

updates

# Aeroelastic Characterization of Real and Artificial Monarch Butterfly Wings

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The annual migration of monarch butterflies, Danaus plexippus, from their summer breeding grounds in North America to their overwintering sites in Mexico can span over 4000 kilometers. Little is known about the aerodynamic mechanism behind this extended flight. This study is motivated by the hypothesis that their flapping wing flight is enhanced by fluid-structure interactions. The objective of this study to quantify the aeroelastic performance of monarch butterfly wings and apply those values in the creation of an artificial wing with an end goal of creating a biomimetic micro-air vehicle. A micro-CT scan, force-deflection measurements, and a finite element solver on real monarch butterfly wings were used to determine the density and elastic modulus. These structural parameters were then used to create a monarch butterfly inspired artificial wing. A solidification process was used to adhere 3D printed vein structures to a membrane. The performance of the artificial butterfly wing was tested by measuring the lift at flapping frequencies between 6.3 and 14 Hz. Our results show that the elastic modulus of a real wing is 1.8 GPa along the span and 0.20 GPa along the chord, suggesting that the butterfly wing material is highly anisotropic. Real right forewings performed optimally at approximately 10 Hz, the flapping frequency of a live monarch butterfly, with a peak force of 4 mN. The artificial wing performed optimally at approximately 8 Hz with a peak force of 5 mN.

# **I.Nomenclature**

Ε	=	Flexural modulus	[N/m <sup>2</sup> ]
EI	=	Flexural stiffness	[Nm <sup>2</sup> ]
F	=	Force	[N]
f	=	Flapping frequency	[Hz]
Ι	=	Second moment of area	[m <sup>4</sup> ]
L	=	Lift force	[N]
l	=	Active length	[m]
т	=	Mass	[kg]
R	=	Length of one forewing	[m]
t	=	Thickness	[m]

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$t^*$	=	Dimensionless time	[1]
V	=	Volume	[m <sup>3</sup> ]
W	=	Width	[m]
α	=	Feathering angle	[deg]
δ	=	Deflection	[m]
ρ	=	Density	[kg/m <sup>3</sup> ]
ζ	=	Flapping angle	[deg]

# **II.Introduction**

**S** tructurally similar to most other butterfly species in the Nymphalidae family, the monarch butterfly (*Danaus plexippus*) is one of the most recognizable butterfly species, yet they boast the longest migration flight among insects, an impressive 4000 km [1]. Although it is presumed that monarchs take advantage of the low atmospheric density at high altitudes to aid in soaring flight [2] and reduce aerodynamic drag, the detailed aerodynamic phenomena that make this three-month flight possible still elude scientists and engineers.

The mechanics behind insect flight, in part, involve unsteady lift enhancement mechanisms such as leading edge vortex generation and shedding, wake-capture, and clap and fling [1,3]. Though butterflies benefit from these unsteady aerodynamic mechanisms, their flight in general has been overlooked and understudied due to their closely coupled wing-body dynamics, and the fluid-structure interaction of their large, thin wings.

In contrast to their large wings, the monarch butterfly has a rather thin body. This produces the lowest wing loading among insects [4], and aids in their unique agility [5–8]. Monarch body undulations are closely linked to the motion of the wings [7,9], which can aid in short term pitch stability during forward flight in butterflies [10], as also shown for hawkmoths [11,12]. Furthermore, the wing-body coupling leads to a noticeable saving in power consumption in monarchs, which can further aid their long-range migration [13].

The wings are flexible structures, deforming significantly during flight. Flexible flapping wings can generate large lift forces, while reducing the amount of power necessary compared to their rigid counterparts [3,5–9,14–24]. The anisotropic nature of the wings, due in part to the combination of membrane and vein (Fig. 1), and also to one-way hinges that use resilin [25], means that the spanwise wing flexibility differs from the chordwise flexibility [10,14,26], and the dorsal flexibility differs from the ventral [4,27,28]. Additionally, the actual wing shape and wing deformation during the wing stroke play an important role in lift generation.



Fig. 1. Monarch butterfly and its right forewing structure. (a) A monarch butterfly with a wing length of *R*. (b) A right forewing. (c) Morphological labels of a monarch butterfly wing, as defined by Emmet and Heath [29]: red – veins; black – membrane spaces; green – anatomical region names.

The working hypothesis of this study is that the fluid-structure interaction between the monarch wings and the surrounding unsteady flow reduces the power consumption subject to a sufficient lift generation. The reduction in power consumption due to the coupled wing-body dynamics as well as presumed aerodynamic efficiency associated with the fluid-structure interaction of the large flexible wings may be one of the major enablers of their long-range migrations. Furthermore, these mechanisms can be utilized to develop butterfly-inspired micro-air vehicles (MAVs) that have the potential to enable long-range flight missions. However, the literature lacks detailed measurements of the flexural stiffness, wing density, and aerodynamic force generation of butterfly wings.

