Journal of Theoretical Biology 289 (2011) 173–180

Contents lists available at SciVerse ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

On the dynamic behaviour of the “click” mechanism in dipteran flight

Bin Tang [a,*], M.J. Brennan [b]

[a] Institute of Internal Combustion Engine, Dalian University of Technology, Dalian 116023, China
[b] Departamento de Engenharia Mecanica, Faculdade de Engenharia de Ilha Solteira (FEIS-Unesp), 15385-000, SP, Brasil

ARTICLE INFO

Article history:
Received 15 July 2011
Received in revised form
27 August 2011
Accepted 29 August 2011
Available online 1 September 2011

Keywords:
Insect flight motor
Mathematical model
Damping
Energy ratio
Bifurcation

ABSTRACT

In this paper, the dynamic behaviour of the “click” mechanism is analysed. A more accurate model is used than in the past, in which the limits of movement due to the geometry of the flight mechanism are imposed. Moreover, the effects of different damping models are investigated. In previous work, the damping model was assumed to be of the linear viscous type for simplicity, but it is likely that the damping due to drag forces is nonlinear. Accordingly, a model of damping in which the damping force is proportional to the square of the velocity is used, and the results are compared with the simpler model of linear viscous damping. Because of the complexity of the model an analytical approach is not possible so the problem has been cast in terms of non-dimensional variables and solved numerically. The peak kinetic energy of the wing root per energy input in one cycle is chosen to study the effectiveness of the “click” mechanism compared with a linear resonant mechanism. It is shown that, the “click” mechanism has distinct advantages when it is driven below its resonant frequency. When the damping is quadratic, there are some further advantages compared to when the damping is linear and viscous, provided that the amplitude of the excitation force is large enough to avoid the erratic behaviour of the mechanism that occurs for small forces.

1. Introduction

The flight mechanism of diptera has been studied for many years, and various mechanical models for this mechanism have been postulated. One such model, accepted by some in the community as being representative of the actual mechanism, involves the “click” mechanism (Boettiger and Furshpan, 1952; Pringle, 1957). Several papers on this topic have been written (for example, Thomson and Thompson, 1977; Miyan and Ewing, 1985, 1988; Bennet-Clark, 1986; Ennos, 1987; Pfau, 1987; Gronenberg, 1996; Brennan et al., 2003). Fig. 1 shows the flight mechanism described by Thompson and Thompson (1977). Brennan et al. (2003) proposed a simple mechanical model of this “click” mechanism, which is shown in Fig. 2a. Referring to this figure, the driving force from the scutellar lever is applied at C. The notum and pleural apophysis are modelled as two cantilever beams BE and DF, respectively. Rigid link ABC and CD, which represent the wing and parascutum, respectively, are pivoted at points B, C and D. The hinge at B represents the wing process. The hinge at C corresponds to the first axillary sclerite. Following analysis of the dynamics of this model they concluded that the “click” mechanism, which is inherently nonlinear, has advantages over a linear resonant mechanism provided that it is operated at a frequency much lower than the resonance frequency, which would be the case for very small flies. In that paper two main assumptions were made. The first was that the energy loss mechanism due to lift and drag forces on the wing could be represented by a linear viscous damper, and second was that the equation of motion of the mechanical model could be simplified to the Duffing equation (Kovacic and Brennan, 2011).

Recently, Cheng et al. (2010) analysed the influence of body rotation on the aerodynamic force and torque production during fast turning manueuvers in the fruit fly *Drosophila*. The damping coefficients and time constants were estimated based on both simulations and experimental results to obtain the effects of passive aerodynamic damping in turning flight. In the flight mechanism of diptera, the damping force due to the aerodynamics is strongly influenced by the Reynolds number. When a body passes through a fluid at high Reynolds numbers, the flow separates and the drag force is nearly proportional to the square of the velocity and can be treated as a quadratic damping force. When the Reynolds number is small the advective inertial forces are small and the damping force can be assumed to be proportional to the velocity (Nayfeh and Mook, 1995). Because of the small size and relatively low flight velocity, the Reynolds number for an insect is smaller than a bird and common air vehicles. For the smallest insects, which weigh about 20–30 μg, the Reynolds number is about 10, while the Reynolds number for large insects, which weigh about 2–3 g is around 5000–10000 (Ellington, 1999; Meuller and DeLaurier, 2003).

---

* Corresponding author.
E-mail address: btang@dlut.edu.cn (B. Tang).

