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レーザビーム変角による昆虫の羽ばたき力の測定

Scanning Beam Method for Measuring the Beating Force of an Insect

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A time-sharing collimation (TSC) method was developed for measuring the beating force of an insect. In this method, a rod with a square cross-section is used as a sensor block to transform the force variation to tilt angle variation, and an acousto-optic deflector is used as a diffractive scanner to measure these angle variations in two directions. We first calibrated the force variation with respect to the tilt angle variation, and found that the uncertainty in force measurement for the TSC system was 8.8×10^{-4} N. We then applied the method to measure the dynamic angle variations and the beating force of a bumblebee.

In the field of biomechanics, the flight performance of insects has been studied extensively. Such studies require highly accurate measurements of the force generated by the beating motion of the insect. Typical measurement methods use a gauge block as a reflector, where one end of the block is attached to a rigid wall and to the other end of the block is attached an insect. We call this gauge block a *sensor block*. The beating motion of an insect causes the sensor block to bend. By measuring the variations in the tilt angle of the bending sensor block, we can calculate the instantaneous beating force. Highly accurate measurements of the beating force require the following conditions: (a) two-directional measurement and (b) the natural frequency of the sensor block must be at least 10 times larger than the beating frequency. Therefore, angle-variation measurements should be done with high resolution and simultaneously in two directions.

Figure 1 shows the configuration of our TSC system, which consists of a He-Ne laser source, an AOD, a 90° prism, a stainless steel sensor block (30 mm long with a cross-sectional area of 2×2 mm^2), a position sensor, and six mirrors (M1~M6).

The AOD is used as a diffractive scanner. Due to the acousto-optic effect, the laser beam passing through the AOD is diffracted an angle θ, which depends on the voltage of the input electrical signal V_i. Here, a voltage-controlling oscillator (VCO) is used as a signal processor to provide the AOD with the required driving power and frequency of an ultrasonic field. By inputting a square wave signal to the VCO, the diffracted beam of the AOD alternately strikes two surfaces of the prism, resulting in Beams 1 and 2. We call this input signal a *scanning signal*, and its frequency, the *scanning frequency*.

The TSC method uses a sensor block with a square cross-sectional area to change the force variation to tilt angle variation. One end of the block is attached to a rigid wall, and at the other end is attached an insect. The beating motion of the insect causes the sensor block to bend. By measuring the resulting variations in the tilt angle of the bending sensor block, we can calculate the instantaneous beating force.

Mirrors M1 and M2 are used to change the direction of Beam 1 (solid line) so that the beam strikes plane A of the sensor block at an incident angle. The beam reflected from A is then converged by lens L1. Mirrors M3 and M4 are used to adjust (a) the direction of the beam shift on the position sensor, and (b) the distance between L1 and the position sensor so that the focus of L1 is on the position sensor. Similarly, Mirror M5 is used to change the direction of Beam 2 (dot-dash line) so that the beam strikes plane B at an incident angle. The beam reflected from B passes through lens L2 and reflects on mirror M6, and then is focused on the same position sensor. Because L1 and L2 have the same focal length, we can get the same angle resolution for two directions. We defined the angles between plane A and coordination plane xoz as α, and that between plane B and coordination plane xoz as β. The scanning by the AOD causes the reflected laser beam from planes A and B to alternately focus on the position sensor. The variations in α and β generated by the bending of planes A and B result in a shift of the beam on the position sensor. Sampling points were set at the rise time and fall time. This TSC method uses a time-sharing technique in which the angle variations $\Delta\alpha$ and $\Delta\beta$ are detected by the same position sensor, thus achieving a high signal-to-noise ratio and making the measurement system compact.

