Insect-Inspired Micro Air Vehicles

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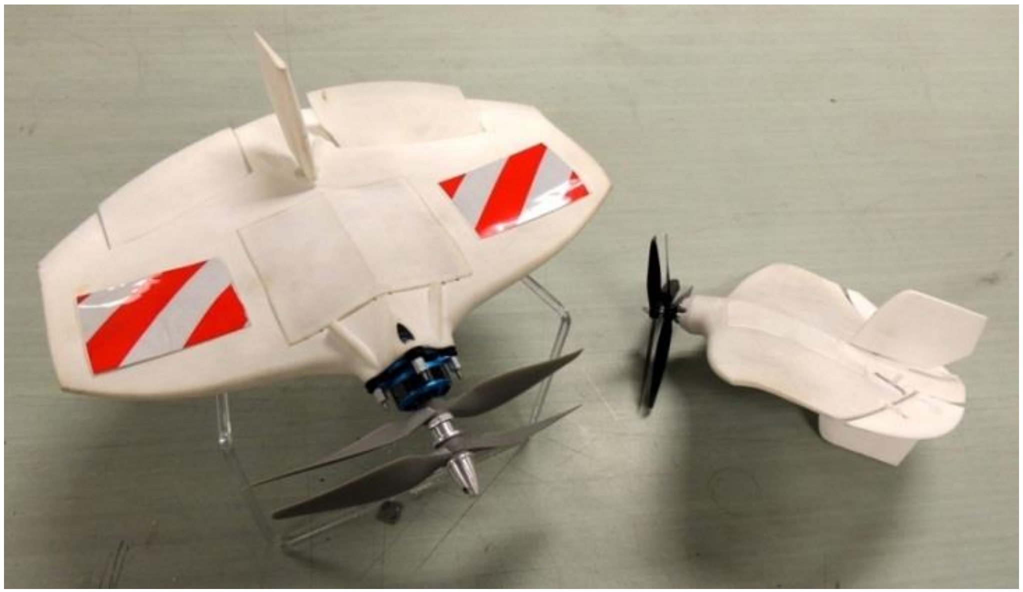
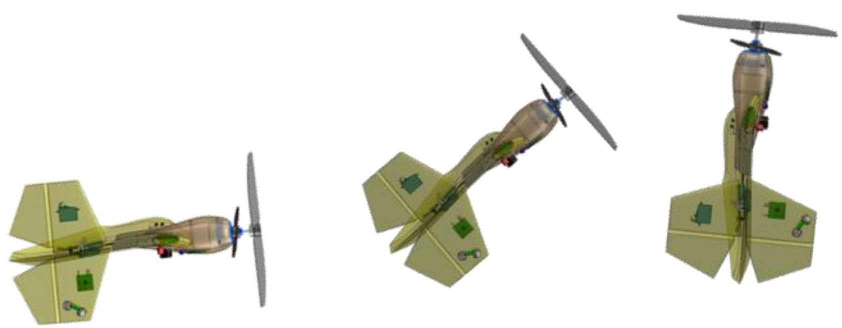
A new closed-return subsonic wind tunnel was recently installed. The facility has a 0.91 by 1.21 m test section and a maximum tunnel speed of ~80 m/s.

The MAV wind tunnel is a closed-loop facility that is capable of airspeeds up to 20 m/s. The tunnel test section is contained within a small room. The nozzle outlet is 0.35 m by 0.45 m

VTOL MAVs

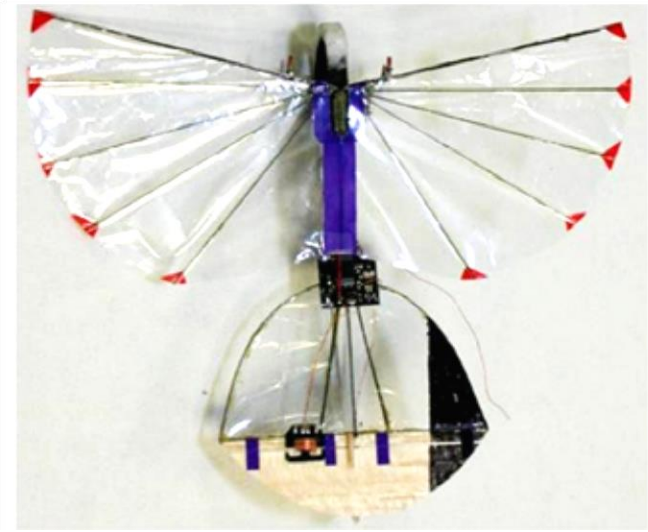


- VTOL MAVs, 12-20-cm wing span
- V = 0-35 MPH, T = 20 min
- Propulsion using contra-rotating propellers and motors
- Autopilot, GPS, sensors



Insect-Inspired MAVs

Locusts (criquet)

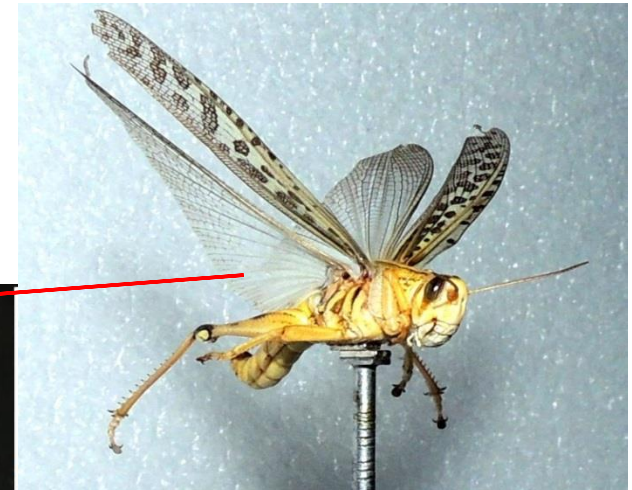


Flapping-Wing MAVs

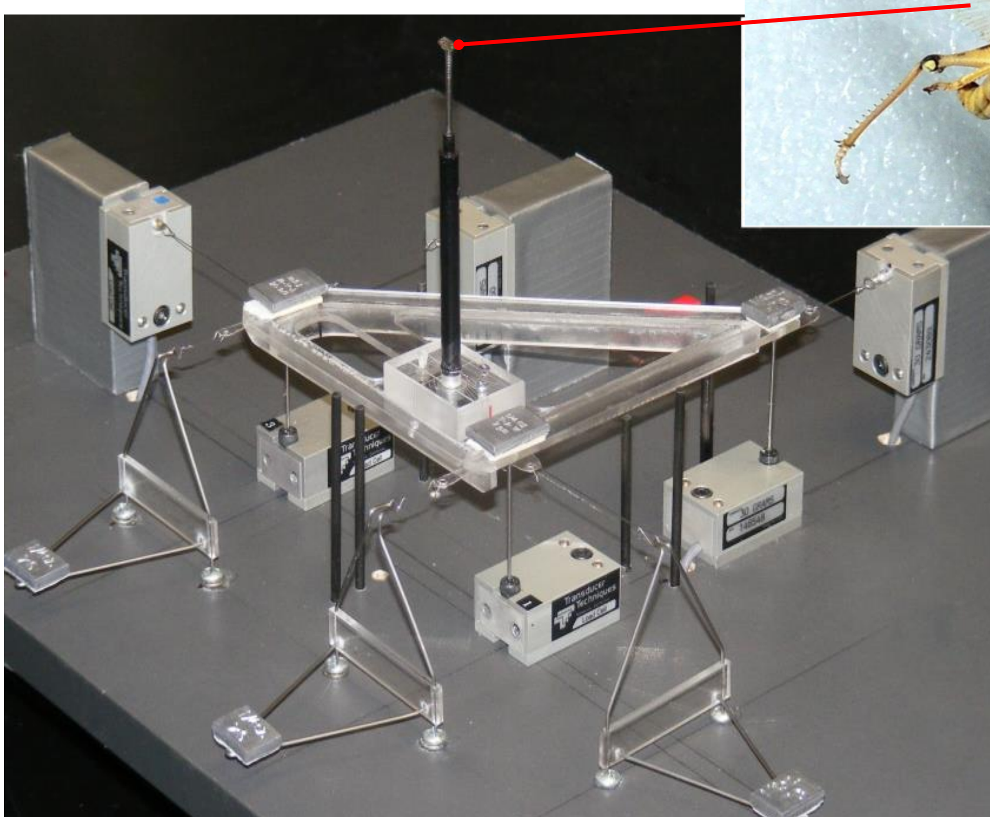
Autonomous
10 cm wing span, W = 2 g
f = 25 Hz, V = 2-4 m/s
flying, walking, jumping
independent control of all wings
wing fold-up
T = 8 hours

?

