Technology Brief 15
Micromechanical Sensors and Actuators

Energy is stored in many different forms in the world around us. The conversion of energy from one form to another is called ***transduction***. Each of our five senses, for example, transduces a specific form of energy into electrochemical signals: tactile transducers on the skin convert mechanical and thermal energy; the eye converts electromagnetic energy; smell and taste receptors convert chemical energy; and our ears convert the mechanical energy of pressure waves. Any device, whether natural or man-made, that converts energy signals from one form to another is a ***transducer***.

Most modern man-made systems are designed to manipulate signals (i.e., information) using electrical energy. Computation, communication, and storage of information are examples of functions performed mostly with electrical circuits. Most systems also perform a fourth class of signal manipulation: the transduction of energy from the environment into electrical signals that circuits can use in support of their intended application. If a transducer converts external signals into electrical signals, it is called a ***sensor***. The charge-coupled device (CCD) chip on your camera is a sensor that converts electromagnetic energy (light) into electrical signals that can be processed, stored, and communicated by your camera circuits. Some transducers perform the reverse function, namely to convert a circuit's electrical signal into an environmental excitation. Such a transducer then is called an ***actuator***. The components that deploy the airbag in your car are actuators: given the right signal from the car's microcontroller, the actuators convert electrical energy into mechanical energy and the airbag is released and inflated.

Microelectromechanical Systems (MEMS)

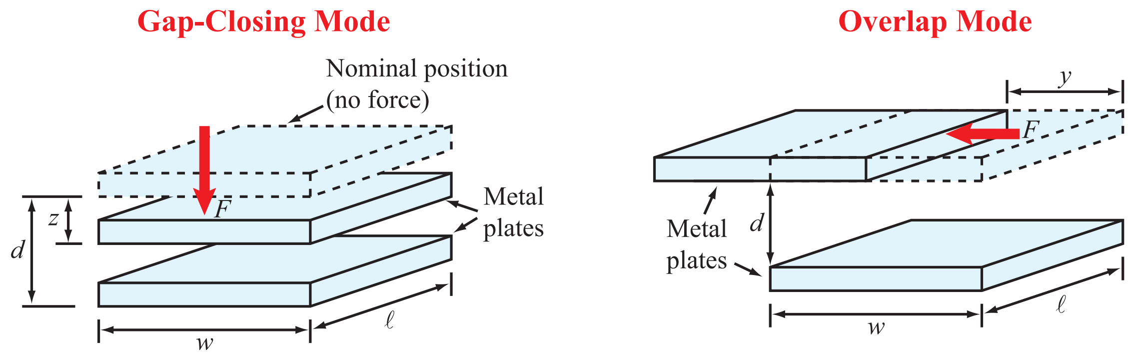
Micro- and nanofabrication technology have begun to revolutionize many aspects of sensor and actuator design. Humans increasingly are able to embed transducers at very fine scales into their environment. This is leading to big changes, as our computational elements are becoming increasingly aware of their environment. Shipping containers that track their own acceleration profiles, laptops that scan fingerprints for routine login, cars that detect collisions, and even office suites that modulate energy consumption based on human activity are all examples of this transduction revolution. In this technology brief, we will focus on a specific type of microscale transducers that lend themselves to direct integration with silicon ICs. Collectively, devices of this type are called ***microelectromechanical systems*** (MEMS) or ***microsystems technologies*** (MST); the two names are used interchangeably.

A Capacitive Sensor: The MEMS Accelerometer

According to Eq. (5.21), the capacitance C of a parallel plate capacitor varies directly with A, the effective area of overlap between its two conducting plates, and inversely with d, the spacing between the plates. By capitalizing on these two attributes, capacitors can be made into motion sensors that can measure velocity and acceleration along x, y, and z.

Figure TF15-1 illustrates two mechanisms for translating motion into a change of capacitance. The first generally is called the ***gap-closing mode***, while the second one is called the ***overlap mode***. In the gap-closing mode, A remains constant, but if a vertical force is applied onto the upper plate, causing it to be displaced from its nominal position at height d above the lower plate to a new position $(d - z)$, then the value of capacitance C_z will change in accordance with the expression given in **Fig. TF15-1(a)**. The sensitivity of C_z to the vertical displacement is given by dC_z/dz.

