SmartEverything and the rise of the microphone array

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Over ten years ago, a major smartphone manufacturer developed a demo of a smartphone with a ten-microphone array. It could pick out and hear a single person's voice in a crowd - an amazing feature with obvious market potential. But the company predicted that 90% of such devices would fail in the field within six months. The compounded fragility of ten microphones killed the concept and was a brutal reminder that microphones are fundamentally mechanical devices.

It was a setback to an idea that now seems inevitable. As electronics become smarter and more pervasive, the screen-based user interfaces of the last decade have not kept up. The impending swarm of "SmartEverything" devices – smartphones, speakers, TVs, wearables/hearables, light bulbs, kitchen appliances, connected/autonomous cars, robots, drones, virtual/augmented reality and entire buildings – demand a form of interaction less obtrusive and more intuitive than small and large screens. Voice interfaces are the obvious candidate, and microphone arrays are the critical component.

But how do we avoid the pitfalls of that early demo? How do we make these arrays last? The first step is to understand the problems that are intrinsic to the architecture of capacitive MEMS microphones. Only by moving to piezoelectric MEMS can we truly eliminate such problems.

Arrays and the human ear

Like most mammals, we have two ears. Their shape and position allow us to find the origin of sounds in our surroundings. This is so natural that we will spin around when we hear unexpected sounds, to help us locate their source. These stereo-acoustic abilities are a constant aid and help to protect our lives. They are a testament to the power of directional audio.

Advanced MEMS microphones improve on nature. We can build very large microphone arrays with sophisticated processing algorithms to pinpoint the origin of sounds, hone in on a specific source (such as one person's voice) or pointedly ignore unwanted sounds (such as the roar of a ventilator duct). These microphone arrays give us a much richer set of acoustic experiences, a greater understanding of our surroundings and more control over our environment.

How does this work? As sounds travels with a finite speed, the wavefront of a sound wave passing over an array of microphones may reach each microphone at a slightly different time. We can exploit this time difference to triangulate the origin of the sound. If a dog barks on my left, my left ear will hear the bark sooner and more loudly than my right ear. The human brain naturally decodes these signals to decipher the location of the dog.

Figure 1 Directional hearing with two ears (left) and two microphones (right)

We can scale this principle to much larger arrays, from the seven microphones in the Amazon Echo to the 300+ microphones in Squarehead Technology's AudioScope. The AudioScope is an ultra-sensitive, disc-shaped array, which when mounted 30 feet above a packed basketball stadium, can pick out the sound of the assistant coach popping his bubblegum in the crowd.

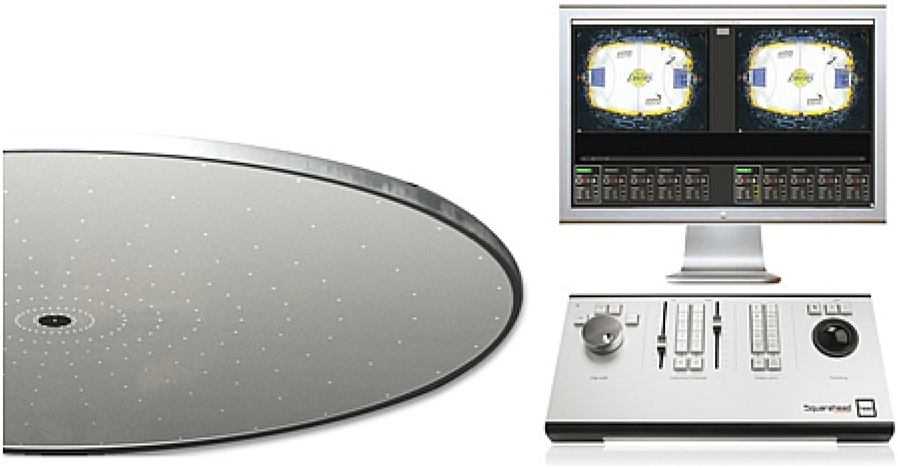

Figure 2 Squarehead Technology's Audioscope array (left) and controls (right)
Image Credit: Squarehead Technology

The use of microphone arrays goes far beyond improving our listening. Every major technology company is now deeply invested in the field of computational linguistics – teaching our connected devices to understand natural human speech. But to understand speech the way we can, they must also hear as clearly as we do. They must emulate the directional, long-ranged hearing that we do instinctively.

Imagine an ‘Arrayphone’ – a future device studded with microphones, powerful and portable, and carried by everyone. How might you use it daily?

1. You are getting dressed to leave your house, and the Arrayphone is 10 feet away. Your hands are occupied, but you have questions to ask and things to do. How cold is it? Will it rain today? Whom will you meet? As you leave, are the lights off and the door locked?
2. You are talking to friends in a noisy room, and you cannot hear them over the crowd. You plug your headphones into the Arrayphone and ask it to reduce the background noise. It finds and clarifies your companions’ voices, blocking out the outside world.
3. Your car is making a strange sound, and you don’t feel safe driving it. You open the hood and turn on your Arrayphone. It tells you which part of the car is making the sound and suggests how to fix it.