Kinematics and Force Measurement on Live Locusts



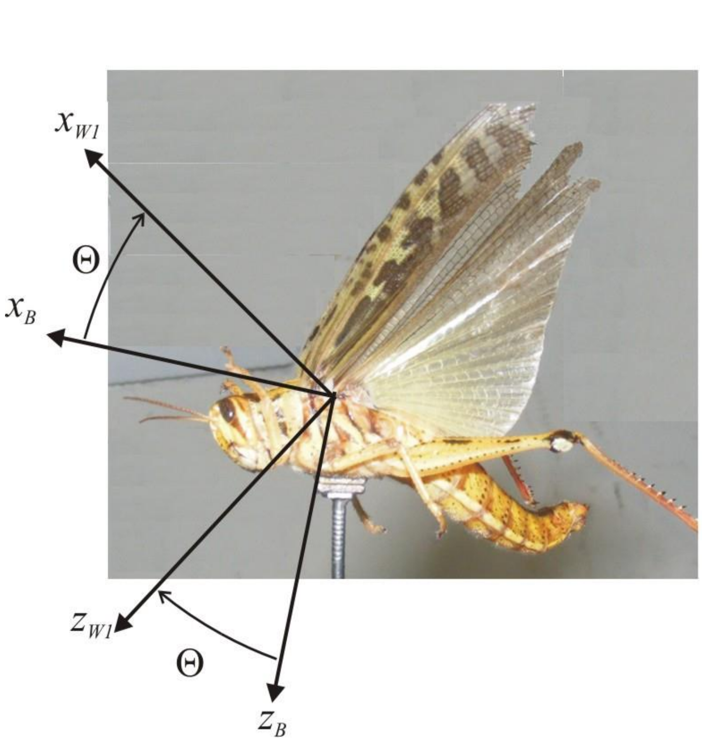
Custom microbalance

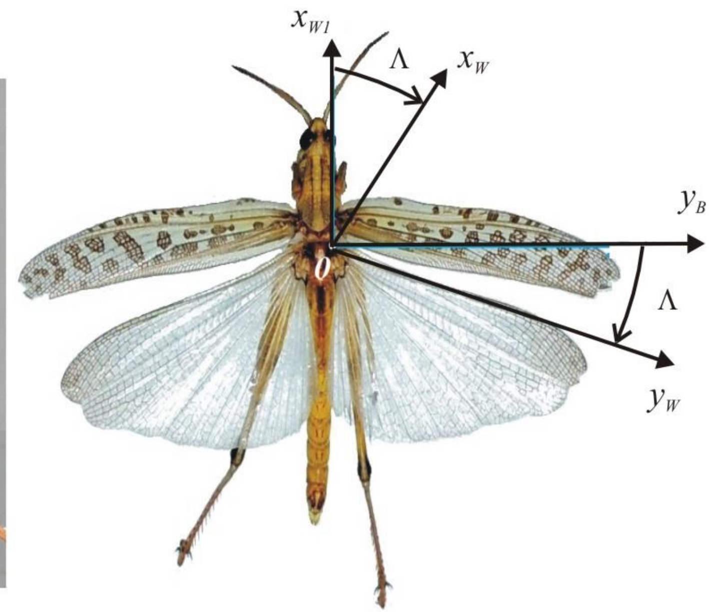


- 6 Load cells, GSO 30 series
- Resolution 5 mg
- Phantom 9.1 cameras at 1,000 fps

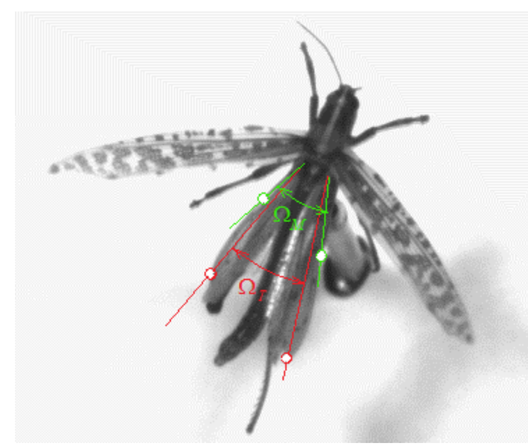
Level flight: Inclination and Sweep Angle

U = 4 m/s, AOA=7 deg., f = 18.5 Hz





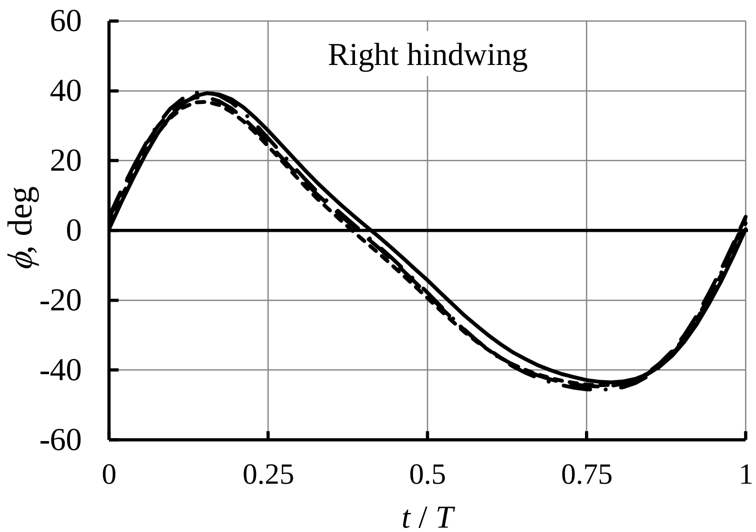
	Forewings	Hindwings
Inclination angle, Θ, deg.	19	19
Sweep angle, Λ, deg.	12	30



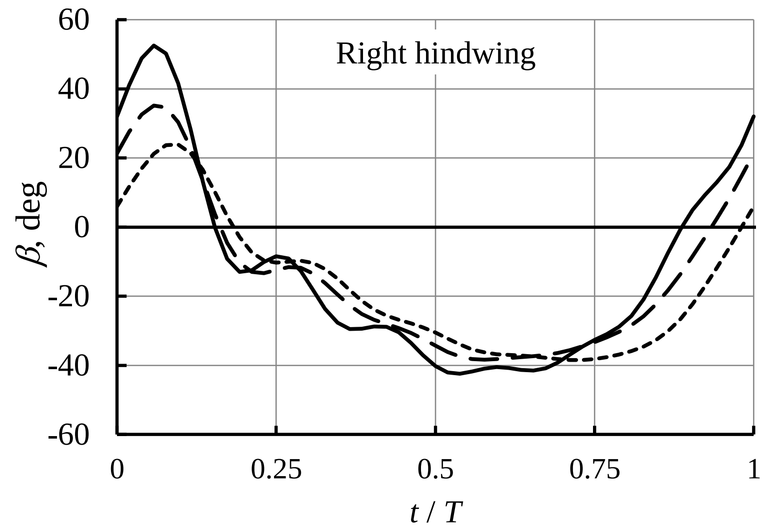
- Swept back hindwings are brought closer together at the highest point initiating clap-and-fling mechanism of aerodynamic forces production

Level Flight: Flapping and Pitching Angles

U = 4 m/s, AOA=7 deg., f = 18.5 Hz



$\Delta\phi_{0.25b}$ = 81 deg

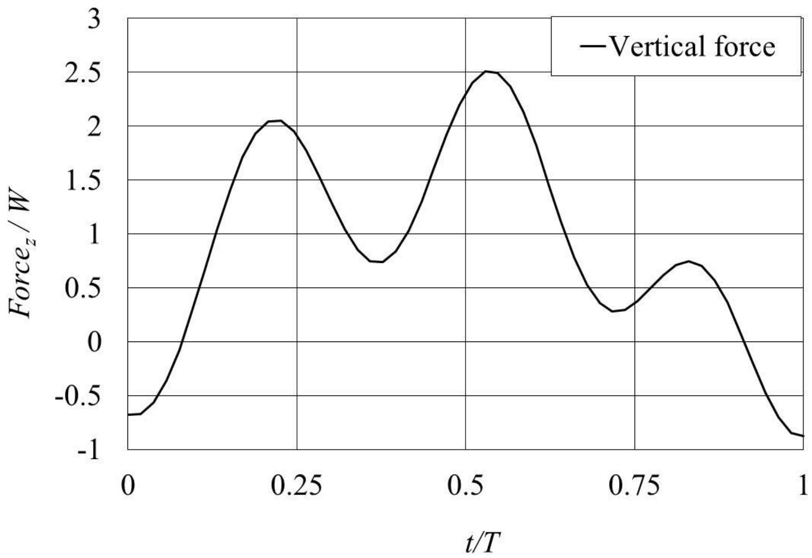


$\Delta\beta_{0.25b}$ = 62 deg

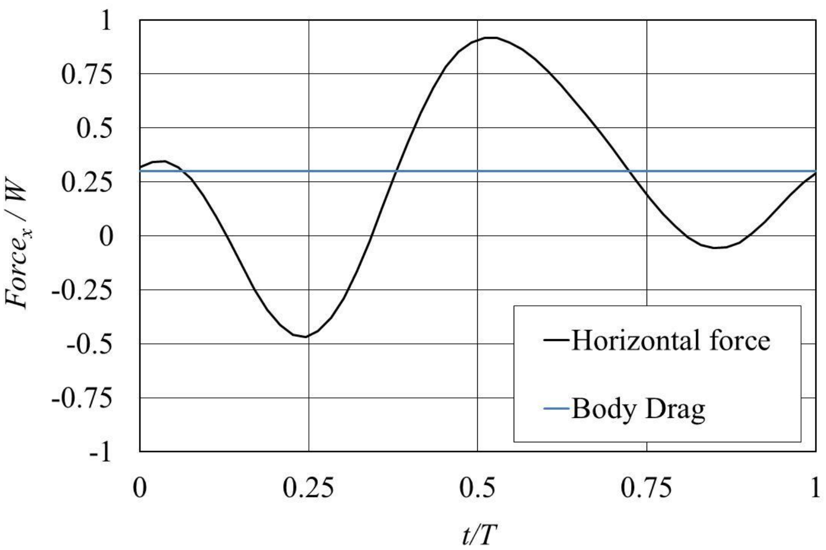
- There is a significant spanwise twist: for hindwing $\omega_{0.25b\,-\,0.75b}$ = 32 deg.
- Phase shifts are found in flapping and pitching angles and in fore- and hindwings

