MEMS-Based Micro Sensors for Measuring Tiny Forces Acting

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Small insects perform agile locomotion, such as running, jumping, and flying. Recently, many robots, inspired by such insect performance, have been developed and are expected to be smaller and more maneuverable than conventional robots. For the development of insect-inspired robots, understanding the mechanical dynamics of the target insect is important. However, evaluating the dynamics via conventional commercialized force sensors is difficult because the exerted force and insect itself are tiny in strength and size. As the force sensor, micro-force plates for measuring the ground reaction force and micro-force probes for measuring the flying force have mainly been developed. In addition, many such sensors have been fabricated via a microelectromechanical system (MEMS) process, due to the process precision and high sensitivity.

insect MEMS probe sensor

1. Introduction

In recent years, many robots, inspired by small animals, including insects with agile locomotion, have been studied [1][2][3][4][5][6]. Examples of microrobots include micro-air vehicles (MAVs) with flapping wings [7][8], walking and jumping robots [9][10][11], and swimming robots [12][13], based on insects and microorganisms. These bioinspired robots are smaller and more maneuverable than conventional robots, so they are expected to operate effectively, even in areas where humans cannot enter. As the common issue, when taking inspiration from small animals, such as insects, how or what kinds of features to take inspiration from is important. One of the most fundamental issues is to duplicate the shape or the movement of the target small insects, which allows researchers to reproduce their locomotion, to some extent, by a robot. However, to systematically establish an insect-inspired method, understanding not only the superficial shapes and movements, but also the mechanical dynamics, is important. One of the reasons is that the dominant forces that form locomotion differ, according to body shape and size [14], and the conventional mechanical system cannot be intuitively applied.

Provided that we focus on the specific locomotion and corresponding forces of small insects, clarifying, for example, on the aerodynamic force acting on flapping wings, in the case of flapping flight, is important. In the case of swimming, the force acting on a body is similar to that in the flapping flight case, and only the fluid is different. In the case of walking, the ground reaction force (GRF) and ground adhesion force (GAF) are important. However, directly measuring such forces has been difficult because these forces are tiny, and the target insects themselves are small. For example, the aerodynamic force per area of flapping wings of a butterfly is several Pa, and the GRF of ants is several tens of μN; we can easily approximate these values from their masses and body shapes. In addition, such forces sometimes change rapidly; for example, the flapping frequency of a fruit fly is approximately 200 Hz. Thus, the indirect methods of estimating such forces have been widely studied. The most basic measurement method is to calculate the acceleration from video images and convert it into the force. Additionally, in the case of flapping flight, the main methods of force estimation are computational fluid dynamics (CFD) [15][16][17] and the use of robotic wings, with the Reynolds numbers matching those of actual insects [18][19][20].

Alternatively, measurement science and technology, utilizing, for example, microelectromechanical systems (MEMS), has been developed, and we can easily obtain a tool to measure tiny forces [21][22][23]. Accordingly, using MEMS-based force sensors, recent studies have reported direct methods for measuring the force exerted by small animals, such as insects, which was difficult in previous studies [24][25][26][27][28][29][30][31][32][33][34][35][36][37]. In these studies, the force sensor itself has been specially developed for the target insect, including the sensor size and structure, force range and resolution, time resolution, resonant frequency, and so on.

2. Development of MEMS Technology

MEMS technology is one of the most developed research areas in the field of mechanical and electronic engineering in recent years. MEMS is defined as a whole range of microdevices that integrate various functions, such as mechanical, electronic, optical, and chemical functions. MEMS devices are fabricated on wafers with layered materials, such as metals; their size is generally on the order of mm or less in total length, and their components are usually on the order of μm. The limitation of the component size is mainly due to the wavelength of ultraviolet (UV) light in photolithography, which is one of the typical processes used to transfer a geometric pattern from a photomask to a photoresist on the wafer.

MEMS processes, other than photolithography, include, for example, deposition processes and etching processes. Due to the photolithography and other process characteristics, a number of chips of the same MEMS device can be fabricated on the same wafer in one process. For example, a 1 mm square chip can be fabricated in units of several thousand on a 6-inch wafer. As the processing wafer, a Si wafer or a silicon on insulator (SOI) wafer are common materials for the MEMS process. Industrially, the MEMS process is manufactured with 4-, 6-, or 8-inch wafers.