Figure 3 Amazon Echo (left), ClearOne Beamforming Microphone Array (center), GFaI Acoustic Camera (right) **Image Credit**: Amazon, ClearOne, GFaI

None of these scenarios are science fiction. **Figure 3** shows real products that already cater to each need. They may be raw, unwieldy or expensive, but the promise is real, and the technology is improving. Microphone arrays play a crucial role in computerizing our world.

Capacitive MEMS microphones make mediocre arrays

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One major hurdle has held up the inevitable explosion of smart devices equipped with large microphone arrays. The capacitive MEMS microphones that have dominated the market for the past 15 years are easily damaged by common environmental contaminants such as water, dust and particulate matter.

They are quite usable in single quantities or in small arrays, but large arrays compound their problems for these reasons:

1. ***Stacked probabilities***. While a single capacitive MEMS microphone may have an acceptable failure rate, the chance that at least one microphone in a 10-microphone array will fail is substantially higher. An array relies on the functioning of every microphone working in unison, and one bad microphone can throw off its performance.

2. ***Obvious failures***. If a speck of dust enters a microphone in a single-microphone system, it will degrade the microphone's sensitivity. Most systems will compensate by increasing gain – resulting in a higher noise floor – but the failure may not be obvious. However, large arrays often interpret sensitivity shifts as directionality cues. The additional functions of a large array (such as locating a sound source) can become noticeably impaired.
3. ***Mechanical requirements***. Most devices are designed to shield the microphone from mechanical harm. In order to fit more microphones into the same space, compromises must be made on their position and orientation. Large-array beamforming often requires fitting the microphones in more vulnerable locations, such as the outer corners of a phone. This increases their chance of failure.

All of these factors lead to the frustrating conclusion: "If we sell this amazing technology that people love, it will break early and often."

This has not prevented the sale of devices that use arrays of capacitive MEMS microphones because arrays are just too useful to ignore. Rather a slew of compromises and workarounds have been required to protect capacitive microphone arrays from water and dust. These include:

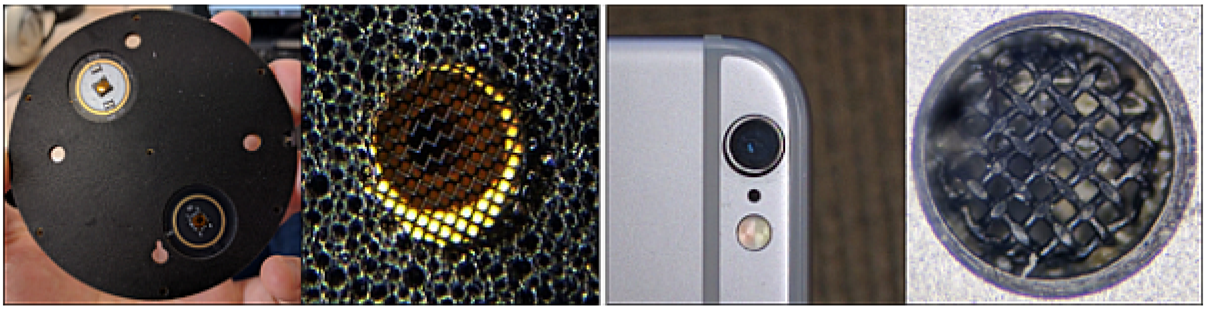

Figure 4 Amazon Echo microphone array & zoom-in of microphone mesh (left), iPhone 6S rear microphone & zoom-in of microphone mesh (right)

1) **Using a mesh**. A microphone can be made more dust-resistant by covering its acoustic port, which is the hole that exposes the microphone to the outside world, with a protective mesh. If the mesh is fine enough, it will substantially slow down liquids entering the acoustic port, as the surface-tension of the liquid will cause it to ball-up against the mesh and only slowly leak through.

While a mesh can help meet minimum reliability requirements, it is not a long-term solution. Dust and grime accumulate on the mesh surface, obstructing the acoustic port and reducing the microphone sensitivity. Very fine particles (micron-scale) are not blocked by a coarse mesh, and can kill a microphone by jamming between its electrostatic plates. And surfactants – liquids with low surface tension, including soapy water and detergents – can flow through a mesh unimpeded.

Mesh protection can be made more effective by increasing the mesh density. However, this has the unwanted effect of reducing a microphone's sensitivity and decreasing its signal-to-noise ratio

(SNR). A water-resistant mesh will degrade SNR by up to 6dB even before it gets clogged with particles. This compromise between protection and performance is a fundamental flaw of mesh protection.

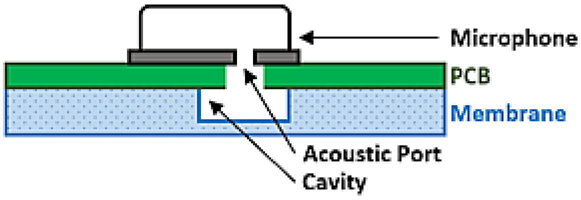

Figure 5 Cross-sectional diagram of MEMS microphone sealed with flexible membrane

2) **Using a flexible membrane**. A more direct method of protecting a microphone is to seal it with a membrane. This membrane is made of a soft material (such as silicone rubber) and is large and flexible enough to allow acoustic waves to pass through. It can provide long-term protection, as long as the membrane has stable mechanical properties.

