

Chapter 10

Testing



MEMS devices are complex, and there are many points in the process where something can go wrong. My advice is to start simple. Use everything at benchtop scale with electronics and components that are off the shelf until you are confident the MEMS sensor or actuator is performing correctly. Then, miniaturize or incorporate one thing at a time until you achieve your final configuration. This will save you a lot of time and frustration in the long run. The following sections are on types of testing you may need to ensure proper performance of your MEMS device, especially when you are down at the microscopic final size (Fig. 10.1).

Electronics

Signal Transduction

Is your device hardwired to a PCB and connectors, or is it using wireless communication? No matter which, your signal transduction is going to be a challenge. Pay attention to wire traces—are they wide enough? Thick enough? Fully formed with no nicks or narrow/thin spots? If you have solder connections, are they solid and clean? No stray/parasitic signal pathways? No fracture or erosion of the solder pads? If you have wire bonds, are they all fused at both ends? Do they accidentally touch each other or have enough length to cause electrical noise? Will they stay connected during expected use/handling conditions?

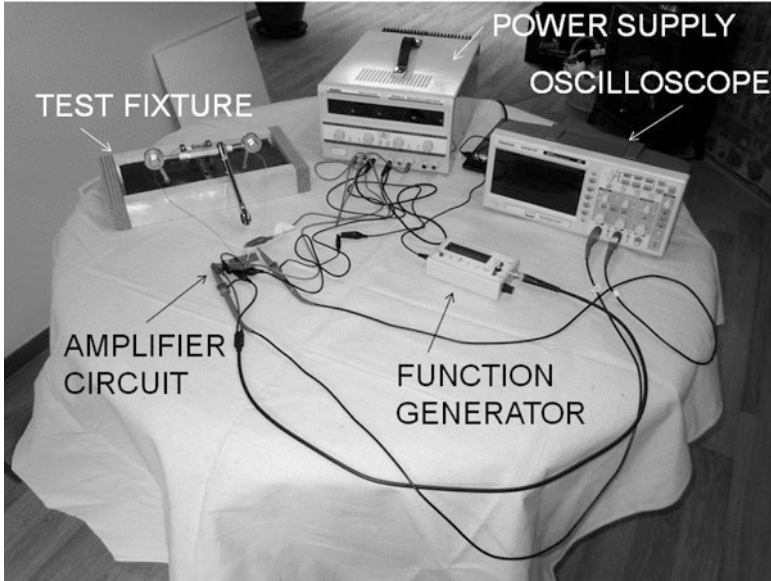


Fig. 10.1 Benchtop testing. MEMS device in fixture and amplifier PCB

Signal to Noise Ratio

The signals generated by your MEMS sensor will be tiny, so you need a means of amplifying them at the source of the signal, long before noise enters the equation. Everything is a potential source of noise at these microscopic scales—humidity, temperature, vibration, fluorescent lights, unshielded wires, nearby materials or power sources, even poor-quality microfabrication. It is important to design with signal quality in mind.

One thing you can do is have your MEMS device generate the largest possible output, such as moving your sensor's capacitive fingers closer together while also making them longer and deeper. Another thing you can do is convert to a digital signal as close to the MEMS device as possible and then amplify the digital signal. This way, it is easier to amplify just the signal without amplifying all the noise along with it. A third thing you can do is shield, shield, shield. Try to determine all your potential sources of noise and shield against their interference—encase your wire bonds in a plastic goop (to keep them from moving, touching, or interacting with each other), print metal, or an insulating glass on surfaces to prevent signal loss and/or the outside environment from entering, and optimize shapes of your MEMS device and packaging to provide the cleanest signal pathway.

Data Storage and Transmission

How are you going to manage your data output? Does it “wake up” and respond when queried, store a value until queried, or continuously transmit data? Depending on your answer, you will need a specific data storage and transmission strategy. Whether you are using an implanted battery or temporarily charging a capacitor during signal transmission, you need to have a strategy for data storage.