The goal of this paper is to quantify the aeroelastic performance of monarch butterfly wings and apply those values in the creation of an artificial wing. First, we measure the force per known deflection of monarch butterfly wings in the chordwise and spanwise directions. We use this information to modify a computer model of a wing, such that it deforms in the same way as the real wing. From this, we determine an elastic modulus of the wing, which aids in determining viable materials for the fabrication of an artificial wing. The third step is to simultaneously measure the force and deformation created by a real monarch butterfly wing using a VICON motion capture system and ATI Nano force transducer. Finally, we compare these results to those of the artificial wing also tested under the same conditions. This will provide information that supports further development of bioinspired long-range micro-air vehicles, which, in turn, supplements our knowledge of how these insects are capable of such an impressive migration.

The experimental methodology is described in Section III, covering the micro-CT scan, deflection measurements, finite element method analysis to calculate the elastic modulus used to identify the material for the artificial wing, and finally the force and wing motion measurements. Then, the results are discussed in Section IV, which includes a summary of the artificial butterfly wing fabrication process (Section IV.E), followed by the lift measurements on the real and artificial butterfly wings (Section IV.F).

### III.Methodology

#### A. Overview of the Experimental Method

The goal of this paper is to produce an artificial wing that mimics a real monarch butterfly wing in both shape, size, material properties, and lift generation. One of the first steps of this process was to digitize a real wing using a micro-CT scanner, as described in Section III.B. From this scan, we determined key morphological parameters of the wing, i.e. the volume (V), thickness of the wing (t), wing span (R), and density ( $\rho$ ).

The second step was to quantify material properties of monarch butterfly wings by measuring the force (*F*) produced by a point load applied at a measured active length (*l*) over a known deflection ( $\delta$ ). The methodology behind this measurement procedure is described in Section III.C.

Using a finite element model (FEM) based on the micro-CT scanned volumetric data of the monarch butterfly wing and the force-deflection measurements, we calculated the elastic modulus (E) of the wing along the spanwise and chordwise directions (Section III.D).

The calculated elastic modulus, *E*, guided the choice of an appropriate artificial wing material for the artificial wing fabrication. The wing vein structure was 3D printed using Polylactide (PLA), and a Poly-L-Lactide (PLLA) membrane was adhered using an organic solvent (Section IV.E).

Finally, the lift generation (L) of a real and artificial butterfly wing was measured at different frequencies (f) (Section III.E). This allowed us to compare the performance of the artificial wing directly to the performance of a real wing under the same conditions (Section IV.F). The gearbox prescribed a fixed amplitude flapping wing motion. In a monarch butterfly flight, the deviation angle changes as the wing passes through different parts of the stroke, while the feathering angle passively changes.



#### Fig. 2. Block diagram showing the key points of this study and how they were integral to the end goal.

#### B. Micro-CT and Anisotropic Characteristics of the Monarch Wing

In order to obtain a highly detailed image of a monarch butterfly wing structure, a micro-CT scan was taken of a forewing at the Small Animal Imaging Shared Facility at the University of Alabama at Birmingham. After removal from the butterfly, the forewing was soaked in a 1% iodine/ethanol solution. Prior to the scan, the wing was removed from the solution and allowed to air dry for approximately twenty minutes, then weighed. The individual forewing was placed in a MILabs U-CT micro-CT scanner (Fig. 3a,b). A micro-CT scanner exposes the sample to X-rays, which are picked up by the machine as discrete slices. These slices are output by the machine for further processing [30]. For our scan, the resulting files were processed using a voxel size of 10, which correlates to a 10 µm spatial resolution. A voxel is a three dimensional volume (pixel) that contains information about the position of the nodes of the volume and the relative density of the object within the voxel. Processing with a voxel size of 20 did not provide the necessary resolution, whereas 4 voxels produced no noticeable resolution difference. This processed data was output as a set of Neuroimaging Informatics Technology Initiative (NIfTI) files, which is a standard file output type for medical machines, more specifically imaging machines such as CT scanners and MRIs.

