Flow Field of Flapping Monarch and Swallowtail Butterfly-like Wings

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This paper presents a part of our ongoing development of a butterfly-like ornithopter (flapping wing) micro-aerial vehicle (MAV). Two kinds of butterfly were selected for studies: Monarch butterfly (Danaus plexippus) and Swallowtail butterfly (Papilio troilus)). The Monarch butterfly is well-known for its ability for long distance migratory flight. The Monarch butterfly is well-known for its high agility. It is also selected as baseline for comparison. The Swallowtail butterfly has unique tails (streamers) at the trailing edge of its hind wings. For both types of butterfly, the flow physics show that during free flights, they use a variety of unconventional aerodynamic mechanisms to generate force: wake capture, two different types of leading-edge vortex, active and inactive upstrokes. Free-flying butterflies often used different aerodynamic mechanisms in successive strokes. For Swallowtail butterflies, the streamer appears to help their flight more stable, by aligning the wake vortices behind its hind wings. The subsequent horse-shoes vortices also help create more vortex lift. For flexible wing, the result from fluid-structure interaction shows that the swallowtail butterfly deflect more than Monarch butterfly.

Key Words: Flapping Wing, MAV, Monarch butterfly, Swallowtail butterfly, Streamer, Fluid-Structure Interaction.

Nomenclature

k	:	reduced frequency
l	:	body length
A	:	half wing's surface area
D	:	drag
L	:	lift
M	:	moment
R	:	wing span
C_L	:	lift coefficient
C_D	:	drag coefficient
C_M	:	moment coefficient
U_∞	:	forward (translating) velocity
U_{ref}	:	reference velocity
Re	:	Reynolds number
ρ	:	air density
ν	:	kinematic viscosity
ω	:	frequency
ϕ	:	stroke angle

1. Introduction

This paper presents a part of our ongoing development of a butterfly-like ornithopter (flapping wing) micro-aerial vehicle (MAV). Butterfly is a class of day-flying insect of the order Lepidoptera. Similar to other insects, they are very agile flyer in nature. Two kinds of butterfly were selected for studies: Monarch butterfly (*Danaus plexippus*) (figure 1) and Swallowtail butterfly (*Papilio troilus*) (figure 2). The Monarch butterfly is well-known for its high agility. It is also selected as baseline for comparison. The Swallowtail butterfly has unique tails (streamers) at the trailing edge of its hind wings. For both types, the lift generated by butterflies is more than what can be accounted for by steady-state, non-transitory aerodynamics.

Fig.1 (left): Monarch butterfly (*Danaus plexippus*)

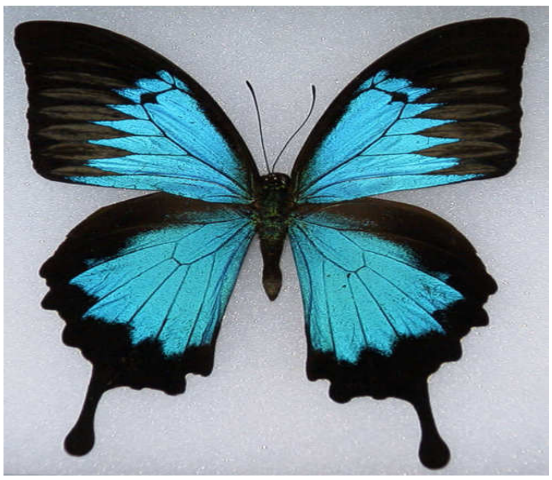

Fig.2 (right): Swallowtail butterfly (*Papilio troilus*)

The unsteady flow and flight characteristics of these butterfly-like flapping wings were numerically investigated in both hovering and translating motions. These butterfly models are considered as semi rigid multi-body system, with limited flexibility on their front and hind wings. The flapping motions are taken from observations of their real natural flights and from available literatures. The average Reynolds number range of these butterflies based on their body (head and thorax) lengths, their maximum wingtip speeds (for hovering), or their freestream velocity (for translating) are Re ~ 500.

2. Finite Element Analyses software

The ANSYS® Multiphysics fluid-structure interaction (FSI) models are used. For fluid part (air flow), the fully 3D unsteady Navier-Stokes equations with Direct Numerical Simulations (DNS) is used. For solid part (flexible wing), the linear deformation modeling is used. The wings are assumed to be moderately stiff. The FSI couplings appear on the boundaries between the fluid and the solid. The Fluid-Structure Interaction interface uses an arbitrary Lagrangian-Eulerian (ALE) method to combine the fluid flow formulated using an Eulerian description and a spatial frame with solid mechanics formulated using a Lagrangian description and a material (reference) frame.

In this paper, we used ANSYS Fluent® Release 13. This software has been existed for extended period of time, and many universities and research institutes around the world are using it (*Fluent, 2001*). Our ANSYS Fluent® Release 13 is under a research license. The machine that ran these problems was a 64 bit computer, Intel® Core i7-2600 CPU at 3.4 GHz, 8 processors, with 16 GByte RAM.

The butterfly geometries are prepared in SolidWorks® 2011, by following the external contour of their respective models (*Sterry & Mackay, 2004*). By symmetry, we use only half model, and include only their heads, their thoraxes (bodies) and their wings.

The fluid domain around the wing extends about 20-40 times of the body length in all directions, as shown in figure 3. The mesh used are unstructured, and there are approximately 10^7 meshes around the wing as shown in figure 4.

For flight conditions, we consider two cases:

1. Both butterflies are under *hovering* motion, during flap down (power stroke) at the frequency of 1 Hz (i.e. $\omega = \pm\pi$ rad/s) and the stroke angle, ϕ of ±80°. We consider when the wings of both butterflies are in planar position, midpoint of either flap up or flap down, i.e. $\phi = 0°$.
2. Both butterflies are under *forward* (translating) motion at U_∞ = 10 cm/s, during flap down (power stroke) at the frequency of 1 Hz (i.e. $\omega = \pm\pi$ rad/s) and the stroke angle, ϕ of ±80°. Likewise, we consider when their wings are in planar position ($\phi = 0°$).