Among MEMS devices, force sensors are one of the typical devices. One of the earliest MEMS force sensors was, for example, a semiconductor pressure sensor [38], which consisted of piezoresistors formed on a Si membrane as a sensing element. Since then, accelerometers/gyroscopes [39][40][41], etc., have been developed as MEMS physical force sensor devices. Most of these sensors consist of specially designed Si structure and sensing elements. As the sensing elements, the piezoresistive, piezoelectric, and capacitive elements are mainly used [42][43][44]. For example, capacitive accelerometers are mainly composed of proof mass and comb structures. In the case of industrial high-performance MEMS sensors, the sensing circuit, including an amplifier, is sometimes additionally integrated on the same sensor chip. In contrast, in the case of one-of-a-kind custom sensor devices, such as for insect measurement, the circuit is separate and configured outside the MEMS sensor chip. Then, the circuit must be placed close to the sensor chip to reduce the electrical noise level. For example, in the case of a piezoresistive sensor, the piezoresistive element is incorporated into a Wheatstone bridge circuit, which converts the resistance change into a voltage change. Then, the voltage change is amplified via an instrumentation amplifier. Because the force exerted by tiny insects is minute, the sensor signal is also weak. In general, the fractional resistance change, as small as the order of 10^{-5}, is a detectable threshold. Thus, when designing the force resolution, the fractional resistance change of that magnitude should be the minimum measurement force.

In recent years, flexible and stretchable MEMS sensors, not based on Si, have also been developed [45][46]. In these devices, polydimethylsiloxane (PDMS) and hydrogels are widely used as device materials, and many studies have been reported in the microfluidics and bioMEMS fields. To form the device structure with these materials, especially PDMS, a moulding process (moulding models are fabricated by a common MEMS process) is usually conducted [47][48]. Hydrogels can be adapted for photolithography by mixing with UV-curing materials. Similar to other fabrication methods, by using microflow channels to mix several liquid materials, the material is chemically cured into the desired shape [49].

To understand the MEMS sensor for the force measurement of insects, here, the common fabrication process will be briefly described. First, the sensor structure, including the position of the sensing element or the metal wiring, is designed according to the required specifications. Simulation or CAD software is used for the design. At the same time, the starting material is determined. If the starting material is an SOI wafer, then the thickness of the device Si layer usually becomes the device thickness. The thickness of the device Si layer is fixed, to some extent, commercially; thus, researchers need to design the sensor structure according to an available wafer. After determining the design, the photomasks are prepared. The number of photomasks is determined by the number of patterning layers. Additionally, preprocessing of the SOI wafer is performed, such as forming a piezoresistive layer with ion implantation and depositing a metal layer with sputtering equipment. Then, the photomask pattern is transferred to the photoresist coated on the wafer by photolithography. Each layer is etched according to the photoresist pattern. Normally, the metal layers are etched via a wet etching process, while the Si layers are etched via a dry etching process with an inductively coupled plasma (ICP)-reactive ion etching (RIE). After fabrication is conducted, the device chip is picked from the wafer via a wafer dicing process. The device chip is attached to a substrate and wire bonded to a pad for electrical connection. A MEMS device is fabricated through a series of these processes.

3. Measurement of Flight/Aerodynamic Forces

3.1. Introduction to Flight and Aerodynamic Forces

The aerodynamic force of the flapping wings of flying animals, which is defined as the force acting at the boundary surface between wings and air, is also one of the most common forces that animals exert during locomotion. Unlike the fixed wing of an airplane, many animals fly by flapping their wings. While some large birds fly with little flapping, small insects constantly flap their wings at a high frequency. For example, the flapping frequencies of a large butterfly and a small fruit fly are 10 Hz and 200 Hz, respectively. The flapping motion produces a pressure difference between the upper and lower surfaces of the wings, which is the aerodynamic force. Here, the flight force was defined as the sum of the aerodynamic force applied to the wing and the force due to motion, such as body vibration.