This method has major shortcomings. Each microphone requires a large, deep membrane, which complicates the device’s industrial design. The stiffness and resonance of the membrane severely compromise the microphone’s SNR and frequency response as well. Protective membranes do not work in high-performance applications.

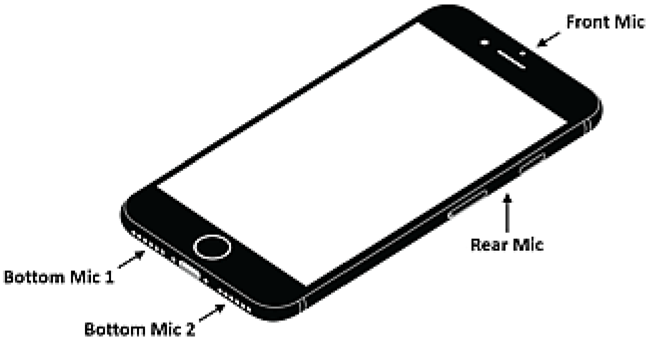

Figure 6 Position of MEMS microphones on an iPhone 7 **Image Credit**: Apple (emphasis by Vesper)

3) **Building a smaller array**. Smartphone manufacturers have built concept phones with six, eight and ten microphones, where the additional microphones were a tangible improvement. Yet no one is currently selling phones with large arrays. Manufacturers’ reluctance could have to do with the fragility of capacitive MEMS microphones. Fewer microphones means a lower statistical chance

of failure, and more space to carefully position and protect each microphone. Smaller arrays – preventing the use of advanced beamforming – is the consequence of this conservatism. Less fragile microphones are an enabling technology for larger, more capable arrays.

Figure 7 Amazon Echo used at a distance (left), Amazon Tap used in hand (right) **Image Credit**: Amazon (right)

4) **Restricting arrays to indoor environments**. Products now exist which use large arrays to respond to voice commands from across a room. They spearhead a new class of hands-free voice-interface devices, but they only work indoors. Portable go-anywhere devices with voice-interfaces also exist, but they have only one microphone and just a few feet of listening range. Compact arrays, which can be used anywhere we go, need to be able to handle dirtier, less-controlled environments. The fragility of capacitive MEMS microphones is restricting where arrays can be deployed.

These workarounds are necessary to shoehorn capacitive MEMS microphones into microphone arrays. Capacitive MEMS microphones rely on the same working principle as condenser microphones, which have been in use since 1916. Their working principle is also the source of their frailty.

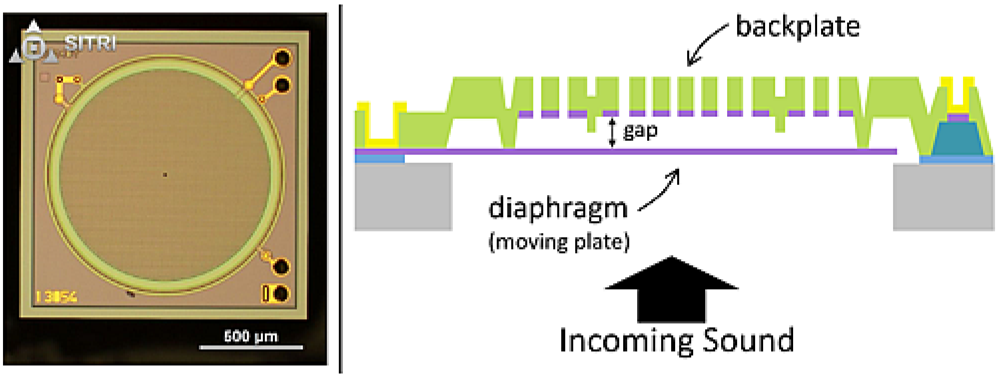

Figure 8 Top-view (left) & cross-sectional drawing (right) of capacitive MEMS microphone

Figure 8 shows a cross-section of the backplate and diaphragm that make up a capacitive MEMS microphone. The diaphragm is distorted by sound pressure, changing its gap (and capacitance) with the backplate. This creates an electrical signal that represents sound.

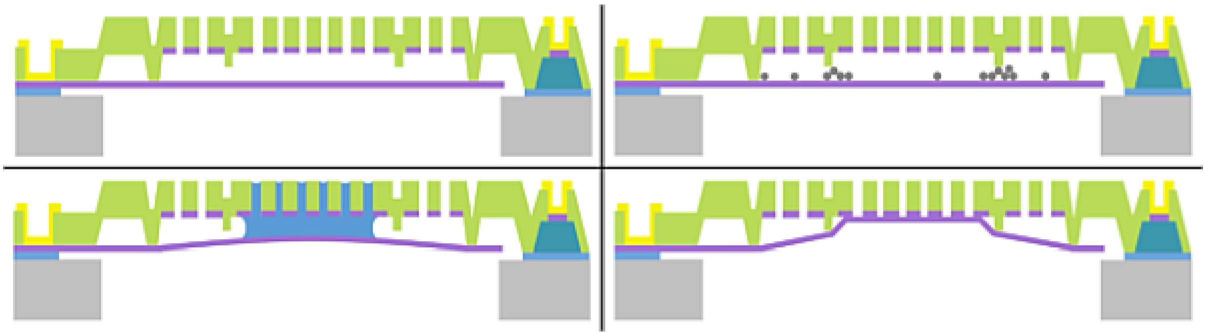

Figure 9 Capacitive MEMS microphone in various failure modes: normal (upper left), dust/particle damage (upper right), water entry (lower left), stiction failure (lower right)