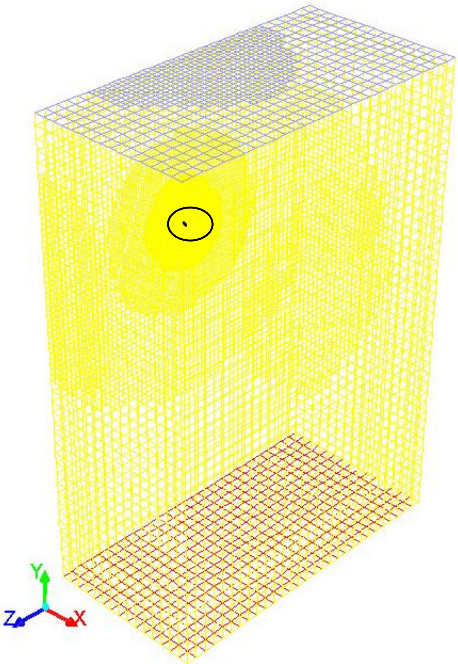

Fig.3 (left): Fluid domain around the wing. The inflow comes from -*y* direction on the top face.

Fig.4 (right): The sample wing inside the fluid domain.

In both cases, the reference velocity will be the maximum wingtip's speed, i.e. $U_{ref} = \omega R$, where R is wing span, and R = 5cm, hence U_{ref} = 0.157 m/s for both butterflies. The reference length is the body length l, measure from head to thorax, of which $l_{monarch} = l_{swallowtail}$ = 29.36 mm. Their corresponding Reynolds number is $Re \equiv U_{ref} l / \nu$, where ν is the kinematic viscosity of air. Therefore, $Re_{monarch} = Re_{swallowtail} = 470$. The corresponding reduced frequency, $k \equiv \omega l/2U_{ref}$ are 0.3, for both butterflies.

For fluid flow studies, we assume the butterflies' wings are rigid. There is no deformation of their wings. This is to simplify the computation process.

3. Monarch butterfly

The flight behaviour of Monarch butterfly (*Danaus plexippus*) serves as the standard for comparison with that of Swallowtail butterfly (*Papilio troilus*), especially the effect of the streamer. Like most other species of the butterflies, the Monarch butterfly is characterized by a high flight velocity (*Steppan, 2000*). With each wingbeat the insect covers a relatively long distance (*Sterry & Mackay, 2004*) , and periodic changes in altitude and direction of flight give it the appearance of fluttering (*Brodsky, 1991*). Such a mode of flight results from rare flaps of broad wings through a large amplitude. (*Tanaka et al*, *2005*). For broad-winged butterflies there are also indications the that wing flaps in just one fixed stroke plane, perpendicular with the body axis (head to thorax) during both upstroke and downstroke. This allows us to simulate in just one plane, and that, we chose the point mid-way of the power stroke (downstroke) at $\phi = 0°$ as a reference for comparison. Another characteristic of butterflies is the frequent use of intermittent gliding. The monarch butterfly, like members of other families of diurnal butterflies, is also capable of sharp jerks forward, performed at high speed with the wings lifted above the body (*Senda et al, 2004*).

3.1. Hovering motion

Table 1 shows the results of the CFD simulation for Monarch butterfly, under hovering and forward motions. Due to symmetry only half of the butterfly is shown. The butterfly's wing was at midpoint of its power stroke. The results from hovering motion are shown at the left side of the table. Along the leading edges of both fore- and hind- wings, a stable leading-edge vortex motion is formed and intensive. This vortex rotates anticlockwise towards the inside (the back) of the wing. There is stopping vortex downstream of the butterfly. Both vortices become part of a new vortex ring connected with the horizontal one by the old stopping vortex (also shown in Figures 5-13). At the bottom of the hind wing, the leading edge vortex just attached along the contour of the edge. There is airflow passes through the gap between the pronating wings moves along the axis of the vertical vortex ring. As soon as it appears, the vertical vortex ring begin to moves backwards. This is similar to wake-capturing mechanism.

3.2. Forward motion

The results from forward motion are shown at the right side of the table 1. The forward motion follow the same setup and phase as the hovering flight. The main difference is that the wings produce a largely tilted leading edge vortex ring. The subsequent vortex formation pattern is different. For forward flight, at the beginning of pronation (starting of the power stroke), the vertical vortex ring moves quickly backwards, by convection due to freestream. At the bottom of the stroke the wings shed the horizontal vortex ring downwards and backwards. Unlike in hovering flight, where the horizontal ring is coupled with the vertical one and is therefore retained near the edges of the hindwings, in migration flight, the clap of the wings at the bottom of the stroke is accompanied by vortex ring shedding. Leaving the wings, the horizontal vortex ring moves downwards and backwards. The ring would move in the same direction in hovering flight if it were released at the bottom of the stroke.

4. Swallowtail butterfly

The Swallowtail butterfly (*Papilio troilus*) is uniquely identifiable by its streamer (tail) at the lower and outer corner of its hindwings (especially Zebra butterfly, *Protographium marcellus*). It is believed that the streamers is meant for better flight control of the butterfly by providing additional vortex-lift from the horseshoe vortex it induced (*Sterry & Mackay, 2004*).

Table 2 shows the results of the CFD simulation for Monarch butterfly, under hovering and forward motions. The aerodynamics are mostly similar to that of Monarch butterfly in both conditions, i.e. there is the dominant leading edge vortices emanated along the leading edges of the fore- and hind- wings of the butterfly. There is also the airflow passes through the gap between the pronating wings moves along the axis of the vertical vortex ring.

The presence of the streamers at the lower and outer corner of its hind- wing introduces the additional horseshoe-like vortices around the edge of the streamer. This is clearly shown in figures 5-13. This horseshoe vortex helps aligning the wake vortices behind its hind wings, and that, makes the Swallowtail butterfly flight more stable. Overall, the structure of leading edge vortices for Swallowtail butterfly is bigger, and hence, larger lift and thrust force produced.

5. Comparison of both butterflies

Tables 3 and 4 show the force and moment generated by both butterflies. In these tables, the lift, drag and moment coefficients are defined as:

$$C_L = L/(0.5\rho U^2_{ref}A) \quad (1)$$
$$C_D = D/(0.5\rho U^2_{ref}A) \quad (2)$$
$$C_M = M/(0.5\rho U^2_{ref}Al) \quad (3)$$

where

$U_{ref} = \omega R$ = 0.157 m/s, for both hovering and forward motions

ρ = air density = 1.225 kg/m^3,

l = body length = 0.03 m, and

A = half wing's surface area, of which $A_{monarch}$ = 21.6 cm^2 and $A_{swallowtail}$ = 35.2 cm^2

Table 3: Force and moment generated by both butterflies, during hovering motion (all values ± 5%)

Hovering motion, flaps at 1 Hz	C_L	C_D	C_M
Monarch butterfly	0.041	0.032	0.040
Swallowtail butterfly	0.074	0.075	0.072

Table 4: Force and moment generated by both butterflies, during forward motion (all values ± 5%)

Forward motion at 10 cm/s, flaps at 1 Hz	C_L	C_D	C_M
Monarch butterfly	4.571	4.980	4.868
Swallowtail butterfly	5.233	6.172	5.113

From tables 3 and 4, the forces and moments of Swallowtail butterfly are more than that of Monarch butterfly by approximately 20%, whereas the area increases roughly 5% only. Since the platforms of both butterflies are almost similar, except the existence of streamers in Swallowtail butterfly, it is clear that the increment in forces and moments come from the streamers contribution. Figures 5-13 below show schematically how the streamers introduce the horseshoe vortices, help align the wake vortices behind its hind wings, provide more vortex lift. and eventually increase the forces and moments.