To evaluate these forces quantitatively, experimental measurement via force sensors is an effective solution, as is simulation. Experimental evaluation of the aerodynamic characteristics of airplane wings has been conducted for a long time [50][51]. In the case of airplanes, pressure sensors are attached to the wing surfaces to evaluate the aerodynamic forces. In the case of the flight force, a wing model, sometimes a total airplane model, is attached to the tip of a probe in a wind tunnel. Then, the force applied to the probe is measured with a 6-axis force gauge. The sensors used for these airplane experiments are adjusted to the aerodynamics of very large airplanes with fixed wings.

Similar to the case of the measurement of the flight force of airplane wings, the non-flapping aerodynamic performance of insect, such as a dragonfly, wings has been evaluated by fixation to a sensitive force probe in a wind tunnel [52]. Since the aerodynamic force is in a static state in such a fixed situation, it is relatively easy to measure. However, such sensor systems are still not suitable for dynamically changing forces. The sensor should be specialized, such as pressure sensors to measure the aerodynamic force of insect wings and force probes to measure the flight force during the actual flapping motion.

3.2. Early Force Probes for Insects

Here, force probes are introduced for the measurement of the flight force of flapping insects. The measurement principle, using a probe-type sensor, is similar to that for an airplane. An insect is attached to the tip of the probe, so that the flight force acting on the insect body is measured during the flapping motion. Thus, the insect is in a tethered state, which is slightly different from free flight, during the measurement. As a required specification of the force probe, the probe must be sufficiently stiff, so that the resonant frequency is higher than the flapping frequency, even if a target insect is attached to the tip of the probe. In addition, measuring the flapping force in multiple axis directions is desirable because the force direction changes every moment, due to the flapping motion. Of course, the sensitivity should be sufficiently high to measure the tiny flight force, which would be of similar order to the body weight. As the target of experiments with the force probe method, flies have been used for a long time, due to their small size and steady flight motion.

The measurement method with a force probe has been proceeding since the 1980s–1990s [53][54][55]. M. H. Dickinson and K. G. Götz developed biaxial flight force measurement using a tethered wire with lasers and photodiodes [55]. A fruit fly (*Drosophila melanogaster*) of approximately 1 mg was tethered to a 60 mm long steel wire, and a shim was adjusted to the boundary of the wire to measure the displacement of the wire along one of the main axes. In the general attachment process, while the fruit fly slept with the application of ice or CO_2 anaesthesia, the sensor was attached to the dorsal position with UV-curing resin. The laser beam was irradiated into the gap between the wire and shim to generate an interference pattern on the other side. Because the interference pattern changed, according to the gap distance, the displacement of the wire, due to the flight force, was detected based on the light intensity measurement by photodiodes at certain points of the interference pattern.

The sensor system realized high stiffness, such that the resonant frequency with a fruit fly was 4.0 kHz; however, the wire displacement, due to force, was only 0.29 nm/μN. The authors mentioned that there were several resonances, due to the vibration of the shim or damped oscillation of the tethered fly. Such vibrations were thought to be generated because the wire was exceedingly long, compared to the target displacement. These influences were suppressed by averaging several flapping cycles. The averaged measurement results demonstrated the flight force components were parallel and perpendicular to the longitudinal body axis in one flapping cycle.

The optical method, with lasers and photodiodes, was also used in the force plate. The optical method has the advantage that the sensing element is constructed without affecting the mechanical property, if the sensor structure is significant large. However, for the sensor structure of a tiny fruit fly, extra shims or mirrors must be installed to the sensor structure, which increases the sensor weight and decreases the resonant frequency. In addition, since the sensor structure is smaller, it is more complicated to build an optical setup. Any difference in the setup will change the response characteristics, so calibration is required each time.