Level Flight: Aerodynamic and Inertial Forces

U = 4 m/s, AOA=7 deg., f = 18.5 Hz



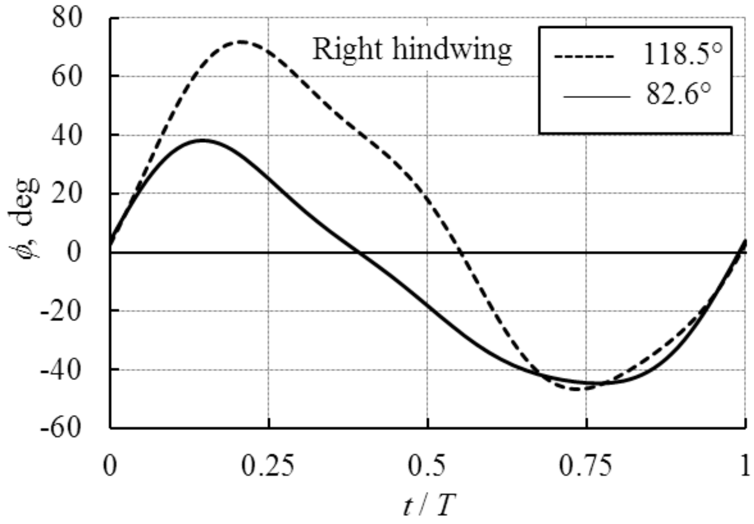
$L_{aver.}$ = 0.917



$R_{x\,aver.}$ = -0.091, $T_{aver.}$ = 0.234

- Body and legs drag diminish horizontal force in significant way

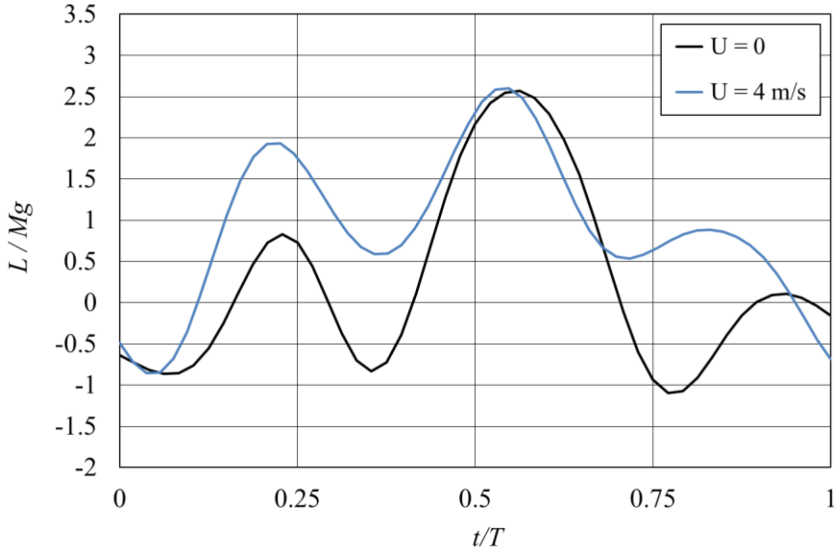
Level Flight vs No-Wind: Flapping Angle

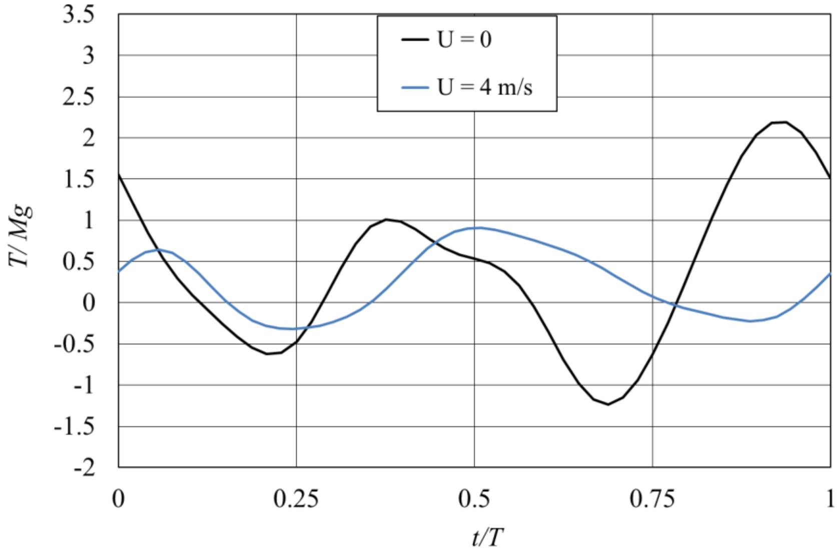


(*Solid line: U* = 4 m/s, *Dashed line: U* = 0 m/s)

- Angular amplitudes are larger in still air
- In level flight, flapping angle in hindwing leads flapping angle in forewing by 0.1 T, while in still air by 0.2T

Level Flight vs No-Wind: Thrust and Lift

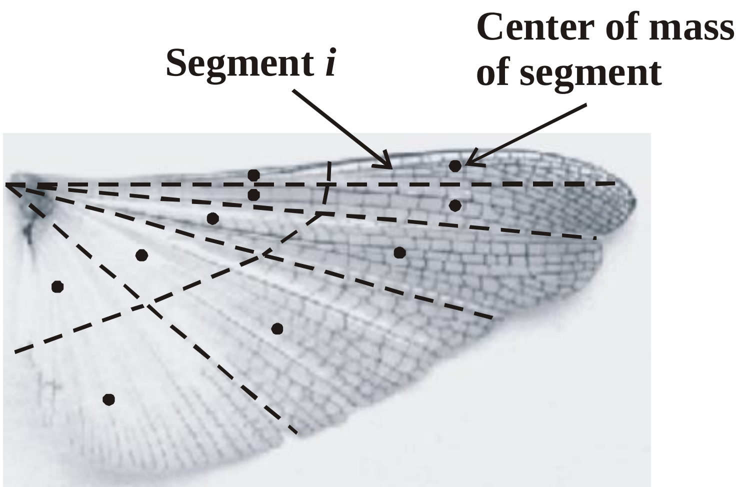


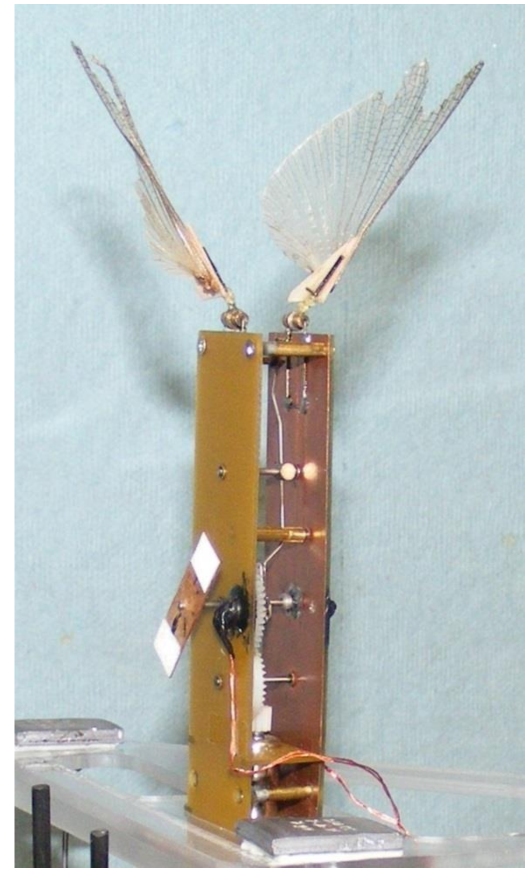


	Stroke-averaged forces		
U, m/s	Thust	Lift	Resultant
4	0.240	0.904	0.936
0	0.402	0.258	0.478

- Despite larger flapping and pitching amplitude, the resultant aerodynamic force is 2 times smaller at zero free stream velocity

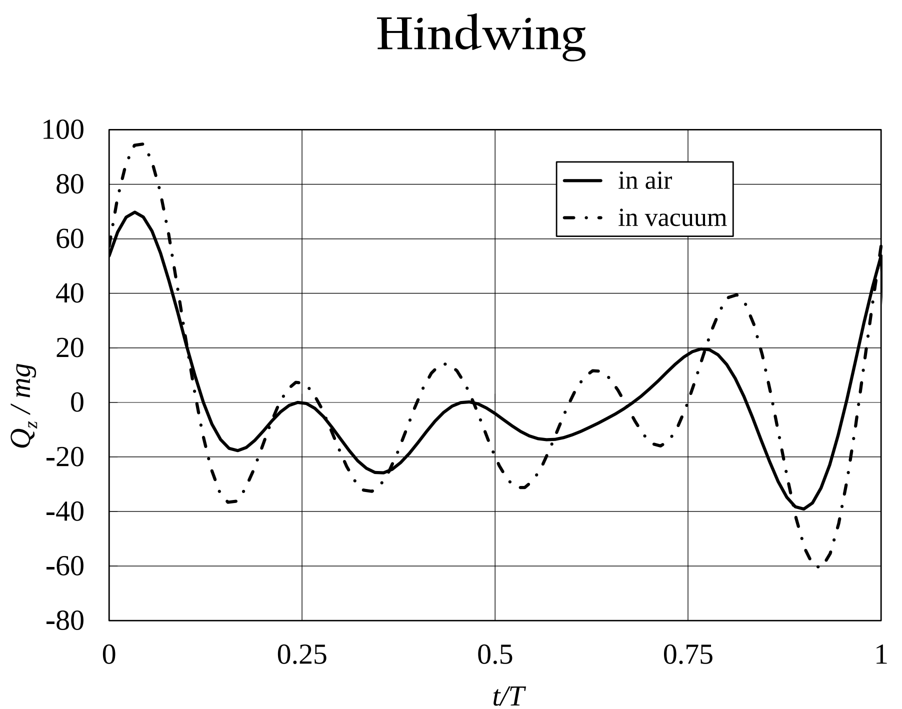
Locust Wing Testing in Air and in Vacuum





