Supplementary material

A Sub-100 mg Electromagnetically Driven Insect-inspired Flapping-wing Micro Robot Capable of Liftoff and Control Torques Modulation

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1 Analysis of the uncertainty of the customized lift/torque test platforms

1.1 The customized lift test platform

The schematic of the customized lift test platform is shown in Fig. S1. The double-cantilever beam transforms the lift produced by the robot into slight parallel displacement along measurement direction of a capacitive displacement sensor (capaNCDT6530, MICRO-EPSILON), thus the real-time lift can be derived by measuring the displacement of the target plate. The double-cantilever beam is made of Invar sheet (4J36). The thickness of the Invar sheet is much smaller than the length and width, which can be considered flexible in the sensitive direction of the sensor shown in Fig. S1 and rigid in other directions.

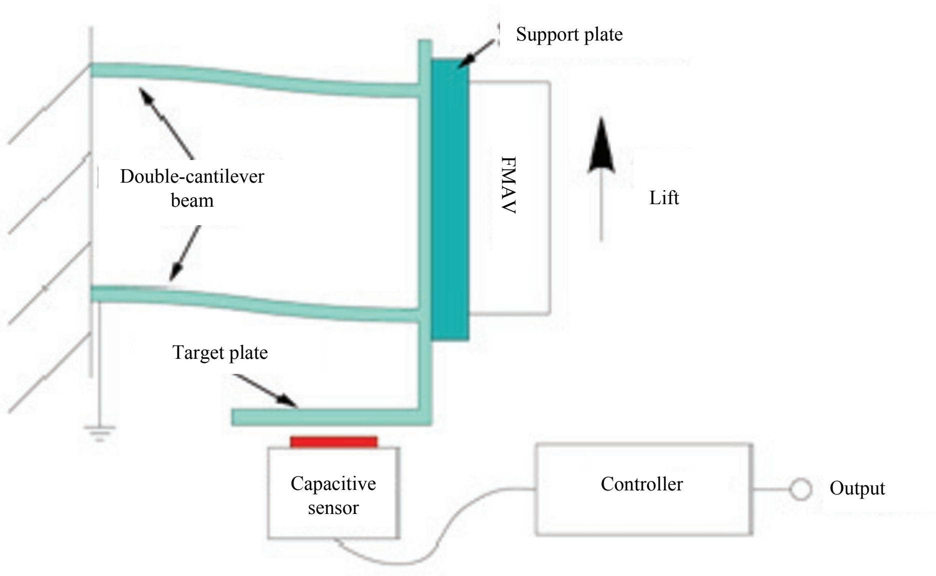

Fig. S1 Schematic of the customized lift test platform.

The theoretical bending stiffness of the double-cantilever beam is calculated as:

$$k_{\text{tot,bend}} = \frac{2E_{\text{in}} w_{\text{can}} t_{\text{in}}^3}{l_{\text{can}}^3}, \quad \text{(s1)}$$

where E_{in} (141 GPa) is the elastic modulus of the Invar sheet, t_{in} (150 μm) is the thickness of the Invar sheet, l_{can} (9.4 mm) and w_{can} (7 mm) are the length and width of the double-cantilever beam, respectively.

The equivalent mass of the entire system is as follows:

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$$m_{\mathrm{tot}} = m_{\mathrm{eff}} + m_{\mathrm{Robot}}, \tag{s2}$$

where m_{eff} and m_{Robot} represent the equivalent mass of the lift test platform (581 mg) and the mass of the designed robot (96 mg), respectively.

Then the undamped first-order resonant frequency of the lift test platform can be expressed as:

$$f_{\mathrm{lift}} = \frac{1}{2\pi}\sqrt{\frac{k_{\mathrm{tot,bend}}}{m_{\mathrm{tot}}}}. \tag{s3}$$

Finally, the total stiffness of the double cantilever beam is 8021 $\mathrm{N{\cdot}m^{-1}}$, the equivalent mass of the entire system is 677 mg, and the undamped first-order resonant frequency of the system is 548 Hz, which is more than 6 times the flapping frequency (80 Hz) of the insect-inspired flapping-wing micro robot designed in this paper. Thus, the dynamic effects of the system during the lift measurement can be neglected.

