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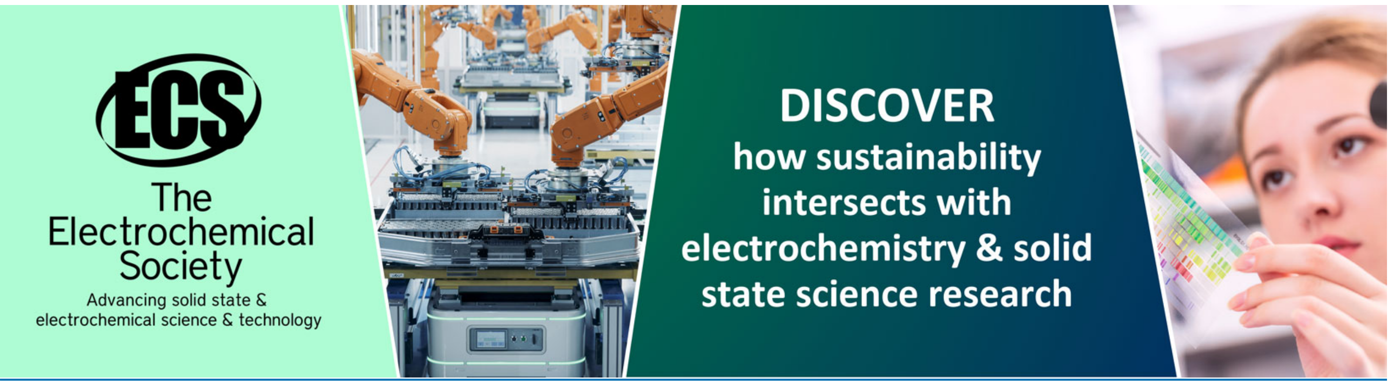

Effect of asymmetry in the restoring force of the "click" mechanism in insect flight

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Abstract. The aim of this paper is to examine the effect of asymmetry in the force-deflection characteristics of an insect flight mechanism on its nonlinear dynamics. An improved simplified model for insect flight mechanism is suggested and numerical methods are used to study its dynamics. The range at which the mechanism may operate is identified. The asymmetry can lead to differences in the velocity in the upward and downward movements which can be beneficial for the insect flight.

1. Introduction

In insects with indirect flight muscles, the muscles are not connected directly to the wing but they cause a deformation of the thorax. This deformation causes movement of the wings. One of the models that is suggested for the dipteran flight mechanism is called the 'click' mechanism and is described by Thomson and Thompson [1]. There is disagreement about the function of the flight mechanism in dipteran between the researchers, e.g. look at [2-4]. A mathematical model of the click mechanism is adopted by Brennan et al. [5] and its nonlinear dynamics is investigated with a linear damping. A nonlinear damping for the same mechanism is considered in reference [6]. The force-displacement of the model they used was symmetric about the mid position of the wings. However, the force-displacement of the flight mechanism of an insect can follow different paths in the up and down strokes due to two reasons; first, the deformation of the thorax can cause a change in parameters that characterize the click mechanism, e.g. the length between the joints; second, axial loads in supporting structures can have either a hardening or softening effect depending on their direction. The notum and wing process act as the springs of the click mechanism which provide the lateral restoring forces. As they also support the linkages, axial loads develop in them. The direction of axial loading, i.e. tension or compression, changes during the up and down stroke of the wing which results in asymmetry in the force-deflection curve of the mechanism.

In this paper a modification to the model presented in reference [5] is suggested that will cause some level of asymmetry in force-deflection characteristics of the model. In first section the model is

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described and its static characteristics have been established. This follows by a nonlinear dynamic analysis which reveals the effect of asymmetry in the insect flight as differences in positive and negative velocities.