This gap is essential for the functioning of the capacitive MEMS microphone, but also causes many failure modes. These include:

1. **Particle damage**. Fine dust can enter and gather inside the gap, eventually obstructing the motion of the diaphragm.
2. **Stiction from water damage**. If water enters the microphone, it will form a film that pulls the diaphragm towards the backplate. This pull becomes stronger as the water evaporates, until the diaphragm and backplate are permanently attached together.
3. **Stiction from mechanical shock or acoustic overload**. Sudden acceleration or loud sounds (acoustic overload) can throw the diaphragm towards the backplate. On contact they electrostatically clamp together, disabling the microphone until it is power-cycled and damaging the delicate protective coatings.

The poor reliability of capacitive MEMS microphones is a direct result of their architecture. The industry is keenly aware of these problems, and product designers are actively seeking a better option. How do you build a microphone without a gap?

Piezoelectric MEMS microphones enable advanced beamforming

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Vesper Technologies presents a fundamentally new solution to this problem. Building on research conducted at the University of Michigan, we have developed VM1000 – the first commercially available piezoelectric MEMS microphone.

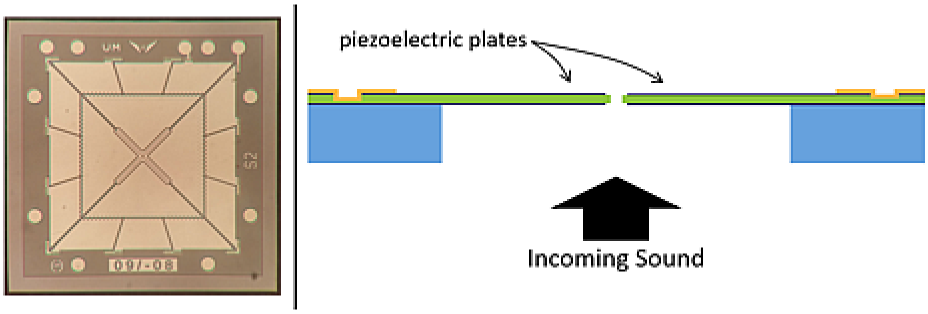

Figure 10 Top-view (left) & cross-sectional drawing (right) of Vesper piezoelectric MEMS microphone, not to scale

Figure 10 shows the structure of VM1000, where the backplate and diaphragm are replaced by a single layer of flexible plates. Changes in sound pressure cause these plates to bend and experience stress. As the plates are built from a sandwich of piezoelectric materials, the stress generates electrical charge, which allows for direct measurement of sound. This creates a microphone that does not need a backplate.

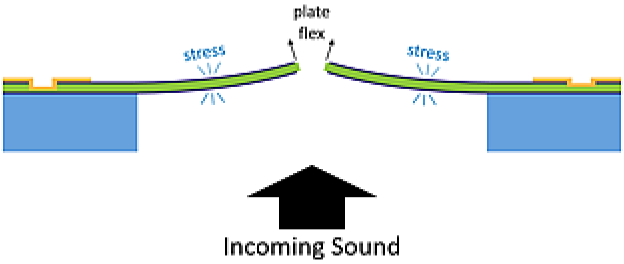

Figure 11 Piezoelectric plate stress in response to sound pressure

By omitting the backplate, VM1000 is a sea change in microphone reliability. There is no longer a narrow, vulnerable gap to trap particles or liquids. The result is an innately dustproof and waterproof microphone that requires no hacks or workarounds to be used in high-reliability arrays. As stiction failure is now impossible, there is also less risk of microphone failure due to acceleration, loud sounds (acoustic overload) or mechanical shock.