Figures 5-9 show the streamlines of both butterflies side-by-side, when both butterflies are in forward motion and flapping down (power stroke) at different viewing angles. In every figures, the left ones are for Swallowtail butterfly and the right ones are for Monarch butterfly.

Figures 10-13 show the vortex structures (iso-surfaces of vorticity) of both butterflies side-by-side, when both butterflies are in forward motion and flapping down (power stroke) at different viewing angles. In every figures, the left ones are for Swallowtail butterfly and the right ones are for Monarch butterfly. As shown in all these figures, especially figure 12, the streamer introduce the additional horseshoe vortices (tongue). This helps align the wake vortices behind its hind wings, provide more vortex lift, which increases forces and moments.

6. Fluid-Structure Interaction (FSI)

For solid part (flexible wing), the linear deformation modeling inside ANSYS Mechanical Design is used. The wings of both butterfly are assumed to be moderately stiff. The FSI couplings appear on the boundaries between the fluid and the solid. The FSI interface uses an arbitrary Lagrangian-Eulerian (ALE) method. The wing material of both butterfly are assumed to be equivanent to elastomer, as it is the only flexible material option inside ANSYS. Figures 14 and 15 show the elastic strain (von-Mises) on both Monarch and Swallowtail butterflies respectively. Likewise, figures 16 and 17 show the total deformation on both butterflies respectively. It appears that Swallowtail deflects more than Monarch (more elastic strain). Since their aerodynamics are roughly the same, it is the relatively more spreading wing and the streamer of the swallowtail that cause more strain and deflection.

7. Conclusions

For both types of butterfly, the flow physics show that during free flights, they use a variety of unconventional aerodynamic mechanisms to generate force: wake capture, two different types of leading-edge vortex, active and inactive upstrokes. For Swallowtail butterflies, the streamer appears to help their flight to become more stable, by aligning the wake vortices behind its hind wings. It is the relatively more spreading wing and the streamer of the swallowtail that cause that Swallowtail butterfly deflects more than Monarch butterfly.

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Table 1: CFD simulation results (streamlines) for Monarch butterfly, under hovering and forward motions, different viewing positions.