2. Mathematical modelling

A modified mathematical model of the click mechanism that has been introduced in reference [5] is shown in figure 1(a) in unloaded position. The mechanism is comprised of linkage BC and CD which are hinged at points C, B and D. The equivalent mass of the mechanism and wings are considered as a point mass at point C. Two linkages are supported by linkages AB and ED which are hinged at both ends. Two springs prevent the linkage movement which produce a horizontal force and are connected to the linkage AB and ED at the top. There are two unloaded stable position, one at the top and one at the bottom which is shown by dashed line. The mechanism is shown at the loaded position in figure 1(b). The positive direction of load is shown by $f(t)$. The free body diagram of the mechanism is shown in figure 1 (c) where a damping force $c\dot{y}$ is added to the mass to consider the dissipation of energy. By applying a negative load at point C, it moves downward up to a specific position where the stiffness becomes zero. A perturbation at this position causes the mechanism to snap through to the other stable position at bottom. The linkages AB and ED which are the modification to the original model in reference [5] are added to simulate the effect of axial load which is discussed in introduction. When point C is forced downward from the position at the top shown in figure 1(a) with solid lines, the internal force f_y facilitates the rotation of linkage AB or DE, hence reducing the stiffness. When the mechanism is at the position that is shown by dashed line in figure 1(a) and moves upward the internal force f_y is resisting the rotation of the linkage AB or DE and cause an increase in the required applied force to move point C upward.

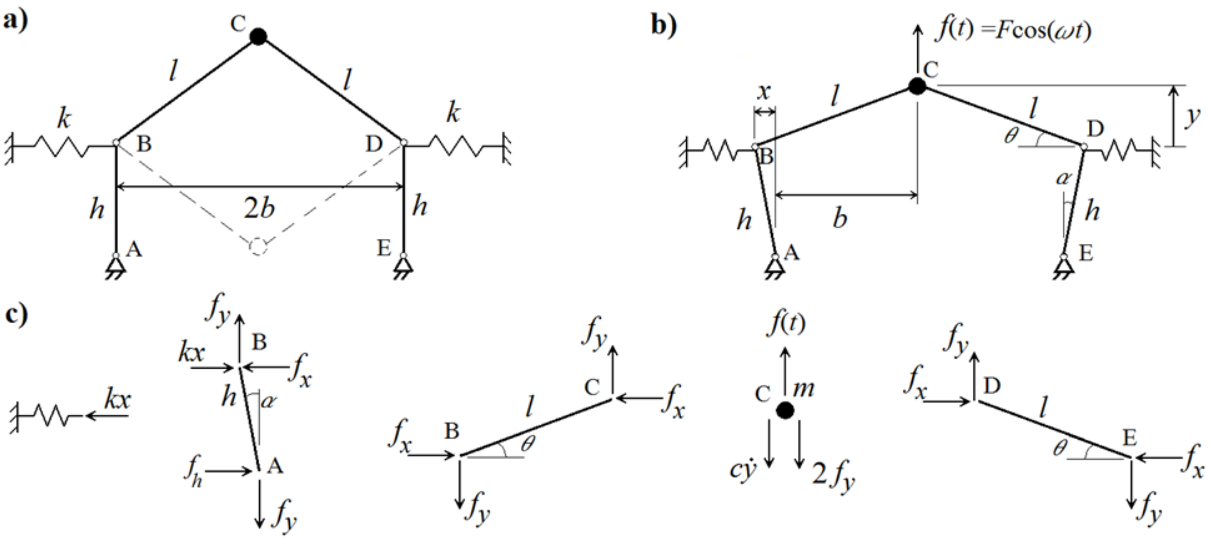

Figure 1. a) the mathematical representation of flight mechanism in unloaded position, b) the loaded mechanism, c) free body diagram.

The following equation can be obtained for f_y by considering the equilibrium condition for free body diagrams shown in figure 1(c),

$$f_y = \frac{-k\left(\sqrt{l^2 - y^2} - b\right)\sqrt{h^2 - \left(\sqrt{l^2 - y^2} - b\right)^2}}{\sqrt{h^2 - \left(\sqrt{l^2 - y^2} - b\right)^2}\,\dfrac{\sqrt{l^2 - y^2}}{y} + \sqrt{l^2 - y^2} - b} \tag{1}$$

which can be written in non-dimensional form as,

$$\frac{f_y}{kl} = \frac{-u\left(\sqrt{1-u^2}-\beta\right)\sqrt{-1+u^2+2\sqrt{1-u^2}\beta-\beta^2+\eta^2}}{u\left(\sqrt{1-u^2}-\beta\right)+\sqrt{1-u^2}\sqrt{-1+u^2+2\sqrt{1-u^2}\beta-\beta^2+\eta^2}} \tag{2}$$