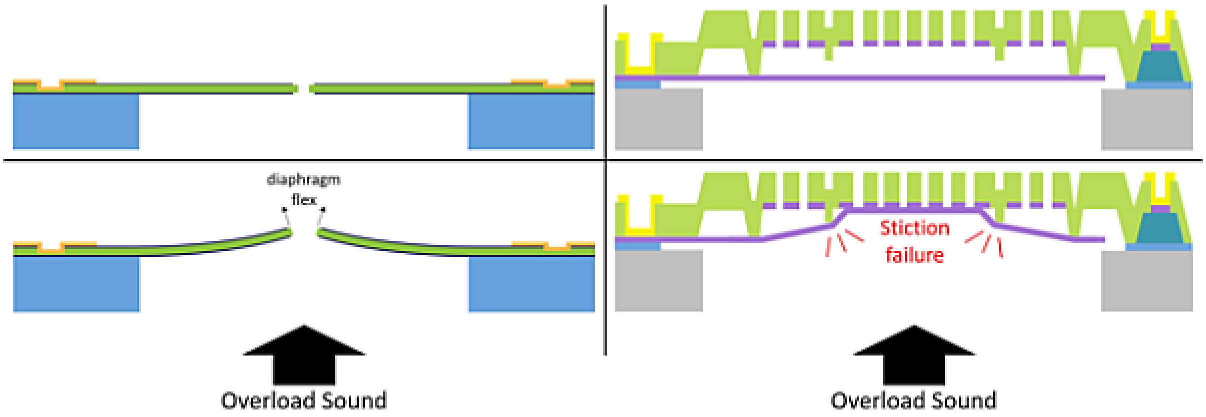

Figure 12 Comparison between acoustic overload behavior of piezoelectric MEMS microphone (left) and capacitive MEMS microphone (right)

The use of piezoelectric materials in MEMS is not new: every smartphone produced today can contain dozens of piezoelectric radio-frequency (RF) filters. The RF filter industry is worth many billions of dollars. Its immense profitability has driven the development of advanced foundry tools to build piezoelectric MEMS.

This is the infrastructure that Vesper is using to mass-produce the first piezoelectric MEMS microphone on the market. Our access to reliable and repeatable manufacturing tools allows us to build microphones with excellent sensitivity matching and stable performance over time – both of which are essential to microphone arrays.

Dust, water, oil and acoustic overload – a MEMS microphone torture test

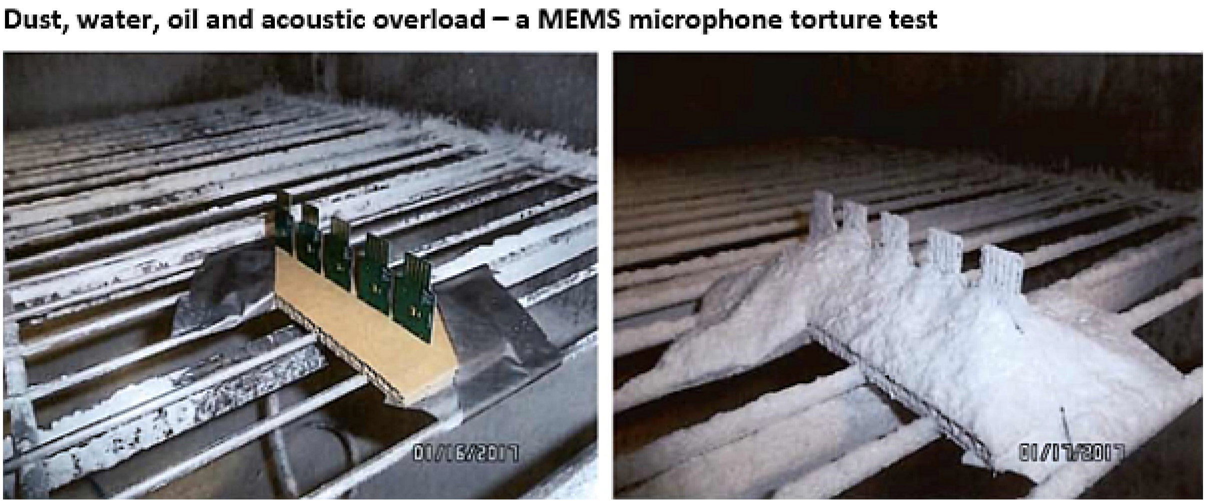

Figure 13 Vesper piezoelectric MEMS microphones mounted on test boards, before (left) and after (right) an IP5X dust test

Figure 13 shows an experimental setup used to compare the dust and particle resistance of microphones. Fine sand (75μm or smaller) is blown inside a test chamber, for a total of 8 hours. Microphones are mounted inside the chamber, and the sand accumulates inside each microphone during the test. We measure the microphone’s frequency response before and after the test, to observe the effect of dust.