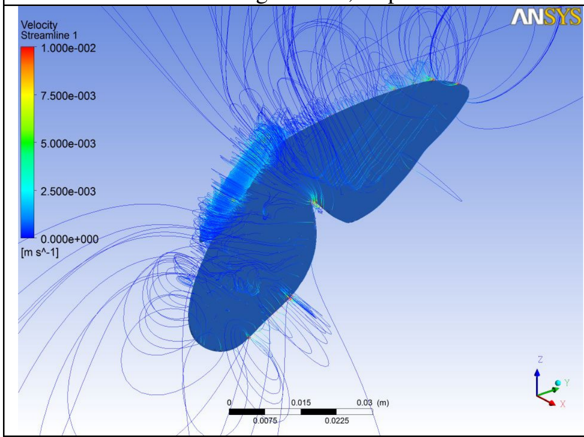
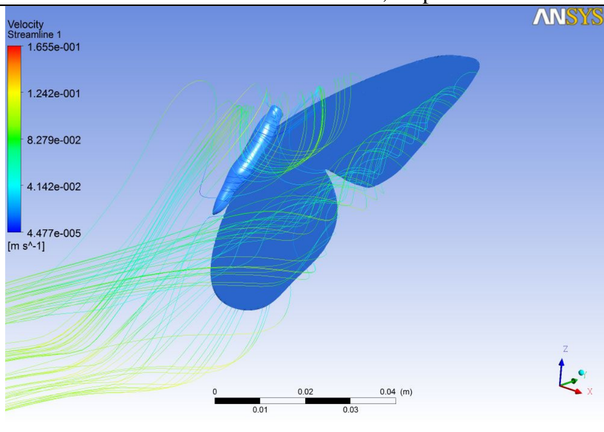
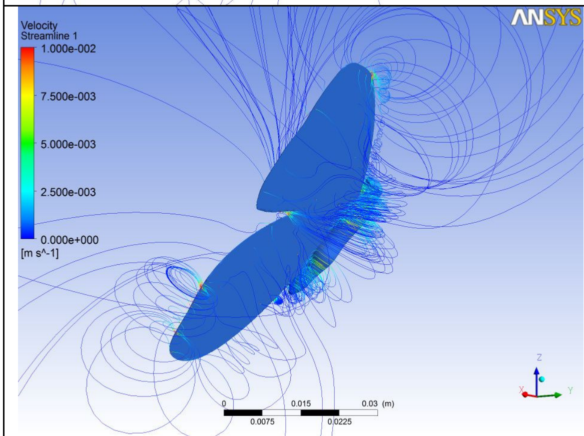
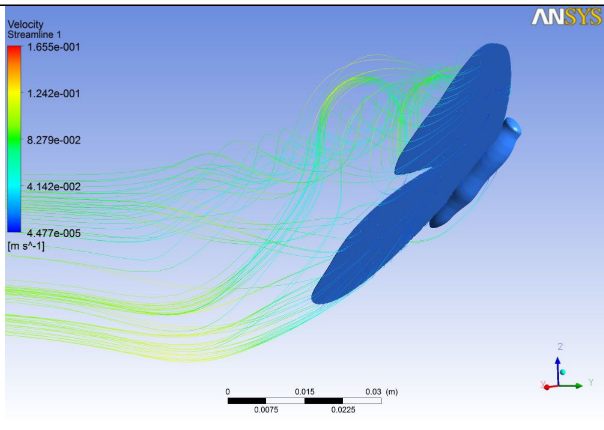
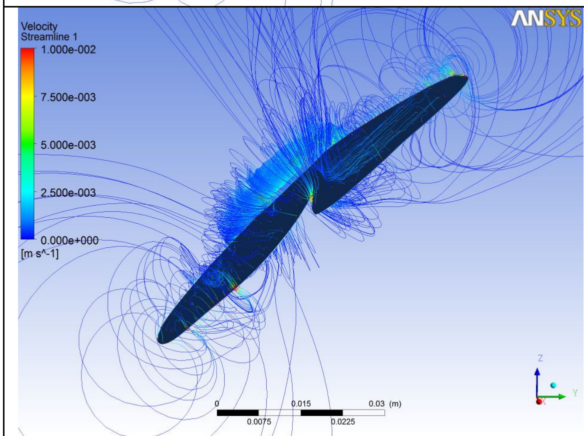
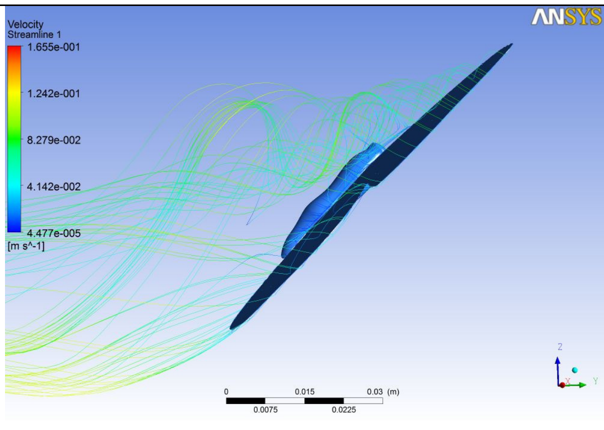
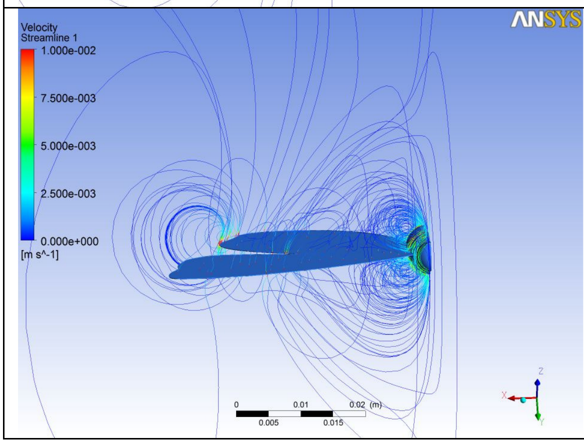
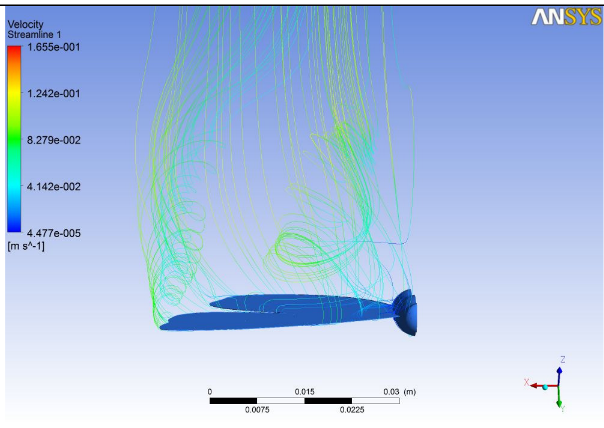
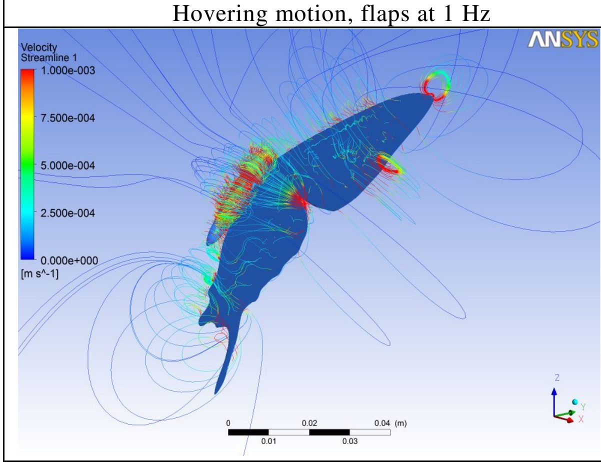
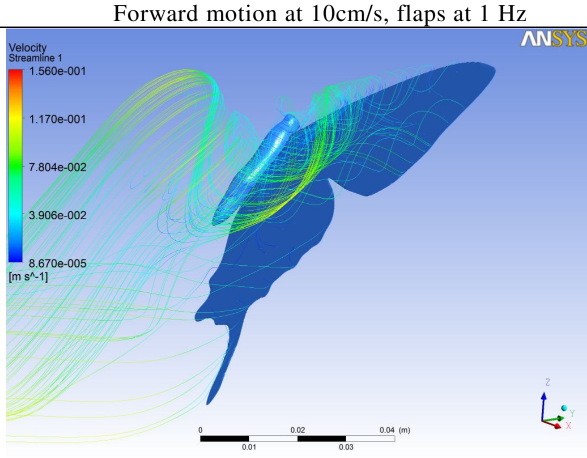
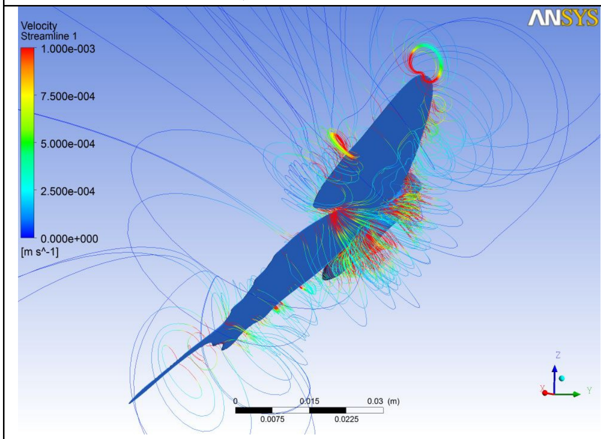
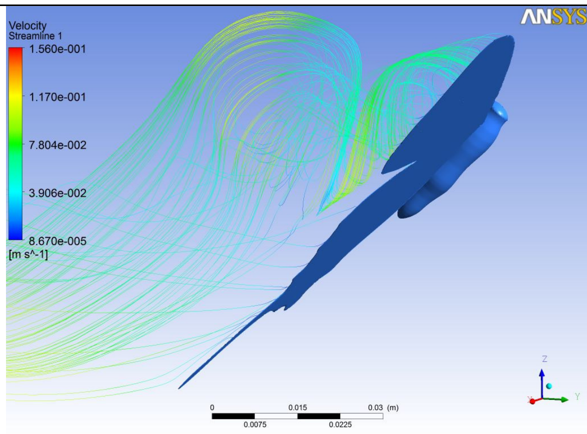
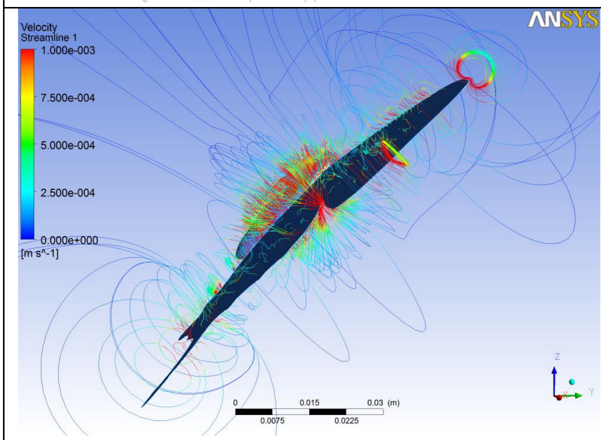
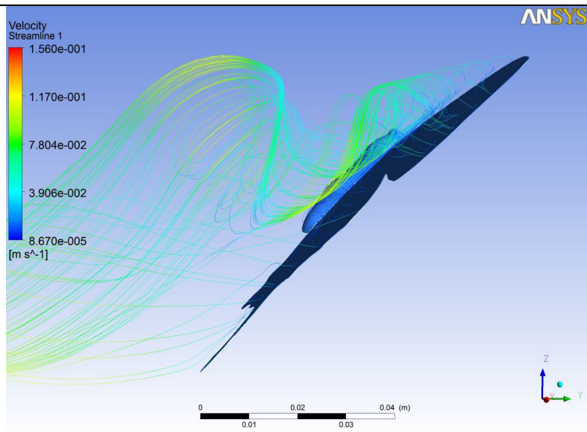
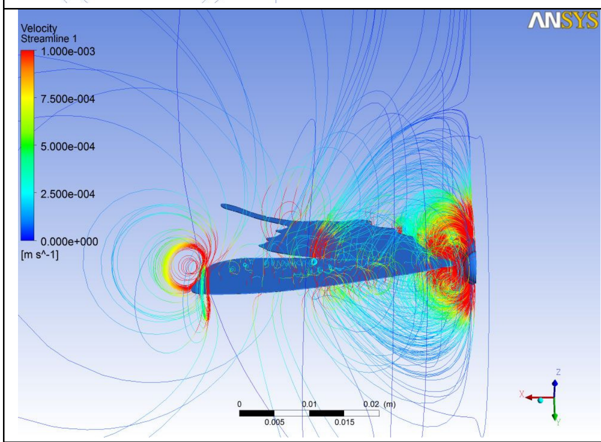
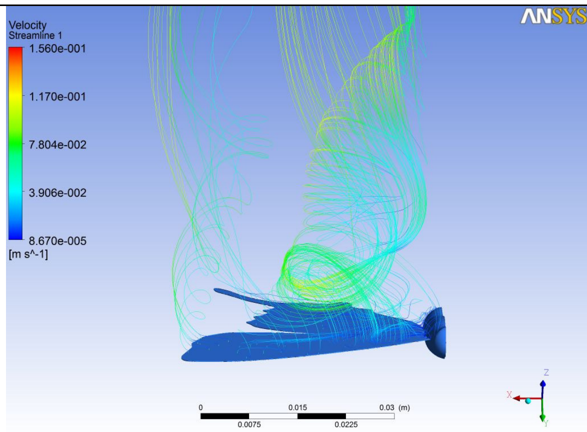
Hovering motion, flaps at 1 Hz	Forward motion at 10cm/s, flaps at 1 Hz
	