R. J. Wood and R. S. Fearing developed a force probe for measuring the flight force of a micromechanical flying robot that was inspired by an insect [56]. The developed force probe was composed of a cantilever-based strain sensor. The sensor concept is to measure the forces generated on the flapping wing by placing sensors on the wing spars; thus, the force is measured directly. By attaching semiconductor strain gauges to the spar in two directions, the biaxial force can be measured. In addition, the authors proposed a similar type of force probe to measure the total flight force applied to the body. The force probe was composed of two dual cantilever-type sensing elements that could measure the deformation of the cantilever via strain gauges. The resistance changes of the strain gauges were measured via a bridge and amplifier circuit, similar to general resistance sensors. By convolving two sensor elements orthogonally, the biaxial force could be measured. The force resolution and resonant frequency of the developed force probe were 40 μN and 325 Hz, respectively. As a demonstration, a blowfly (*Calliphora*) was tethered to the developed force probe using methods similar to those of the M. H. Dickinson group’s research for *Drosophila*. The experimental results showed that the measured force varied according to the flapping motion, at a flapping frequency of 160 Hz. Additionally, the blowfly produced a maximal force of 15 mN, which was as much as 12 times its body weight. The force probe was custom, handmade, and structurally similar to the force plates that measure GAF. In the literature, the flight force measurement was just a demonstration, and a blowfly was selected as a suitable size for the measurement. Thus, the blowfly size is considered the limitation of the size and measurable force range of the handmade force probe.

3.3. Early MEMS Piezoresistive Force Probes

One of the first MEMS force probes for insects was proposed by the M. H. Dickinson group [30]. The target insect here was also a fruit fly. The proposed force probe was designed to be L-shaped, and four piezoresistors were formed on the L-shaped beam surface to measure the lift, thrust, and yaw forces. The widths of the beams close to and far from the tip were 250 μm and 400 μm, respectively. The force probe was fabricated on a Si wafer. As the piezoresistive layer, an N-doped poly-Si layer was deposited on the wafer, and the fabrication process was similar to that of the MEMS piezoresistive force plates described before. The fabricated force probe chip was mounted on a substrate and wire bonded. Then, the piezoresistors were connected to a bridge and amplifier circuit. The authors mentioned that forces of 100 μN were measured by attaching small weights at the tip of the sensor, and the resonant frequencies were higher than the flapping frequency, typically approximately 200 Hz. As the initial experiment, a fruit fly (*Drosophila melanogaster*) was tethered to the fabricated force probe. Then, the force measurement was conducted while the fly was flapping. However, the authors concluded that, even though the sensor signal was observable, the actual flight forces in a single flapping cycle were too small to be measured with the force probe. There was a possibility that the noise would become sufficiently low by averaging the flapping cycles, similar to the approaches of M. H. Dickinson and K. G. Götz [55] mentioned before. The authors also suggested that the sensor should have a force resolution of at least 0.1 μN, in the range of less than 50 μN, in order to measure the flight forces produced by a fruit fly. One of the reasons for the low sensitivity is that the piezoresistive layer is formed on the surface Si layer, while the in-plane directional deformation, i.e., F_{lift} and F_{thrust}, is the measurement target. This problem is similar to the discussion before, which is about the early MEMS force plate for a cockroach. With a single surface piezoresistive layer, it is difficult to measure the multi-axis flight force of “mg”-mass insects.

3.4. MEMS Capacitive Force Probes

The B. J. Nelson group developed MEMS highly sensitive capacitive force probes for a fruit fly [31][32][33][34][35]. They also measured the cellular force using the same force probe. The force probe was composed of a Si cantilever and supporting spring beams, so that the cantilever deformed in the in-plane longitudinal direction. A comb structure was formed behind the cantilever. A comb structure was also formed in the surrounding area, so that capacitive elements were realized. Provided that the cantilever deforms due to a longitudinal force, the gap between the two comb structures changes. By detecting the capacitive change of the comb structures, the applied force can be measured. The width, length, and thickness of the probe were designed to be 50 μm, 50 μm, and 3 mm, respectively. The width of the comb structures was 5 μm. The force probe was fabricated on an SOI wafer of a device Si layer of 50 μm. The sensor structure was fabricated by a common DRIE etching process. The capacitances of the sensor were connected to a buffer amp and synchronous demodulator circuit. The force resolution and measurable range were 0.68 μN and ±1 mN, respectively. The authors also mentioned that the bandwidth, which corresponded to the resonant frequency, was 7.8 kHz. A fruit fly (*Drosophila melanogaster*) was attached to the tip of the fabricated force probe. Thus, the measured force corresponded to the lift directional flight force. The experimental results demonstrated that the measured flight force was periodic at a fundamental frequency of approximately 200 Hz, which corresponded to the flapping frequency of fruit flies. In addition, the averaged force in one cycle was 9.3 μN, which corresponded to the range of the typical body weights of fruit flies.

