean yaw rates was approximately 77% less for the flexible wing group (median = 857° s⁻¹) than for the stiff wing group (median = 3787° s⁻¹), but for collisions that occurred during the second half of the stroke (0.5–1 wing stroke phase), the distribution of mean yaw rates was only 24% less for the flexible wing group (median = 1205° s⁻¹) than for the stiff wing group (median = 1585° s⁻¹).

### 4. Discussion

We found that a collapsible wing tip dampens airframe rotation rates by absorbing shock impulses from wing collisions, and the extent to which yaw rates were reduced depended on where in the stroke cycle the collision occurred. Whereas airframe yaw rates in the stiff wing group depended on wing stroke phase—with the highest RoboBee yaw rates occurring early in the stroke cycle—yaw rates in the flexible wing group were lower overall and did not depend on wing stroke phase (figure 2). The relationship between yaw response and wing stroke phase in the stiff wing group can be explained by the combined effects of wing momentum at the moment of collision and the actuator force corresponding to the wing position at collision, which acts to leverage the airframe around.

Although the wing collision tests performed in this study were conducted in a constrained experimental set-up that only allowed body motion around one axis of rotation, we
expect that the general pattern we observed would also apply in free flight conditions where the body is free to move in six degrees of freedom. That is, collapsible wingtips would likely reduce collision-induced angular velocities of the body in free flight as well, though the magnitude of the effect would depend on the specific circumstances surrounding the physical interaction.

We did not explicitly test the effects of a collapsible wingtip on flight control, primarily because the on-board flight control system for RoboBee is still in development, but it is still useful to place our results in a biological context. The RoboBee yaw rates that we measured for the stiff wing group in particular are at the high end of extreme body angular velocities that have been measured in flying insects. Fruit flies often display rapid in-flight turns called saccades in which they can change their heading by approximately 90° in 50 ms [20], a manoeuvre that requires an average body rotation rate of approximately 1800° s⁻¹. In a study that involved subjecting flying honeybees to bursts of compressed air—a flight perturbation that would be extreme in a natural setting—the authors measured bees suddenly rolling 90° about their roll axis (the bee body axis with the smallest moment of inertia) at an average angular velocity of 2031° s⁻¹ before they begin to arrest their rotation roughly 20 ms after the onset of the perturbation [19]. In both of these cases, the reported insect body rotation rates are higher than most of the RoboBee mean yaw rates that we measured in the flexible wing group, but close to the median yaw rate in the stiff wing group.

What can the biological performance benchmarks above tell us about the potential significance of collapsible wingtips for flight control? If RoboBee were equipped with a flight controller that matched that of honeybees, for example, it is reasonable to assume that sudden body rotations resulting from collisions of flexible wings could relatively easily be handled by the flight control system, while the more extreme body rotation rates resulting from stiff wing collisions—particularly collisions that occur early in the stroke cycle—would have unknown consequences because they exceed the highest measured body rotations induced by an experimental flight perturbation. This lends support to the idea that collapsible wingtips may indeed represent a biomechanical adaptation for simplifying flight control in some insects, though it does not exclude the possibility that selective pressures related to wing wear mitigation have also played a role in the evolution of this particular morphological feature.

In reality, however, flying insects display flight control abilities that greatly outperform current technologies, and it is much more likely that RoboBee’s flight control system will not actually rival those of insects for quite some time. Thus, viewed from the engineering perspective, incorporating bioinspired collapsible wingtips into emerging MAV platforms like RoboBee may well facilitate their development and deployment. By dampening unpredictable body perturbations caused by wing collisions, collapsible wingtips are likely to relax the strict performance requirements of a flight control system that is capable of supporting controlled flight in cluttered environments, and enable the use of somewhat less sophisticated sensory and control systems with higher latencies.

In this study, we introduce a scalable flexure hinge design that reversibly transitions from stiff to compliant when the applied load exceeds a certain threshold. Just like the wasp costal break, our bioinspired buckle hinge remained mostly rigid throughout the wing stroke cycle, enabling the entire wing surface to efficiently transmit aerodynamic force, but collapsed readily upon impact with an obstacle, allowing the wingtip to deflect out of the way. Although we did not test the effect of our hinge on wing damage, we speculate that it would also help increase wing longevity in MAVs by decreasing wear and tear caused by repeated collisions, just as the costal break mitigates wing wear in wasps [3].

We were unable to identify a generalized quantitative model that would allow us to predict hinge flexion dynamics based on hinge geometry, TPE material properties, wing dimensions and kinematics. Even more powerful would be a model that enabled us to predict RoboBee yaw dynamics resulting from collision of a wing with an integrated buckle hinge. Such a model would require detailed knowledge about the characteristics of the actuator and the conditions at the time of the collision, however, and the speed at which the buckling event happens (extremely fast) would likely introduce hysteresis, an additional complexity. We pursued an experimental approach as an alternative to more rigorous analytical methods such as these.

Strain weakening flexures have the potential to transform the next generation of collision-prone MAVs and other robotic devices. In a recent study similar to this one, Mintchev et al. [21] introduced a compliant origami flexure that was also inspired by the wasp costal break. In their case, they constructed a dual-stiffness flexure using a prestretched elastomeric membrane sandwiched between rigid tiles to mimic the behaviour of the costal break. They demonstrated the utility of their origami structures by embedding them into both a gripper that can be used for rigid grasping but will soften to avoid overloading the object, and the arms of a pocket-sized quadcopter that could withstand aerodynamic forces within the flight envelope but soften during collisions to prevent permanent damage [21]. In a general sense, their motivation and outcome were similar to ours in terms of using bioinspired technology to improve the design of collision-prone aerial vehicles. However, it is also interesting to note how their approach with a pocket-sized quadcopter differed from our approach with a micro-scale flapping robot: they used a different construction technique and embedded their flexures into the quadcopter frame rather than its aerofoils. These differences raise salient questions about whether the design and optimal placement of such mechanical devices is size-scale dependent. The answers to these questions will inform both biologists who seek to understand the evolution of wing morphology in flying insects, and engineers who wish to incorporate bioinspired nonlinear flexures into various robotic devices.

Data accessibility. RoboBee kinematic data for wing collision trials: OSF doi:10.17605/OSF.IO/ZSRCM.

Authors’ contributions. A.M.M. conceived and designed the experiment, collected and analysed the data, and drafted the manuscript; E.F.H. participated in the experimental design and data collection for the collision trials; R.J.W. helped analyse and interpret the data. All authors revised the paper critically for important intellectual content, gave final approval of the manuscript for publication, and acknowledge joint accountability for its content.

Competing interests. We declare we have no competing interests.

Funding. This study was funded by National Science Foundation (CCF-0926148).
References