We calibrated the TSC system, and found that the beating force in horizontal and vertical directions with a uncertainties of 9.2×10^{-4} N and 7.4×10^{-4} N, respectively. We then applied the TSC system to measure the tilt angle variations caused by the beating force of a bumblebee. We attached (using adhesive) a bumblebee at its mesoscutum to the tip of the sensor block. The beating motion of the bumblebee caused the sensor block to bend. The beating force in the horizontal and vertical directions were measured from the tilt angle variations during one beating period. The scanning frequency was 2 kHz. We measured the flapping angle simultaneously during the force measurements by recording the wing motion at 2250 frames per second using a high-speed video camera. The beating frequency was about 132 Hz. Figure 2 shows the results. The results indicate that the variations in the total vertical force generated by the beating motion were almost five times the bumblebee's weight, and the horizontal force, eight times.

A new time-sharing collimation (TSC) method has been described that uses an AOD and a position sensor to measure dynamic angle variations simultaneously in two directions. Tile angle variations in two directions are measured by the same position sensor by using a time-sharing technique, thereby generating a high signal-to-noise ratio while making the measurement system compact. By combining the measured beating force with the beating motion photographed using a high-speed video camera, the inertial and aerodynamic forces in the beating motion can be calculated precisely with respect to the instantaneous flapping angle.

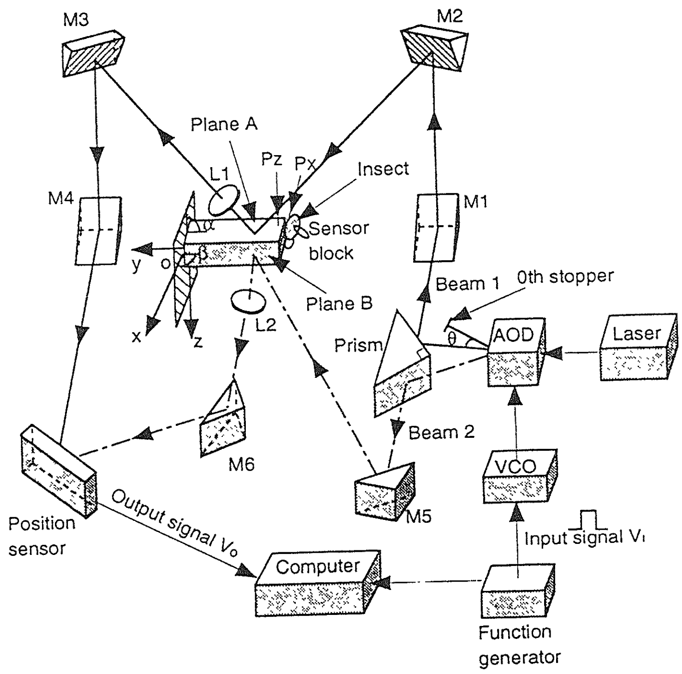
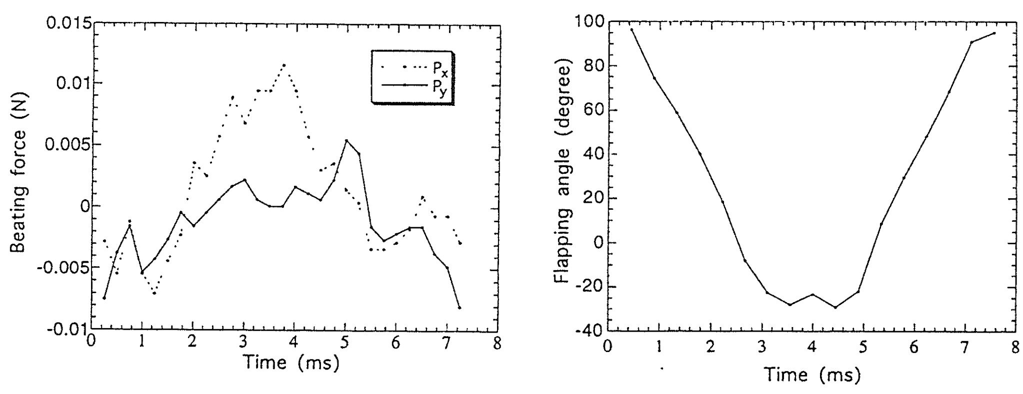


Fig. 1 Configuration of the TSC system



(a) (b)

Fig. 2 Beating motion of a bumblebee
(a) beating force, (b) flapping angle