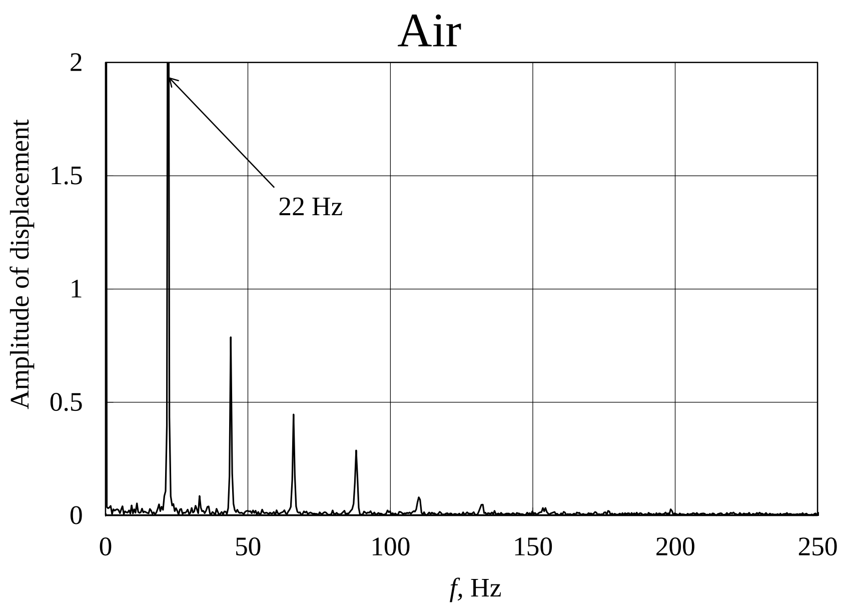
- Mass of each segment and coordinates of its center of mass were measured and averaged over eight wings. Ink markers were placed at center of mass
- Locust wing kinematics was quantified to design flapping-pitching transmission

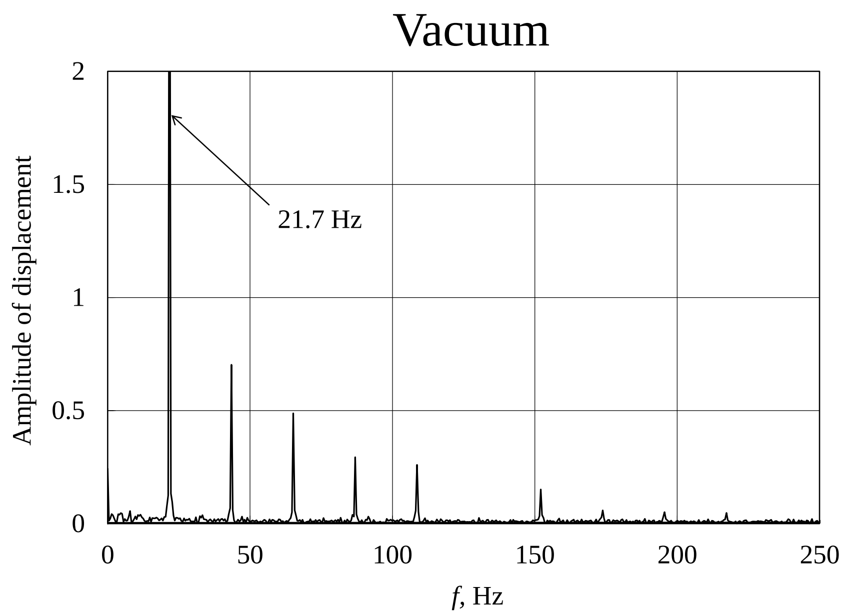
Inertial Forces in Air and in Vacuum



- Inertial forces generated by flapping motion of hindwings in vacuum are much higher than those in air, by 45%.

Spectral Analysis

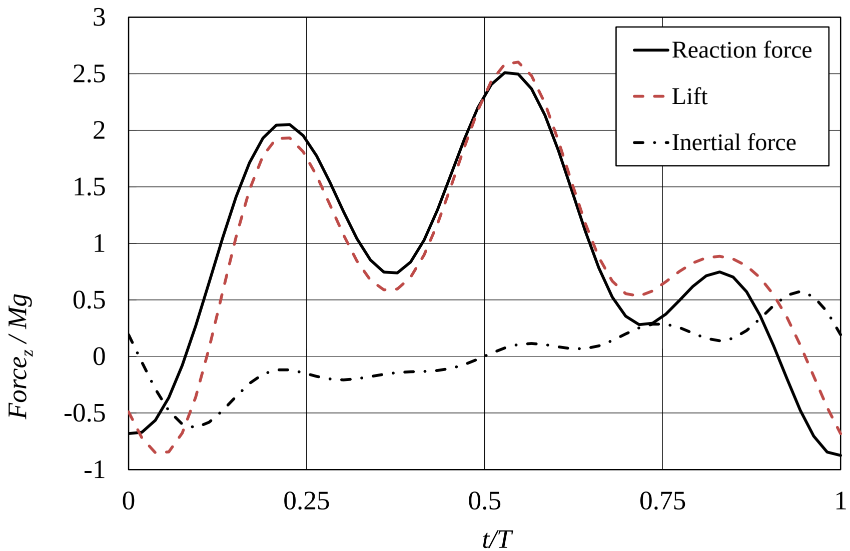


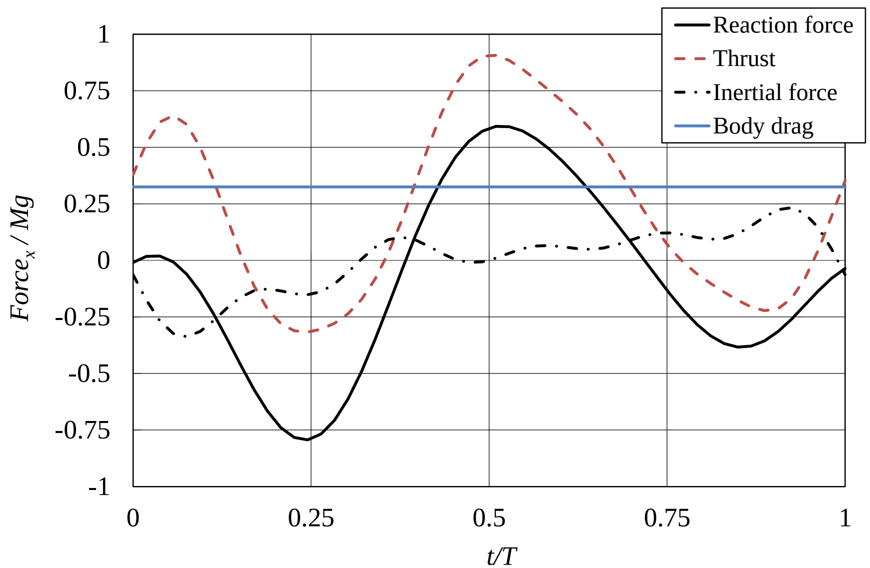


- For the same harmonic, displacement amplitudes in air and in vacuum are close to each other, except for the fifth and seventh harmonics, for which they are an order of magnitude higher in vacuum
- Consequently, it results in much larger contribution of higher harmonics to the peak-to-peak amplitudes of acceleration and inertial force in vacuum
- Thus, aerodynamic forces are damping high-frequency oscillations (fifth harmonic and higher) resulting in a substantial reduction of inertial forces in air

Level Flight: Aerodynamic and Inertial Forces

U = 4 m/s, AOA=7 deg., f = 18.5 Hz





$L_{aver.}$ = 0.917

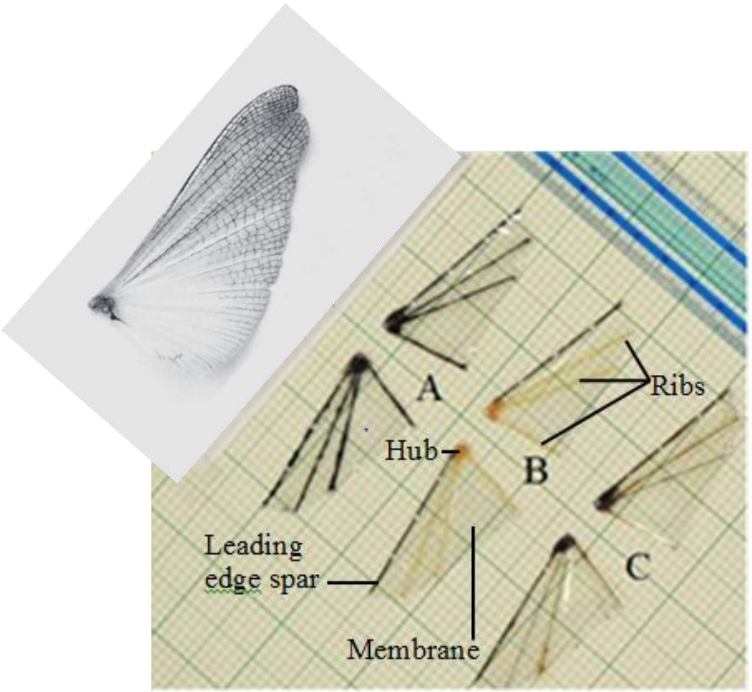
$R_{x\,aver.}$ = -0.091, $T_{aver.}$ = 0.234

Insect-Inspired Design Considerations

- Nature suggests a membrane-batten design, with a stiff leading edge spar in addition to radially-oriented stiffening elements, as observed in locusts
- The wing kinematics of locusts can be referenced to infer appropriate kinematics for MAVs of a similar scale

Is it possible to approximate complex wing kinematics using a simple system composed of a single motor and transmission mechanism?