After the initial processing at 10 voxels, the NIfTI files were manipulated using the program 3D Slicer. To produce the 3D image of the wing from the NIfTI file stack, a Hounsfield number between -500 and -600 was chosen to filter out voxels that were not the butterfly wing. The Hounsfield unit (HU), or Hounsfield number, is a value used to quantify the density of a scanned object, by relating it to water (HU = 0) and air (HU = -1000) typically in a reconstruction of the CT slices as a greyscale image. There is a linear relationship between the two numbers, and a specimen that is denser will appear brighter in the resulting image, while a specimen with a lower density will appear dark.





Fig. 3. (a) Micro-CT scanner at the University of Alabama at Birmingham's Small Animal Imaging Facility. (b) The right forewing of a monarch butterfly positioned in the tray of the scanner.

ParaView was used to reduce the number of elements in the model, and to measure the cross section of the wing model to determine the size and thickness of both the veins and membrane. Finally, the program Meshmixer was used to determine the volume of the wing model. This volume, along with the weight of the actual wing that was recorded prior to the scan, allowed us to calculate the density of a monarch butterfly wing.

#### C. Deflection, Force, and Stiffness Measurements

To quantify spanwise and chordwise material properties of monarch butterfly wings, we measured the force produced by a point load applied at a measured active length, l, over a known deflection,  $\delta$ . Figure 4 shows a schematic of the measurement apparatus. The experimental apparatus is inspired by the pioneering study by Combes and Daniel [4]. A thin, pointed rod was attached to an ATI NANO 17 Titanium force transducer and used as the sting for the point load application. The force transducer was connected through a Data Acquisition system (DAQ) to a computer for data recording. To control the relative distance of the sample, a Wixey WR200 Digital Height Gauge with a tolerance of  $\pm 0.025$  mm, was used to measure vertical deflections. An adaptor was printed using PLA to hold the sample to the height gauge during the experiment.

Figure 1 shows the geometry and vein pattern of a typical monarch butterfly. The span of the forewing is defined by the distance, R, from the wing root to tip. Butterfly wings, as well as other insects, have anisotropic characteristics in their wings [4,10,14,25–28]. Often the wing deforms differently depending on where the force is applied on the wing, and which side of the wing it is applied on (dorsal versus ventral). This is due to the wing composition, which is not homogeneous, as well as the venation pattern, which allows the structural support of the wing to vary.

To help characterize this anisotropy, the force was always applied at a point to the ventral side of the wing, but at two different locations. We chose a point location at approximately 70% of the span length, next to the leading edge vein, to measure the deflection capabilities of the wing in the spanwise direction (Fig. 5a). In the chordwise direction, a point load was applied at approximately 70% of the maximum chord length, right next to a vein (Fig. 5b). The loads were not applied directly on the vein, as the point moved off as the load was applied, but it was placed as close as possible. In the chordwise direction, the load was applied on the leading edge side of a vein, so that as the wing deformed, the sting would catch on the vein, rather than slipping off the wing.



Fig. 4. Butterfly wing stiffness measurement apparatus. Force balance apparatus including the height gauge for measuring the deflection,  $\delta$ , with active length, *l*. The forces measured by the ATI Nano Titanium force transducer is relayed through USB connection to a computer.

The sample was mounted between two  $76 \times 25 \times 1.0$  mm glass microscope slides using cyanoacrylate, this was then placed in the adapter (Fig. 4b). The height gauge was used to lower the sample onto the sting, which was positioned below. The sting was connected to the force transducer, so that when the sample was lowered a specific relative distance, the forces were transmitted to the DAQ, and, subsequently, recorded by the computer.



Fig. 5. Schematic of spanwise and chordwise stiffness directions: (a) For spanwise stiffness, the deflection,  $\delta$ , of a wing mounted at the root was measured with a force applied at 70% of the span. (b) For chordwise stiffness, the deflection,  $\delta$ , of a wing mounted at the leading edge was measured with a force applied at 70% of the maximum chord.

For verification measurements, we measured the stiffness of a No. 1  $60 \times 24$  mm glass coverslip. As a way to introduce variation to ensure the apparatus was working properly, one glass slide was mounted by gluing down 10% of the total length, and another was mounted using 15%. These samples were then mounted in the apparatus, and the point load was applied near the end of the sample for six runs at each deflection value. The second moment of area, *I*, for a rigid beam was calculated as [4]

$$I = wt^3/12,$$
 (1)

where w is the width of the coverslip in meters, and t is the average thickness in meters. The flexural modulus, E, was calculated with a static beam deflection equation as [4]

$$E = F l^3 / 3\delta I, \tag{2}$$

where F is the force in Newtons, l is the active length (the distance between where the coverslip is glued down and where the point load is applied) in meters, and  $\delta$  is the deflection in meters.

