euspen's 18th International Conference &
Exhibition, Venice, IT, June 2018
www.euspen.eu

Insect-sized flapping-flight robot using dry friction–based self-excited vibration

Shinji Koganezawa[1], Takahiro Fujiwara[2], Taiki Usami[2], Ryo Kawasaka[1], Lu Renguo[1], Hiroshi Tani[1], Norio Tagawa[1]

[1] *Department of Mechanical Engineering, Kansai University*
[2] *Graduate school of Science and Engineering, Kansai University*

skoga@kansai-u.ac.jp

Abstract
It is expected that, in the future, quadrotor helicopters (quadcopters) will be employed in many applications, several of which require the quadcopters to be extremely small. However, it is difficult for smaller quadcopters to achieve a sufficient lift force for flight because, with reduction in the propeller diameter, the lift force decreases more sharply than the mass does. To miniaturize flying robots, we developed a flapping-flight robot employing self-excited vibration based on dry friction, inspired by the flight mechanism of bees. The proposed structure uses a simple DC motor and is easy to control; a large flapping angle can be obtained by operating at the resonant frequency using dry friction–based self-excited vibration with robustness. The designed flapping-flight robot is similar to a hornet in size with a body length of 5.4 mm and wingspan of 57.2 mm; it weighs 970 mg, including the weight of a motor and battery.

Flapping-flight robot, self-excited vibration, dry friction, insect-sized robot

1. Introduction

Currently, quadrotor helicopters (quadcopters), typified by drones, are widely utilized, especially to obtain a bird's-eye view of cityscapes, construction sites, and geographical features. Furthermore, it is expected that, in the future, quadcopters will be employed for observing internal conditions of narrow spaces, such as collapsed houses in disaster situations and artificial pollination in fields, which are applications that require the quadcopters to be extremely small. However, it is difficult for smaller quadcopters to achieve a sufficient lift force for flight because, with reduction in the propeller diameter, the lift force decreases more sharply than the mass does. Nevertheless, in nature, various insects, even with body lengths on the order of a few millimetres, fly fluently by flapping. Flapping flight is generally said to achieve a sufficient lift force easily. Therefore, to miniaturize flying robots, we developed a flapping-flight robot employing self-excited vibration based on dry friction, inspired by the flight mechanism of bees. The goal of our research is to develop an insect-sized flight robot capable of performing fully autonomous flight.

2. Design

2.1. Structure and flapping mechanisms

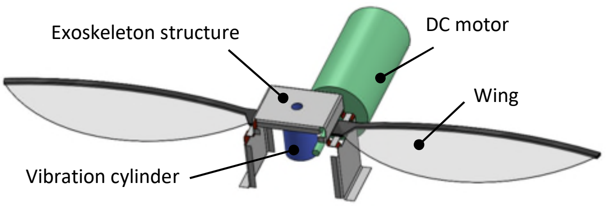
We applied an electromagnetic actuator for flapping actuation. Electromagnetic actuators are generally thought to be unsuitable for small-sized robots, because they are difficult to be structurally miniaturized. However, piezoelectric and electrostatic actuators, which are often applied to small structures, need extremely high voltages (e.g., several hundred volts) [1], and their power-supply circuit tends to be large and heavy. In contrast, the driving voltage of electromagnetic actuators are much lower; therefore, electromagnetic actuators are advantageous because of their low weight including a driving circuit and battery, even for an insect-sized structure.

The structure of the proposed flight robot is shown in figure 1. It consists of an exoskeleton structure, which imitates the structure of insects; two flapping wings; a vibration cylinder; and a DC motor. The exoskeleton structure has a displacement-magnifying mechanism based on the principle of leverage for flapping wings.

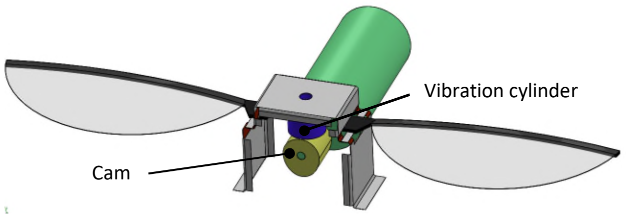
Two flapping-actuation methods are applicable for this structure to flap the wings: self-excited vibration drive and forced oscillation drive.

In the self-excited vibration drive (figure 1 (a)), the rotational shaft of the DC motor is in contact with the side wall of the vibration cylinder, exerting a contact force. When a DC current is applied to the DC motor, the cylinder is excited by the friction force between the cylinder and the rotational shaft, resulting in friction-induced vibration. Hence, the exoskeleton structure and flapping wings are excited at the resonant frequency of the flapping-motion vibration mode, and a large flapping angle can be obtained. It is important for the drive to select the appropriate material for the vibration cylinder and to adjust the contact force in order to obtain a large flapping amplitude. Therefore, the self-excited vibration drive needs more effort compared to the forced oscillation drive to obtain a large flapping amplitude.

In the forced oscillation drive (figure 1 (b)), an eccentric disk cam is installed at the end of the rotational shaft, which is in contact with the bottom of the vibration cylinder and exerts a contact force. When a DC current is applied to the DC motor, the cylinder is excited at the rotational frequency of the DC motor. The flapping amplitude is determined by the cam profile and the displacement-magnification ratio of the exoskeleton structure, and a large flapping amplitude can be easily obtained with this drive. However, the driving frequency, which strongly affects the lift force, should be less than the flapping resonance frequency of the structure, which is a disadvantage of this drive.