The MEMS capacitive force probe, described above, was a single-axis sensor. The B. J. Nelson group also developed MEMS multi-axis force probes utilizing sophisticated comb structures [57][58]. By forming the units of the comb structures in the orthogonal directions, the in-plane two-axis force could be detected. In addition, by utilizing a double SOI wafer with two overlapping device Si layers, a vertical directional gap could be applied to the comb structures, so that the out-of-plane axis force became detectable. The authors reported that the force resolution was less than 0.2 μN, with a measurable range of approximately ±200 μN. Using multi-axis force probes, the flight forces of a fruit fly during flapping motion in three-dimensions can, in principle, be measured.

Capacitor-type sensors realize high force sensitivity. Therefore, the high sensitivity and wide measurement range can be simultaneously satisfied. Meanwhile, the DC component is difficult to measure, due to the detection principle. Therefore, even if the variation of the force during one flapping cycle can be revealed, it is difficult to evaluate its absolute value.

In the case of a capacitive element, the dimensional sensitivity characteristics are contrary to those of piezoresistive element. In-plane deformations can be measured with high sensitivity, but out-of-plane deformations are not suitable for detection because the capacitive element of a simple comb electrode does not distinguish positive or negative sensing in the out-of-plane direction. Therefore, to realize a multi-axis force probe with more than three axes, one must conduct complex processes on an expensive double SOI wafer.

3.5. MEMS Piezoresistive Multi-axis Force Probes

The H. Takahashi and I. Shimoyama group developed MEMS force probes for a fruit fly [36][37], in addition to the force plates described before. The developed force probe was based on a piezoresistive-type multi-axis force probe previously reported by their group [59], the fundamental principle of which was the same as that for their MEMS force plates. The force probe was composed of a Si cantilever and four supporting beams. Two beams had sidewall-doped piezoresistors to detect the *x*-*y*-axis in-plane force applied to the tip of the cantilever, while one beam has a surface-doped piezoresistor to detect the *z*-axis out-of-plane force. The other beam worked as the electric ground. Thus, the triaxial force applied to the tip of the cantilever could be detected by measuring the resistance changes of the three beams at the same time. Since the responses to the triaxial force were orthogonal to each other, low crosstalk could be realized.

The width, length, and thickness of the probe were designed to be 360 μm, 1.4 mm, and 50 μm, respectively. The force probe was fabricated on an SOI wafer of a device Si layer of 50 μm. The fabrication process of the force probe was almost the same as that of the MEMS force plate array for ants [25]; only the mask pattern was different. The piezoresistors of the sensor were connected to a bridge and amplifier circuit with a common electric ground. The force resolutions along the *x*-, *y*-, and *z*-axes were 0.2 μN, 0.3 μN, and 0.6 μN, respectively, in the range of ±120 μN (unpublished data). A fruit fly (*Drosophila melanogaster*) was attached to the tip of the fabricated force probe. Then, the resonant frequency of the force probe with a fruit fly was measured to be 680 Hz along the *z*-axis, which was the lowest stiffness axis (unpublished data). The experimental results showed the triaxial flight force during the flapping motion. The measured flight force was demonstrated to be synchronized with the flapping motion of the fruit fly.

3.6. Differential Pressure Sensors for Insects

The H. Takahashi and I. Shimoyama group developed not only MEMS force probes, but also MEMS differential pressure sensors for butterflies [60][61]. The MEMS differential pressure sensor was composed of a piezoresistive cantilever 125 μm × 100 μm × 0.3 μm in size. The fundamental principle was similar to that of their MEMS force plates and force probe described above. Thus, the fabrication process was also similar. The piezoresistive layer was formed on the surface of the cantilever. The cantilever deformed when differential pressure was applied between the upper and lower surfaces of the cantilever. Due to the micron-size gap surrounding the cantilever, air leakage from the gap was sufficiently low, such that the cantilever deformed as theoretically expected, without being affected by the leakage. The sensor realized a pressure resolution less than 0.1 Pa, due to its highly sensitive piezoresistance and sub-micron thick cantilever structure in the range of −20~+20 Pa. The resonant frequency of the cantilever was over 10 kHz, which was sufficiently higher than the flapping frequency. Additionally, the sensor did not respond to acceleration, due to the sub-micron thickness. Thus, even if the sensor is attached to the wing surface, there is little influence of the acceleration from the flapping motion.