The overlap mode (**Fig. TF15-1(b)**) is used to measure horizontal motion. If a horizontal force causes one of the plates to shift by a distance y from its nominal position (where nominal position corresponds to a 100 percent overlap), the decrease in effective overlap area will lead to a corresponding change in the magnitude of capacitance C_y. In this case, d remains constant, but the width of the overlapped areas changes from w to $(w - y)$. The expression for C_y given in **Fig. TF15-1(b)** is reasonably accurate (even though it ignores the effects of the ***fringing electric field*** between the edges of the two plates) so long as $y \ll w$. To measure and amplify changes in capacitance, the capacitor can be integrated into an appropriate op-amp circuit whose output voltage is proportional to C. As we shall see shortly, a combination of three capacitors, one to sense vertical motion and two to measure horizontal motion along orthogonal axes, can provide complete information on both the velocity and acceleration vectors associated with the applied force. The capacitor configurations shown in **Fig. TF15-1** illustrate the basic concept of how a capacitor is used to measure motion, although more complex capacitor



Capacitance: $C_z = \dfrac{\varepsilon w\ell}{d-z}$

Sensitivity: $\dfrac{dC_z}{dz} = \dfrac{\varepsilon w\ell}{(d-z)^2}$

Capacitance: $C_y = \dfrac{\varepsilon(w-y)\ell}{d}$

Sensitivity: $\dfrac{dC_y}{dy} = -\dfrac{\varepsilon\ell}{d}$

Figure TF15-1: Basic capacitive measurement modes. For (b), the expressions hold only for small displacements such that $y \ll w$.

geometries also are possible, particularly for sensing angular motion.

To convert the capacitor-accelerometer concept into a practical sensor—such as the automobile accelerometer that controls the release of the airbag—let us consider the arrangement shown in **Fig. TF15-2(b)**. The lower plate is fixed to the body of the vehicle, and the upper plate sits on a plane at a height d above it. The upper plate is attached to the body of the vehicle through a spring with a ***spring constant*** k. When no horizontal force is acting on the upper plate, its position is such that it provides a 100 percent overlap with the lower plate, in which case the capacitance will be a maximum at $C_y = \varepsilon W\ell/d$. If the vehicle accelerates in the y-direction with acceleration a_y, the acceleration force F_{acc} will generate an opposing spring force F_{sp} of equal magnitude.

Equating the two forces leads to an expression relating the displacement y to the acceleration a_y, as shown in the figure. Furthermore, the capacitance C_y is directly proportional to the overlap area $\ell(w-y)$ and therefore is proportional to the acceleration a_y. Thus, by measuring C_y, the accelerometer determines the value of a_y. A similar overlap-mode capacitor attached to the vehicle along the x-direction can be used to measure a_x. Through a similar analysis for the gap-closing mode capacitor shown in **Fig. TF15-2(a)**, we can arrive at a functional relationship that can be used to determine the vertical acceleration a_z by measuring capacitance C_z.

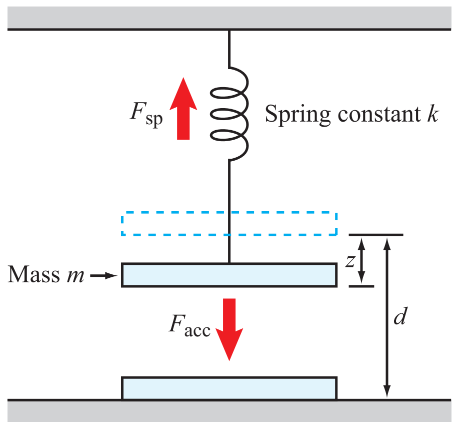
For example, if we designate the time when the ignition starts the engine as $t=0$, we then can set the initial conditions on both the velocity u of the vehicle and its acceleration a as zero at $t=0$. That is, $u(0) = a(0) = 0$. The capacitor accelerometers measure continuous-time waveforms $a_x(t)$, $a_y(t)$, and $a_z(t)$. Each waveform then can be used by an op-amp integrator circuit to calculate the corresponding velocity waveform. For u_x, for example,