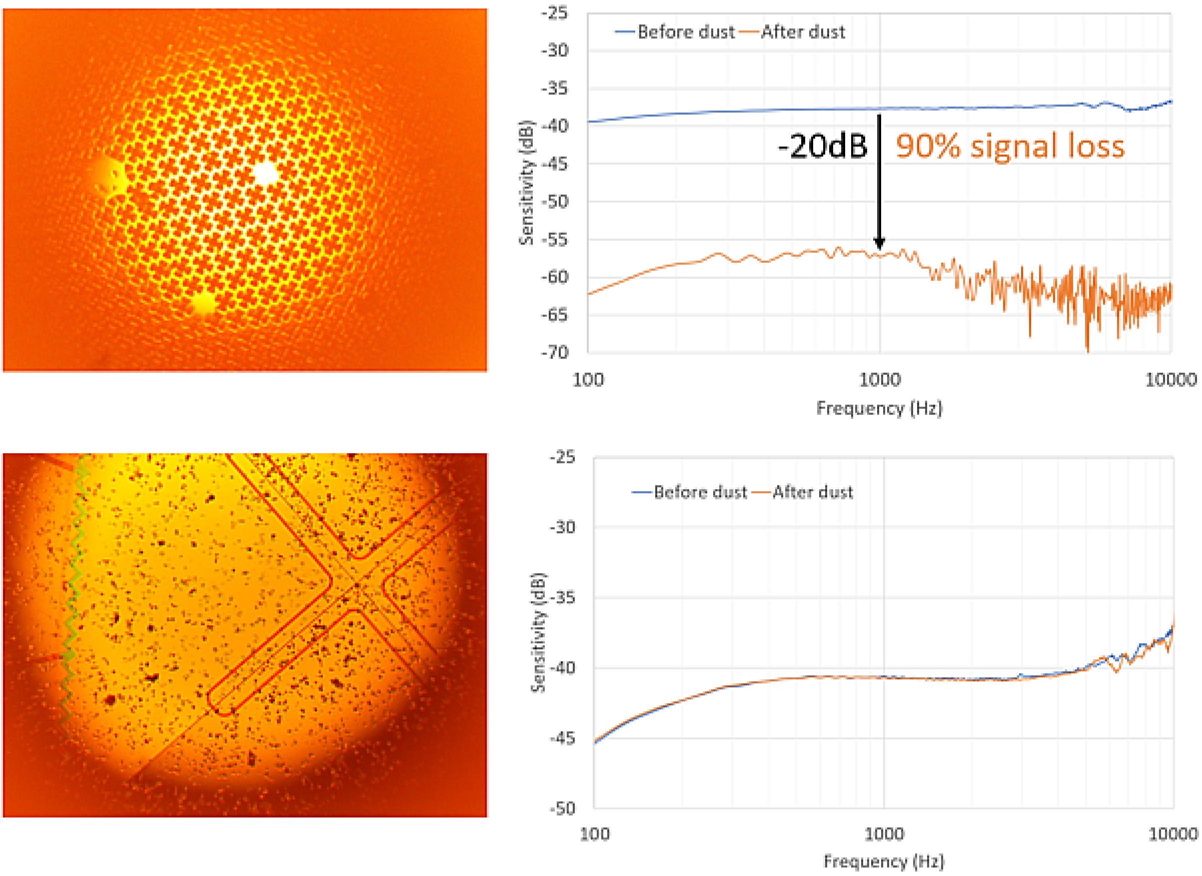

Figure 14 Dust-test image and results of capacitive MEMS microphones as viewed through the acoustic port (upper), Dust-test image and results of piezoelectric MEMS microphones as viewed through the acoustic port (lower)

Figure 14 shows the results of this dust test. The capacitive MEMS microphone has dust trapped between its diaphragm and backplate, and consequently loses 90% of its sensitivity. This loss of sensitivity would have occurred unevenly among the microphones in an array, disabling the array as the microphones are no longer matched. Meanwhile, the piezoelectric MEMS microphone is completely unaffected.

Figure 15 Microphone water-testing apparatus (left), microphones tested with acoustic ports face-up (right)

Figure 15 shows an apparatus for testing the water-resistance of microphones. Each microphone is submerged in soapy water, inside a sealed tank which is pressurized to a depth of 15 meters, for a duration of 24 hours. As with the dust test, we measure the microphone’s frequency response before and after submersion.

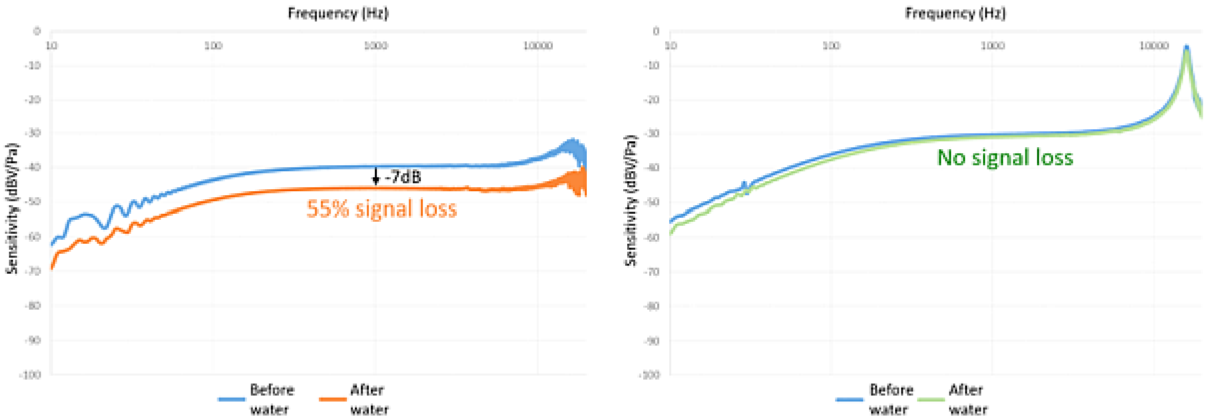

Figure 16 Water-test results of capacitive MEMS microphone (left) and Vesper piezoelectric MEMS microphone (right)

Figure 16 shows the results of the water-test. The capacitive MEMS microphone has been severely affected, losing 55% of its sensitivity. As with the dust-test, this degradation will unevenly affect each microphone in an array, disabling it due to poor matching. The piezoelectric MEMS microphone is unaffected by the water test – this is equivalent to an IPX8 rating, indicating that the microphone can survive continuous submersion.