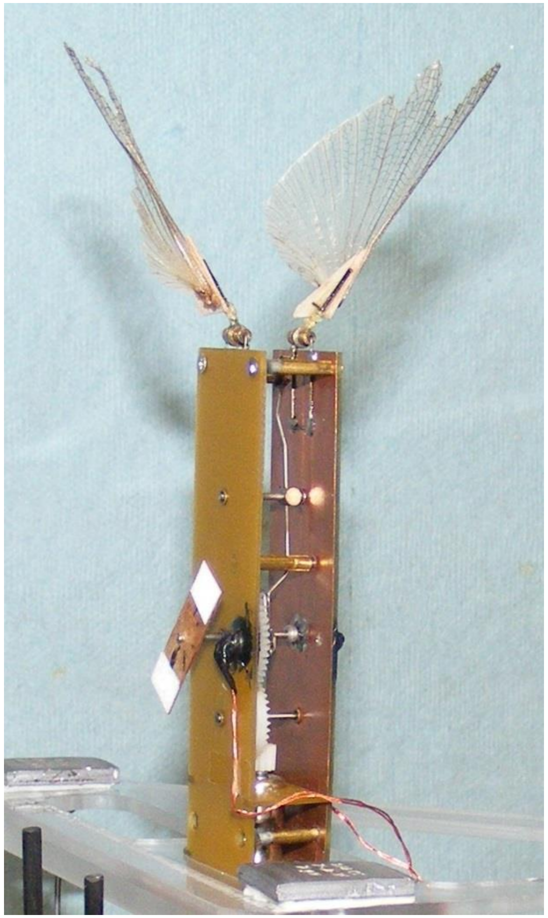
Flapping Wing Design



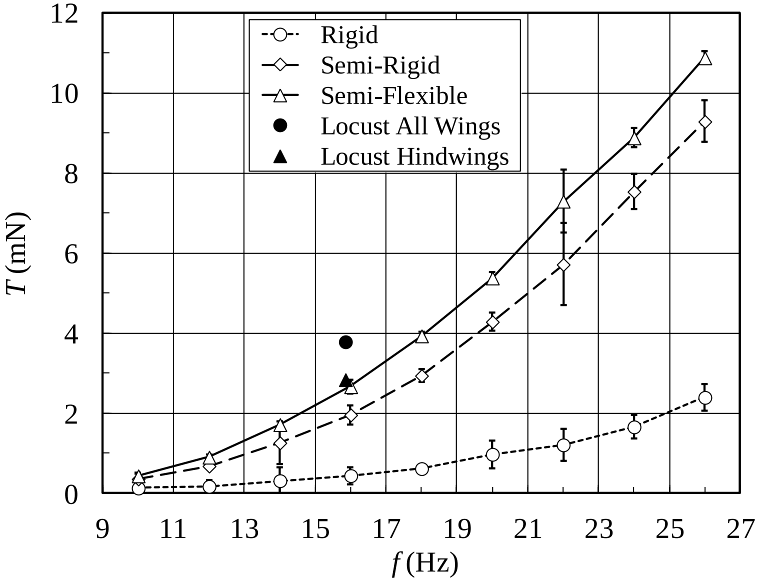
Art. Wing	Hub	Adhesive	Ribs (dia.)	Mass (mg)
Rigid (A)	Balsa Wood	Speaker Cement	Carbon Rod (250 mm)	40.3
Semi-Rigid (B)	Balsa Wood	Epoxy	Kevlar Thread (150 mm)	31.2
Semi-Flexible (C)	Fiberglass	Rubber Cement	Music Wire (130 mm)	33.6

Parameter	Artificial	Locust
Wing Length (mm)	49	45.8
Max chord length (mm)	24	22.8
Planform Area (cm^2)	15.8	16.2
Aspect Ratio ($4R^2/S$)	6.1	5.2
Mass (mg)	31-40	14

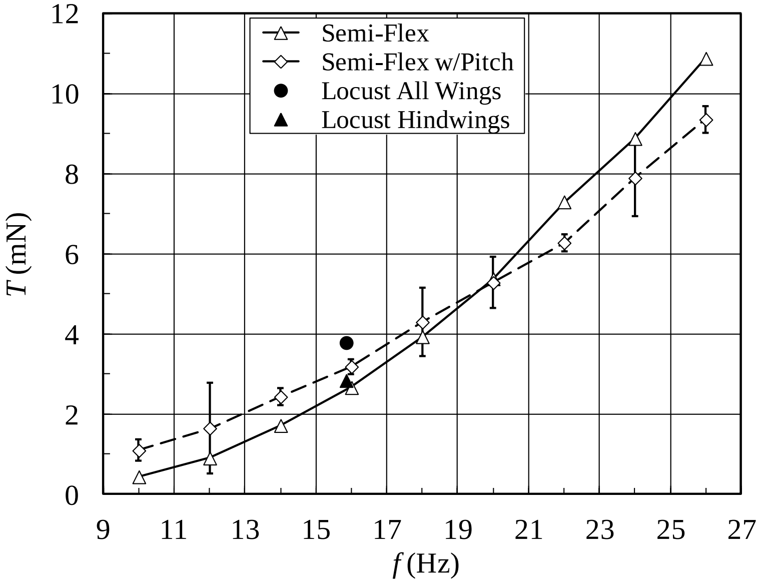
Artificial vs Locust Wings



Flapping

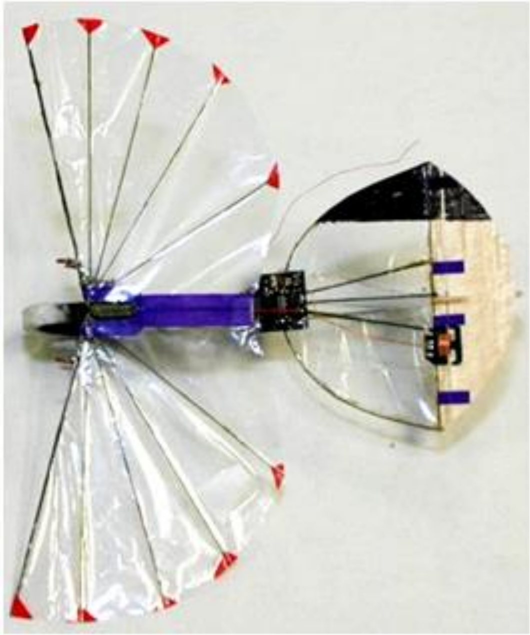


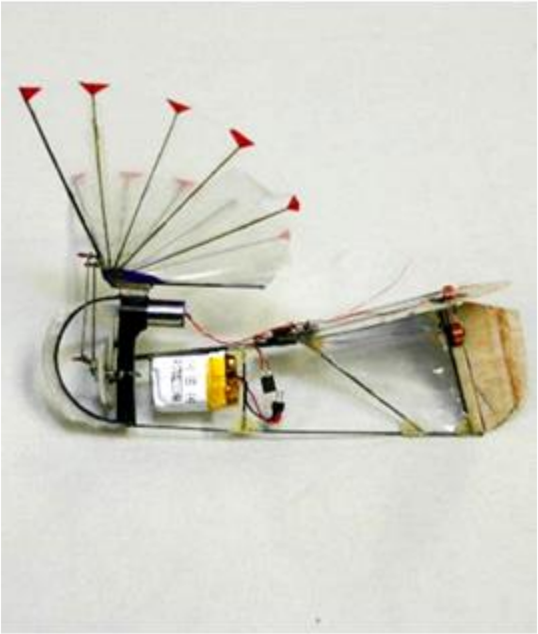
Flapping-pitching



- Two transmission were used: flapping and flapping-pitching

Flapping-Wing MAV

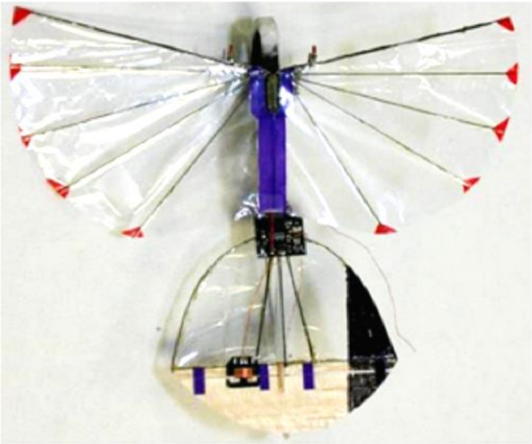




Component	Description	Mass, gram
Flapping wing	0.3-0.5mm carbon rods	0.24
Tail assembly	0.3mm carbon rods	0.70
Gearbox	Didel M0.30mm gears	1.27
Electric motor	7mm Super Slick 2.2 Ohm	2.87
Actuators	Plantraco HingeAct	0.50
RC receiver	Deltang RX43	0.28
Battery	80mAh 3.7V Li-Po	2.30
Total		8.16

Locusts vs MAVs

Autonomous
10 cm wing span, W = 2 g
f = 25 Hz, V = 2-4 m/s
flying, walking, jumping
independent control of all wings
wing fold-up
T = 8 hours