Often, your frequency of data collection is extremely high (100 Hz, 1000 Hz, or more), which means you will be drowning in data output. It rarely makes sense to store all of that raw data, so you will need some means of consolidating it for storage and/or transmission. Let us say you are operating at 100 Hz and collect data for 3 seconds. That is 300 data points. Can those all be averaged into a single value? If so, great! It is much easier to store and transmit one value than 300. If the value is stored for later retrieval and transmission, you will need to store it digitally and have some kind of onboard storage, like a read-only memory (ROM) chip.

Analog-to-Digital Conversion

As mentioned previously, signals are easier to consolidate, amplify, and transmit if converted to digital. If you are making a cantilever and measuring the deflection of a proof mass, the electrical strain from bending the cantilever is an analog, continuously varying signal. Using an analog-to-digital converter (ADC), you can discretize the signal into millivolt steps. If you have an 8-bit ADC, then you can discretize your signal into 2^8 steps, or 256 increments. If you have 1 volt (1000 mV), then you will be able to detect a $1000/256$, or 3.9-mV change. For a 12-bit ADC and 1000 mV, you will be able to detect a 0.24-mV change.

Batteries

Most implanted MEMS devices still require an internal power source in the form of a battery to provide enough power to operate. It is possible to use external excitation (such as from radiofrequency waves, often called RF) to charge up a device enough to transmit a small signal, and this technique is used for passive RFID tags, such as the chips put in pets to locate their owners. However, if your device needs to continually operate or has to transmit signals, you will most likely need a battery. Pacemakers use batteries that are hermetically sealed within a titanium canister, and they last 5 years without replacement. Although recharging batteries through the skin is also feasible, it is important to consider the risks that pose to the patient. For pacemakers, it is safer to perform a replacement surgery of the canister every 5 years, unplugging the leads into the heart and plugging them back into the new device.

Batteries are biotoxic, no matter what type is used, but some are safer than others. They come in all shapes and sizes, as well as various voltages, so selecting an OTS one for your needs is usually feasible. Because they are dangerous, you will need to pay careful attention to the waterproof sealing of your package and the intended lifespan of the implanted device when using batteries for power.

Finally, consider your power requirements. If you are purchasing OTS components, especially microcontrollers or amplifiers, know that they all have different peak power requirements. You will need to do a power profile for your system and determine the worst-case peak load. Let us say you add up all the power requirements of your components during worst-case usage and you need 5 mW (power in watts is volts multiplied by amps). That is not the whole story, as you also need to know the average power requirements and the amount of time you want your device to last. Usually, you want your medical device to last years, so the capacity of your battery must (1) meet your peak load needs and (2) have enough capacity to last, which is your average power multiplied by the amount of time, usually given in watt-hours (Wh).

Batteries are made of a wide variety of materials/chemistries, so not all batteries have the same performance. Lithium ion batteries have the highest energy density, so they are small and light, and they are commonly used in handheld electronics, like your phone. However, they have to have additional circuitry to control their charging and discharging rates, as well as monitor their temperature, as they can explode. This makes them undesirable for many medical applications. Lithium iron phosphate batteries are also compact and can deliver higher power, with the added advantage of not being susceptible to explosion or dangerous swelling. A third option, which is larger and heavier, is nickel metal hydride, which suffers from no memory effects and is safe, plus rechargeable, but these batteries self-discharge. So, you will have to find low discharge rate versions. For more information on batteries, go to <http://BatteryUniversity.com>.

Algorithms

You will need some means of converting (and perhaps digitizing, amplifying, or manipulating) your MEMS device's output into a usable form. This is accomplished via electronics and your circuit, but often you will need a microcontroller as well to manage signal traffic and control what happens in different phases of signal transduction. For prototyping, I recommend using an Arduino, which is a cheap, readily programmable microcontroller with thousands of software algorithms (in C or C++ programming language) that have already been written and made available for free. You can easily download a similar piece of code and tweak it to meet your needs. If you have never used Arduino, you can buy starter kits that include a guidebook with projects as well as all the electronic components you will need to build those projects.

After prototyping, however, you will need to miniaturize your microcontroller and program that device to meet your long-term needs. There are countless varieties of microcontrollers out there, and the programming languages are standard, usually C or C++, but sometimes others. If this is not your forte, there are many C programmers out there that can write you a suitable code and test it for you.

When dealing with software algorithms, the hardest part is troubleshooting. Do yourself a favor and incorporate visible output from your device, especially in the prototyping phases, but also in the final product. There is nothing more reassuring than an LED lighting up to let you know a device is working!