The aerodynamic force was measured by attaching the sensor chip to the wing surface, at the point where a through hole penetrated. As the target insect, a spangle butterfly (*Papilio protenor*) was used because of both the large wing area and heavy weight among lepidopterans; it can tolerate the additional weight of the sensor system. A flexible electrode was used for the sensor attachment. A sensor chip of 1 mm × 1 mm × 0.3 mm in size was attached to the edge of the electrode, while two Au wires were connected to the opposite side of the electrode. Then, the electrode was adhered to the vein of the wing. In terms of weight, the sensor chip was 0.7 mg, which was small enough for a single wing. The total weight, including the Au wires, was less than 10% of the body weight, which was thought to be within the acceptable range, considering that the food is approximately 1/10 of the body weight. Using the sensor-attached butterfly, the differential pressure on the wing was measured during the take-off motion. At the point of the centre of the forewing, periodic and symmetric differential pressure was induced, according to the upstroke and downstroke. The maximum differential pressure reached approximately 10 Pa, which was 10 times larger than the wing load.

Aerodynamic force measurement, using MEMS differential pressure sensors, has been adapted to insect-like ornithopters, as well as to an actual butterfly. The advantages of using insect-modelled ornithopters are that researchers can focus on and extract the characteristic points in flight performance and that reproducible experiments can be easily conducted. Because of its large payload, a datalogger, including an amplifier circuit and a battery, was mounted on the ornithopter to record the sensor data. Thus, the measurement could be conducted in completely free flight. The sensor system was applied, not only to the moth-modelled ornithopter, but also to a dragonfly-modelled ornithopter, with different phase lags between the forewings and hindwings [62], as well as a beetle-modelled ornithopter with fixed forewings [63]. In each study, the differential pressure during flight was measured, and the aerodynamic performances were evaluated when the characteristic parameters were varied.

Additionally, by placing the MEMS differential pressure sensors on the ground, the ground pressure caused by the downstroke when an insect took off was detected [64]. In the experiment, a spangle butterfly (*Papilio protenor*) was also used. The maximum pressure was approximately 1 Pa. The local maximum pressure was generated on both the downstroke and upstroke. The measurement system could allow researchers to evaluate the ground effect with tiny differential pressure [65].

In these studies, only spangle butterflies were tested as actual insects. At the present stage, it is difficult to apply this method to insects smaller than spangle butterflies. The bottleneck is not the MEMS differential pressure sensor chip, but the wiring. The wiring becomes a non-negligible size to the wing and inhibits the flapping motion. The authors attached the same setup to a swallowtail butterfly, which is approximately 200 mg; then, the butterfly could not take off (unpublished). If thinner wiring is available, the sensor system is applicable to smaller insects. The MEMS cantilever structure, which is the sensing element, is on the order of 100 μm; thus, the size can be further miniaturized, in principle. However, the manual post-process is the size limitation.

3.7. Wearable Sensor for Wing

Although they do not directly measure the force, wing wearable sensors have been developed to measure the flapping frequency [66]. The sensor is composed of a thin silicone polymer film with silver particles, so that the resistance changes when a bending deformation occurs. The film was 0.25 mm thick. The fabricated sensor was attached to the wings of a tethered silk moth and a tethered dragonfly. Then, the flapping frequency was obtained by measuring the change in resistance when the wings flapped. While it is less computationally expensive than high-speed camera images, it is more invasive because the sensor is directly fixed to the wing. Especially, it is currently necessary to attach electrodes via wires. If the target insect is tethered, the force probe is considered more suitable for measuring the flapping frequency because the calculation process cost is similar. However, if it is possible to be completely wireless and measure more localized strain, the wearable sensor will be useful for measuring the distribution of the wing deformation during the flapping motion.

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