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Aaron G. Norris

Anthony N. Palazotto
Air Force Institute of Technology

Richard G. Cobb
Air Force Institute of Technology

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Experimental Structural Dynamic Characterization of the Hawkmoth (*Manduca Sexta*) Forewing

Aaron G. Norris[1], Anthony N. Palazotto[2] and Richard G. Cobb[3]
[1]Air Force Research Laboratory, Munitions Directorate
[2]Distinguished Professor, Air Force Institute of Technology, Department of Aeronautics and Astronautics
[3]Associate Professor, Air Force Institute of Technology, Department of Aeronautics and Astronautics

ABSTRACT

While many bio-inspired flapping wing micro air vehicle wing designs continue to be conceived and studied in earnest, a general consensus of which physical attributes of the biological entity are important for flight is still at-large. It is proposed herein that the eigenstructure of the wing should figure prominently among rigorous engineering metrics for guiding flapping wing micro air vehicle wing designs at the scales of large insects. With virtually no compelling work done in this area to date, the method and results of system identification tests for the forewings of a representative sample of hawkmoth (*Manduca Sexta*) are presented, revealing the underlying structural nature of this incredibly agile flyer's wings. Despite their inherent biological variability, these wings show very little variability in eigenstructure which may suggest it as a critical attribute for robust flight. Further supporting this hypothesis, the wings of four other insect species are briefly examined and show remarkable similarity with the hawkmoth wing's eigenstructure.

1. INTRODUCTION

While the lure of the micro air vehicle (MAV) stems from its promise of operational capabilities that have been well documented [1,2,3,4], the attraction of the MAV within the research community is at least partly attributable to its low cost of entry into its field of study. Indeed, the large and expensive R&D infrastructure associated with larger scale and conventional aircraft development can be reduced to small indoor flight arenas, bench top engineering equipment and instrumentation, as well as the vast and affordable computing space offered by desktop computers, as illustrated in [5]. Arguably, it has been this ease of entry that has enabled the worldwide explosion in MAV related research over the past 10-15 years [6]. As a review of literature will reveal, from the first coining of "MAV" by Francis and McMichael [1], the locus of MAV related flight research quickly migrated toward bio-inspired wing designs and almost exclusively to flapping wing designs for hummingbird-size and smaller variants to include larger species of flying insect. While there are physical and operational arguments to reject more conventional fixed or rotary wing designs at MAV scales, perhaps the most compelling reason for partiality toward flapping wings is the perception that conceiving a design capable of rivaling the elegance of the solution that nature has already provided for flight at small scales is unlikely. Though this is intuitively compelling, bio-inspired design is not without fault.

This paper briefly presents a case for tempering MAV flight researchers' zeal for bio-inspired wing design with a consideration of those features of natural design that may be important, if not required, for successful flapping flight, especially at large insect scales. This consideration naturally leads to an argument for why the eigenstructure of the insect wing, having neither skeletal nor musculature features, should figure prominently among MAV wing design parameters. Following this discussion, the methodology and results of system identification tests that reveal the eigenstructure of a sample population of hawkmoth (*Manduca Sexta*) wings is presented and discussed. Unless otherwise noted, the scale of MAVs hereafter is constrained to the definition first put forth by Francis and McMichael [1], loosely stated here, as weighing no more than 100 grams with no dimension exceeding 6 inches. In effect, the discussion is primarily focused toward the scale of large flying insects.

2. "MIMIC-WORTHY" TRAITS

Just as early attempts of human flight looked to animals for inspiration, so too are the early attempts of developing flying machines at hummingbird and insect scales. But students of human flight history are keenly aware that its path is littered with cautionary tales of failed attempts that sought no more than to mimic the mechanics and form of animal flight in order to leap skyward. The reader is invited to perform a simple internet search (keyphrase: "early flight movies") for vintage film footage of a handful of these early attempts. While arguably humorous to watch or study, many early attempts at human flight were made by pioneers that learned the difficult and often tragic lessons of trying to blindly mimic nature's flyers. As is often the case with having the luxury of hindsight, not to mention the benefit of more than a century of scientific discovery and achievement, it is easy to look back and see the fallacy of these early flight researchers.

As early flight pioneers can attest, in all research and design endeavors when existing or previous designs - whether engineered or natural/biological - are considered as a basis of inheritance or inspiration, the intent of any feature of the original should be known and thoroughly understood. While undoubtedly there is much that can and arguably should be learned and leveraged from the hundreds of millions of years of design trade studies in the laboratory of nature, due caution is warranted. In considering nature's designs, determining *intent* is not as simple as consulting the original designer, engineering drawings, or design pedigree. In fact, in most, or arguably all, cases of animal morphology, *intent* is not known or is at best a reasoned hypothesis with "proof" subject to an incomplete fossil record. To complicate matters further, nature often confounds by shrouding *intent* in apparent complexity.

As any undergraduate biology textbook will attest, animal morphology is a product of *competing* demands for *survival of the species*. According to Darwin's generally accepted theory, an animal's form is the result of a *natural* process that *selects* for individual traits - whether behavioral or physical - among a field of other traits that *collectively* tend toward enhancement of the overall *fitness of the species*. His theory does not guarantee optimization of any single trait toward a specific function. To the contrary, Darwin's theory would more likely argue against optimization of any single trait when viewed among a sea of competing fitness demands. So, while many engineers may intuitively argue the flight efficiency of nature's fliers and therefore take comfort in their bio-inspired designs, biologists will counter that the natural flier is not necessarily an efficient design from the point of view of flight alone. In fact, the design could be quite far from optimal.

As one simple but appropriate example, consider the wing of a moth. It's certainly hard to argue against the *intent* of the wing as an appendage for locomotion. But to blindly mimic any or every feature of the moth's wing carries the potential of inheriting artifacts that may adversely, or at least non-optimally, affect flight. The competing demands of thermal regulation, ornamentation for attracting mates, or camouflaging from predators, to name only a few other wing functions [7], may sub optimize the wing's design away from the exclusive function of flight. Admittedly, because of the enormous energy demands of flight, the morphology of any animal must be quite tuned for its given set of competing traits [8]. That is to say, that a given animal is probably as good a flyer as it can be given the constraints placed on its collective morphology by other competing fitness demands. But this does not imply an efficient design for flight - just an efficient design for overall fitness.

So, if bio-inspired MAV wing design was to have a disclaimer, and maybe it should, it would read something like "*hidden traits – designers beware*". An obvious question is how does one know what traits are the important ones to inherit or mimic? Unfortunately that's a question easier posed than answered. The trivial answer is simply to *not* mimic any attribute whose function is not understood. Of course, that is neither particularly satisfying nor instructive since the function of any particular wing attribute can be speculative at best, or worse, not understood at all. Returning to the wing of a moth for a moment, consider the possible function of the tiny hairs found on their wings. Some biologists think that they serve, at least in part, to attenuate bat sonar thereby making them more invisible to bats [9]. One exchange with a practicing biologist also suggested that they might well serve as an escape mechanism from the webs of spiders or as irritating agents for would-be predators. Aerodynamicists undoubtedly may propose that they serve some aerodynamic benefit by adding drag-reducing surface roughness. Maybe their primary intent was to serve as an insulating mechanism to aid in thermal regulation? Unfortunately, nobody can know with certainty and to some degree each hypothesis may hold some merit. But the degree to which any plays in the overall fitness of the species – to include flight – is likely unknowable. So this puts the MAV flight researcher in a bit of a quagmire. On the one hand they should strive to avoid traits that aren't fully understood but on the other hand there appears to be no way to do that when the function of any particular attribute is either entirely unknown, fuzzy at best, or coupled with one or more other attributes, the extent which is likely unknown. The following discussion proposes a plausible way forward.