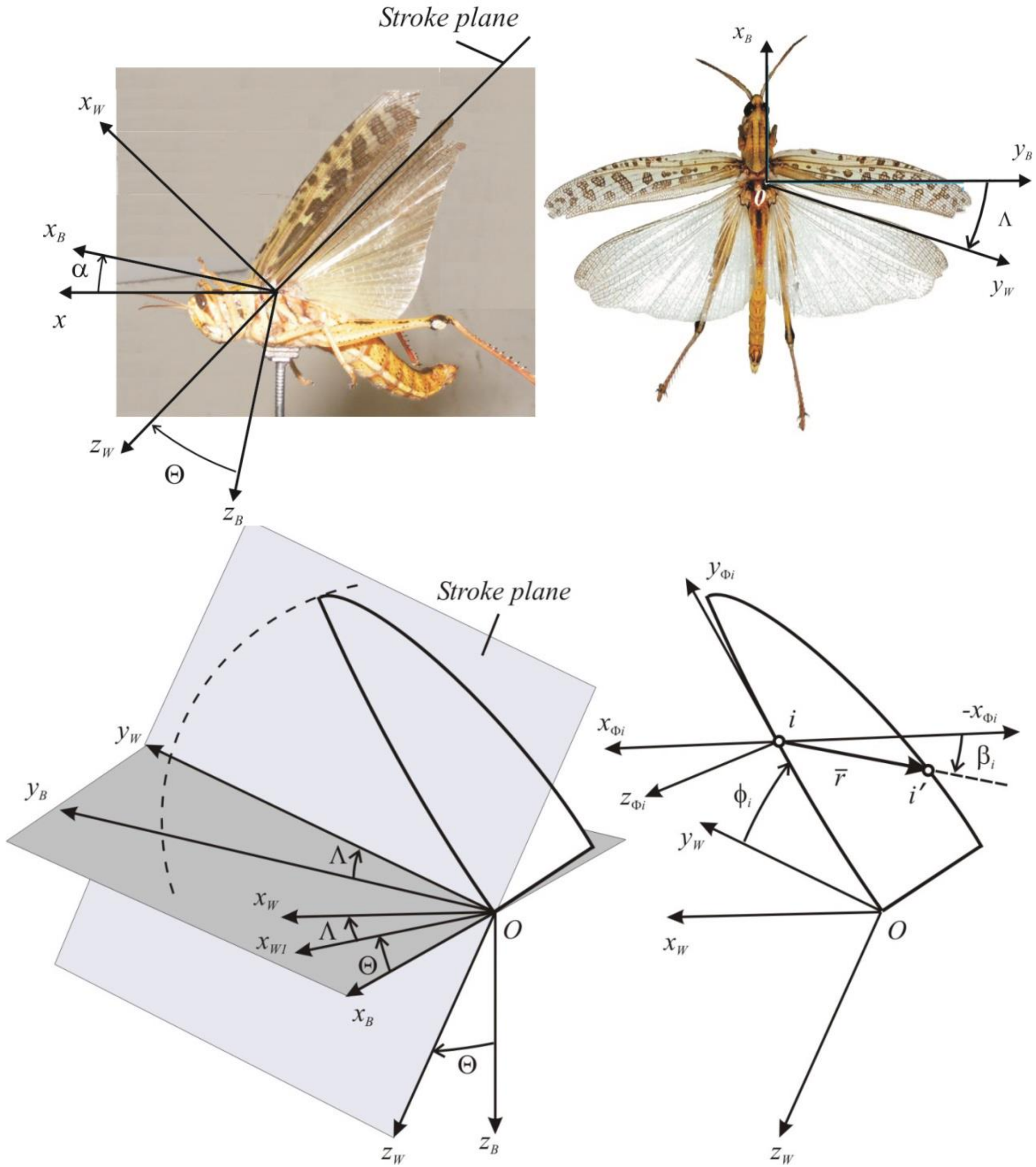
RC controlled
14 cm wing span, W = 8 g
f = 25 Hz, V = 2-4 m/s
T = 3 min

Thank you

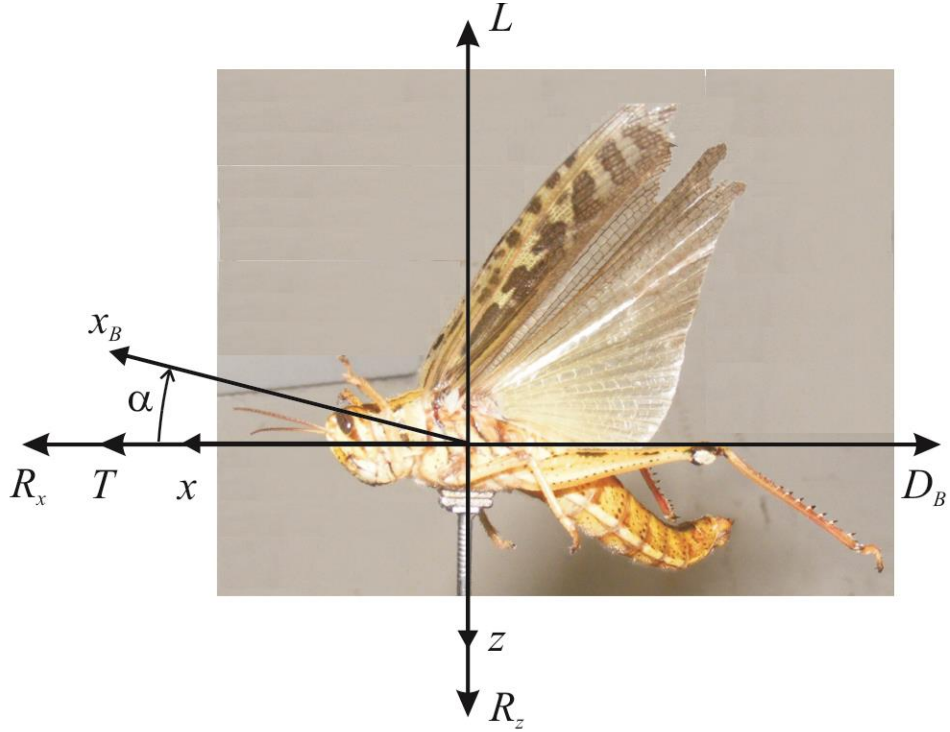
Concluding remarks

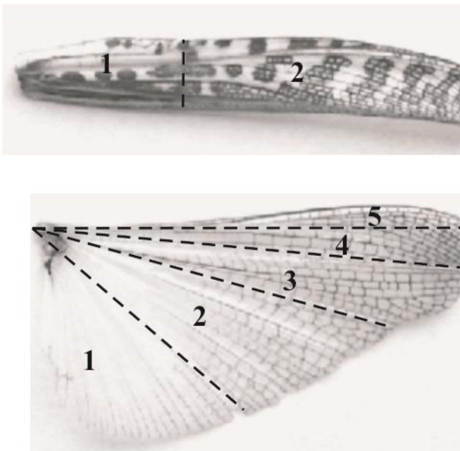
- ✓ This talk provided a literature review relevant to bio-inspired micro air vehicle design, with emphasis placed on flapping locust wings.
- ✓ Inertial forces and kinematics of freshly extracted wings of locusts, *Schistocerca americana*, were investigated experimentally.
- ✓ Competition between inertial and aerodynamic forces is examined. Aerodynamic damping of the wing tends to reduce the inertial forces.
- ✓ Live locusts were tested at level flight (U = 4 m/s) and no-wind conditions.
- ✓ The locusts flapped with much larger amplitudes both in flapping and pitching at no-wind condition. They generated more lift at reference velocity. However they generated very little lift at no-wind conditions. Locusts produced net drag except for no-wind condition, where they were able to generate net thrust.
- ✓ General ornithopter design and fabrication options are considered. Three sets of artificial wings are designed, constructed and tested.
- ✓ A 14-cm wingspan radio-controlled ornithopter is designed and built using some considered concepts. The aircraft was successfully tested in flight.

Kinematic parameters of flapping wings



Aerodynamic, Inertial, and Reaction Forces





Writing Newton's second law gives equations of motion of wings

$$T - D_B - R_x = \sum_{i=1}^{N} m_i \ddot{x}_i$$

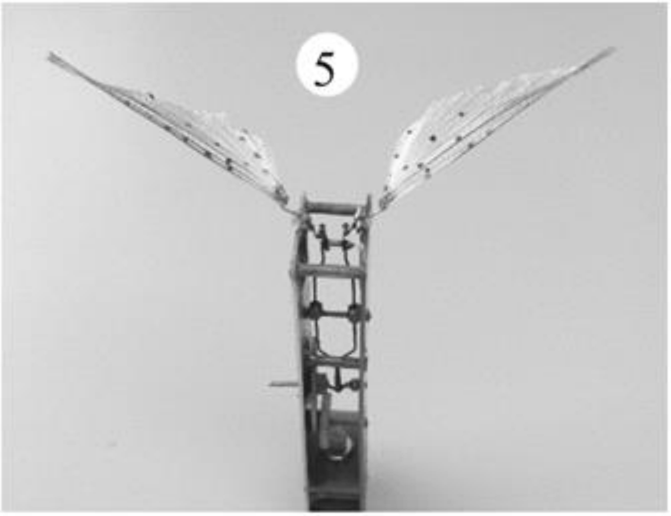
$$R_z - L = \sum_{n=1}^{N} m_i \ddot{z}_i$$