Mechanical

Structure of Device

You need to find a way to test the mechanical structure of your device. Your calculations may predict that 5 μm of bending at the base of your cantilever will produce 1 mV of output, but does it? You wanted a range of motion of 20 μm , but can the cantilever withstand that without breaking? Mechanical testing is hard to do at such low loads and small dimensions, so utilize your larger-scale prototype to do the majority of the work. It is relatively easy to make your MEMS device five times or ten times bigger in order to test it. Only after this step, use the AFM to apply the tiny loads to check your final device.

Remember that at these microscales, you have to consider other aspects of physics that you would normally ignore as negligible. For instance, cantilevered beams will bend under their own weight, and if they get close enough to the substrate, they can get “glued” to the substrate due to van der Waal’s intermolecular attraction forces (called stiction, for “static friction”). Stiction in MEMS is when adhesive forces exceed restoring forces, so on this same cantilevered beam, stiction could be caused by moisture/capillary forces or even ionic forces. In addition to these examples, there are many other phenomena to consider, so get the advice of technical staff at the lab while designing your structure to understand what risks exist.

Mounting

Although robotic pick-and-place equipment, solder masks, and reflow soldering equipment exist for production runs of MEMS devices, you are going to start by doing everything manually. Releasing, handling, and mounting a tiny device are tricky. It requires care, patience, and an understanding of the ways in which the device is most vulnerable to damage. If you have long, cantilevered fingers, any force applied to those fingers will likely break them; however, in the surface plane, the device can be safely picked up with tweezers.

You are going to have to hand mount and solder your MEMS device, so keep that in mind and design “large” solder pads and/or places you can apply pressure. Think about how you are going to release the device from the wafer, mount it in place, and solder it, or you will suffer. I used a “moat and tether” design for prototypes. To remove a device from the wafer, I covered it with dicing tape and then broke the tethers with a needle while looking through a microscope. I then picked up the device with the dicing tape and adhered the tape on one side to my specimen. I folded the device back to reveal the underside and applied CA glue and then folded the device back down to adhere onto my specimen like you would a copper foil strain gauge. I applied light pressure with two needles in safe regions until dry and then gently pulled off the dicing tape, keeping the angle close to zero.

Then, I wire bonded from the solder pad “bars” to larger, more robust solder pads, and I soldered insulated wires between the solder pads and my PCB. I later trained a student to surface-mount solder all the OTS components to the integrated circuit, which required manually positioning the component on the dabs of solder paste and using a fine-tip soldering iron to reflow the solder just long enough to get it to melt, but not so long as to heat damage the component or the silicon wafer PCB. You will need to develop a procedure that works for your device.

Packaging

At some point, you will need to place your MEMS device and possibly its integrated circuit or PCB into a housing. This entire, complex process is simply called “packaging.” I have separated out “mounting” as a pre-step, but that is often described under the umbrella of packaging as well. Be prepared for this to be difficult. IC chip manufacturers have it easy compared to MEMS fabricators. For a chip, you can often melt a conformal coating over the top and be done. With a sensor or an actuator, the device has to *interact* with its environment, and that makes packaging a challenge.

Also, if you are trying to wirelessly transmit your data, your packaging geometry, thickness, and material are prime considerations. Before you fabricate your packaging, I advise you to have an electromagnetic field (EMF) study done in a computational model with finite element analysis (FEA) and EMF computational fluid dynamics (CFD); otherwise, you will be guessing. Everything about your packaging will affect the quality of your signal transmission, so you will need to vary parameters until you find the configuration that works the best. Then after your device and package are constructed, you can have them tested in a chamber to make sure they are performing correctly. Both computational modeling and signal transmission testing can be outsourced to vendors who specialize in these fields.

Bonds

Wire bonding, usually gold wire of 18–60- μm diameters, is commonly used to electrically connect a microscopic MEMS device to the rest of the circuit, but these bonds are fragile and prone to an array of problems. First, the bond connection can break, which happens frequently. Thus, you need to use three or more wire bonds for each connection. Second, the wires can break, so you need to protect them. One common way is to encase them in a polymer, such as parylene, to give them extra strength. Third, the wire is not insulated, so if two wires touch that should not, your circuit will not work correctly. In addition, “long” uninsulated wires can interfere with each other and increase noise in your signal. Encasing the wires in a polymer helps for this issue, too.

