AERODYNAMIC FORCES AND POWER OF A HOVERING HAWKMOTH IN DIFFERENT WING MOTION

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Summary The aerodynamic forces and power in a robotic model which can closely mimic the movements of hovering hawkmoth have been examined. In these experiments, two types of the wing motion are used: one is the typical curve of hovering; the other is a simplified motion. The results reveal that wing motion is very important in hovering hawkmoth: only the mean lift in hovering motion can afford a hawkmoth weight; the power requirement and the specific power (power/ lift) in simplified motion is little smaller.

MATERIAL AND METHOD

Hawkmoth is a common model organism of insect flight research due to its wonderful flight ability. The flight mechanism have been carefully discussed by many researchers since 1950s: several experimental and numerical studies have been performed with the aim of characterizing the unsteady aerodynamics. However the flow around the insect wings is highly unsteady and vortical, there is no simple way to answer all the questions. The present investigation is focused on one aspect of those: how about the influence of the wing motion in hovering hawkmoth? A novel robotic hawkmoth model which can be programmed to act any flight motion in the air has been made. The aerodynamic forces and power results show us that wing motion is significantly important to the lift generation and power requirement in hovering. It is also a reference of the flapping micro air vehicles (FMAVs) research to optimize the flapping mechanism.

Robotic Model of Hawkmoth

The flapping model is a useful equipment of insect flight research. Dickinson [1] made a flapping robofly model which moves in oil to investigate the aerodynamics of fly; Charles P. Ellington [2] made a large scale flapping hawkmoth model to examine the leading-edge vortex.

In order to measure the aerodynamic forces of hovering hawkmoth in the air, here a light weight hawkmoth model has been designed and made. Four small servos which are from the remote control hobby have been improved and used to drive two model wings. Micro controller is employed to control the servos and sample back the angular signals to PC. For each wing, one servo controls the stroke motion; the other controls the angle of attack. The servos can be separately configured from PC terminal and work together. The motion code for each servo is downloaded from the PC and stored in the micro controller. The mechanical frames of this model are exactly guided by the real hawkmoth. The frames have been designed very small and compact due to the servos' small sizes. The micro controller is fitted in the body part of the model hawkmoth, as well as the servos. A cover for the body part which is made by plastic foam is used to obtain smooth surface of the model body. Wings are also the proportional size of the body part. They are ultra light weight by using carbon fiber as vein and very thin PET film as membrane.

Only one two-component strain-gauge force sensor is equipped to measure the unsteady force. One end of the sensor is connected to the bilateral symmetrical position of the model thorax, and the other end is connected to the support rod of the whole model. It is a conventional way to place force sensors at wing base area of robotic flight models, but it's preferred to use only one sensor here: the sensor must keep moving as the wing if it's attached to the wing base part, the inertial force would be difficult to subtract; by the similarity theory the flapping frequency of the model in the air must be fast than in oil, but the mean lift should be as small as the weight of a hawkmoth! As the consideration above, using one sensitive and static sensor would be better. The force signals also can be synchronously recorded by the micro controller when angular signals are sampled.

Calculation of the Forces and Power

The force measured by the sensor should be converted to the local lift and drag forces which is relative to the stroke plane coordinates. Assumed the horizontal force is F_h and vertical one is F_v, the lift and drag is F_L and F_D, so that:

$$\begin{cases} F_L = F_H \sin\beta + F_V \cos\beta \\ F_D = F_H \cos\beta - F_V \sin\beta \end{cases} \tag{1}$$

Where β is the stroke plane angle that is calculated by:

$$\beta = a\tan\frac{\overline{F}_H}{\overline{F}_V} \tag{2}$$

The aerodynamic power can be calculated by the forces, velocities and morphological values. Assumed the stroke angle is φ, angle of attack is α, mean chord length is c and wing span is R, so that:

$$\begin{bmatrix} P_{Trans} \\ P_{Rot} \end{bmatrix} = \begin{bmatrix} F_h \cdot 0.6R & F_h \cdot \frac{\overline{c}}{4}\sin\alpha + F_v \cdot \frac{\overline{c}}{4}\cos\alpha \end{bmatrix} \begin{bmatrix} \dot{\varphi} \\ \dot{\alpha} \end{bmatrix} \tag{3}$$

Where P_{Trans} is the aerodynamic power in the wings' translation phase and P_{Rot} is the aerodynamic power in the wings' rotation phase. The sum of these two terms is the total power.