2.1 Consider Universal Attributes

In terms of insect wings, features such as size, ornamentation, and planform are nearly as varied as the species themselves. While some flying insects have two wings others have four. Some wings are covered in scales or hairs - or "butter" as the layperson may say - while others have none. Some have complex networks of "veins" that are seemingly too many to count while others have just a few. And to go one step beyond, wing flapping kinematics are arguably all over the map, not only across but even within species. With all of this variability that just scratches at the surface, how does one make any sense about which wing attributes are relevant or even required for flight? Alarmingly, uncertainty of the answer to this question has not slowed the pace of research. The reader is encouraged to review the volumes of MAV-related literature and see for themselves the abundance of bio-inspired designs that have been established as departure points for study. More alarmingly, the pace of study is only increasing as the computational tools of the aerodynamics trade have advanced so far that turning out one solution after another has become almost trivial. But without being able to justify the features of the design used for study - whether planform, vein patterns (venation), number of wings, wing beat kinematic, etc. - how is this path any different than that traversed by early flight pioneers who sought no more than to mimic nature? If the stakes for the MAV flight researcher were life or limb, how many casualties would have already been suffered?

In fairness, a great many researchers, a number of them biologists and animal physiologists with particular affinities toward aerodynamics, have elucidated the nature of flapping wing flight, and in particular the flight of insects. The exhaustive works of Ellington [10,11,12,13,14,15] stand out amongst many other noteworthy researchers. Even more recently, Dickinson [16] and Dickson [17] together have arguably gone further than any other to broaden the understanding of flapping wing flight. While their work and that of many others have made giant strides toward a deeper understanding of insect wing kinematics and the ensuing aerodynamic mechanisms of delayed stall, wake capture, and rotational circulation, those strides have been made without specific attention to which attributes of the wing structure make the intricate aeroelastic "dance" of insect flight possible. Some recent research suggests that wing flexibility, a hallmark of insect wings and in particular larger species of flying insect, is likely an important attribute for flapping flight [18,19]. Robustness and efficiency may very well demand it. But with wing flexibility covering the waterfront, from the more rigid paddle-like wing structures of small flies, to the moderately flexible wings of dragonflies, to the more supple and compliant wings of moths and butterflies, the nature and magnitude of what constitutes beneficial flexibility is still at-large. So, again the question is asked of what attributes of the insect's wing are important, if not required for flapping insect flight?

The answer offered here is admittedly simple. *Focus only on what is universal to flying insects*. With all of their variability and diversity, it turns out that the only *truly common* attribute across them is that they all achieve aerial locomotion through a *set of structures* (wings) that they articulate through some sort of *dynamic excitation* (flapping) originating at their root/base (basal excitation). Furthermore, these wing structures are all common in that they all lack muscular and skeletal features. Unlike birds and bats that are equipped with these systems, allowing them to actively control wing shape through muscular flexure and actuation of joints, insect wings effectively *respond passively* to forcing. Considering the insect wing through this *universal* lens naturally leads to a structural dynamic feature worthy of more attention.

2.2 Eigenstructure

A review of basic vibration theory [20] will confirm that any *passive structure* that is *dynamically excited*, whether through direct forcing (e.g. basal excitation) or indirect forcing (e.g. resulting aerodynamic loading) will respond in a manner that relates back to its *eigenstructure*. So, along with its rigid body wing kinematics originating from its base, the wing will *act on* and *react to* the surrounding air according to its eigenstructure. Therefore, the eigenstructure of the insect wing must be indelibly intertwined with the wing's aerodynamic response and hence directly with the overall flight worthiness of the insect wing design.

Recall that eigenstructure, or a system's natural frequencies and corresponding modeshapes (i.e. it's System Identification), is *independent of applied loading*, being completely determined by the system's mass and stiffness distributions; functions in continuous form or matrices in discrete form. They are a property or identifying feature of the system. The eigenstructure can therefore be thought of as a sort of "fingerprint" of the system, or more appropriately for the current discussion of insect wings, a "wingprint". Because of the insect wing's extreme complexity, diversity, and variation even within the same family of insect, continuous functional forms or discrete matrix representations of an actual insect wing's mass and stiffness arrays would prove both troublesome and elusive. But system identification offers a quantifiable way of "measuring" the mass and stiffness matrices without necessarily knowing their element-by-element compositions. Much as the concepts of linear algebra enable a conceptual view of n-dimensional space, system identification enables one to measure the resultant structure of the mass and stiffness distributions of the wing taken together. The reader is encouraged to consult [21] or any of the numerous available texts that develop the theory and application of system identification in detail.

With their eigenstructure revealed, comparative metrics between the wings of different species of insect can begin to be made. Examination of underlying eigenstructure may reveal commonalities shared across orders, families, and species of flying insect, potentially identifying features that may be either required or desirable for flapping flight or envelopes of flight such as hovering. With modern aeroelastic computer codes, structural models that isolate or extract modes from the overall eigenstructure of the wing can be developed and analyzed for a variety of basal excitations in order to understand how specific modes participate in the overall aerodynamic response of the wing. Is it possible that one particular structural mode or a unique coupling between multiple modes could provide the mechanism for passive wing response that aids in the development and control of a flapping wing's leading edge vortex critical for the aerodynamic mechanism of delayed stall? Answers to questions like this could help to form a foundation of understating necessary for eventually "designing out" sub-optimal or even degenerate structural features that may be present in biological entities, or could begin to pave the way for formulating a basis of design rules/metrics of how to exploit flexibility in flapping wing designs.

2.3 Previous Work

The first step to paving this road is to begin with revealing the eigenstructure of insect wings. That road, so far, has been virtually untraveled with no compelling work to be cited prior to the authors'. Only two previous and praiseworthy attempts at revealing the modes and modeshapes of an insect wing were made by two independent researchers [22,23]; both on dragonfly wings. Each missed, or at least failed to communicate, the potential significance that eigenstructure may play in insect wing design and flight. And each was fairly limited in providing highly resolved estimates of modeshapes due to limitations of their experimental apparatus, especially when compared to the state-of-the-art in laser vibrometry. Nonetheless, it was largely their work that inspired this research. The research presented hereafter is inspired toward motivating others to begin the process of uncovering and broadening an understanding of the underlying eigenstructure of insect wings.

3. EXPERIMENTAL METHODOLOGY

3.1 Why the Hawkmoth?

As the title suggests, the experimental specimens of this research were hawkmoth wings. The reader may legitimately inquire why the hawkmoth was selected. In truth, any flying insect would have done. Pragmatically though, the hawkmoth's size alone made it both a convenient and attractive subject for MAV study. As Figure 1 illustrates, even with readily available consumer technology, useful payloads could be reasonably integrated onto a MAV at the scale of a hawkmoth. The same could not be said for insects at the scale of the fruit fly, whose relative size can also be seen (barely) on the head of the dime in Figure 1. Of course there are many other species of insect with similar scale to the hawkmoth. In fact, if the choice were based on size and performance (and beauty), then the dragonfly, widely accepted as the king of the flying insects for its aerial maneuverability, would likely top the list. But the life cycle of the dragonfly, potentially up to 5 years long from egg to nymph and then adult, make using it as a controlled subject difficult, particularly when there are no known captive colonies in the US. On the other hand, butterflies and moths are readily available as most major universities with biology or entomology departments maintain active colonies. What's more, a large variety of butterfly and moth pupae may even be purchased from online vendors and shipped to most addresses in the US.

