How Insects Fly

Based in the paper:

"Nonlinear time-periodic models of the longitudinal flight dynamics of the desert locust Schistocerca gregaria", Graham K Taylor and Rafal Zbikowski

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Abstract

In this work is introduced an alternative approach to simulate flight of insects. Based in the set of equations (Newton-Euler equations with four variables: position of the insect, horizontal and vertical velocity and angular velocity) to simulate a 2D flight which is similar to the one used for simulation of airplanes or helicopters. However, there is a significant difference in the part regarding to the production of forces. Basically, in this work are considered forces from wing flapping which will be considered in a simulation of a longitudinal flight. Data were taken from experiments; these data were fitted in Fourier series until the eight harmonic order. Once the Fourier series were representing forces, then the set of equations to simulate a flight were plugged with these Fourier series. A first simulation is done including the zero (Nonlinear time invariant model) and eight order harmonics(Nonlinear time periodic model). Simulation is starting at the quasi-static equilibrium adding a small perturbation in order to check stability. Finally, for the nonlinear time invariant system is being showed through a 3D plot how the position of the insect is changing with reference to the other three variables considered in the system.

Introduction

Many investigations have been done to analyze stability of aircraft which has been explored from different approaches. These approaches can be split in three ways: the first one based in experiments commonly cited as flow visualization and the second one based in a theoretical frame usually called computer fluid dynamics. Flow visualization requires of using complex and well-designed set up in order to recover information wanted while computer fluids dynamics requires of representative values in the coefficients which are part of the equations to simulate the system. In both ways a strong background is required and also an adequate interpretation of results would be important. However, there is an alternative approach which is simplified in terms of application and also with wide versatility. This third approach is called aircraft stability which in general follows a framework similar to the one used to study airplanes or helicopters stability.

Adapting aircraft stability to the flight of insects should be made since insects can fly by means of forces produced in the wings flapping. This implies that insects follow a particular kinematics. Wings can be widely studied since they represent just a minimum fraction of the total weight but producing enough force to lift up. But, in this work what matters from wings is the total force and/or moment produced.

Some characteristics

- All locusts are significantly different in sizes
- A typical locust flies in cruise speed of 4 m/s
- The span is around 0.1m
- It is flapping at 20Hz
- As any insect has 4 wings
  - 2 forewings which sweeps 110°
  - 2 hindwings which sweeps 70°
- A locust use its antennae and hair on the head to sense the air speed
- Center of mass is fixed (because 4% of the total weight is in the wings)
- Body is symmetric in the longitudinal axis

Newton-Euler Equations

This set of equations is important to say that simulation is going to consider a 2D simulation flight which is going to be longitudinal with respect to the insect. Formally, u and w are the velocity with respect to the horizontal and vertical axis correspondingly, q means the angular velocity with respect to the center of mass of the insect and θ is the angle with respect to the horizontal axis.

$$\dot{u} = -wq + \frac{X}{m} - g\sin\theta$$

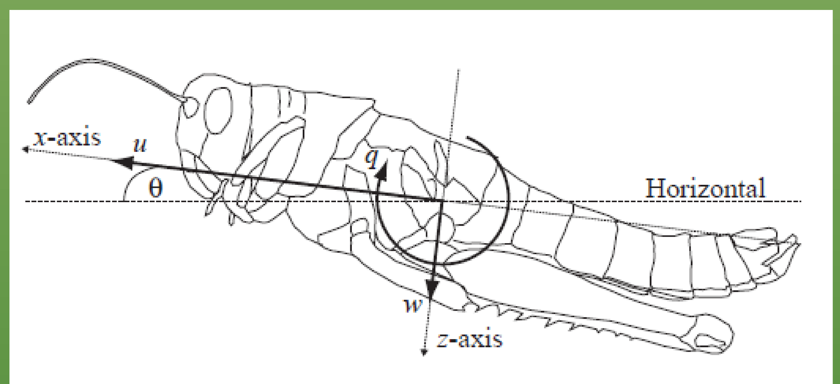
$$\dot{w} = uq + \frac{Z}{m} + g\cos\theta$$

$$\dot{q} = \frac{M}{Iyy}$$

$$\dot{\theta} = q$$

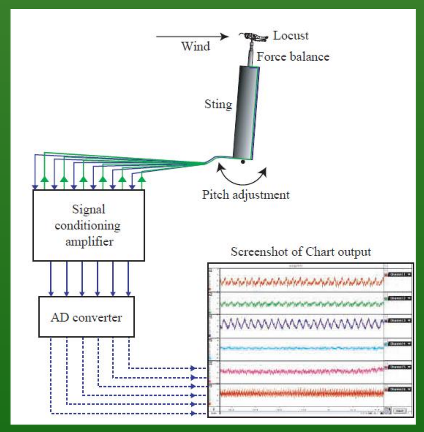
Some assumptions

- ❑Center of mass is fixed
- ❑Body is symmetric in the longitudinal axis
- ❑Four state variables
- ❑Constant mass, moment of inertia and gravity