At deflections of 0.5 mm and 1.0 mm, the glass slide with 10% length glued down produced average *E* values of  $7.69 \times 10^{10}$  N/m<sup>2</sup> and  $6.27 \times 10^{10}$  N/m<sup>2</sup>, respectively. The slide with 15% of its length secured produced *E* values of  $7.22 \times 10^{10}$  N/m<sup>2</sup> and  $5.62 \times 10^{10}$  N/m<sup>2</sup> for those same deflections. These values are consistent with the known Young's modulus of glass which is  $6.9 \times 10^{10}$  N/m<sup>2</sup> [31]. Tanaka and Wood [28] also used glass slides as a verification tool and produced values from 6.6 to  $6.9 \times 10^{10}$  N/m<sup>2</sup>.

This procedure was repeated for the mounting and measurements of the monarch butterfly wing (Fig. 4). Morphological parameters for the six different specimens of the current study can be found in Table 1. The wing area was determined from an image of the wing using wingImageProcessor version 1.1 [32]. The wing was mounted with 5% of the total span (R in Fig. 4) glued between two glass microscope slides. As mentioned previously, the point load was applied at approximately 70% of the total span (or maximum chord), near a vein.

Table 1.	Morphological	parameters f	or monarch	butterfly	specimens	considered	in the	current	study.	The
wing len	gth and wing ma	ass are for the	right forew	ing only.						

Parameter	Specimen						
	1	2	3	4	5	6	7
Wing length, $R (\times 10^{-3} \text{ m})$	51.61	51.73	54.13	50.74	5.067	52.663	50.431
Wing area $(\times 10^{-4} \text{ m}^2)$	9.71	8.661	9.418	8.379	8.2652	9.0291	8.3828
Wing mass (g)	0.0179	0.0164	0.0196	0.0166	0.0165	0.0176	0.0152
Butterfly gender	М	Μ	F	F	Μ	F	Μ

Force required were measured for deflections of approximately 3 mm to 7 mm in the spanwise direction, and 2 mm to 7 mm in the chordwise direction, using the force transducer with an effective sampling rate of 200 Hz. The recorded force values were then put through a 1D moving-average, digital filter, using a window size of 400 (t = 2s). The applied force magnitude, which became nearly constant after around ten seconds, was calculated by taking the force value and subtracting the unloaded force reading, taring the force readings.

Due to the assumptions inherent in Eqs. (1) and (2) as calculations for a beam with a uniform rectangular crosssection, they were not used to determine the flexural modulus of the real monarch butterfly wing. The flexural modulus, calculated as an elastic modulus, was found as described in the next section.

#### **D.** Elastic Modulus Determination

Due to the irregular shape of the wing, a simple beam deflection model was not an ideal characterization. Thus, the elastic modulus, *E*, of a real wing was determined using a FEM solver.

An image of a monarch butterfly wing (specimen 1 in Table 1), with the scales removed so the vein pattern could be more easily identified, was traced and used to create a FEM of the wing in Solid Edge ST10. The final design of the wing closely mimicked the real wing as much as possible, however, certain limitations were present. The vein structures were rectangular, and though the vein tapered towards the distal edge of the wing, the hollow tube structure within the veins had a constant diameter. The veins varied in thickness from root to tip (spanwise direction), and from leading edge to trailing edge (chordwise direction).

To model the wing and determine the corresponding E, a series of finite element meshes were created. In order to determine the mesh size, a sensitivity analysis was conducted with different element sizes (Table 2). The first two mesh sizes were too coarse, however, the maximum displacement converged at 9.5 mm for Mesh 10. Since an increase in the number of elements from 142,000 to 169,000, and changing the maximum angle of tolerance did not alter the maximum displacement, we determined that the 142,113 element mesh was sufficient to maintain accurate results.

Nodes	Elements	Mesh Coarseness	Force	Max Displacement (mm)
			(mN)	
50,249	25,089	Mesh 8, coarse	10	9.33
92,974	47,235	Mesh 9, medium	10	9.41
272,080	142,113	Mesh 10, fine	10	9.49
272,990	142,565	Mesh 10, max angle tolerance from 25° to 15°	10	9.49
320,745	169,841	Mesh 10, max angle tolerance from $15^{\circ}$ to $1^{\circ}$	10	9.5

Table 2. Mesh coarseness data for a linear FEM solver using a constant vein thickness, and elastic modulus (*E*) of  $1.2 \times 10^9$  N/m<sup>2</sup>.