A drawback of butterflies and moths is that they are, in general, considered to be clumsy fliers, so turning to them for design inspiration may carry with it some scrutiny. The hawkmoth is an exception to this rule. It is an incredibly agile flier, having the ability to perform a variety of aerial maneuvers including hovering, backward, and inverted flight. In fact, when seen flying toward dusk hours it is frequently confused with a hummingbird. From a performance perspective, any MAV researcher should be happy to call this "bug" their biological inspiration. What's more, the Daniel's Lab at the University of Washington confirms that hawkmoths are capable of sustained and controlled flight with their hind wings removed, making the forewing alone a flight worthy design and thereby eliminating the complexities associated with structural and/or fluidic interactions of tandem or overlapping wings. Furthermore, its relatively short 2 to 3 month lifecycle from egg, to larvae, to pupae, and then adult, makes it an ideal candidate for study. Finally, in the words of a behavioral biologist, the hawkmoth is the "white lab rat" of the insect world making it the subject of a wealth of other research and a "comfort specimen" among scholars.

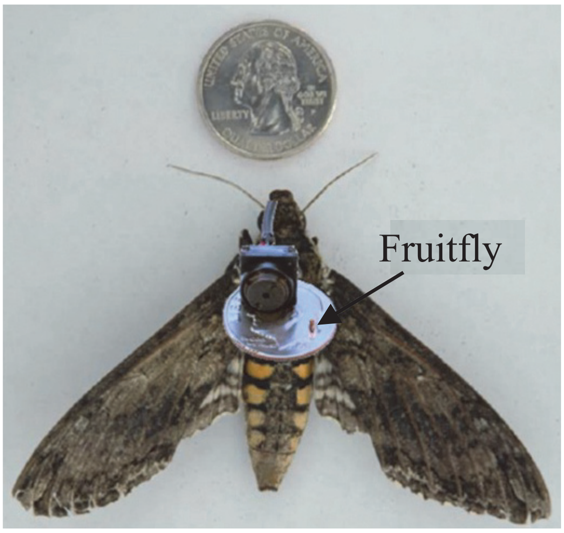

Figure 1. Top view of the hawkmoth (*Manduca Sexta*) specimen as compared with as US quarter, noting its relative size to the fruit fly and a small commercially available 1-megapixel digital video camera.

3.2 Selection and Handling

The hawkmoths used in this research were female members of a captive colony maintained at the Willis Lab at Case Western Reserve University in Cleveland, Ohio. Technicians hand-picked each pupae specimen for gender and shipped them, usually 5-10 at a time, overnight to the Air Force Institute of Technology in Dayton, Ohio. Only females were selected to avoid any potential added variability due to a gender bias. The pupae were typically received 3 to 10 days prior to eclosing, or "hatching" from their "cocoon" to use laymen terms. Once received, the pupae were immediately transferred to an emergence chamber where they were kept at room temperature conditions from 70°F to 75°F and on a natural light-dark cycle by keeping them in a room with an external window. Failure to keep them on a natural light-dark cycle would result in their failure to eclose and an eventual demise. The emergence chamber amounted to a small cardboard box lined with paper towels and covered with a screened top. The moths emerged from their pupae with very moist and crumpled wings. Within minutes of emergence, they climbed up the paper towel-lined vertical walls of the chamber and hung upside down from the screened top where they inflated their wings with hemolymph (insect blood) and air, allowing their wings to dry in a fully expanded state. If the moths failed to make the vertical trek in a timely fashion their wings would dry in a crumpled state and render them useless for both flight and testing purposes

Recently emerged moths with fully dried and expressed wings were marked on their abdomen with a small dot of colored paint to identify "birth date" which was then recorded on an electronic data sheet. Twelve to twenty-four hours later they were transferred to a terrarium where they were typically housed until commencing system identification testing 5 to 7 days later, consistent with the typical timeline when the Willis Lab normally performed behavioral flight tests. To keep the moths from damaging their wings against the boundaries of the enclosure, the terrarium was place in a room on a full light cycle to keep them from flying. Since the hawkmoth is nocturnal, it only flies when the ambient light is dimmed or dark. Preventing flight was the best measure from keeping their wings in a pristine state and avoiding the added variability of an unknown quantity of wing fatigue. The moths were initially provided a source of nourishment through a sugar water receptacle placed in the enclosure. However, after prolonged observation indicated they were not consuming, the source was removed. Water was kept in the enclosure in a screened plastic container that helped to maintain humidity in the enclosure and to offer a hydration source, although the moths were never observed to drink.

3.3 Wing Specimen Preparation

Of course the experimental specimens were not the hawkmoths themselves, but their wings. In order to liberate their wings in a humane fashion, the moths were placed by hand into a sealed plastic bag and then into a small freezer where they were cooled for 15 to 20 minutes and then removed in an anesthetized state. The full mass of the moth was then measured by placing it on a highly sensitive scientific scale capable of measuring to one ten thousandth of a gram. The forewing was then detached from the thorax of the moth using small surgical scissors and a teasing needle. Careful attention was made to clip the wing as close to the moth's thorax as possible and as consistent as possible between wings and moths. The forewing was then weighed and its mass recorded, along with liberation time and total refrigeration time. The moth was then put back in the refrigerator with only one of the forewings removed. Only the forewing was liberated and subsequently tested. Once the system identification testing was complete for the liberated wing (procedure described later) the wing's mass was measured once more so that the mass loss during testing due to handling and moisture loss could be recorded. The host moth was then taken back out of the refrigerator and the same process repeated for its other forewing (excluding measuring total bug mass).

3.4 Testing Apparatus

3.4.1 Scanning Laser Vibrometer

The lightweight nature of insect wings demands that a non-contact system identification technique be employed. As such, Polytec's PSV-400-3D scanning laser vibrometer was utilized to extract the natural frequencies and corresponding modeshapes from specimens of hawkmoth forewing. The specific details of the system and the methodology it employs to perform system identification are outside the scope of this paper but can be referred to by visiting the Polytec website (www.polytec.com). The basic experimental arrangement used in this research is shown in Figure 2 and is comprised of a shaker head (A) that excites the wing's vibrational modes, a reference laser vibrometer (B) to measure the actual velocity output of the shaker head, a scanning laser vibrometer (C) that measures the velocity response of the wing at predefined locations on the wing called scan points, and a control unit (D) composed of velocity decoders and a waveform generator that enable setting operating parameters for the vibrometers as well as the excitation signal waveforms for the shaker head. Polytec's interface computer (E) and accompanying software was an integral part of the setup and served as the primary user interface for interacting with each hardware component, defining test parameters, triggering test execution, and visualizing results.