From experiments

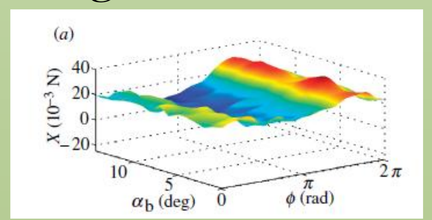
- ❑Three type of locusts
- ❑It is used a wind tunnel
- ❑Data collected under different angles (from 0 to 14 degrees)
- ❑Data collected under different velocities of the wind tunnel (from 2 to 5.5 m/s)
- ❑It was taking between 2-3h for collecting data for each locust



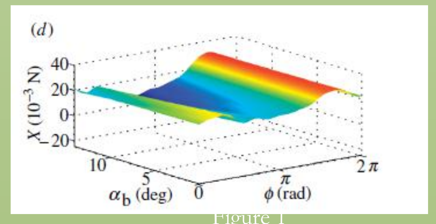
Results

- ❑Incomplete data in locust that failed in the experiment were discarded
- ❑A systematic variation in wing beat frequency will alter the dynamics
- ❑Data from experiments can be well fitted in Fourier series using until the eight harmonics order.

Original data

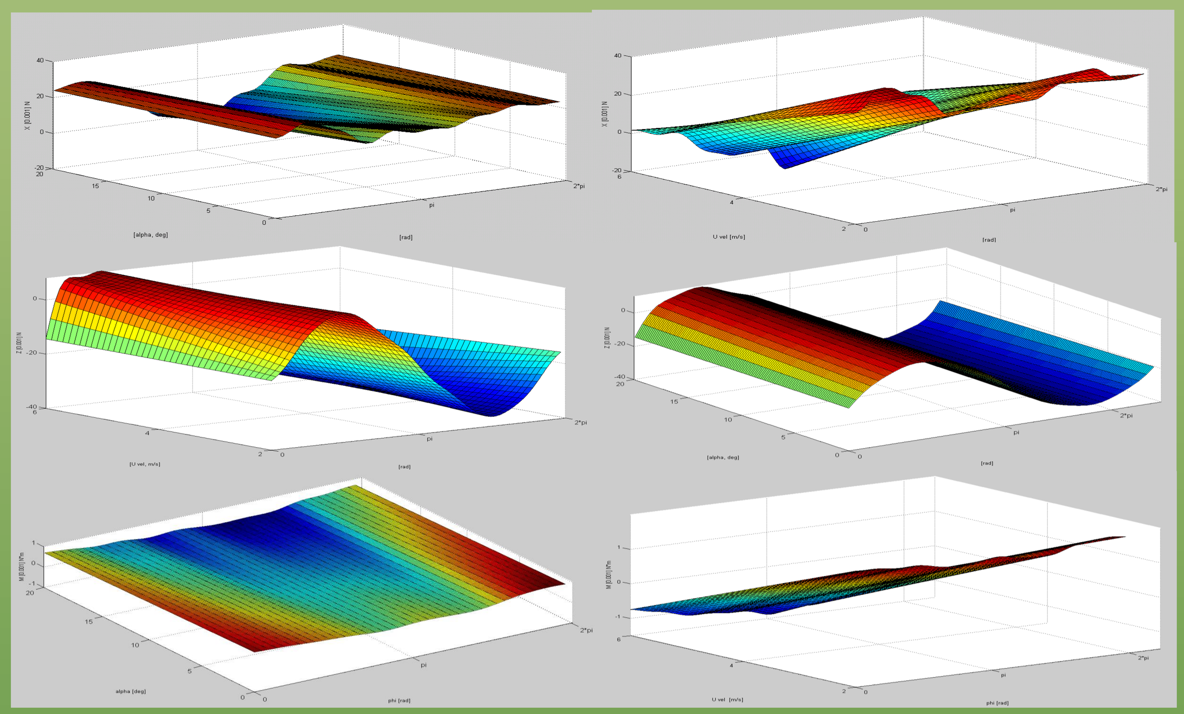


Fourier series data



Plot reproduced for the X and Z forces and M moment for one wing beat period

At different angles (α) | At different values of U velocity



Fourier Series and modeling

$$P(t) = \sum_{n=0}^{h}(a_n \cos n\omega t + b_n \sin n\omega t)$$

- ❑Nonlinear time invariant (NLTI) model just considering the zero harmonics
- ❑Nonlinear time periodic model (NLTP) considering until the eight harmonics

Equations used to represent forces and moment

$$P(\alpha, U, t) = P_{ref}(t) + P_{\alpha}(t)(\alpha - \alpha_{ref}) + P_U(t)(U - U_{ref})$$

where P involves a vector with the forces:

$$P = [X, \quad Z, \quad M]$$

New set of equations:

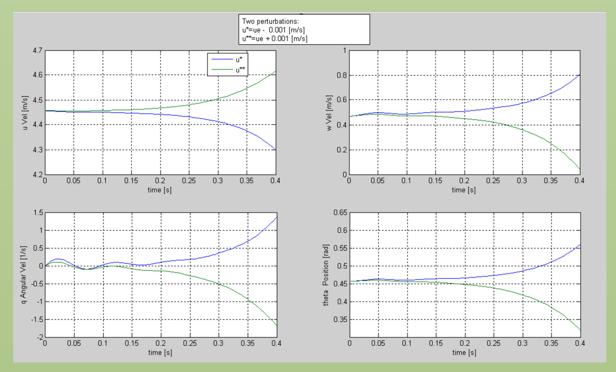
$$\dot{u} = -wq + \frac{X_{ref}(t)}{m} + \frac{X_{\alpha}(t)}{m}\left(tan^{-1}\frac{w}{u} - \alpha_{ref}\right) + \frac{X_U(t)}{m}\left(\sqrt{u^2 + w^2} - U_{ref}\right) - g\sin\theta$$

$$\dot{w} = uq + \frac{Z_{ref}(t)}{m} + \frac{Z_{\alpha}(t)}{m}\left(tan^{-1}\frac{w}{u} - \alpha_{ref}\right) + \frac{Z_U(t)}{m}\left(\sqrt{u^2 + w^2} - U_{ref}\right) + g\cos\theta$$

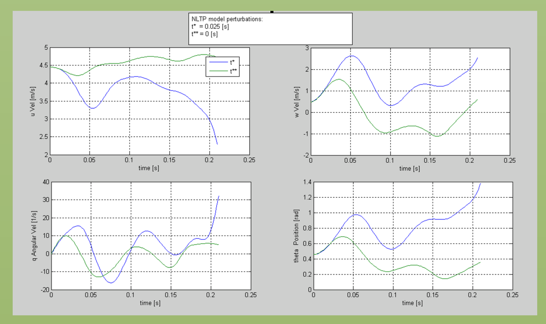
$$\dot{q} = \frac{M_{ref}(t)}{I_{yy}} + \frac{M_{\alpha}(t)}{I_{yy}}\left(tan^{-1}\frac{w}{u} - \alpha_{ref}\right) + \frac{M_U(t)}{I_{yy}}\left(\sqrt{u^2 + w^2} - U_{ref}\right)$$

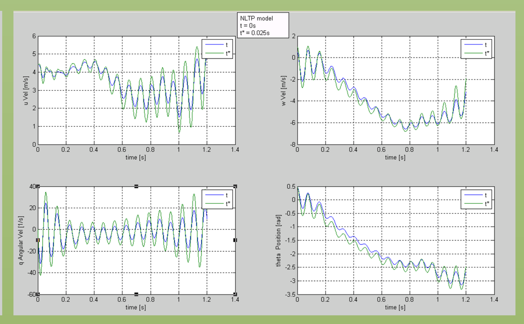
$$\dot{\theta} = q$$

Response for locust type "R" to minimum changes in the horizontal velocity for the Nonlinear time invariant model (NLTI)



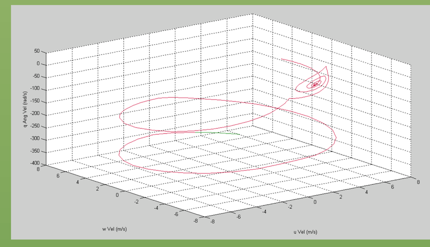
Response to two different locusts to minimum changes in the initial value of time for the Nonlinear time periodic(NLTP) model.

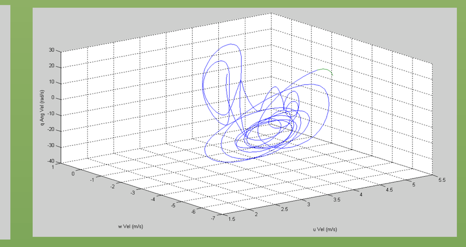




Locust type "R" | Locust type "G"

How the value θ is changing with respect to the other variables (u, w and q):





Locust type "R" | Locust type "G"

Discussion and conclusions:

Since the model is based in forces recorded, it is suspicious that forces do not represent a real free flight. This is possible since several factors were limiting it; for instance, forces were not accurate because of the instruments used, the insect can have different reactions under this "altered conditions" to simulate the flight. Additionally, some assumptions were made as the gravity, weight and moment of inertia are constant which is not true and it is easily noticed how change the moment of inertia because of the flapping.

Additionally, when the experiments were performed, there was a recording of forces in an open loop. Under this situation, it is assumed that the insect does not control the flight, which is not true. Then forces to manipulate the flight might already be included in the set of data given in the Fourier series; however so far it is not possible to obtain those forces apart.

References:

Graham K Taylor, Adrian L. R. Thomas. 2003 "Dynamic flight stability in the desert locust *Schistocerca gregaria*" Journal of Experimental Biology 206, 2803-2829

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