Fatigue

If your MEMS device works through repeated bending, vibration, thermal expansion, or other repetitious motion (or is subjected to these environments), you will need to do a fatigue analysis. For natural frequencies, this is also called modal analysis, and for controlled, repeated testing is called cycle life testing. Determine what your fatigue failure modes are using a standard decision tree, such as a failure mode and effects analysis (FMEA) and then design a way to test your device under each of those isolated and compounded conditions. FEA and a computational model are a good way to start, but eventually, you will need to do physical testing. You may need to fabricate other MEMS devices as test fixtures to then apply the conditions you need to do fatigue analysis on your sensor.

Soldering

Soldering while looking through a microscope requires a lot of fine motor skill and a steady hand. Many things can go wrong when you are soldering, such as overheating the solder or the component, wicking solder into regions it does not belong, breaking the MEMS device from pressure or heat, misalignment of components, accidentally “unsoldering” wires and connections, or losing your grip on something—the solder wire, the electrical wire, the component, or the integrated circuit board. I have made numerous fatal mistakes while soldering, so keep extra supplies and components on hand to account for attrition.

Environmental

Environmental testing is critical, especially for implanted or consumer use medical devices. Regulatory bodies require that you test for a host of environmental factors, assuming worst-case conditions and maximum end-of-lifetime points. If you are placing a sensor on/in a total hip implant, for instance, you will need to mimic *in vivo* conditions, such as 10 million loading cycles, a corrosive saline environment, electrical transmission through tissue (which can cause tissue heating), and worst-case scenario failure modes (i.e., the device leaks and the battery is exposed). The following are some common environmental considerations.

Waterproofing

One of my favorite sayings is, “Moisture finds a way.” If there is a way for moisture to get into your packaging, it will. Maybe it will survive a few months or a year, but eventually, moisture will get in and destroy your device. Depending on what materials and components you have used and where the device is located, that moisture may allow biotoxic contaminants to enter the body.

So, your waterproofing strategy depends upon the risk. If the device is a long-term medical implant, you should choose a hermetically sealed package. Nothing else is going to gain regulatory approval, so incorporate those design constraints into your packaging from the beginning. If you are trying to transmit a wireless signal, you will need to have a radiolucent housing. If you need a large antenna, it may not fit in your packaging, and you will need to consider hardwired leads that connect to your MEMS device packaging through hermetically sealed leads. If you have a transcutaneous connector to an external device, such as an insulin pump, you will have to consider the additional hazard of infection and how that will impact your housing.

Sterilization

Medical implants need to be sterilized, but gamma radiation destroys electronics, and autoclaves are often too hot or too steamy for MEMS devices, which leaves ethylene oxide (EtO). This is safe and effective, but is not commonly available. You will not find it at the microfabrication facilities, but since most of the facilities are at research universities, you might find an EtO sterilizer at the hospital. Otherwise, to perform this test and how it impacts your device, you will need to send it to an outside vendor.

Wireless Signal Transmission

Although we often think of wireless as a single transmission frequency, that is entirely inaccurate. The FCC publishes a series of frequency bands that can be used for medical devices, and they range from kilohertz to hundreds of gigahertz. Frequency is the main parameter to consider for power requirements, distance for signal to travel, tissue heating, and compatibility with OTS receivers, so it is a key design feature to consider. In general, the higher the frequency, the smaller the antenna and the longer the distance you can travel. Unfortunately, the higher the frequency, the more tissue is heated and the more power is required, so it is a trade-off. Table 2 provides some commonly used frequency bands. Currently 13.56 MHz, which is in the RF band, and 2483.5 MHz, which is Bluetooth, are the most commonly used for medical devices (and electronics in general), but they may not be the most desirable bands for your application (Table 10.1).