The wings were then tested using the linear FEM solver in Solid Edge ST10. The results were compared to those of the experimental data taken in Section III.C. By knowing the magnitudes of the applied force and the corresponding deflection, E could be determined. First, a value for E was guessed, then the root of the wing was fixed to replicate the experimental setup and a known force was applied to the wing at 70% span (Fig. 6a). The displacement was calculated at this point using the linear FEM solver and compared to the real wing's displacement for the corresponding force. If the displacement was too high, the E value was raised, if the displacement was too low, the E value was lowered. This was repeated until the displacement calculated from the FEM matched that of the experimental data.



Fig. 6. Finite element model of a real monarch butterfly wing. (a) Model fixed (blue dots) at the root to measure a point load applied at 70% of the span (black dot), in the spanwise direction. (b) Model fixed (green dots) at the leading edge to measure a point load applied at 70% of the maximum chord (purple dot), in the chordwise direction.

To determine the elastic modulus in the chordwise direction, the same method was repeated with the wing fixed at approximately 50% of the span, and a force was applied at 70% of the maximum chord length (Fig. 6b). The load was applied directly next to a vein to mimic the experimental setup.

#### E. Deformation and Force Measurements of Artificial and Live Butterfly Wings

The deformation and force measurement experimental setup for the artificial and real monarch butterfly wings consisted of an ATI Nano 17 Titanium Force Transducer and a set of VICON T40s motion capture cameras (Fig. 7). We mounted a Micron Wings [33] 6 mm Ornithopter gearbox to the ATI Nano force transducer such that the *-y*-axis of the force transducer was aligned with the lift direction of the gearbox (Fig. 7). Though gearbox can accommodate four wings, two on either side, we mounted a single wing on the left side of the gear box. The test stand was surrounded by six VICON T40s cameras.

We placed three small reflective markers on the wing and two reference markers on the longitudinal axis of the body, along -y direction of the gearbox. The three-dimensional positions of the markers were acquired at a sampling rate of 200 Hz using the VICON system for a duration of 5 s. Each reflective marker was  $6\times2.34$  mm in size. The total mass of the three markers was around 1.9% of the total mass of a monarch butterfly, and 52% of the mass of the individual wing. The force generated by the butterfly wing motion was recorded by the force transducer at a sampling rate of 200 Hz for 5 s. Before the start of each trial, the transducer was set up such that the load due to the butterfly's weight was zeroed. The VICON camera recording and the force transducer recording were simultaneously triggered such that the time histories of wing motion and forces were correlated. We previously used the same optical measuring technique to measure the three-dimensional wing kinematics and the body motion of freely flying monarch butterflies [34].



Fig. 7. VICON system setup to record the deflections of a wing attached to a gearbox. The wing was attached to a force transducer which simultaneously recorded the forces produced during the flapping.



Fig. 8. STL of micro-CT scanned monarch butterfly wing. Cross-sectional slices of the micro-CT model of the monarch butterfly wing at six spanwise locations.

The flapping, feathering and deviation angles of a real monarch wing were determined using the position of the three markers on the left wing and a reference marker on the gearbox. The flapping frequency was obtained by taking the Fast Fourier transform (FFT) of the time history of the flapping angle. The force transducer output was connected to a National Instruments DAQ and the measured data was saved to an external computer. The wing motion data were smoothed using a low pass filter with a cut off frequency of 30 Hz. The recorded force data, which included higher frequency oscillations, were also filtered using a low pass filter with a cut off frequency of 30 Hz. The VICON wing kinematics data was only taken for the real butterfly wings, as the artificial wing produced significant amounts noise that could not be filtered efficiently.

# **IV.Results and Discussion**

## A. Micro-CT Scan Reconstruction and Wing Morphology Determination

As described in Section III.B, the monarch butterfly wing (specimen 1, Table 1) was scanned and reconstructed into a 3D model (Fig. 8). The reconstructed model was dissected at discrete locations to determine a profile of the thickness variation of both the veins and the membrane of the wing (Fig. 8b). The membrane had a relatively constant thickness (Table 3). The veins, however, varied considerably both from the other veins, and individually as a function of distance from the root. For construction of the artificial wing, the leading edge vein at 30% span (the left vein in Fig. 8) was used as the model thickness for all of the veins.