3.4.2 Vacuum Chamber

Because of their lightweight and delicate nature, it was surmised that the affects of an *added air mass* could have a pronounced effect on the wing's structural dynamic character compared to more massive and stiff structures where the affect can most often be ignored. Of course, this added mass also complicates the ability to anchor future structural models, so it would be nice to dispense with it altogether. In order to do so, a custom vacuum chamber (Figure 3) was designed and built so that the system identification testing could be performed in vacuum. This 24-inch cubical chamber was made of stainless steel and incorporated large optical quality acrylic panes that were over 2-inches thick, designed to deflect no more than 0.003 inches at their centers. Only the shaker head with wing attached

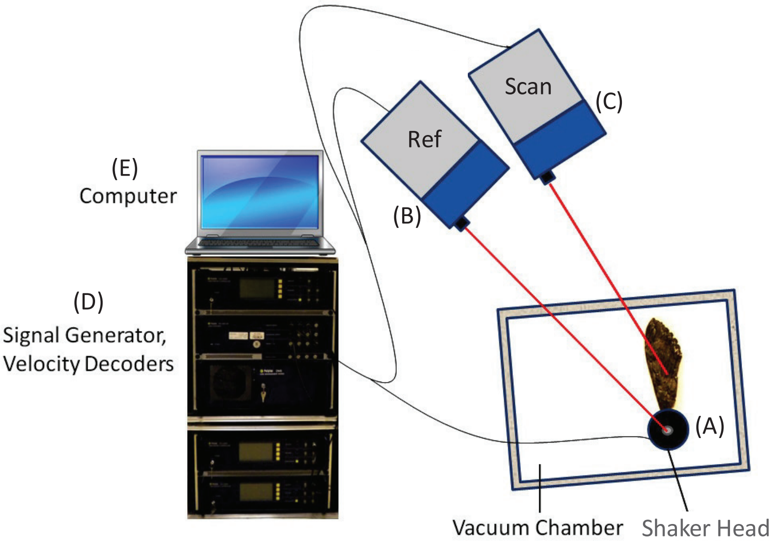

Figure 2. Schematic of the experimental apparatus and arrangement.

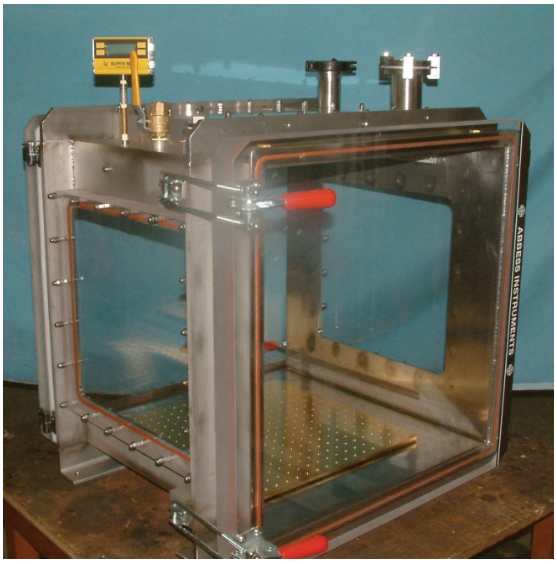

Figure 3. Custom stainless steel vacuum chamber with 24-inch optical quality acrylic viewing panes.

was placed within the chamber during testing. Preliminary tests confirmed that the acrylic pane of the vacuum chamber *did not* contribute to any shift in system identification results, provided the lasers were aligned so that they passed through the pane at oblique angles. If the laser was positioned perpendicular, or nearly perpendicular to the pane then the response of the acrylic pane (negligible for the relatively small forcing used) was measured and not the wing. This effect was readily apparent and easily corrected for by slightly angling the laser heads. The vacuum pump and plumbing fixtures were purchased off the shelf and are not shown here only in the interest of space. The pump was capable of drawing down the chamber to less than 1 Torr in less than 10 minutes.

3.4.3 Clamping Assembly and Shaker Head

A custom made clamp assembly was used to attach the wing to the shaker head. The clamp was functionally composed of two rigid plates, each with a layer of 1/8th inch hobby foam affixed to one side. As illustrated in Figure 4 B-C, the sides with foam faced each other and served to sandwich the root of the wing when the plates were drawn together with a small securing bolt and locknut. The same

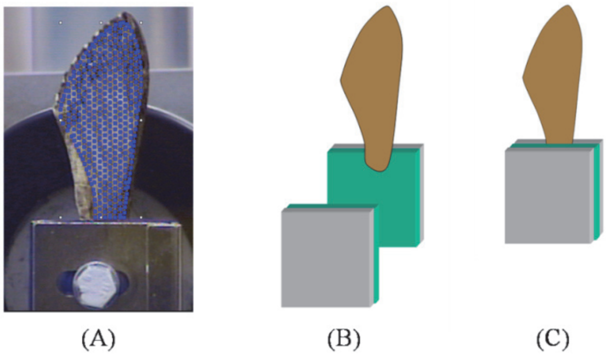

Figure 4. Shown is (A) a typical measurement grid and schematics of (B) an exploded and (C) clamped view of the wing clamping assembly.

bolt secured the clamp to a threaded hole on the shaker head. For illustration purposes, the 1/8th inch (at most) of the wing that was actually clamped in testing is grossly exaggerated in Figure 4B. This "sandwiching" technique ensured a snug fit of the wing, approximating a clamped boundary condition. Early trial tests revealed that using rigid plates without cushioning foam damaged the veins at the wing root and also induced deformation throughout the wing by forcing the veins at the root to unnaturally lie in a plane, effectively "squeezing" the natural camber out of the wing root. Incidentally, gluing the wing's root to the shaker head or clamp would induce the same phenomenon and was therefore abandoned as an option.

4. SYSTEM IDENTIFICATION

4.1 Testing Procedure

Immediately following wing liberation as described previously, the wing was mounted into the shaker through use of the clamp assembly. Well before wing liberation, the laser vibrometer system was setup and cued, so that once the wing was mounted into the clamp and shaker head, testing commenced almost immediately. It took only a few minutes to interactively create a grid of approximately 250 measurement (scan) points mapped to the wing's surface (Figure 4A), fine tune the system's operating parameters that yielded the highest possible signal-to-noise ratio (i.e. optimize coherence) and take a photo of the wing used to record dimensional detail. A small ruler was placed in the scene in order to calibrate the image. With these steps complete, the Polytec system was manually triggered and its software orchestrated the collection of frequency response data at each scan point defined in the measurement grid. Typical scans of a single wing took place in less than 15 minutes. Therefore, the time from wing liberation to completion of system identification testing was normally completed in less than 30 minutes for every wing in the study. In all, 42 individual hawkmoth forewings were tested in this way.

After the first 42 wing specimens were tested for system identification in air, a good sense of the eigenstructure in air was in-hand. Only 12 remaining wings were tested for system identification in both air *and* vacuum. This was primarily due to the availability of vacuum equipment and not by design. All vacuum tests were conducted in air first and then vacuum. No change in the setup of the apparatus was required between testing in air and vacuum. The wing was clamped in place to the shaker head and then placed in the vacuum chamber. The acrylic door was closed and testing commenced in ambient conditions first. Once complete, the chamber's pressure was drawn down to vacuum and system identification testing was repeated. There was some concern initially that subjecting the wings to vacuum may impart damage or introduce a drying or brittling effect on the wing, thereby making it difficult or impossible to associate any shift in structural dynamic properties to a true added mass effect. To address this concern, system identification tests were performed in air, immediately before and after the vacuum testing, for the first 3 of 12 wings tested in both air and vacuum. No apparent difference was noted between pre-vacuum and post-vacuum system identification results and so it was concluded that the vacuum did not introduce any deleterious effect on the wing's structure. All system identification tests performed in vacuum were initiated at pressures of approximately 1 Torr with the vacuum pump turned off. Because pressure was not actively controlled, and since all vacuum chambers have a finite leak rate, the pressure at the end of each test varied between 2-3 Torr.