Table 10.1 Common signal transmission frequencies for medical devices

Standard	Frequency	Data Rate	Range
Inductive Coupling	<1 MHz	1–30 kbps	<1 m
Wireless Medical Telemetry System	608–614 MHz, 1395–1400 MHz, 1427–1429.5 MHz	> 250 kbps	30–80 m
Medical Device Radiocommunication Service (MICS)	401–406 MHz	250 kbps	2–10 m
Medical Micropower Networks (MMNs)	413–419, 426–432, 438–444, 451–457 MHz		<1 m
Medical Body Area Networks (MBANs)	2360–2400 MHz	10 kbps - 1 Mbps	<1 m
802.11a Wi-Fi	5 GHz	54 Mbps	120 m
802.11b Wi-Fi	2.4 GHz	11 Mbps	140 m
802.11g Wi-Fi	2.4 GHz	54 Mbps	140 m
802.11n Wi-Fi	2.4–5 GHz	48 Mbps	250 m
802.15.1 Bluetooth Class I	2.4 GHz	3 Mbps	100 m
802.15.1 Bluetooth Class II	2.4 GHz	3 Mbps	10 m
802.15.4 Zigbee	868, 915 MHz, 2.4 GHz	40 kbps, 250 kbps	75 m
World Interoperability for Microwave Access (WiMAX)	2.5 GHz	70 Mbps fixed, 40 Mbps mobile	6–10 km
RFID/Near Field Communication (NFC)	13.56 MHz	1–464 kbps	<10 cm

Electrical Noise

When dealing with minute output signals, electrical noise has to be tested for, controlled, and filtered out. A lot of this can be done with good packaging design, but there are also clever electrical engineering solutions, such as band-pass filters. If your device operates at 100 Hz and transmits at 13.56 MHz, you can use a filter to attenuate all the common sources of noise, such as 60-Hz AC power. You can also filter out high-frequency noise above the RF band you are using.

Another way to minimize electrical noise is to use insulated wires and short traces. Even very-small-diameter wires can be purchased with insulation, which often has a clear coating you can strip at the endpoints for soldering. You can rearrange your PCB layout to make your traces short, direct, and well-spaced to reduce noise as well.

You can also create a Faraday cage around your device to protect it from stray noise. A Faraday cage is any type of metal shield (which can be deposited via sputter deposition or made of metal) that creates an enclosure used to block electromagnetic fields. The shield is then grounded and whatever is inside is protected.

Vibration

MEMS sensors and actuators are often used in vibratory environments, such as the sensors on car airbags or on rotating machinery. Even wearable sensors are subjected to vibrations when the person walks or rides in a vehicle. So, the environment in which your device will be used needs to be simulated as part of your testing plan. The key is to make your mounting and packaging robust, so that the sensor is insensitive to its environment. Know what frequencies it will experience and then use a modal analysis to make sure none of the components have a mode of vibration near one of the expected resonant frequencies.

There are vibratory platforms you can use to do accelerated vibratory tests. Place your packaged device on the platform, turn it on at the expected frequency, and see if your sensor still works.

Biointeractions

How will your device interact with the body? If it is a wearable device, will it corrode with sweat? Will it cause an allergic reaction due to the adhesive or materials? If it is implanted, will the body treat it as a foreign body and have an immune reaction? Silicon is a type of glass and is ignored by the body, but if you are making deep brain stimulators for Parkinson's disease, the electrodes "irritate" the brain tissue and are enclosed with scar tissue over time. So, give some consideration to biointer-

actions, especially chemical and material allergens, and determine what kind of testing you may need to minimize/prevent adverse reactions.

Heat or Cold

Like most materials, silicon expands and contracts with temperature. It is also heated by physical movement and the passage of electricity through it. These effects are usually minor, but should be considered, especially if the operation of the device is dependent on physical movement, like a strain gauge. In those cases, thermal expansion would be read as increased strain, unless some kind of compensating Wheatstone bridge circuit is employed.

Packaging and PCBs also expand and contract. Like vibration, if they move too much, solder and wire connections can break. The human body is a fairly constant, medium temperature, but if your device is a wearable and could be used while someone is snow skiing or could be left in the sun for prolonged exposure, you will need to test for that.

System-Level Performance

In addition to independent tests of components, you will want to do some overall level system performance tests. The following is a reiteration of ideas already presented.