Table 3. Monarch butterfl	y wing parameters d	letermined from t	he micro-CT scan

Parameter Variable   Volume, V (m <sup>3</sup> ) 4.82 × 10 <sup>-8</sup> Mass, m (kg) 1.481×10 <sup>-5</sup>		
Parameter	Variable	
Volume, $V(m^3)$	$4.82 \times 10^{-8}$	
Mass, <i>m</i> (kg)	1.481×10 <sup>-5</sup>	
Density, $\rho$ (kg/m <sup>3</sup> )	307	
Leading Edge Vein thickness (mm)	0.39	
Membrane thickness (µm)	54	

The density was obtained by dividing the mass of the wing, taken prior to the micro-CT scan, by the volume, calculated from the reconstructed model,  $\rho = m/V$  (Section III.B). This produced a value of 307 kg/m<sup>3</sup>. This value is significantly different from the standard value of 1200 kg/m<sup>3</sup> [35]. The difference in these values likely stems from the accuracy of the experimental method utilized during the calculation. We used a micro-CT scan with a resolution of 10 voxels (10 µm) to generate a volume. Also, here we determined the density of a monarch butterfly wing, *D. plexippus*, whereas the frequently referenced value of 1200 kg/m<sup>3</sup> is given for the genus *Phormia* [35].

# B. Force Generation by Deflection of Monarch Butterfly Wings

We considered six butterflies (specimens 2-7, Table 1) to determine the stiffness of the monarch wings. Typically, one forewing of a butterfly was used for measurements along the leading edge, in the spanwise direction, and the other was used for trailing edge measurements in the chordwise direction. We recorded the forces at five deflection distances (3 mm to 7 mm). Figure 9 shows the forces generated by these specimens at each deflection. The forces produced by the spanwise deflection range from approximately 2 mN to 14 mN, whereas the chordwise deflection produces approximately 0.5 mN to 2.5 mN forces.

Insect wings are highly anisotropic with different material properties depending on the stiffness direction [4,27,28] - spanwise versus chordwise, and dorsal versus ventral. The force data shows an order of magnitude difference between the two directions for the same deflection, indicating the monarch butterfly is not an exception. Our data was taken when the point load was only applied to the ventral side of the wing to analyze just the difference between the span and chord direction flexibilities. Within the spanwise direction (Fig. 9a), the forces appear relatively linear for the lower deflections, and either leveled off or decreased once a force of approximately 1.3 mN was achieved. This suggests that there may be a maximum point force, approximately 14 mN, that the wing is capable of. During the experiment, after this force magnitude was reached, the wing likely failed and either slid off the sting or the leading edge creased and the wing slid off the sting.



Fig. 9. Force, F, measured with different monarch butterfly wing specimens in the (a) spanwise direction, and (b) chordwise direction. Each color corresponds to a unique specimen (Table 1): specimen 2 – blue, specimen 3 – green, specimen 4 – red, specimen 5 – magenta, specimen 6 – yellow, and specimen 7 – black.

In the chordwise direction (Fig. 9b), the forces recorded did not show as consistent of a trend with deflection as in the spanwise direction. This is could be due to a lack of support structure connecting the leading edge to the trailing edge, or potentially the point load not remaining exactly at location as intended. The magnitudes were larger than along the spanwise direction, suggesting that the monarch wing is less stiff (more flexible) in the chordwise direction. Within the spanwise direction (Fig. 9a), the forces follow a relatively linear trend as the deflection values increase. Especially within the lower deflections, the forces generated appear consistent among the different specimens, potentially indicating an evolutionarily conserved material property inherent to the wing.

#### C. Elastic Modulus Determination from FEM

Figure 10 shows the relative spatial wing deformation, produced by the FEM analysis, from the undeformed position (the translucent wings), with the surface mesh visible on the deformed wing.



Fig. 10. Surface mesh and deflection from FEM of monarch butterfly wing with (a) point load applied at 70% of the total span (blue arrow) and (b) point load applied at 70% of the maximum chord (green arrow). The undeformed wing is shown for reference. The contour levels indicate the wing deformation in mm.

The elastic modulus, E, values of the wing model are presented in Table 4. The E in the spanwise direction is approximately an order of magnitude higher than that in the chordwise direction. This result is supported by both Combes and Daniel [4], as well as Steppan [27], who found similar trends. Butterfly wings are anisotropic, and thus deform differently at different locations along the wing. In this instance, however, the model used in this study was given a homogeneous material property with tapering veins. Because the material is homogeneous, the difference in E suggest that the wing material is anisotropic. Furthermore, the veins were tapered, making the supporting structure thinner towards the distal parts of the wing. Additionally, in regards to the spanwise measurement (Fig. 10a), the support structure, which offers the most resistance, is next to the point load, and fixed such that the leading edge acts as a cantilever beam. In the chordwise direction (Fig. 10b) the wing is fixed along the leading edge, but there is no rigid structure running from there to the location of the point load. Therefore, unlike in the spanwise direction, the chordwise direction is able to deform much more readily. Note that this model does not take into consideration the effects of the hindwing.