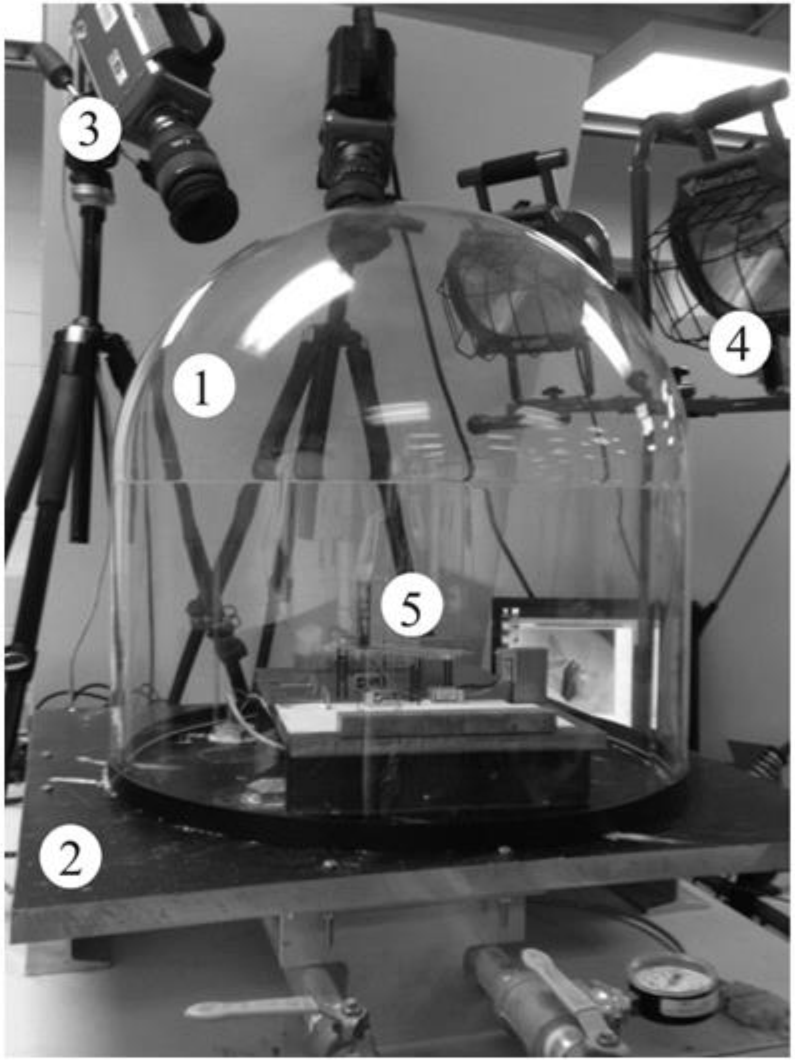
Lift and thrust can be found

$$T = D_B + R_x + \sum_{i=1}^{N} m_i \ddot{x}_i$$

$$L = R_z - \sum_{n=1}^{N} m_i \ddot{z}_i$$

Experimental Setup

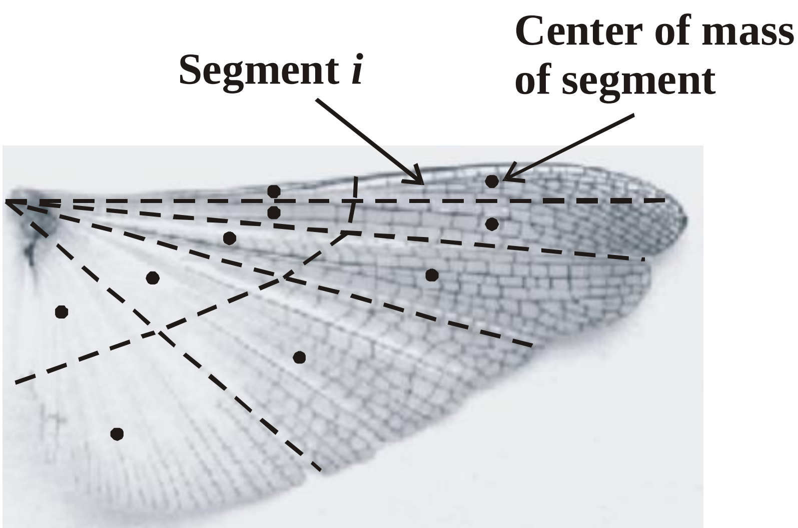




1) acrylic bell jar
2) aluminum base plate
3) Phantom v9.1 cameras
4) halogen lights
5) wings mounted
on transmission

Determination of inertial forces

Dynamic model of the flapping wing is introduced as a system of rigid segments or particles



Writing Newton's second law for a segment and summing equations over all segments obtains

$$F_x + R_x = \sum_{i=1}^{N} m_i \ddot{x}_i$$

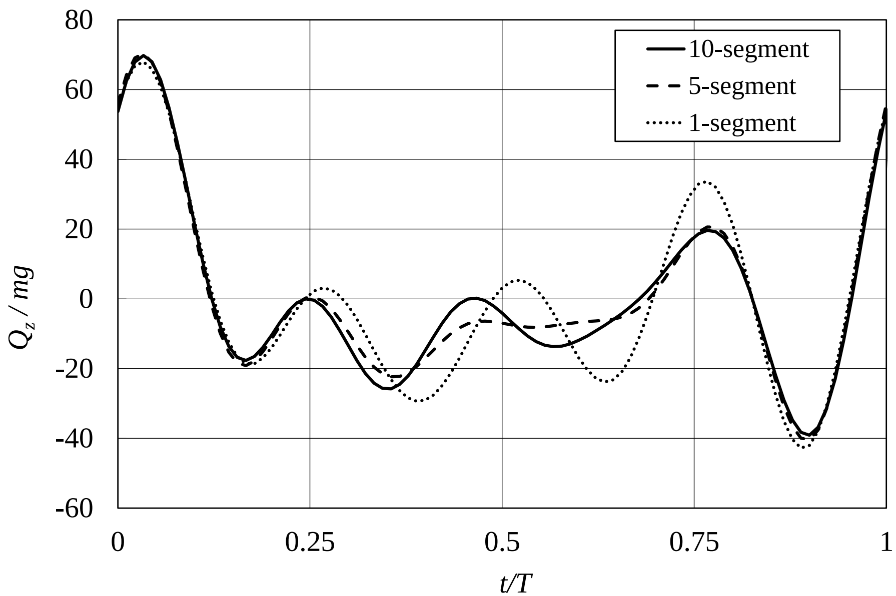
$$F_z + R_z = \sum_{n=1}^{N} m_i \ddot{z}_i$$

$$Q_x = -\sum_{i=1}^{N} m_i \ddot{x}_i$$

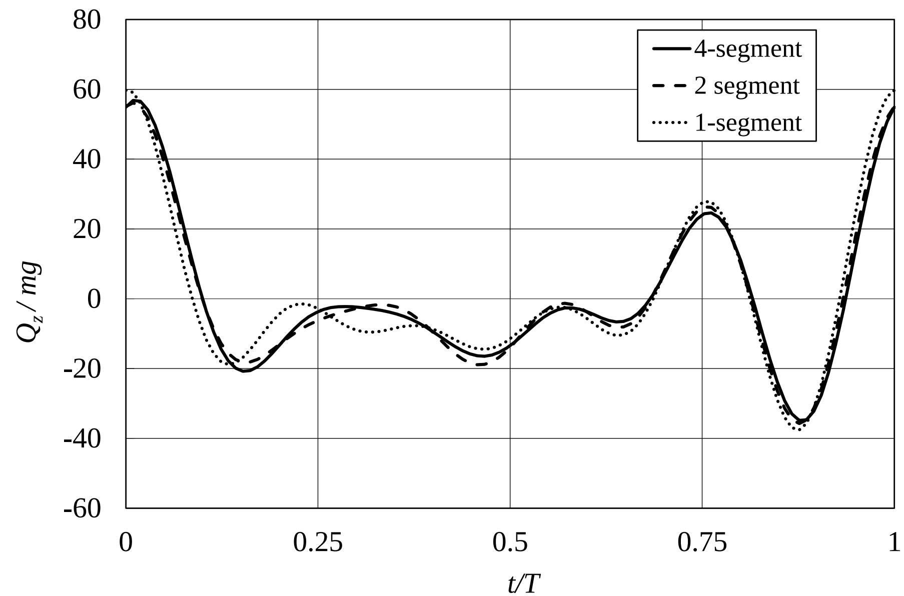
$$Q_z = -\sum_{n=1}^{N} m_i \ddot{z}_i$$