(a) Self-excited vibration mode.



(b) Forced oscillation mode.

Figure 1. Structure of the proposed flying robot.

2.2. Design specifications

Table 1 lists the specifications of the designed flapping-flight robot as well as the corresponding range of values for the Japanese hornet, vespa simillima xanthoptera. The robot is similar to a hornet in size with a body length of 5.4 mm and wingspan of 57.2 mm; it weighs 970 mg, including the weight of a motor and battery. A prototype of the robot is shown in figure 2.

Table 1 Specifications for the designed flight robot

Item	Specification	Vespa Simillima Xanthoptera
Length [mm]	5.4	24 ~ 36
Wingspan [mm]	57.2	43 ~ 58
Weight [g]	0.97	0.6 ~ 1.4
Flapping Angular Amplitude [°]	35	35 ~ 65
Flapping Frequency [Hz]	70	105 ~ 190
Driving Voltage [V]	1.55	-

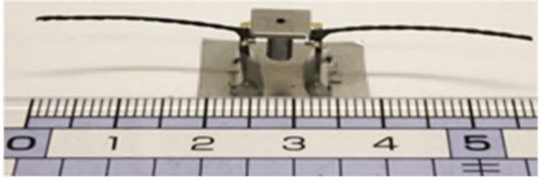


Figure 2. Prototype of the flapping-flight robot.

3. Measurement of the flapping properties

3.1 Amplitude of flapping

The flapping amplitude was measured using a laser Doppler vibrometer (LDV) by applying each of the two drives. The rotational speeds of the DC motor for the self-excited vibration drive and forced oscillation drive were 146 Hz and 74 Hz, respectively. Figure 3 shows the amplitude spectra. In the amplitude spectrum for the self-excited vibration drive, the flapping resonance mode at approximately 61 Hz was dominantly observed, although a sharp feature at the motor-rotation frequency is slightly visible in the spectrum at 146 Hz. This result indicates that the self-excited vibration drive appropriately works. However, the flapping amplitude was only 0.1 mm rms. The driving condition, rotational speed of the motor, contact force and friction coefficient between the vibration cylinder and rotational shaft of the DC motor, and material of the vibration cylinder should be further researched to increase the flapping amplitude with this drive. For the forced oscillation drive, sharp features were observed in the spectrum at the rotational frequency of the DC motor and its higher harmonics. The flapping amplitude was approximately 2 mm in this case.

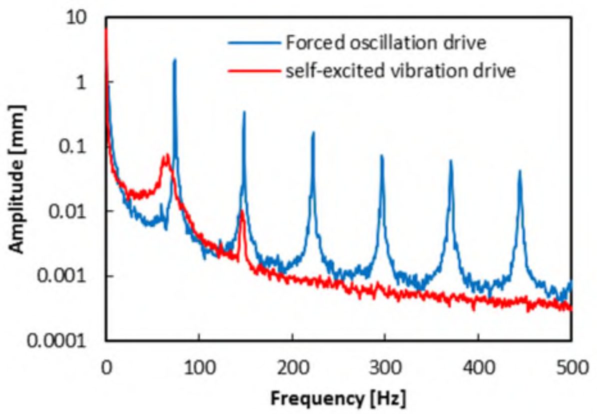


Figure 3. Spectra of the flapping amplitude

3.2. Lift force measurement

The lift force caused by flapping was measured using the measurement tool shown in figure 4. Springs support the robot, and the resonance frequency of the vertical vibration mode of the measurement tool was 158 Hz, which is sufficiently high. When a DC current is applied to the motor, the robot flaps and vibrates in the flying direction by the fluctuation of the lift force. The vibration in the flying direction was measured by an LDV, following which the lift force was calculated from the DC component of the displacement and the stiffness of the springs. Because the flapping amplitude with the forced oscillation drive was larger, the forced oscillation drive was employed for the measurement. The lift force was 0.54 mN. According to a finite-element analysis using a coupling analysis between mechanical and fluid dynamics, we estimated that a lift force greater than 10 mN—the minimum lift required for flight—can be obtained with a flapping angle greater than ±15° at 200 Hz.

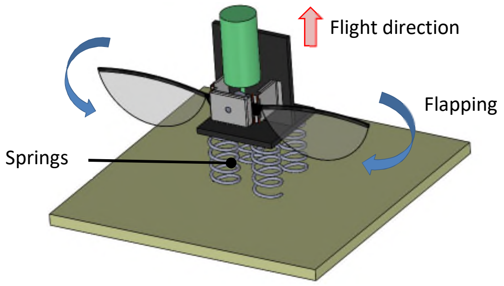


Figure 4. Measurement setup for lift force

4. Conclusion

We developed an Insect-sized flapping-flight robot. Flapping was achieved using dry friction–based self-excited vibration. However, the flapping amplitude was small, and the condition to increase the friction force should be further researched to increase the amplitude.

Acknowledgement

This work was financially supported by a Grant for Research Group on Tribotronics of ORDIST, Kansai University.

References

[1] Zhang X, Lok M, Tong T, Lee S K, Reagen B, Chaput S, Duhamel J P, Wood R J, Brooks D and Wei G-Y 2017 A Fully Integrated Battery-Powered System-on-Chip in 40-nm CMOS for Closed-Loop Control of

Insect-Scale Pico-Aerial Vehicle *IEEE J. of Solid-state circuits* **52** 9 2374-87.