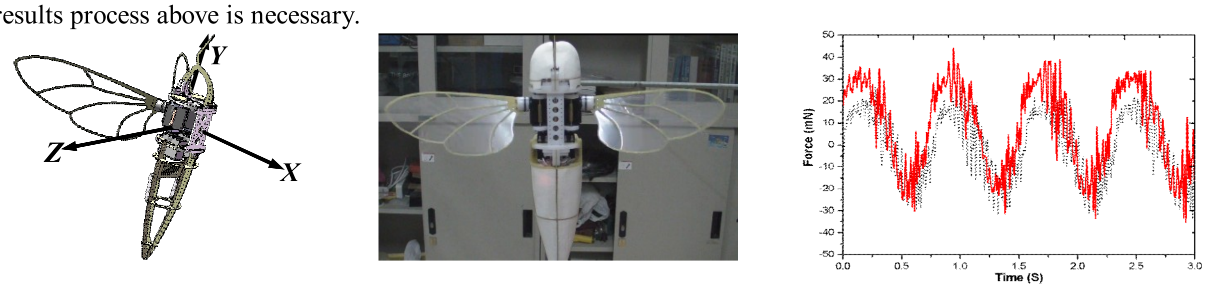
As a comparison of the experimental results, the theoretical calculation by quasi-steady model is mentioned here. The quasi-steady model employed here consists of three components forces: translational forces, wingspan rotational force and added-mass force. The morphological and kinematic parameters, curves of lift/drag coefficients, rotational force formulas and downwash velocity calculation are as the same as the references, so they are not repeated here.

Process of the Experiments

Forces measurements should be very careful here, because according to the similarity theory the mean lift force of the model in the air can just equal to the weight of a live hawkmoth. Therefore the measurements here need three steps: the forces generated by using integrated wing pair are recorded in the first step, and then forces caused by the same motion are recorded again but using the special wing pair that doesn't have membrane. In the final step, the two results above are independently pre-processed and the special wing result has to be subtracted from the integrated wing result.

RESULTS AND DISCUSSION

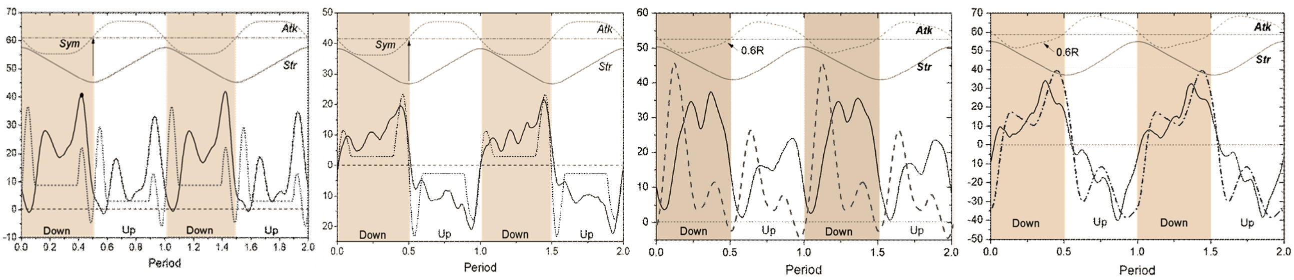
The robotic hawkmoth model is about 290g in all. The wingspan length of each wing is about 220mm and the weight of each wing is approximately 2.2g. The error of the wing motion at any time is less than 0.5°. Its flapping frequency is about 1.3Hz when the Reynolds number is 6300(it's close to the real hovering hawkmoth). The force sensor can measure 0.01g and the original force results can be seen as below (see Fig.1c). It's obviously that the three steps results process above is necessary.



(*a*) Coordinates (*b*) Hawkmoth Model (*c*) The original force results

Fig.1 the robotic hawkmoth model

After the experiments, the lift and drag results can be obtained (see Fig.2). It reveals that wing motion is very important in hovering: the mean lift in hovering motion can reach 19mN, but in simplified motion it's only 15mN.



(*a*) lift in simplified motion (*b*) drag in simplified motion (*c*) lift in hovering motion (*d*) drag in hovering motion

Fig.2 lift and drag forces in different wing motion

The mean lift coefficient in simplified motion is just 0.55, however it is 0.72 in hovering motion. The difference of these wing motions is not remarkable, but the lift generation is really different: 19mN could be enough for hawkmoth hovering but 15mN is obviously not enough. The mean power requirement in simplified motion is about 38.4mW, and it is 58.6mW in hovering motion. This means the specific power (power/ lift) in simplified motion is about 2.5W/N, and it is 3.0W/N. It indicates that hovering motion can generate more lift but more power is required. The quasi-steady results (dash line in Fig.2) are smaller not only in hovering motion but also in simplified motion. Although the mean lift coefficient of quasi-steady model is just 0.4 in hovering motion, the curves are still similar.

CONCLUSIONS

A robotic model is made and two types of the wing motion are considered. The results reveal that wing motion is very important in hovering hawkmoth, and it could help the FMAV design.

References

[1] Dickinson, M. H., Lehmann, F., Sane, S. P.: Wing rotation and the aerodynamic basis of insect flight. *Science* 284, 1954-1960, 1999.
[2] Coen Van Den Berg, Charles P. Ellington: The vortex wake of a `hovering ' model hawkmoth. *Phil. Trans. R. Soc. Lond. B*352, 317-328,1997.