For all system identification testing, a pseudo random waveform was provided to the shaker head, subjecting the wing to broadband transverse base excitation from 0 to 800 Hz. Since a hawkmoth's maximum wingbeat frequency is near 40 Hz (during hover), it is unlikely that modes over 400 Hz, or approximately 10 times the max wingbeat frequency, participate substantially in the wing's forced response. Nonetheless, frequency response in excess of 20 times the maximum wing beat frequency of a hawkmoth was considered. The custom wing clamp assembly was independently tested for system identification to ensure its response did not feed into the response of the wing. Its lowest natural frequency was near 1000 Hz, so 800 Hz was a suitable cutoff frequency to avoid any possibility of introducing extraneous forcing from possible clamp dynamics. A sampling rate was selected to achieve a frequency resolution of 1 Hz, thereby minimizing the chance of "stepping over" any closely spaced modes.

4.2 Post Processing

Strictly speaking, the Polytec system returns the *operating deflection shape* (ODS) of the wing at a given frequency. To ensure that only modeshapes were extracted from the data, the frequency response data from the Polytec system was exported and analyzed in Vibrant Technology's *MEScope* software analysis package. Among other functions, this software employs modal curve fitting techniques whereby the frequency response function (FRF) of all measurement points are fitted with a series of orthogonal basis functions so that the requirement of orthogonality between modes, as established by the expansion theorem [20], is satisfied. An example FRF overlay plot is shown in Figure 5. This particular plot is that of a small butterfly forewing tested in vacuum and is discussed later in the paper. The top half of the plot shows the FRFs (magnitude vs. frequency) for each of the scan points in the measurement grid. The bottom half of the plot shows a modal peaks function (log magnitude vs. frequency) which amounts to an "average" FRF over the entire wing and assists in more precisely locating modes. Once a possible mode was identified its corresponding modeshape was then animated and plotted. The process of testing and interactive analysis with *MEScope* yielded estimates of modes, modeshapes, and damping for each wing and was completed for every sample in the wing population (n=54).

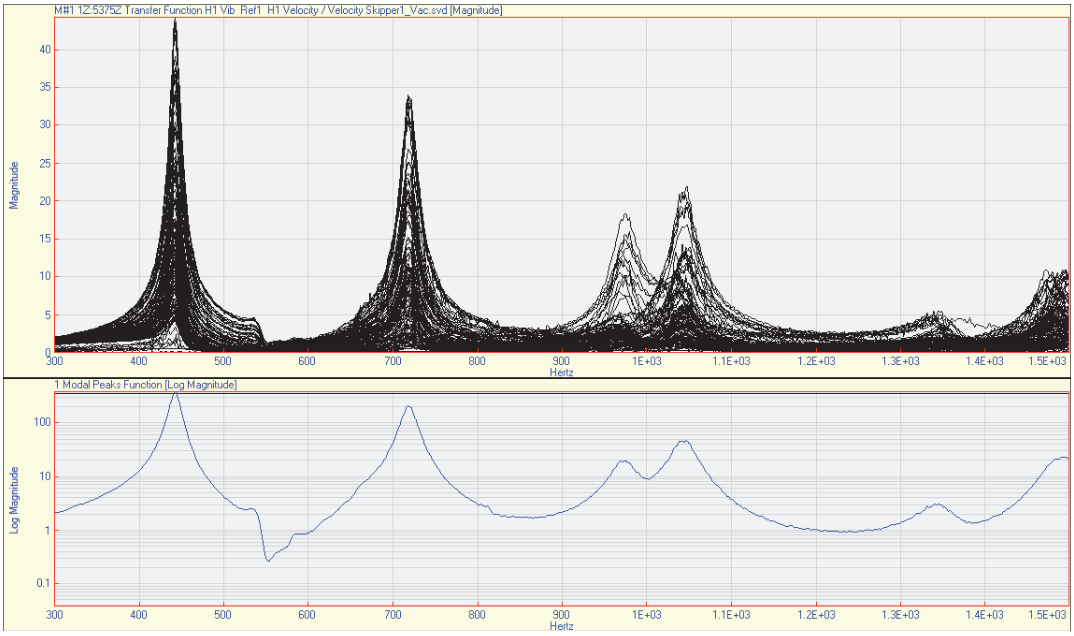

Figure 5. A typical frequency response overlay plot (top) and modal peaks function plot (bottom) output by *MEScope* used for locating the natural modes of the wing.

5. RESULTS & DISCUSSION

5.1 Modeshapes (Eigenvectors)

The first four modeshapes of the hawkmoth's forewings were revealed as a 1st spanwise bending, 1st spanwise torsion, 1st chordwise bending and 2nd chordwise bending as shown, from left to right, in Figure 6. They're coined here as the *flap, feather, saddle,* and *bisaddle* modes respectively, in order of ascending frequency (mode). The bisaddle mode was the highest consistently discernible mode to be observed and was typically found at frequencies 4-8 times higher than normal hawkmoth wingbeat frequencies of 20 to 40 Hz. Some evidence of higher order modes was noted, but appeared to be a localized phenomenon (membrane modes between adjacent veins or along the wing's trailing edge fringe) that made it difficult to distinguish from noise. The modeshapes themselves were consistent across all wings in the study, in both air and vacuum, showing virtually no differences despite the presence of implicit biological and test-to-test variation. The feather mode was least excitable for the method of transverse basal excitation employed, and was not apparent in about 20% of the wings tested. Each of these wings had slightly higher than average aspect ratios making them more slender and therefore less excitable in torsion/feather. In hindsight, forcing these wings slightly more vigorously would likely have excited their feather mode.

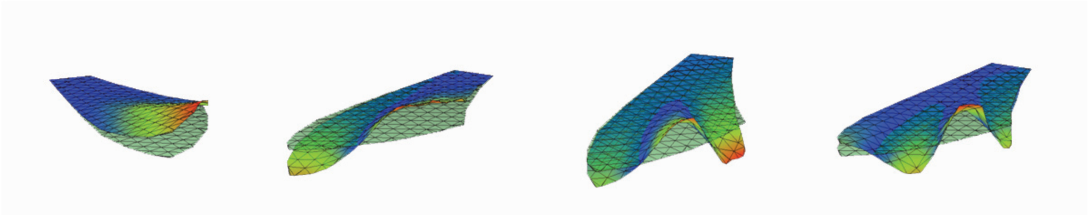

Figure 6. From left to right are the flap, feather, saddle, and bisaddle modeshapes of the hawkmoth's forewing shown with respect to an undeformed wing planform.