$$u_x(t) = \int_0^t a_x(t)\, dt,$$

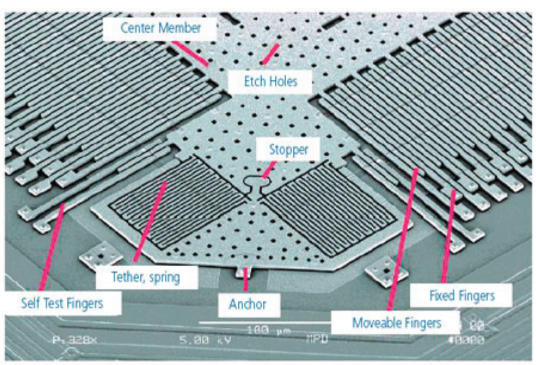
and similar expressions apply to u_y and u_z.

Commercial MEMS Accelerometers

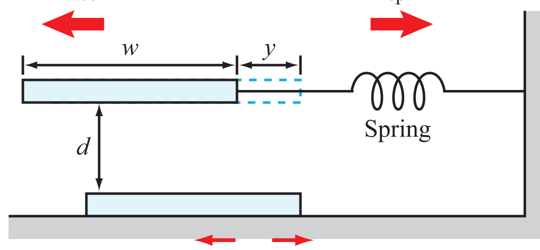
Figure TF15-3 shows the Analog Devices ADXL202 accelerometer which uses the gap-closing mode to detect accelerations on a tiny micromechanical capacitor structure that works on the same principle described above, although slightly more complicated geometrically. Commercial accelerometers, such as this one, make use of negative feedback to prevent the plates from physically moving. When an acceleration force attempts to move the plate, an electric negative-feedback circuit applies a voltage across the plates to generate an electrical force between the plates that counteracts the acceleration force exactly, thereby preventing any motion by the plate. The magnitude of the applied voltage becomes a measure of the acceleration force that the capacitor plate is subjected to. Because of their small size and low power consumption, chip-based microfabricated silicon accelerometers



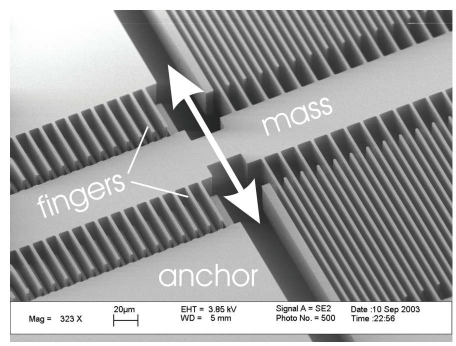
$$F_{sp} = F_{acc}$$
$$kz = ma_z$$
$$z = \frac{ma_z}{k}$$
$$C_z = \frac{\varepsilon w \ell}{\left(d - \frac{ma_z}{k}\right)}$$



(a) The ADXL202 accelerometer employs many gap-closing capacitor sensors to detect acceleration. (Courtesy Analog Devices.)



$$F_{acc} = F_{sp}$$
$$ma_y = ky$$
$$y = \frac{ma_y}{k}$$
$$C_y = \frac{\varepsilon \ell (w - y)}{d} = \frac{\varepsilon \ell \left(w - \frac{ma_y}{k}\right)}{d}$$



(b) A silicon sensor that uses overlap mode fingers. The white arrow shows the direction of motion of the moving mass and its fingers in relation to the fixed anchors. Note that the moving fingers move into and out of the fixed fingers on either side of the mass during motion. (Courtesy of the Adriatic Research Institute.)

Figure TF15-2: Adding a spring to a movable plate capacitor makes an accelerometer.

are used in most modern cars to activate the release mechanism of airbags. They also are used heavily in many toy applications to detect position, velocity and acceleration. The Nintendo Wii, for example, uses accelerometers in each remote to detect orientation and acceleration. Incidentally, a condenser microphone operates much like the device shown in **Fig. TF15-2(a)**: as air pressure waves (sound) hit the spring-mounted plate, it moves and the change in capacitance can be read and recorded.