	
	
	

Table 2: CFD simulation results (streamlines) for Swallowtail butterfly, under hovering and forward motions, different positions.

Hovering motion, flaps at 1 Hz	Forward motion at 10cm/s, flaps at 1 Hz
	
	
	
	

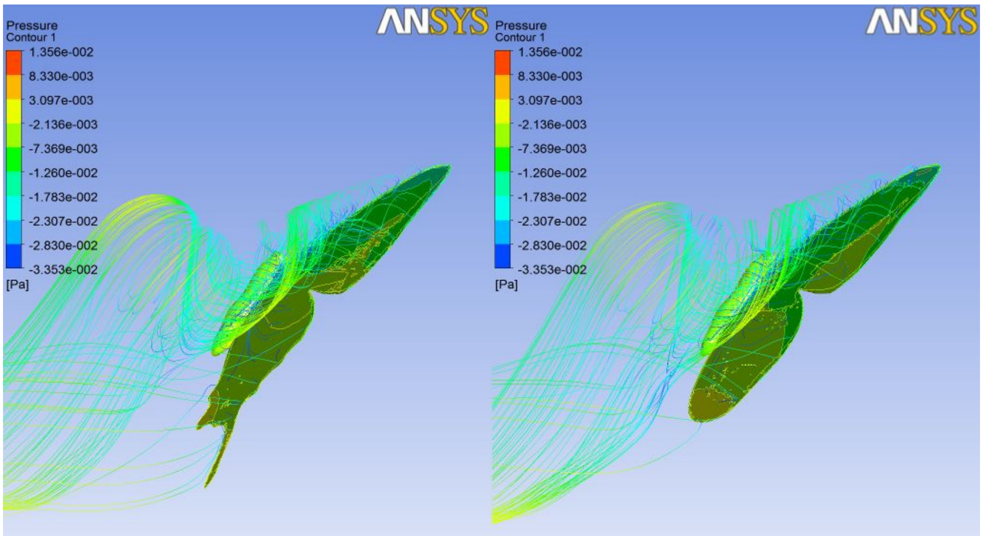


Fig. 5: Comparison of streamlines of both butterflies side-by-side: isometric view, behind