5.2 Modes (Eigenvalues/Natural Frequencies) and Modal Ratios

Because of variations in the sizes of wing specimens in the sample population tested, one should expect a variation in modal frequencies. For example, consider the expression for the modes of a prismatic and isotropic cantilevered beam having parameters of length, cross sectional area moment of inertia, material modulus of elasticity, and mass per unit length given respectively as L, *I*, *E*, and *m*.

$$\omega_i = C_i \sqrt{\frac{EI}{mL^4}} \tag{1}$$

It can be shown for the first three modes, $\omega_{1\text{-}3}$, that $C_{1\text{-}3}$ are 3.5160, 22.0345, and 61.6972 respectively. This expression implies, as expected, that longer beams have lower frequency modes since frequency scales by the inverse of the square root of length cubed.

However, the ratios of modes given by:

$$\frac{\omega_2}{\omega_1} = 6.267 \frac{\omega_3}{\omega_1} = 17.548 \tag{2}$$

are invariant. Indeed, all prismatic, isotropic, cantilever beams will share the ratios shown in eqn (2). Accordingly, the magnitudes of the modes of the hawkmoth's wing are likely to indicate more about the overall mass and/or dimensional aspects of the wing than of underlying structural dynamic features. But, taken with their accompanying modeshapes, the wing's modal ratios should also be distinguishing features that identify them as a hawkmoth wing. These ratios, in effect, represent the relative *dynamic* stiffness of each mode of vibration. Even though no such simple relation like eqn (1) exists for insect wings, or for any but the most basic structures for that matter, it should follow, within some expected variation, that similar structures will share similar modal ratios. Insect wings should be no exception. In fact, this is exactly what the data confirmed for hawkmoths.

Table 1. Average structural dynamic characteristics of a hawkmoth forewing. Modal ratio (MR) averages are presented as 95% confidence intervals.

			In Air			In Vacuum		
Mode	Name	Description	Freq, Hz	MR	Damp, %	Freq, Hz	MR	Damp, %
1	Flap	1st Spanwise Bending	60	1.0	5.0	85	1.0	2.5
2	Feather	1st Spanwise Torsion	84	[1.39, 1.43]	5.0	105	[1.28, 1.32]	2.5
3	Saddle	1st Chordwise Bending	107	[1.80, 1.86]	5.0	138	[1.59, 1.65]	2.5
4	Bisaddle	2nd Chordwise Bending	142	[2.38, 2.48]	5.0	170	[2.16, 2.26]	2.5

As summarized with their other structural dynamic characteristics in Table 1, the average feather-to-flap, saddle-to-flap, and bisaddle-to-flap modal ratios, in air, were approximately 1.4, 1.8, and 2.4 respectively. In vacuum the modal ratios shifted down by an average of 10% across modes, largely due to the wing's first mode being more sensitive to the added mass effect of the surrounding air than its higher modes. The modal ratios were normally distributed with 95% confidence intervals amounting to no more than approximately 2% of each of their arithmetic means, indicating these modal ratios to be tightly controlled parameters. Of course, arithmetic mean is one measure of central tendency, but perhaps a more useful metric is a "fit" of modal ratios over the range of observations. To that end Figure 7 includes linear fits (all with R^2 values greater than 0.75) of the modal ratios observed in air and vacuum. Note that the slopes of each of the straight line equations are not exactly equivalent to the modal ratios since the lines were not constrained to pass through the origin. The data indicates that the modes of

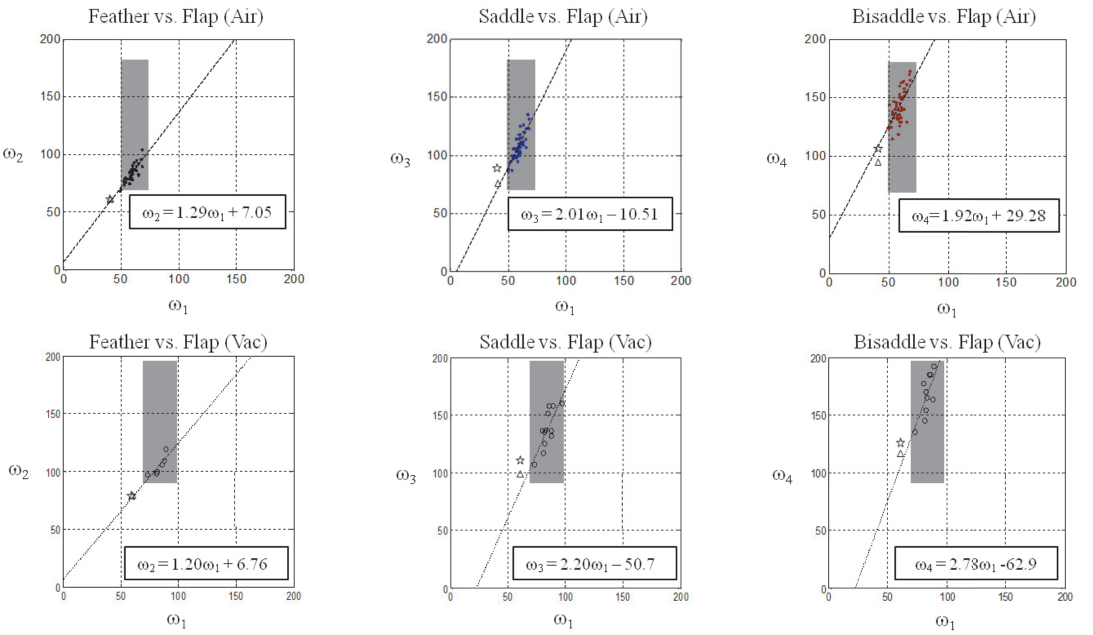

Figure 7. Bounded by the shaded regions are the hawkmoth wing's feather, saddle, and bisaddle modes plotted against its flap mode in air (top row) and vacuum (bottom row). The points outside of the shaded region correspond to butterfly specimens (see Section 5.5).

hawkmoth wings reside in a fairly narrow band of natural frequencies, as depicted by the grey shaded regions also shown in Figure 7, and when plotted against their first fundamental mode fit a linear model quite well. An increase in frequencies observed across modes between air and vacuum ranged from +42% for the flap mode, to +20% for the bisaddle mode. Clearly an added mass effect is present and is too large to be disregarded as it often can be for more massive engineered structures.

5.3 Air Damping vs. Structural Damping

Wing structural damping was also considered and estimated using the half power bandwidth method employed by *MEScope*. Damping of the wing in air was determined to be approximately 5%. Tests in vacuum revealed structural damping of 2.5%. Therefore, half of the wing's damping in air was attributable to the presence of air, and the other half to structural damping. This damping value is surprisingly consistent with many engineered structures and is often used as a typical "rule of thumb" in design and analysis when the actual damping is unknown.