where $u = y/l$, $\beta = b/l$ and $\eta = h/l$. The force-displacement of the mechanism obtained from the above equation is shown in figure 2 for $\beta = .7$ and different values of η. As it can be seen in the figure, the force-deflection is not symmetric about the origin. For $\eta = .7$, the load can increase to 0.11 before the stiffness become negative while it reduces only to -0.08 before the stiffness become positive again. By increasing the length of the lever AB and ED, i.e. increasing η, the effect of asymmetry reduces where for $\eta = 15$, it is almost symmetric about the origin.

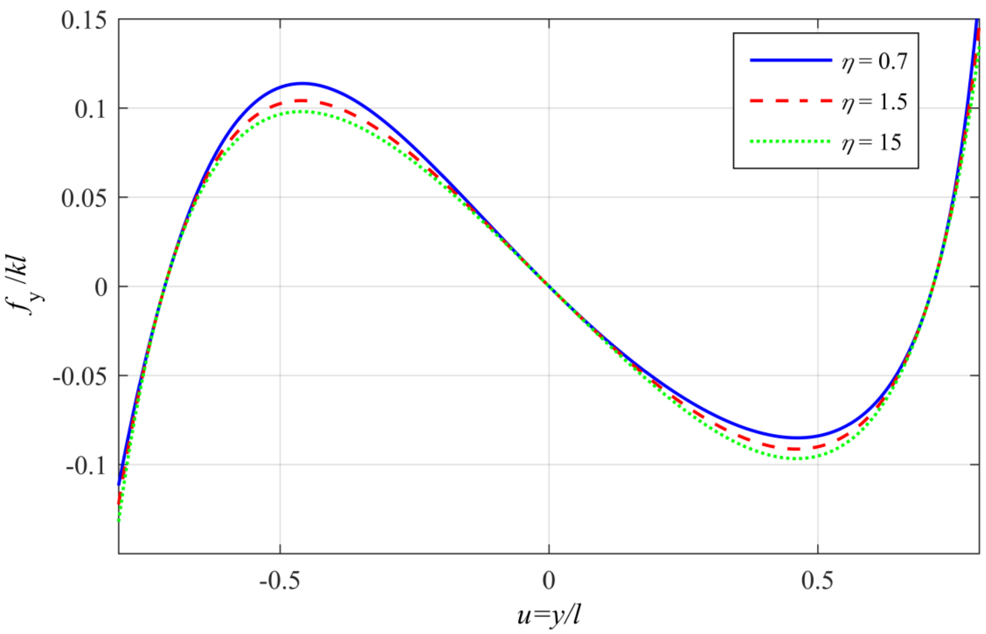

Figure 2. Restoring force of the flight mechanism as a function of displacement for $\beta = 0.7$.

The dynamic model of the flight mechanism can be obtained by considering the mass and damping of the system and by applying the Newton's second law to the free body diagram shown in figure 1(c),

$$m\ddot{y} = -c\dot{y} - 2f_y + f(t) \tag{3}$$

where c is the damping coefficient which is due to internal friction and also the generated lift resulted from insect flapping. The above equation can be written in non-dimensional form as,

$$u'' + 2\zeta u' + f_n = f_1 \cos\Omega\tau \tag{4}$$

where,

$$\tau = \omega_n t, \qquad \omega_n = \sqrt{\frac{k}{m}}, \qquad \Omega = \frac{\omega}{\omega_n}, \qquad u = \frac{y}{l}, \qquad \zeta = \frac{c}{2m\omega_n}, \qquad f_n = \frac{2f_y}{kl}, \qquad f_1 = \frac{F}{kl} \tag{5}$$

and $(\bullet)'$ indicates differentiation with respect to non-dimensional time, τ. Such a nonlinear oscillator possesses a rich dynamics and even can become chaotic for certain set of parameters [5]. However for large damping ratio, the response to a harmonic force is not chaotic but periodic with the same period as the forcing function. The damping ratio in the Equation (4) results mainly from the production of the lift through flapping wings. Thus a highly damped system is expected.