A Capacitive Actuator: MEMS Electrostatic Resonators

Not surprisingly, we can drive the devices discussed previously in reverse to obtain actuators. Consider again

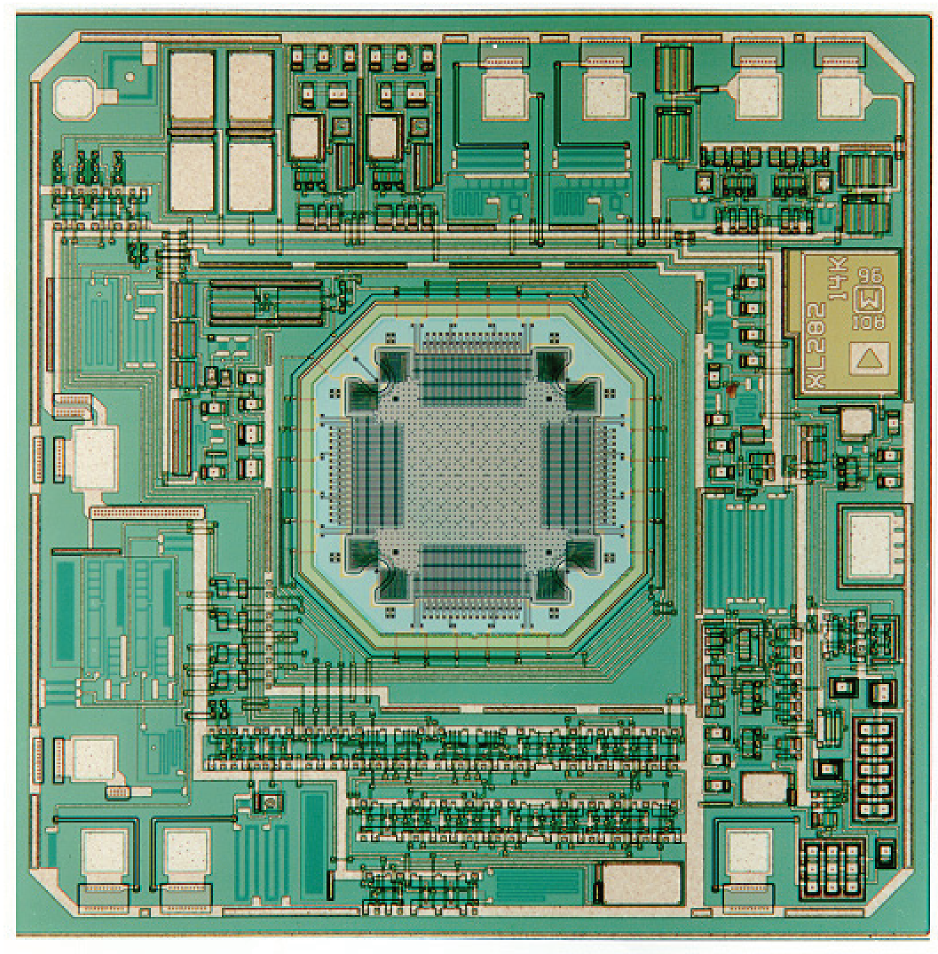


Figure TF15-3: The complete ADXL202 accelerometer chip. The center region holds the micromechanical sensor; the majority of the chip space is used for the electronic circuits that measure the capacitance change, provide feedback, convert the measurement into a digital signal, and perform self-tests. (Courtesy of Analog Devices.)

the configuration in **Fig. TF15-2(a)**. If the device is not experiencing any external forces and we apply a voltage V across the two plates, an attractive force F will develop between the plates. This is because charges of opposite polarity on the two plates give rise to an electrostatic force between them. This, in fact, is true for all capacitors. In the case of our actuator, however, we replace the normally stiff, dielectric material with air (since air is itself a dielectric) and attach it to a spring as before. With this modification, an applied potential generates an electrostatic force that moves the plates.

This basic idea can be applied to a variety of applications. A classic application is the ***digital light projector*** (DLP) system that drives most digital projectors used today. In the DLP, hundreds of thousands of capacitor actuators are arranged in a 2-D array on a chip, with each actuator corresponding to a pixel on an image displayed by the projector. One capacitive plate of each pixel actuator (which is mirror smooth and can reflect light exceedingly well) is connected to the chip via a spring. In order to brighten or darken a pixel, a voltage is applied between the plates, causing the mirror to move into or out of the path of the projected light. These same devices have been used for many other applications, including microfluidic valves and tiny force sensors used to measure forces as small as a zeptonewton (1 zeptonewton $= 10^{-21}$ newtons).