Indicator Signals

Design in ways to give yourself feedback that the system is working. LEDs are tiny and make great indicator signals. They can turn on and off, change to different colors, flash, and even provide Morse code-type messages to you about the status of your device.

Another great indicator is sound or haptic (vibratory) feedback. When light is not appropriate, consider using a “beep” or a buzzing sensation as indicators.

A third indicator, especially useful when prototyping with an Arduino, is written output on your computer. Have the code tell you what step it is at, what input it is looking for, and the value(s) of the output data. The more information you can get on the screen, the quicker you will determine where the system is hanging.

Subsystem Testing

No matter how tempting it may be to hook everything together and test the overall system, you should *test each subsystem separately*. If you are not sure what is causing the problem in a subsystem, be careful to *change only one parameter at a time* and see how that effects the outcome.

You will probably ignore this advice the first time, but eventually you will come to value what you gain from taking a system-level approach, validating each subsystem and each component as you build towards your final goal. The fact is, even if you get extremely lucky and your system works the first time, (1) you will not know why and (2) you will not know which parameters are controlling the outcome.

Intermediate Outputs

Collect and evaluate data at various intermediate steps. Try changing a parameter and see what effect that has on the output. Does it make a difference, or is your system insensitive to that parameter? Knowing what controls your MEMS device design, its circuit, and packaging parameters will lead to the best long-term success. Using this approach, you will know what is important the next time you want to fabricate a batch, and you will not flounder and wonder why it is not working this time when “you did not change anything.” Instead, you will be able to adjust the key parameters and get consistently good results.

Animal Testing

Assuming you are creating a Class III medical device, after all of your cleanroom, outsourced, and benchtop testing, you will eventually need to perform some animal testing before you will be allowed to conduct a human trial. For orthopedics, this is often sheep or goats, and there are university and private facilities in a few locations around the United States that will accept studies from industry. These animal research facilities vary in their level of study control and in what animal models they allow. You will need to work with the facility directly or with a university research partner to conduct an animal study, so start researching what will be involved as soon as possible. Key considerations are as follows:

- Animal species (and quantity) you intend to use—the larger the animal, the more expensive the study
- How your device will be implanted, monitored, and extracted
- Whether your device requires continual data monitoring or runs independently
- The duration of your study

It is important to work with a biostatistician to design your study. They will determine how many animals, how much data, and what data needs to be collected in order to show a treatment effect. Publications often refer to “statistical significance,” which is based on the probability of being wrong (reported at P less than or equal to 0.05, or 5%, or P less than or equal to 0.01, or 1%). However, other important factors are the power of the study (few animals leads to low power), the correlation coefficient (how well does the data “fit” the regression curve), and your control of other variables that may inadvertently effect the outcome. For this last factor, you often have a “control group” which is identical to the other animals in all ways, except they do not receive the treatment.

Testing Equipment

Equipment for conducting the various tests you need comes from a variety of sources. The following are the main places.

Within NNCI Facility

Microscopes and metrology equipment are readily available within the NNCI facilities. Any measurements you want to take on a MEMS device, including electrical measures, can usually be done in-house.

Available at University

Other types of test, and even some manufacturing at the macroscale, can often be done within the university. For instance, the University of Washington has a full electronic testing lab and a machining lab that can do wire EDM. Universities with on-site hospitals often have EtO sterilization, and they definitely have autoclaves. Still others have veterinary hospitals and animal research facilities staffed by knowledgeable people familiar with sensors and electronic systems who can conduct your study.

Outsourced

Some testing will need to be outsourced, especially things like FEA or wireless signal transmission tests. I also used outsourcing to fabricate my pattern masks and to do the electropolishing. For previous research projects, I outsourced the mount-

ing of microscopic strain gauges onto my specimen, as I was not dexterous enough to bond them and solder on the lead wires. If the NNCI lab you are working with does not know to whom you could outsource a task, often you can find a lead through another unit at the university or even through other industry users at the lab.

Purchased by You

There are times when you will need or want your own test equipment. If you purchase your own, you will know exactly how to operate it, you will have the same calibration every time, and the equipment will always be available to you. Some of the items I have purchased are a power supply, function generator, oscilloscope, soldering iron, and digital multimeter, along with a bunch of handy supplies, like electronic components, wire, dicing tape, CA glue, and solder paste.