3. Dynamic analysis

Equation (4) can be solved numerically using Matlab's ode45 solver and the amplitude of the response at the excitation frequency can be obtained. The Frequency Response Curve (FRC) of the fundamental amplitude for three different ratios of η is shown in figure 3 for a harmonic excitation with non-dimensional amplitude of $f_1 = 0.4$. The damping ratio is chosen $\zeta = 0.6$ to be an example of a flight mechanism which is producing lift in insects. The amplitude of the response is about 1 at low frequencies. This amplitude is not achievable in practice as geometrical constraint will limit the movement of the mechanism which is considered beyond the scope of this paper. The amplitude starts to drop at a non-dimensional frequency of about 0.4.

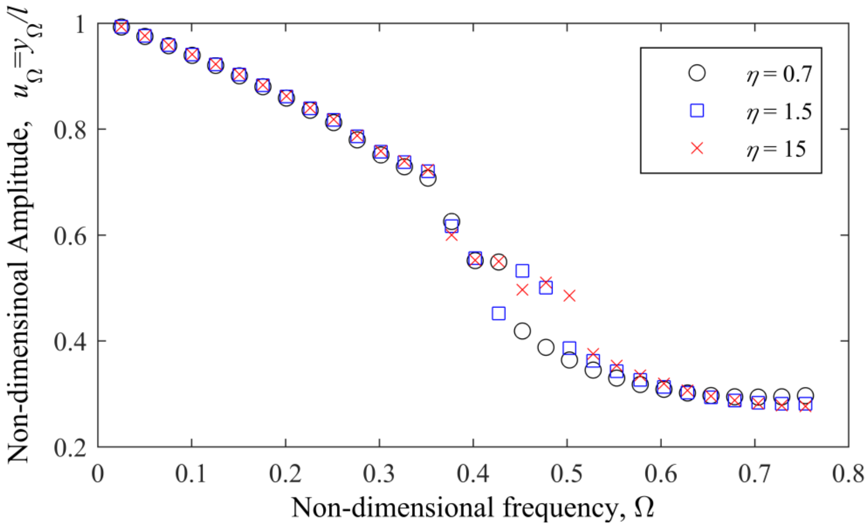

Figure 3. FRC of the response at the excitation frequency for $f_1 = 0.4$, $\zeta = 0.6$, $\beta = 0.7$ and different values of η.

To have a complete flapping action, the amplitude needs to be large enough to makes the wing pass through the neutral position at $u = 0$. Displacement of the mass m as a function of time is shown in figure 4 for two different excitation frequencies of $\Omega = 0.3$ and $\Omega = 0.5$. As it can be seen in the figure at the lower excitation frequency a cycle includes both positive and negative displacements which can be considered as a complete flapping action. However at the higher frequency of $\Omega = 0.5$ the displacement only possess negative values. This is oscillation about only one of the two stable equilibrium point and cannot be considered as a complete flapping cycle. This corresponds to smaller amplitudes of response for frequencies higher than drop down frequency at about $\Omega = 0.35$. Thus, only the frequencies lower than $\Omega = 0.35$ can be considered as suitable range for operation of the insect flight.