	Spanwis	e	Chordwise				
Force, F (mN)	Displacement, δ (mm)	Elastic Modulus, E (×10 <sup>9</sup> N/m <sup>2</sup> )	Force, F (mN)	Displacement, δ (mm)	Elastic Modulus, E (×10 <sup>9</sup> N/m <sup>2</sup> )		
1.3	1.0	1.4	0.67	2.0	0.24		
5.3	2.0	2.7	1.2	3.0	0.27		
4.0	3.0	1.4	0.74	4.0	0.13		
6.8	4.1	1.8	1.0	5.0	0.14		
9.1	5.1	1.9	1.7	6.0	0.20		
9.2	6.0	1.6					
ŀ	Average	1.8	I	Average	0.20		

Table 4. Elastic modulus of the hollow, tapered vein determined using FEM in both the spanwise and chordwise directions.

## D. Wing Angles for a Real Monarch Wing

Figure 11 shows the wing angles for a single wing at 1.1 V, from six repeated measurements. As shown, there is minimal variation in the flapping angle between the repeated measurements, indicating a consistency in the performance of the gearbox and wing. The wing frequency was determined from the flapping angle time history and was also used to convert the input voltage to the motion frequency of the artificial wing (Section IV.F). Figure 11 also shows that the deviation angle is zero, indicating the wing was not moving in an unanticipated direction. The feathering angle, which is due to wing deformation and hence passive, is non-zero. The feathering angle shows an oscillation indicative of the wing deforming during flight. During the downstroke, the passive feathering angle reduces to zero. During the upstroke, the passive pitch angle increases. The flapping angle has an amplitude of 17.0°, and a phase lag of around 160°. There is a difference between the peak of the downstroke and the peak of the feathering angle, which is approximately the time it takes for the wing to passively deform after the beginning of the upstroke.

Analysis of the time histories of the flapping motion was performed on each of the different voltages. The average flapping amplitude, defined as half of the difference between the maximum and minimum flapping angle, increases linearly as the voltage, and thus frequency, increase (Fig. 12a). The pitching amplitude also increases relatively linearly with an increasing frequency, showing that the faster flapping caused the wing to passively deform more. This would aid in generating a higher lift during flight.

The phase lag (Fig. 12b) shows that the flapping angle peaks, followed by the pitching angle with a phase between 100° and 160°. A phase lag of 180° would imply that the pitching motion is a half-stroke behind the flapping motion. The phase lag reduces as the motion frequency increases. This delay stems from the passive deformation of the wing during the stroke of the wing. The average amplitude and phase lag, as well as the errors are shown in Fig. A1.



Fig. 11. Representative time histories of the flapping angle, feathering angle, and deviation angle of a real monarch butterfly wing mounted on the gearbox and operated at an input voltage of 1.1 V. The FFT analysis of the flapping motion indicates that the flapping frequency is 10 Hz. The grey bars indicate the downstroke, and the white bars indicate the upstroke. The black line is the average of each subplot.



Fig. 12. (a) The mean flapping (red) and pitching (blue) amplitudes of a real butterfly wing versus voltage and the corresponding frequency. (b) The mean phase offset of the pitching angle from the flapping angle versus voltage and the corresponding frequency.

#### E. Production of an Artificial Monarch Butterfly Wing

We fabricated an artificial forewing using a standard PLA, which has a flexural modulus of  $3.15 \times 10^9$  N/m<sup>2</sup> [36]. Though this value is not the same as that found by our model with a spanwise *E* of  $1.8 \times 10^9$  N/m<sup>2</sup> (Table 4), it was the closest one that was compatible with our fabrication limitations.



Fig. 13. (a) High resolution image of the vein structure of a monarch butterfly right forewing, taken after removing the scales from the wing. (b) CAD model created from the vein structure image. The dimensions for this model correspond to specimen 1 summarized in Table 1. (c) 3D printed monarch butterfly wing compared to a real monarch wing, printed using PLA veins (yellow) with a PLLA membrane.

To manufacture a 3D printed artificial wing, we created a CAD model of the venation pattern of a monarch butterfly wing. First, we removed the scales of a real monarch butterfly wing, then took a top-view photograph of the wing in a high-resolution (maximum of 6000×4000 pixels). From the photograph, the vein structure was digitally selected and converted into a CAD model in SolidEdge ST10 (Fig. 13a,b) for the biomimetic wing design. Some small variations were made: a few veins had to be widened, a vein along the leading edge was removed, and the others shifted for better resolution in the printing. A uniform, rectangular thickness was determined due to the limitations in printing resolution of the Monoprice Maker Select 3D printer, despite the fact that an actual wing has rounded veins with a gradient height. The vein structure was printed with a thickness of 0.5 mm, in accordance with the value determined from the leading edge vein of the micro-CT scan (Table 3).