The invar sheet is shaped by UV laser in two-dimension, then folded and soldered into three-dimension structure. Calibrated by standard weights, the lift test platform has an actual stiffness of 457 $\mathrm{N{\cdot}m^{-1}}$, a dynamic resolution of 0.457 μN (0.0466 mg), and a sensitivity of 2.1866 $\mathrm{\mu m{\cdot}mN^{-1}}$. Its performance satisfies the requirements for lift measurement of the insect-inspired flapping-wing micro robot.

1.2 The customized torque test platform

The schematic of the customized torque test platform is shown in Fig. S2. The cross-shaped beam transforms the torque about the central axis of the beam into slight rotation of the target plate, which can be regarded as parallel displacement. Thus, the real-time torque can be derived by measuring the displacement with the capacitive displacement sensor (capaNCDT6530, MICRO-EPSILON) used in the lift measurement.

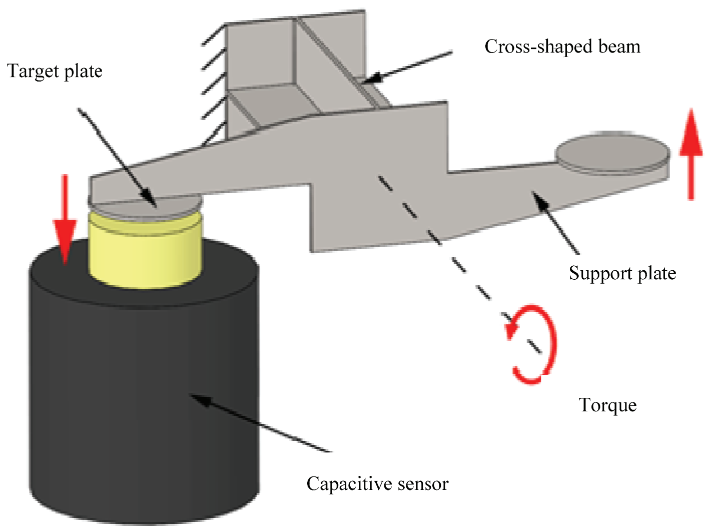

Fig. S2 Schematic of the customized torque test platform.

The cross-shaped beam is also made from the same Invar sheet used in the lift measurement, and its torsional stiffness can be calculated as:

$$k_{\mathrm{tot,tor}} = \left(\frac{w_{\mathrm{cross}}}{t_{\mathrm{in}}} - 0.373\right)\frac{4G_{\mathrm{in}}t_{\mathrm{in}}^{4}}{3l_{\mathrm{cross}}}, \tag{s4}$$

where G_{in} is the shear modulus of the invar sheet (55 GPa), l_{cross} and w_{cross} are the length and width of the cross-shaped beam, respectively.

The total moment of inertia of the system about the central axis is as:

$$J_{\text{tot}} = J_{\text{eff}} + J_{\text{Robot}}, \tag{s5}$$

where J_{eff} is the equivalent moment of inertia of the torque test platform (6.1 μgm^2), and J_{Robot} is the moment of inertia about the central axis of the designed robot (1.5 μgm^2).

Then, the undamped first-order resonant frequency of the torque test platform can be expressed as:

$$f_{\text{torque}} = \frac{1}{2\pi}\sqrt{\frac{k_{\text{tot,tor}}}{J_{\text{tot}}}}. \tag{s6}$$

The final torsional stiffness of the cross-shaped beam is 121.6 mNm·rad^{-1}. The undamped first-order resonant frequency of the system is 637 Hz, which is more than 7 times the flapping frequency of the robot designed in this paper. Thus, the dynamic effects of the system during the torque measurement can be neglected.

After calibration, the torque test platform has an actual torsional stiffness of 94.2 mNm·rad^{-1}, a dynamic resolution of 0.0111 μNm, and a sensitivity of 0.09027 m·Nm^{-1}, which satisfies the requirements for torque measurement of the robot.