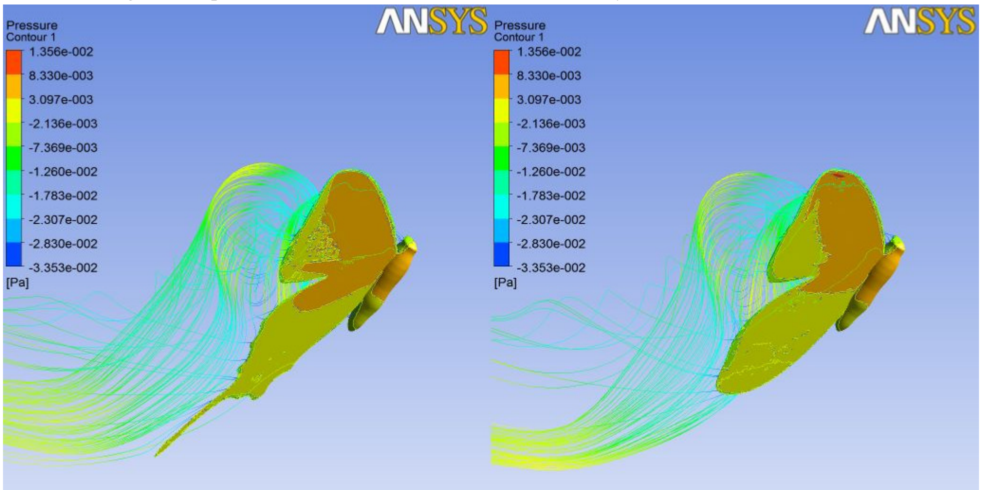


Fig. 6: Comparison of streamlines of both butterflies side-by-side: isometric view, front4

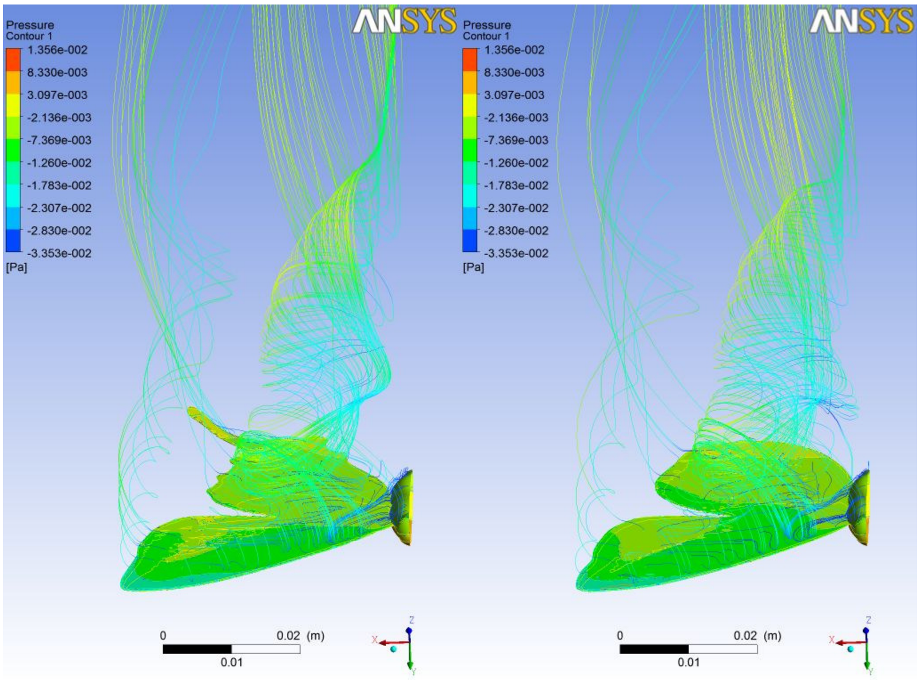


Fig. 7: Comparison of streamlines of both butterflies side-by-side: 3D view, front

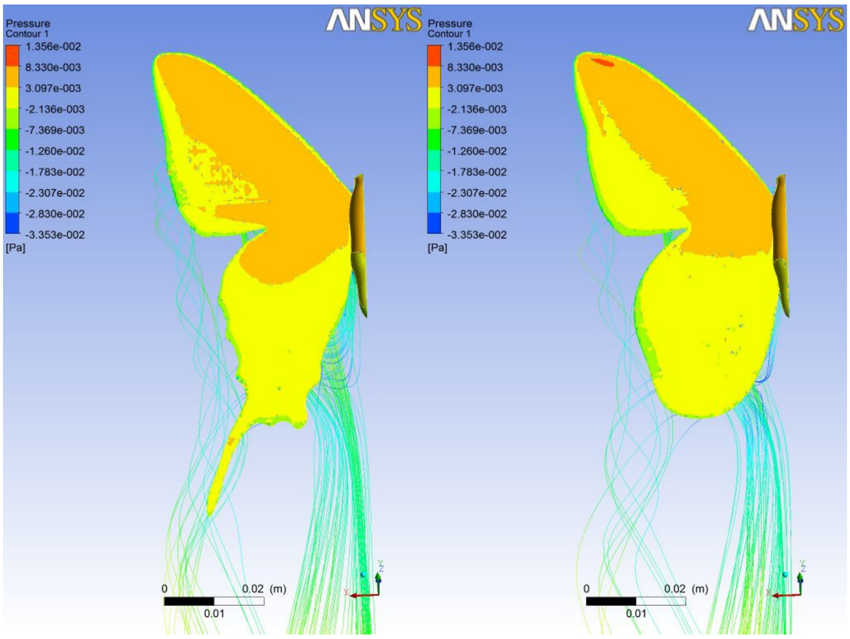


Fig. 8: Comparison of streamlines of both butterflies side-by-side: 3D view, below