After printing the vein structure, a 0.05 mm sheet of Poly-L-lactide (PLLA) was adhered to emulate the membrane of a real wing. We used the organic solvent tetrahydrofuran (THF) to partially dissolve the vein structure before placing it on the PLLA sheet and applying light pressure. As the THF evaporated, the structure of the PLA reformed. Since the vein structure material (PLA) is the same as the thin plastic (PLLA), the two structures fused together during the solidifying process, creating a wing structure with the veins and membrane (Fig. 13c).

#### F. Force Generation by an Artificial Monarch Wing

As described in Section III.E, both the real monarch butterfly wing, and the artificial wing were attached to a gearbox, and the forces generated were recorded (Fig. 14). The lift direction for both the real and artificial wings was in the -y direction (Fig. 7). The gearbox's flapping peak-to-peak angle was 40°. Since monarch butterflies flap at an peak-to-peak amplitude of almost 130°-160° [34], these results only represent the lift production at a relatively small amplitude. Force measurements at larger amplitudes will be considered in the future. Average forces and associated errors for the lift are shown in Fig. A2.



Fig. 14. Forces produced by real and artificial wings in the y-directions. The discrete voltages correlate to the frequencies along the top axis. The lift direction of the system was along the -y-axis, so the lift, L, plotted is equivalent to negative force in the y-direction.

A real wing was mounted to the gearbox so that the lift generated by the artificial wing could be more directly compared to that of the real wing. Figure 14 shows that while both types of wing do produce lift, they peak at different flapping frequencies. The real wing peaks when the frequency is approximately 10 Hz (corresponding to 1.1 V), which is the same as a monarch butterfly's natural flapping frequency [34]. The mean magnitude is 3.8 mN. Hence, this flapping frequency allows the butterfly to produce the lift necessary compensate for its weight. The lift generated also allows the butterfly overcome external forces it encounters during flight, such as sudden changes in wind speed or wind direction.

The artificial wing produces a similar peak lift of 4.5 mN. However, it peaks at approximately 8 Hz, or 0.9 V. This difference could be due to a number of factors. The PLA composing the artificial wing did not have exactly the same *E* value as we determined for the real wing, and was homogeneous, whereas a monarch butterfly's wing is anisotropic. This difference is integral to the wing's ability to deform in the chordwise direction such that the passive feathering angle changes, which is a metric for the angle of attack, closely related to lift generation. Additionally, the artificial wing did not possess hollow veins, which would potentially change the rigidity of the vein structure. This difference in structural properties would cause the wings to aerodynamically perform differently, allowing their optimum flapping frequencies to differ.

# **V.Conclusion**

Through the characterization of the monarch butterfly wing by measuring the force per deflection in both spanwise and chordwise directions, we can identify the optimal material to create an artificial monarch wing. From a micro-CT scan, we determined the volume of the real monarch butterfly wing, and generated a high-resolution 3D model of that wing.

The density of the real monarch butterfly wing, as calculated from the weight and volume of the wing, was 307 kg/m<sup>3</sup>, significantly lower than the value frequently used in the literature. This calls into question the accuracy of the density values in the literature, as the technology used here to determine volume is more advanced than what would have been available in 1976.

We also used the model of the wing in a linear FEM solver to determine the elastic modulus of a real monarch wing. The resulting elastic modulus was highly anisotropic with  $E = 1.8 \times 10^9$  N/m<sup>2</sup> along the span and  $E = 0.2 \times 10^9$  N/m<sup>2</sup> along the chord. The resulting value was utilized to identify a material, PLA, for the fabrication of a bioinspired wing.

We determined the forces generated by both a real monarch wing and the artificial wing during flapping motion. While the real wing performed optimally at a flapping frequency of 10 Hz, which is the flapping frequency of the species' flight, the artificial wing performed best at a flapping frequency of 8 Hz. The difference likely stems from the artificial wing's material not having exactly the same elastic modulus as the real wing, and the artificial veins being solid material, rather than hollow tubes. Further tests and modifications to the artificial wing design may yet produce a wing capable of a flight as efficient as that of a monarch butterfly.



Fig. A1. Box plot of the averaged values and associated errors, using 95% confidence, of the (a) flapping amplitude (red) and pitching amplitude (blue), and (b) phase offset, as a function of the input voltage and frequency. Circles indicate outliers.



Fig. A2. Box plot of the averaged values and associated errors, using 95% confidence, of the force magnitudes on the real wing (red) and artificial wing (blue) as a function of the input voltage and frequency. Circles indicate outliers.

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