5.4 Age Sensitivity Testing

Some degree of skepticism, rightfully so, concerning the quality of data was anticipated due to the inherent "shelf life" of biological entities. Indeed, the wings began to desiccate virtually from the moment they were detached from the host moth. A simple time sensitivity study of a hawkmoth's forewing was conducted in order to bound the effect of drying on eigenstructure. Using the same procedures previously described, a wing was prepped and tested for system identification in air. At the conclusion of the initial test, approximately 20 minutes after wing liberation, the wing was left undisturbed, in the clamped configuration, and subsequently tested at 1, 2, 12, 24, 36, 48 and 72 hours later. This test series was repeated for two wings to verify repeatability. The results (Figure 8) showed that dramatic changes in modes and modal ratios occurred over the first 36 hours and then stabilized. Damping also fell from 5.0% to 2.5% and then stabilized after 36 hours, indicating that half of the wing's damping is due to its moisture content. The results showed that by limiting the time between wing liberation and conclusion of system identification testing to 1 hour, no more than a 3% increase in any given frequency (mode) or modal ratio should be expected as well as no measureable change in damping. The results also indicated that modeshapes were virtually impervious to drying, indicating that wing desiccation is a fairly homogeneous process that does not disrupt the balance between mass

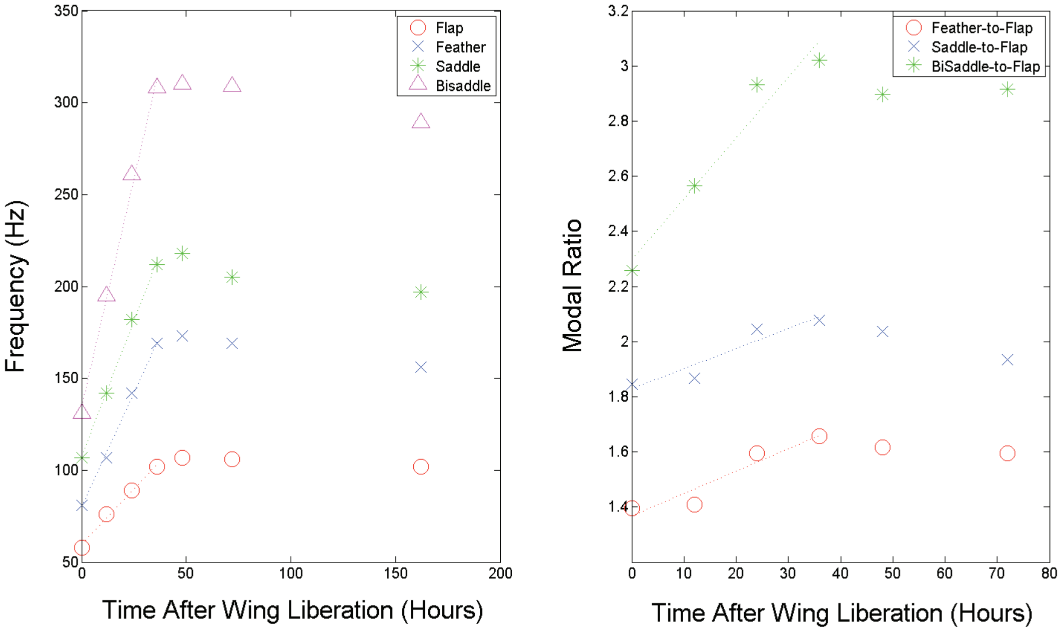

Figure 8. Results of a time sensitivity study showed that by limiting the time between wing liberation and conclusion of system identification testing (to 1 hour or less) that no more than a 3 percent increase in any frequency or modal ratio is expected.

and stiffness distribution within the wing. One implication of this finding suggests that one could legitimately perform system identification of preserved insect wings (e.g. insect collections) and glean relevant modeshapes, although the modes and modal ratios would not be indicative of "fresh" wings. For purposes of accurate and complete system identification testing, a fresh wing is one that has been removed from its host for no more than about an hour.

5.5 Other Insect Wing Testing

During a break in hawkmoth testing, pure intellectual curiosity led to performing system identification on the forewings of three butterflies. In biological terms each butterfly considered, a monarch, swallowtail, and skipper, resides in the insect order *Lepidoptera,* just as the hawkmoth does. As Figure 9 depicts, while their wings share some geometric similarity, their planforms all differ from the hawkmoth and the Skipper is even an order of magnitude smaller in scale. What make their wings even more unique are their distinct venation patterns. The monarch and swallowtail are arguably similar but differ significantly from the hawkmoth and Skipper. By virtue of their unique venation patterns alone, not to mention the differences in vein and membrane thicknesses that attribute to overall differences in wing mass, one would reasonably expect to see differences, perhaps dramatic, in the eigenstructure of their wings. The monarch and swallowtail wings (~0.02 grams) were less than half the mass of an average hawkmoth forewing (~0.04 grams) and the Skipper (~0.001 grams) was an order of magnitude lighter. Nonetheless, the results showed that the modeshapes of all of these butterflies to be virtually identical with the hawkmoth and with each other (Figure 10). Moreover, the modal ratios were found to be quite consistent with the fit of hawkmoth modes. The meticulous reader may have noticed the addition of two data points outside the lower left hand side of the gray shaded regions in Figure 7. The triangle and star represent the results for the monarch and swallowtail respectively. Not shown on the

Figure 9. Shown from left to right are hawkmoth, monarch, swallowtail, and skipper forewings with graphical overlays of venation pattern roughly to relative scale. Skipper venation is set to the far right and enlarged to show detail.

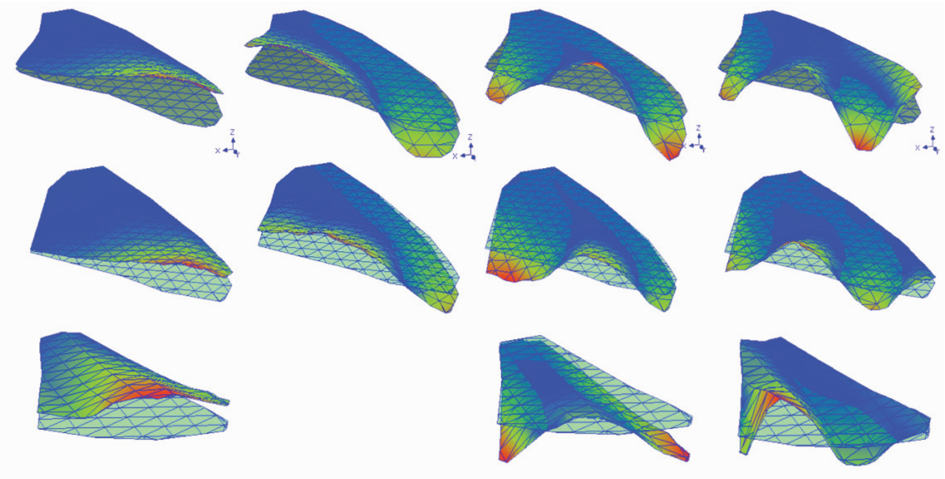

Figure 10. Shown from top to bottom are the first four modeshapes of the forewings of the monarch, swallowtail, and skipper butterflies relative to their undeformed planforms.

plots due to scaling are the Skipper forewing's flap, saddle, and bisaddle modes which were respectively 300, 539, and 774 Hz in air and 446, 720, and 1050 Hz in vacuum. Incidentally, the FRF overlay plot shown earlier in Figure 5 are the results of vacuum testing on the Skipper's wing. Inspection of this FRF suggests some likelihood that the feather mode resides at approximately 550 Hz which would fit the hawkmoth mode data (Modal Ratio) within 2%, but the modeshape could not be confirmed by the data. While not directly observed in this single sample, its feather mode likely exists but the method of transverse basal excitation, as discussed before, did not excite it as readily as the bending modes. Its observed modes in air and vacuum were within an average of 18% of the linear fit of hawkmoth mode data.