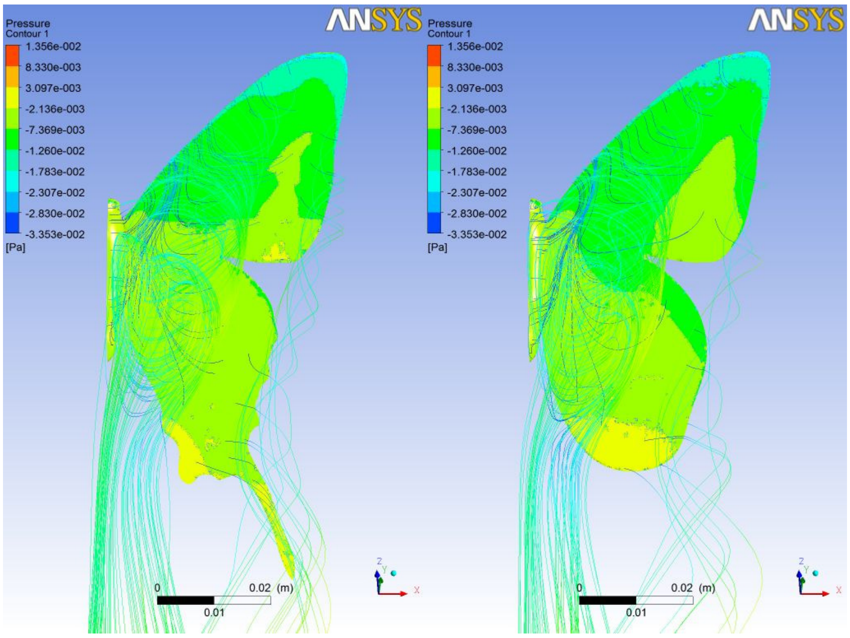


Fig. 9: Comparison of streamlines of both butterflies side-by-side: 3D view, top

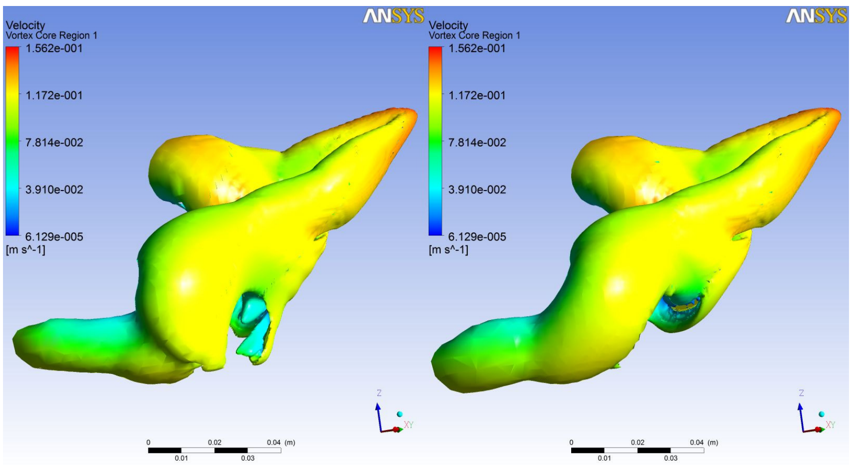


Fig. 10: Comparison of vortex structures of both butterflies side-by-side: isometric view, behind

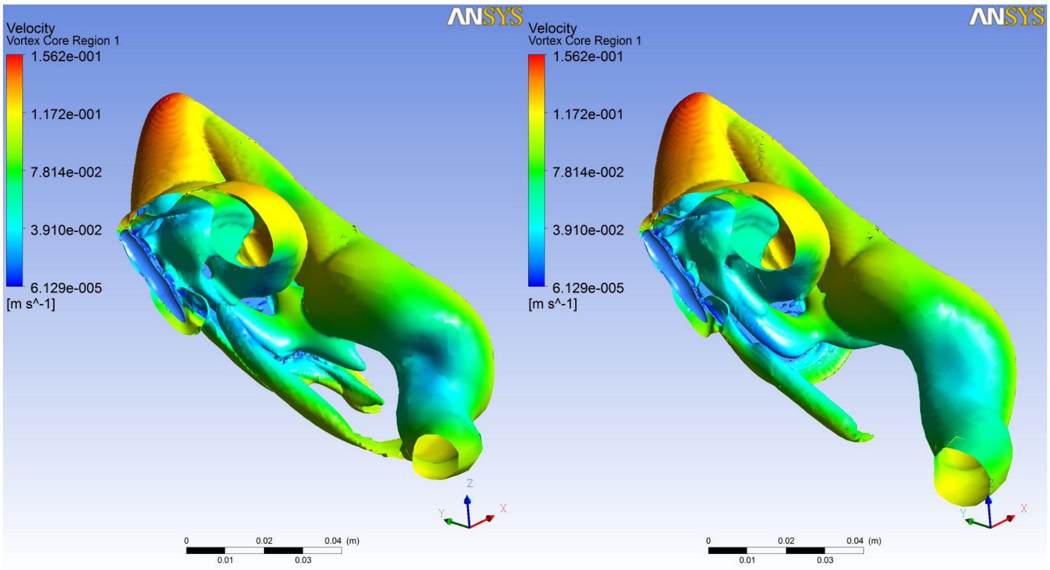


Fig. 11: Comparison of vortex structures of both butterflies side-by-side: isometric view, front

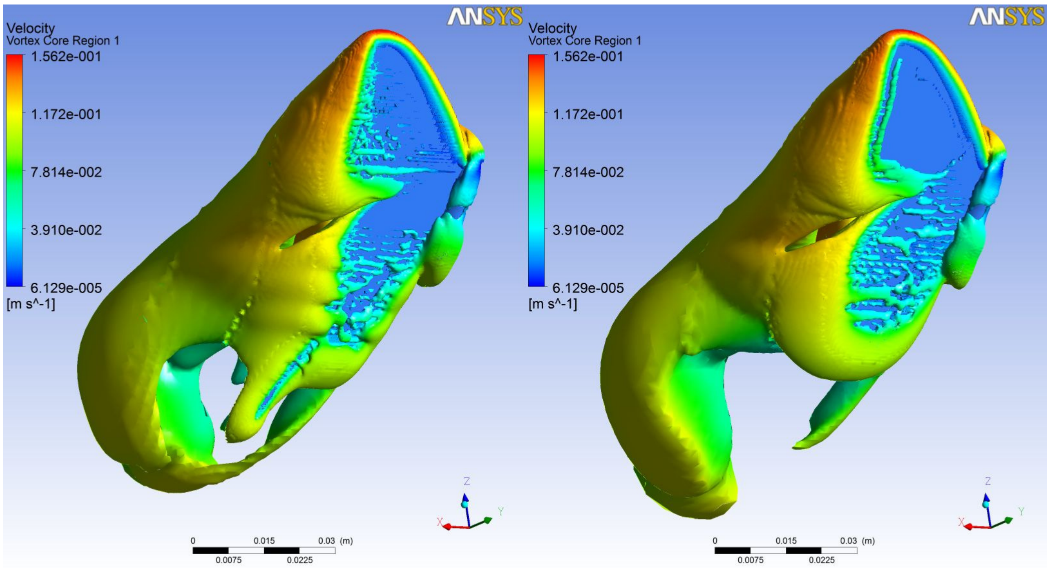


Fig. 12: Comparison of vortex structures of both butterflies side-by-side: isometric view, below