Time-resolved Inertial Force in Air

Hindwing

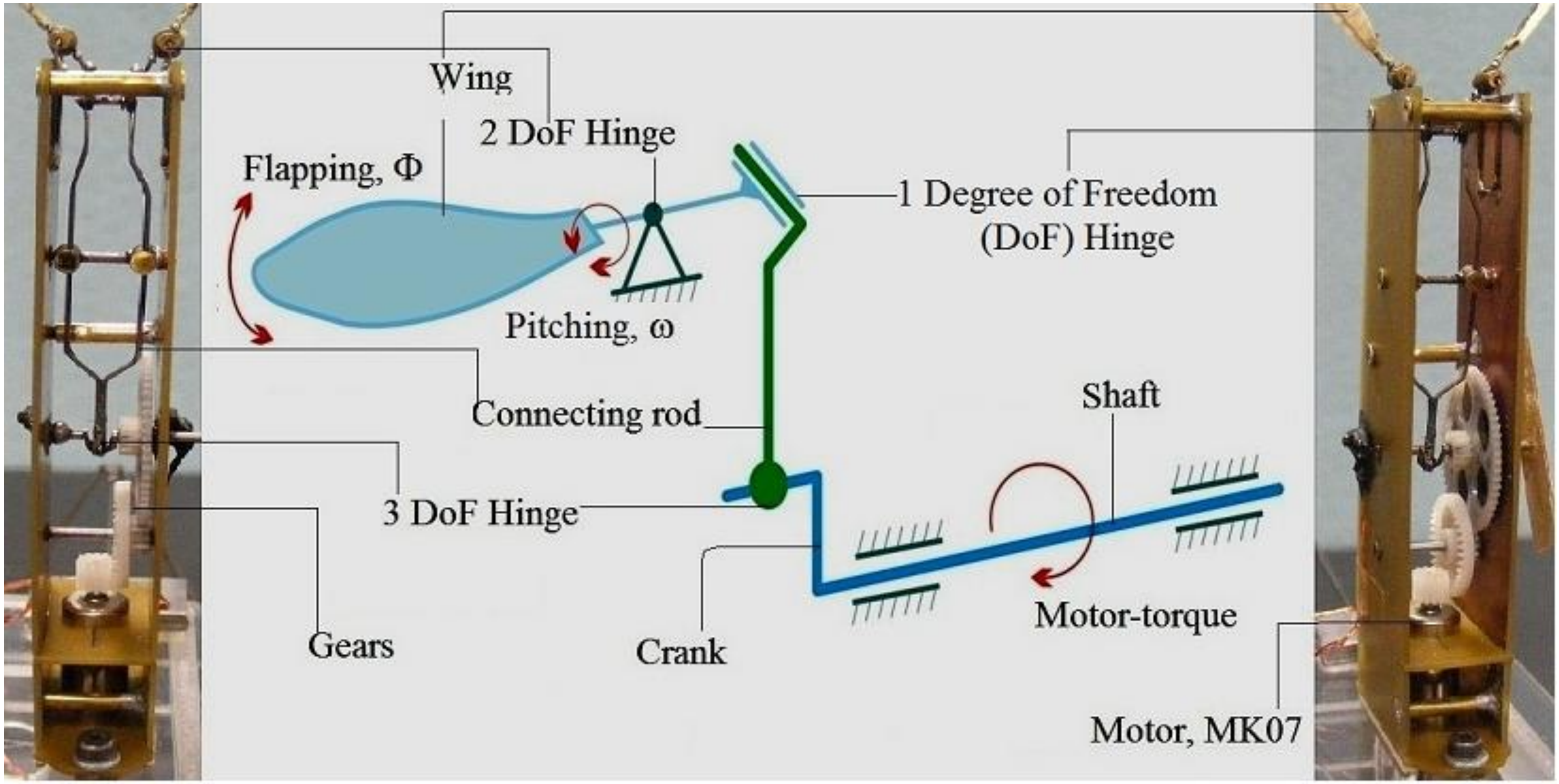


Forewing



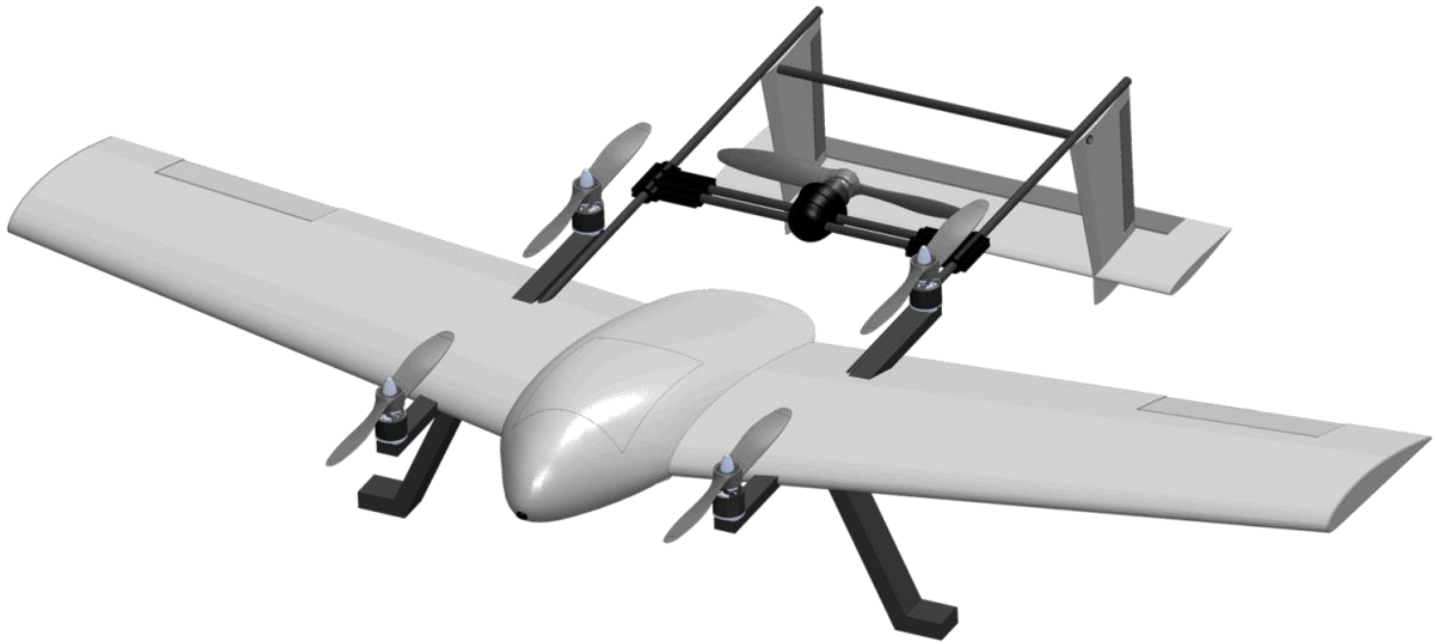
- Results obtained on the single-segment mesh, embracing the entire wing, deviate more from those obtain for two other meshes.
- Overall, the 5-segment mesh for hindwings and 2-segment mesh for forewings provide accurate determination of inertial forces.

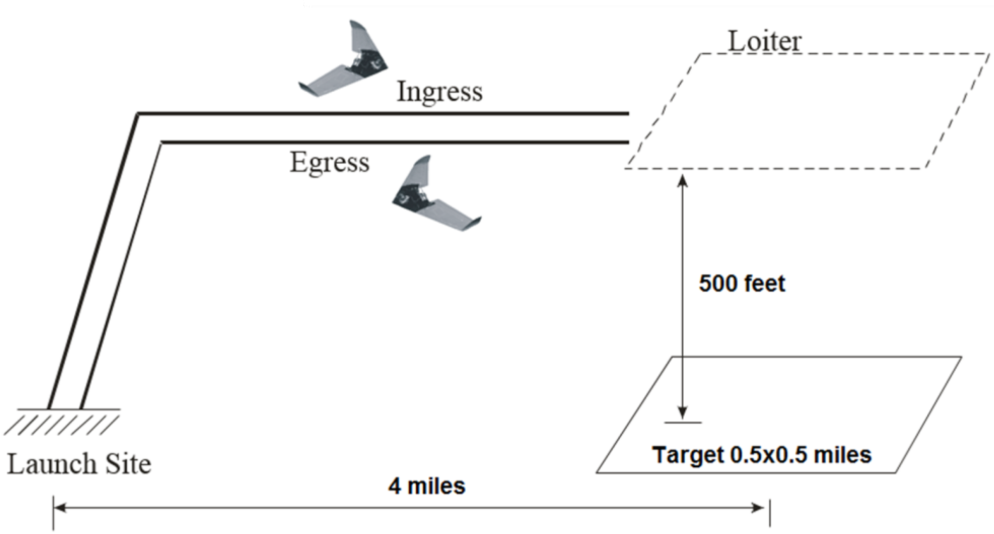
Kinematics of flapping-pitching mechanism



Actuated amplitudes: 66 and 85 deg for flapping and 60 deg for pitching

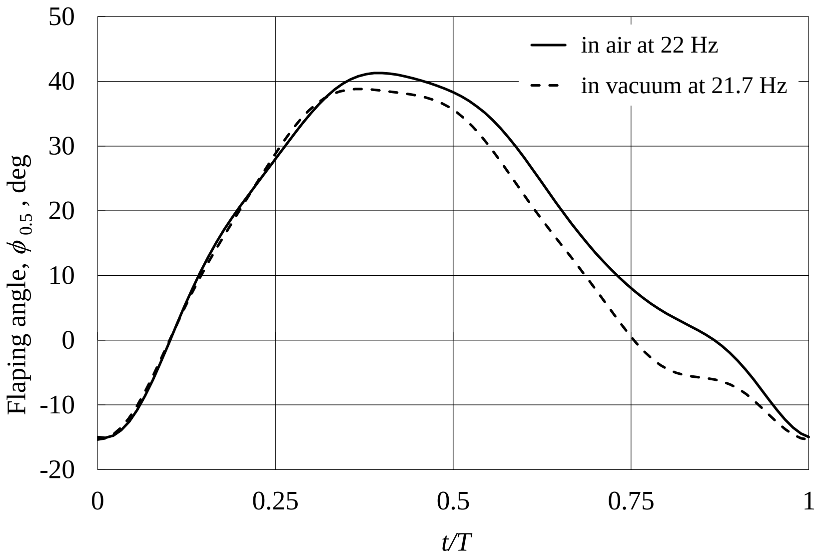
Hybrid UAVs

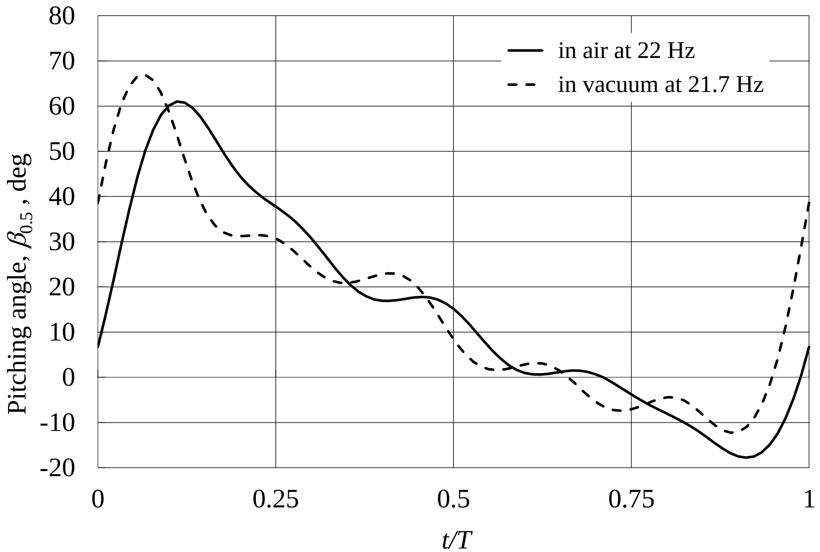




- Takeoff weight 5 kg
- Payload 1 kg
- Cruise speed 50 km/h
- Hover time 10 min
- Range 6 km

Time-resolved flapping and pitching angles in hindwings





- Time-resolved flapping and pitching angles are close in air and in vacuum