0022-5193/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jtbi.2011.08.039

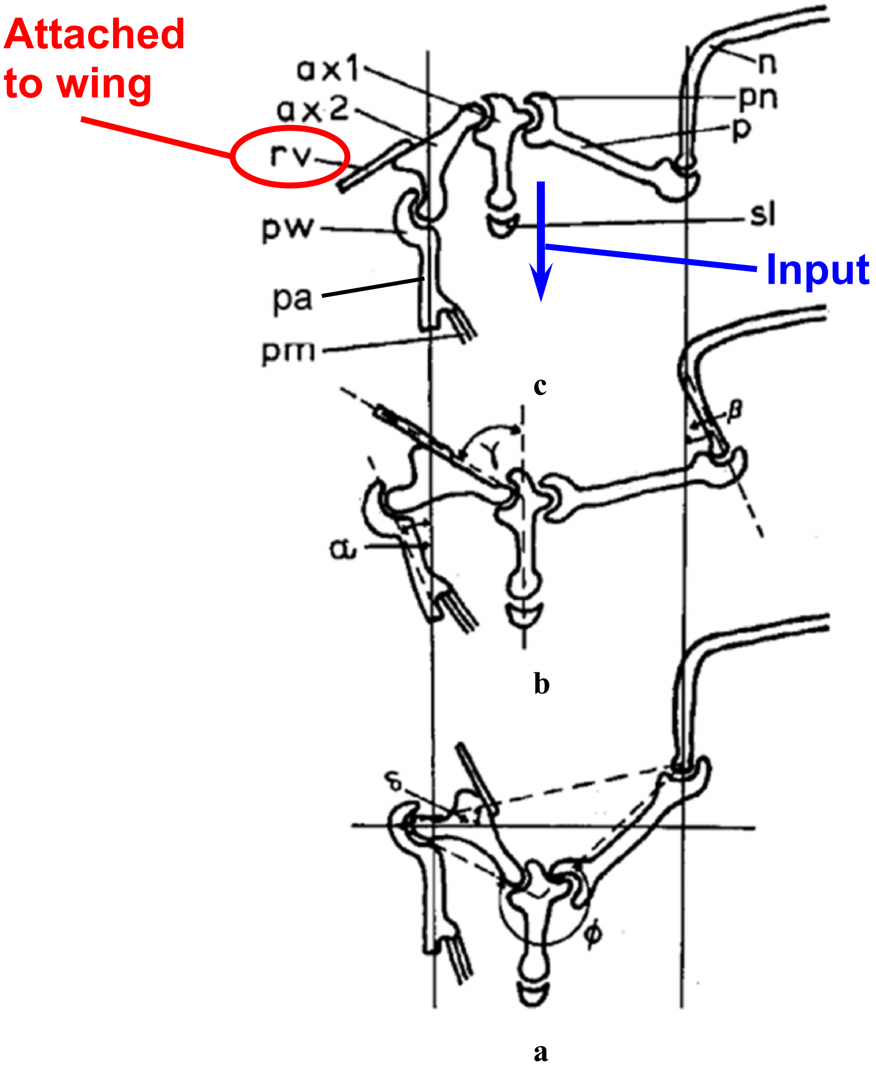

Fig. 1. (a–c) Diagram showing the flight motor of an insect and three successive positions of the wing articulation during the course of a beat, from the up position (a) to the down position (c); ax1, ax2—axillary sclerites 1 and 2; n—notum; p—parascutum; pm—pleurosternal muscle; pn—anterior notal process; pw—wing process; rv—base of radial vein; sl—section through scutellar lever (after Thomson and Thompson, 1977); pa—pleural apophysis (shown in Pringle, 1957).

Thus, for small diptera, the damping force may lie somewhere between linear and quadratic forms.

The aim of this paper is to further investigate the dynamic model of the "click" mechanism investigated by Brennan et al. (2003). The assumptions they made (given above) are revisited and a more accurate description of the dynamic behaviour of the model is sought. The relative influence of linear and quadratic damping forces is investigated and a numerical method is used to investigate the dynamic behaviour.

2. Dynamical model

The perturbed model of the flight mechanism of Fig. 2a is shown in Fig. 2b. The displacement of the mass y is the instantaneous elevation of C from BD and x is the lateral bending of the cantilevers. This model has three static equilibrium positions as shown in Fig. 2c. When the cantilevers have no deformation, there are two stable static equilibrium positions corresponding to the dotted and the dashed-dotted lines. When C lies on the line BD, such that the wing is in the horizontal position, the system is in a static unstable equilibrium position; any perturbation results in the system to move to one of the stable equilibrium positions. The mass C can move in positive and negative directions along the y axis. The potential energy of the system shown in Fig. 2b is given by

$$U=k\left(-b+\sqrt{l^2-y^2}\right)^2 \tag{1}$$

where k is the bending stiffness of each of the two vertical uniform cantilever beams, $2b$ is the distance between the two cantilever beams and l is the length of BC or CD. The restoring force can be obtained by the taking the derivative of the potential energy to give $2k(-1+b/\sqrt{l^2-y^2})y$. When this is combined with the mass m, and a sinusoidal exciting force of amplitude P and frequency ω is applied, the resulting equation of motion is given by

$$m\ddot{y}+2k\left(-1+\frac{b}{\sqrt{l^2-y^2}}\right)y=P\cos\omega t \tag{2}$$

Assuming linear viscous damping with damping coefficient c_1 a non-dimensional equation of motion can be written as

$$u''+\gamma_1 u'-\alpha u+\alpha\beta\frac{u}{\sqrt{1-u^2}}=F\cos\Omega\tau \tag{3}$$

where $u=y/l$, $\gamma_1=c_1/m\omega_0$, $\omega_0^2=2k(1/\beta^2-1)/m$, $\beta=b/l$, $F=P/ml\omega_0^2$, $\tau=\omega_0 t$, $\Omega=\omega/\omega_0$, $\alpha=\beta^2/(1-\beta^2)$ and $(\bullet)'$ denotes differentiation