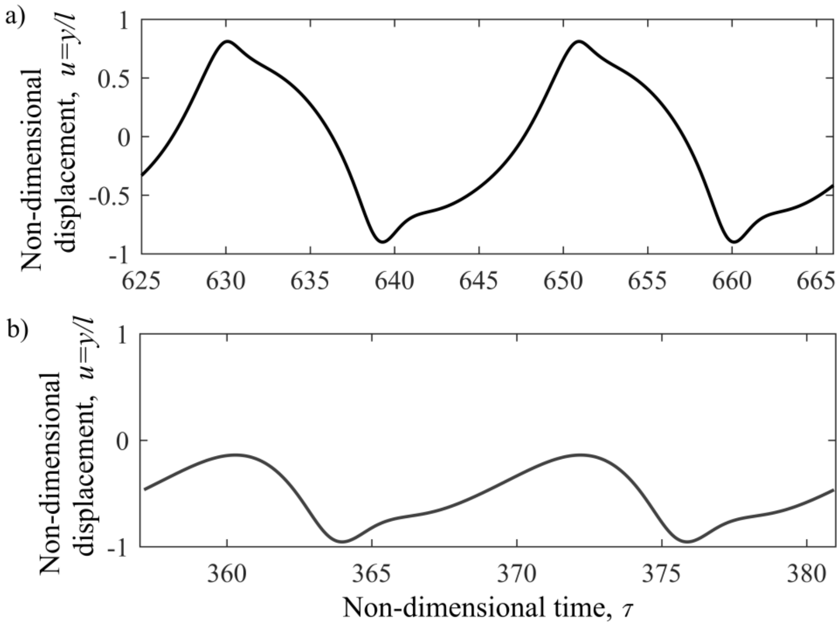

Figure 4. Time history of displacement for $f_1 = 0.4$, $\zeta = 0.6$, $\beta = 0.7$ and $\eta = 0.7$. a) excitation frequency $\Omega = 0.3$, b) excitation frequency $\Omega = 0.5$.

There is not a substantial difference in the amplitude of the response to a harmonic load for different level of asymmetry in force-deflection but by investigating the displacement shown in figure 4, one may find that the motion is not completely symmetric. This results in a difference in upward and downward velocity of wing during flapping which can be beneficial to the lift [7]. The difference between maximum positive and negative velocities in each cycle is obtained as percentage of maximum positive velocity and is plotted for three different value of η in figure 5. It can be seen that the difference between two velocities can be up to 35%. The negative value of the percentage is due to a higher absolute value for negative velocity when compared with the absolute value of the maximum positive velocity. By increasing η which makes the force-deflection symmetric, the difference between absolute values of positive and negative velocities decreases and become almost zero for $\eta = 15$ which is the case for a symmetric system. This difference may result in an increase in lift which can improve the performance of the insects.

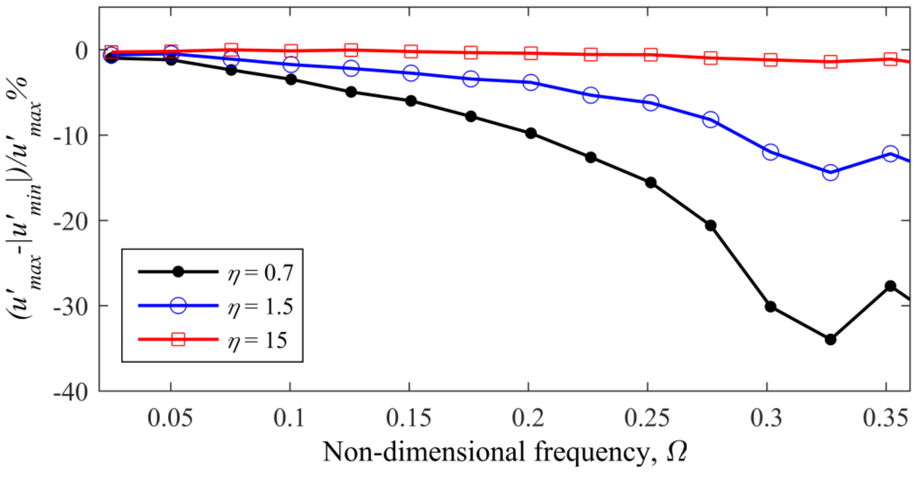

Figure 5. Difference between maximum velocity and minimum velocity as percentage for $f_1 = 0.4$, $\zeta = 0.6$, $\beta = 0.7$ and different values of η.

4. Conclusions

A simple mechanism similar to the click mechanism of insect flight has been developed that possess asymmetry in its force-deflection curve. It is shown that the level of asymmetry is a function of the geometrical parameter of the system. Numerical integration was used to obtain the dynamic response of the system to a harmonic excitation. The frequency range at which the oscillator can complete the flapping movement is obtained. The amplitude of the response is not very sensitive to the asymmetry but the velocity of the oscillator in up and down stroke can be different. The difference depends on the excitation frequency and a difference up to 35% is achievable.

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