The similarities observed with these closely related insects naturally begged the question of what about more distant relatives in the larger space of flying insects? To that end, the forewings of three more insects were tested for system identification; a dragonfly, damselfly and bumble bee. Unfortunately, the data of the dragonfly and damselfly, while absolutely suggesting the presence of the characteristic modes reported above, was sufficiently noisy to preclude positive identification. Several other modes may also have been present in their wings but the frequency response data was too noisy to gleam conclusive results and therefore results are not reported here. The transparent nature of these wings allowed much of the laser's energy to pass through the wing rather than be reflected back to the vibrometer. Even with a light powder coating, coherence of the laser return was tenuous at best. The bumble bee wing on the other hand, while slightly opaque, did permit testing with just a slight powder coating of Magnaflux Spotcheck applied to it. This treatment added 0.0001 grams to the wing's overall mass, effectively adding a 10% distributed mass load, so the untreated wing's modes would be higher than those observed. This distributed load which represented only a scaling of the mass matrix leaves stiffness undisturbed, rendering the modeshapes and modal ratios of the treated wings valid representations of the untreated wings. Its feather-to-flap, saddle-to-flap, and bisaddle-to-flap modal ratios were 2.4, 4.8 and 5.8 Hz in air, and 2.3, 4.3, and 5.3 in vacuum respectively which do not compare well with the hawkmoth. However, as Figure 11 shows, the similarities of its first four modeshapes with all other insect wings tested in this study is indisputable. There is clearly an underlying commonality to all of these fliers.

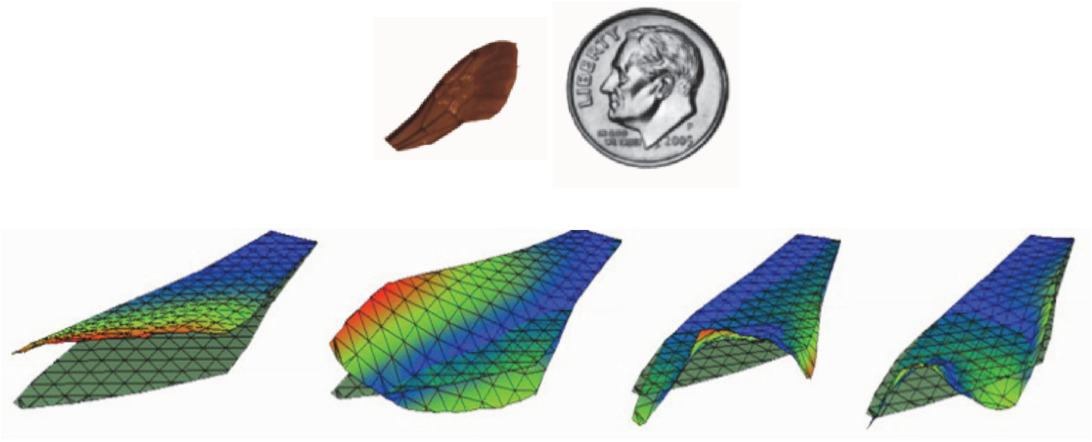

Figure 11. An image of an actual bumble bee forewing in comparison with a US dime, shown above its first four modeshapes relative to an undeformed planform.

5.6 Paper Stencil System ID - A Confidence Boost

By now the reader may be questioning, as the authors did, if there was any irregularity in test setup. After all, how could such apparently different structures share such common underlying eigenstructure? As a sanity check, system identification testing was performed on a paper stencil of a hawkmoth wing. A photocopied image of one of the hawkmoth wings used in the study was carefully cut out and then tested exactly as all other biological wings in the study. As Figure 12 indicates, other than having the spanwise bending (flap) and torsion (feather) modes that should be expected in any cantilevered structure, the paper wing bore no resemblance to the biological entity. Its feather-to-flap modal ratio of nearly 5 was dramatically different from all insect wings tested. In fact, the modeshapes of the paper wing were much more consistent with plate behavior, having no indication of saddle or bisaddle modes. A finite element analysis using plate elements confirmed with great accuracy the experimental results of the paper wing. With this corroborating evidence, a high degree of confidence in the results throughout this study is warranted and concludes a clear commonality between all insects successfully tested.

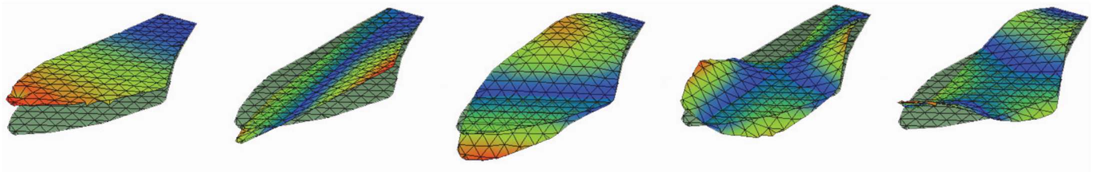

Figure 12 The first five modeshapes of a paper stencil of a hawkmoth forewing planform relative to its undeformed state.

6. CONCLUSION

The intent of this research was to develop a robust methodology for performing structural dynamic testing (system identification) on an insect wing and to present the finding for a hawkmoth forewing. To that end the research was successful. As important, or more so, return for a moment to what motivated the search for the eigenstructure in the first place. It stemmed from asking the initial question of *what is truly common among flying insects*. At that point there was truly no expectation that the eigenstructure itself might actually be that feature. The results however would appear to suggest just that. Eigenstructure appears to be a common trait, at least to the insects tested herein. And, the apparent small variability observed in the hawkmoth results alone seems to support the notion that it *may* be an important trait for flight of these agile fliers. Considering the connection between a passive structure's eigenstructure and its response to forcing, it is exceedingly hard to conceive of it not being important for the flight of flapping wing insects. Indeed it is the wing structure that responds to and acts upon the airflow so how could its underlying structural dynamic nature not be important?

There are certainly other features of insect wings, like roughness or small corrugations to name just two, not to mention the kinematics of the wing stroke that affect aerodynamics. But, to draw an admittedly imperfect analogy, the eigenstructure is to the flapping insect wing what the underlying wing structure is to the fixed-wing airfoil. It sets up the instantaneous wing shape and, along with rigid body wing kinematics and freestream conditions, the local airflow features about the wing that taken together determine aerodynamic response. Nobody would argue that seemingly negligible features of the wing (fixed or flapping) cannot produce, enhance, or degrade flow phenomenology that could have appreciable or even dominant roles on the wing's overall aerodynamic response; aerodynamic theory is clear on that. But the aircraft designer does not throw out the contribution of the airfoil to achieving desired fixed-wing aerodynamics; good designs start with the airfoil. Perhaps the eigenstructure will prove to be a starting point for small flapping wing designs of the future.

One of the major questions from the totality of the results of this study is why? Why should these very diverse creatures, having wildly different scale, planform, venation pattern, and even wingbeat frequency and kinematics be so similar in their underlying eigenstructure? Is there something about these modeshapes that have made them successful adaptations for flight? Perhaps a "golden" design rule? How many other insects share these modeshapes? Are they all required for flight or just a subset? How important are the modal ratios and what happens when they're upset? It's too early to answer any of these. Hopefully the findings and insights presented in this paper will motivate future research to consider how the eigenstructure presented herein and hopefully still to be revealed in other insects, might benefit flight and even answer some of the questions posed above in the process.

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