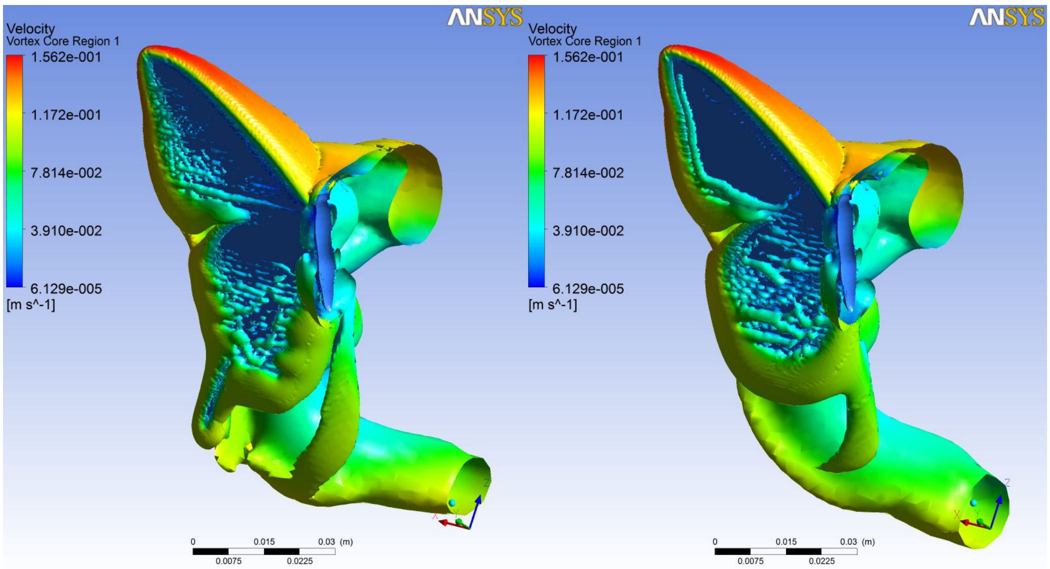


Fig. 13: Comparison of vortex structures of both butterflies side-by-side: isometric view, below

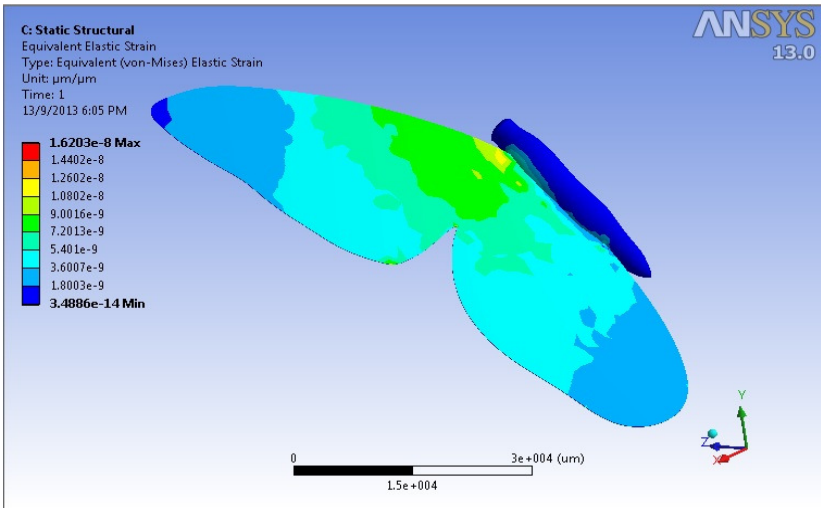


Fig.14: Equivalent elastic strain (von Mises strain) on Monarch butterfly

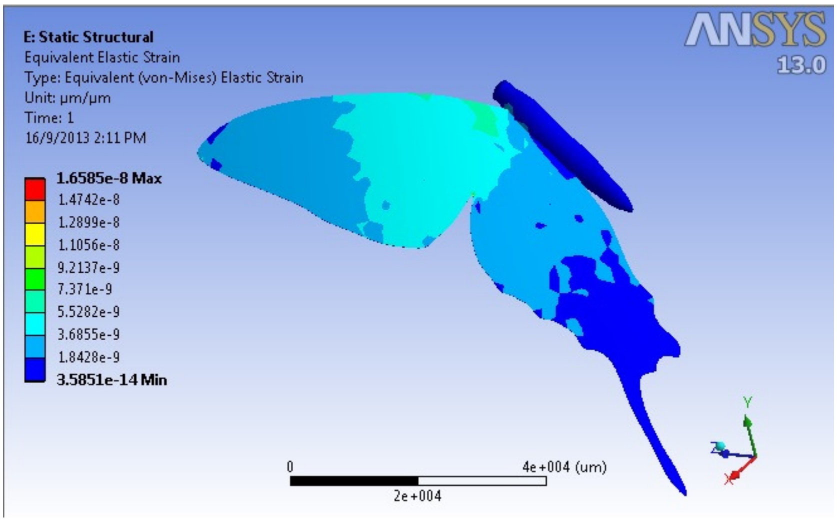
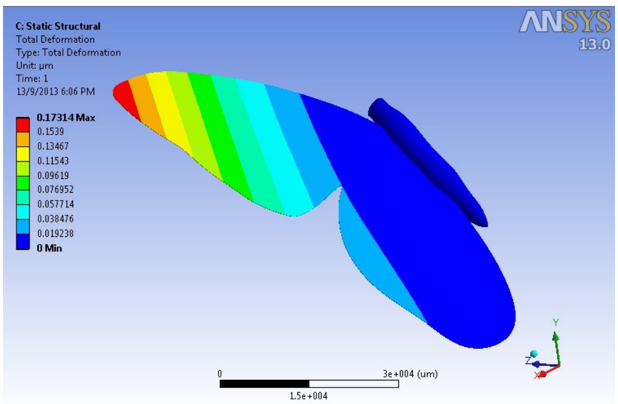


Fig.15: Equivalent elastic strain (von Mises strain) on Swallowtail butterfly



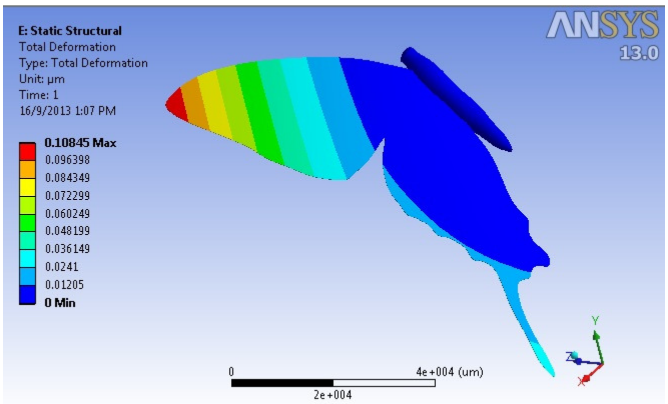


Fig.16 (left): Total deformation on Monarch butterfly

Fig.17 (left): Total deformation on Swallowtail butterfly