Kitchen oil contamination test

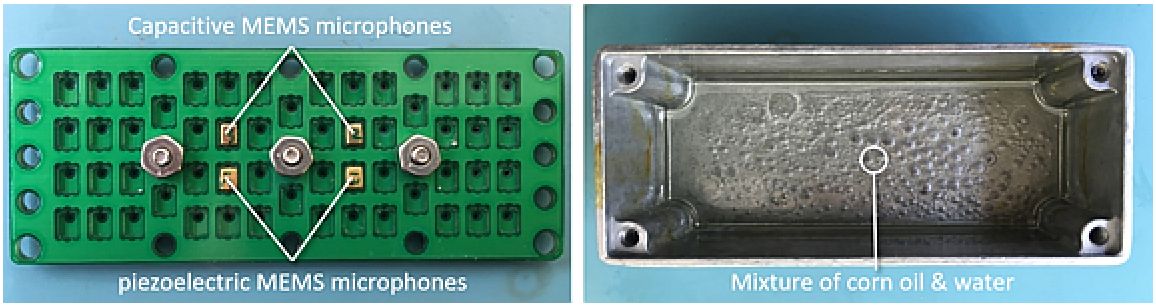

Figure 17 Apparatus for depositing kitchen oil on the surface of microphones, with lid (left) screwed onto an oil chamber (right)

Going beyond the standard tests for microphone reliability, we have also developed a method to stress-test MEMS microphones with cooking oil. **Figure 17** shows an apparatus for depositing corn oil directly onto the surface of several microphones. As we heat up the oil chamber, the oil vaporizes and coats the inner structure of each microphone. This is a realistic scenario for microphones used in kitchens, where the hands-free advantage of voice interfaces is highly valuable.

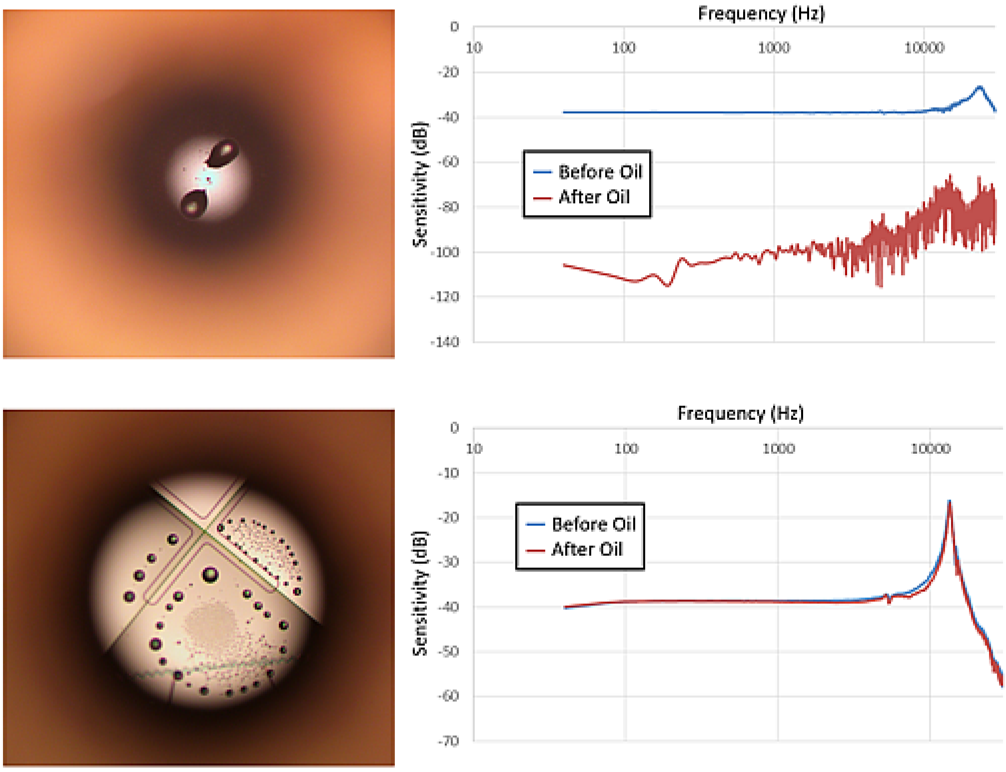

Figure 18 Oil-test image and results on capacitive microphones (upper), Oil-test image and results of piezoelectric MEMS microphones (lower)

Figure 18 shows the results of this oil-test and pictures of the MEMS taken through the acoustic port.

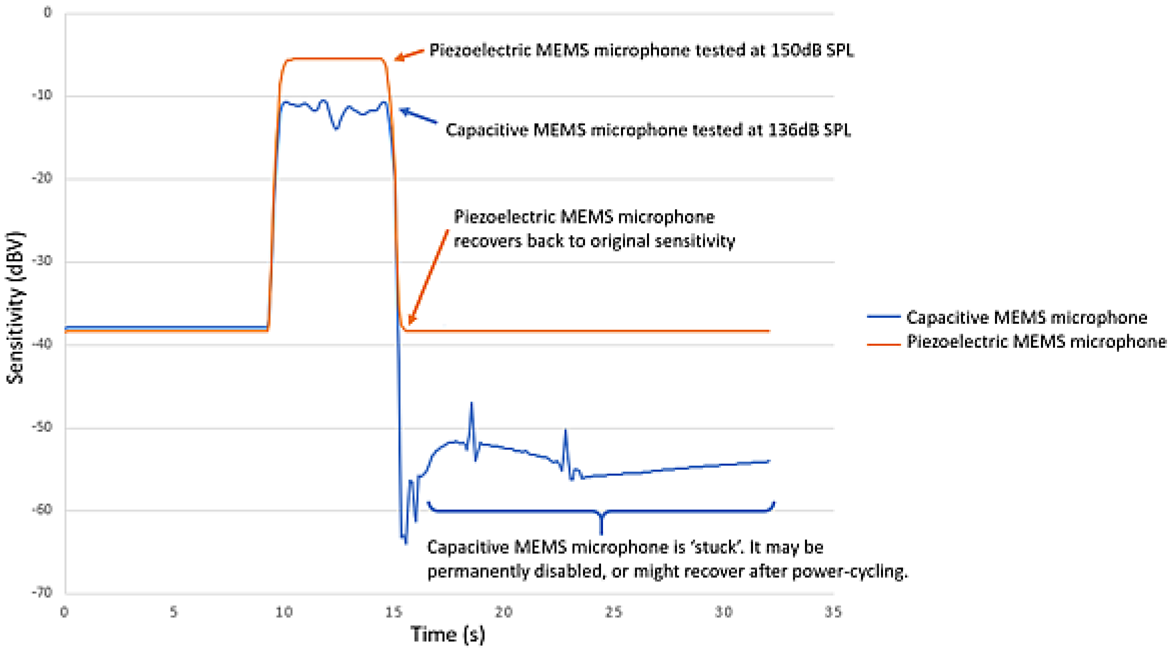

Figure 19 Acoustic overload test results of capacitive MEMS microphones (blue line) and Vesper piezoelectric MEMS microphones (orange line)

Piezoelectric MEMS microphones can also withstand extremely loud sounds without failing. **Figure 19** shows the results of an Acoustic Overload test, where microphones were tested before and after being subject to very high sound pressure levels.

After enduring a sound pressure level of 136dBSPL, the capacitive MEMS microphone could not recover: it stopped functioning due to stiction failure. In comparison, the piezoelectric MEMS microphone recovered quickly and gracefully after enduring a sound pressure level of 150dBSPL (5x higher than 136dBSPL). This indicates that the Vesper piezoelectric microphones will not fail sporadically due to loud sounds (such as a car door slamming).

These results show the durability of individual piezoelectric microphones under a variety of harsh environmental conditions. The piezoelectric MEMS microphones maintained consistent performance in situations where the capacitive MEMS microphones degraded or died.

Durable microphones create durable arrays

Microphone arrays and voice interfaces can connect, inform, and protect us. These technologies are undoubtedly the frontier of consumer electronics, and require large numbers of tough, stable, and well-matched microphones. However, such microphones are not yet widely available. In the interim, the industry has relied on capacitive MEMS microphones, despite their many reliability problems.

Capacitive MEMS microphones are easily damaged by dust, water, and mechanical shock. These reliability problems get worse when multiple microphones are used in arrays. The larger the array, the higher the failure rate: very large arrays are simply unusable.

There are workarounds to improve the reliability of capacitive MEMS microphones, but they all have downsides. Cost is increased and performance is sacrificed for only temporary protection. A tougher, cheaper, better solution would be to use innately robust microphones with superior environmental resilience.

Piezoelectric MEMS microphones have built-in dust-proofing, water-proofing and oil-proofing. They have excellent matching and stability, and are immune to stiction failure. They are ideal for building large and reliable microphone arrays. There is no additional cost for protecting them, and they maintain their performance in hostile conditions over the long-term.

Piezoelectric microphones are more than a hardened replacement for existing technologies. Their incredible durability enables new applications that simply did not exist before. In one extreme test of waterproofing and acoustic overload, Vesper microphones were hung off the side of a moving boat and plunged into seawater. Despite the chemically aggressive water and the turbulence of the waves, the microphones were able to record the song of nearby whales.

Arrays of Vesper microphones have also been used in gunshot detection systems, where the sound of passing bullets is analyzed to locate shooters and protect soldiers. Like the ultra-expensive military-grade microphones they replaced, the Vesper microphones were unscathed by the shock waves of supersonic rifle rounds. This could make gunshot detection systems cheap enough to defend cities, police and the general public.

These are the kinds of microphone applications which were previously unthinkable, which now seem obvious, and which will become entirely mainstream as piezoelectric MEMS microphones become widespread. Piezoelectric MEMS microphones are a major driver in bringing pervasive voice-interaction to the masses.

Also see:

- Microphones: A sound technology choice for communication and control
- Basic principles of MEMS microphones
- Acoustic Design for MEMS Microphones
- Creating JARVIS - Smart microphones enabling the digital butler