ASPECTS OF THE USE OF MEMS MICROPHONES IN PHASED ARRAY SYSTEMS

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ABSTRACT

Not long ago MEMS microphones started pushing into the market enabling engineers to simplify their work by omitting analog signal processing. Though mainly designed for voice transmission some companies began using them for measurement purposes as well.

This contribution is about investigations on the technical parameters of MEMS microphones compared to other inexpensive microphones and what can be done to compensate for their technical drawbacks considering the multitude of channels in phased array systems.

Common interfaces of the microphones and the complexity of the different downstream processings are mentioned, key parameters are identified, datasheets are analyzed, own measurement results are shown and improvements between 2015 and 2017 are pointed out.

Phased Array systems are hungry for channels but to be able to sell them cost aspects have to be taken into account. A way is presented to decrease the weaknesses of a digital MEMS microphone array to make it almost as good as one with conventional analog microphones.

Keywords: MEMS, Microphone, Array   I-INCE Classification of Subjects Number: 74

1. INTRODUCTION

The first electrical microphones were developed in the second half of the 19th century and the condenser microphone was invented in the first half of the 20th century. The next important step was the electret condenser microphone first made by the Bell Laboratories in 1962 and by the late 1970s the device accounted for more than one-third of the production of all commercial high-fidelity microphones (1).

Until the end of the 20th century wires were the common method to connect microphones. Surface-mount technology was already developed in the 1960s and became widely used in the late 1980s (2), but it took a long time until it was used for microphones. The American company Knowles claims to have made the first surface mount microphone in 2001 (3).

It was about that time when the abbreviation MEMS was one of the new trendy words and no wonder it was used for all those little rectangular surface mount microphones from then on. According to the English Wikipedia a MEMS (Micro-Electrical-Mechanical-System) microphone is also called a microphone chip or silicon microphone. A pressure-sensitive diaphragm is etched directly into a silicon wafer by MEMS processing techniques. Most MEMS microphones are variants of the condenser microphone design (4). Following this trend, designs with two chips are called MEMS microphones too.

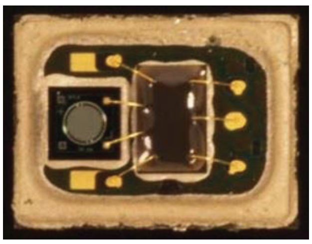

Figure 1 – two chip MEMS microphone

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Apart from rectangular MEMS microphones there are still a lot of inexpensive conventional electret condenser microphones on the market and interestingly enough, they are almost always round.

Figure 2 – typical electret microphone capsule

Acoustic Cameras belong to the family of phased array systems; they need more than just a few microphones and that is why expensive measurement microphones are out of the question. Due to current market conditions one can only choose between surface mount MEMS and conventional electret microphone capsules. The MEMS are available with analog and different kinds of digital output whereas all conventional capsules contain analog output amplifiers.

2. COMMON MICROPHONE INTERFACES AND SUBSEQUENT PROCESSINGS

2.1 Analog microphones

A great variety of microphones with analog output exists. Most conventional electret capsules contain output amplifiers with just one JFET transistor and their output impedance ranges between 600Ω and 2400Ω. The amplifiers of most analog MEMS microphones are supposed to be more complex because their output impedance ranges between 200Ω and 350Ω. One can also find some with differential outputs.

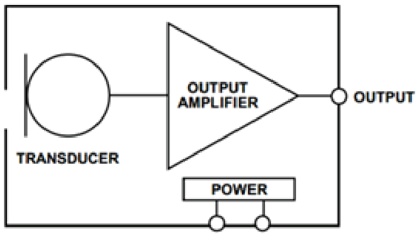

Figure 3 – analog microphone with output amplifier

Those output impedances are not low enough to allow for more than just a few meters of cable. So in case more cable length is needed the first thing to add is a cable driver with lower output impedance. At the end of the cable EMC filters and ESD protectors followed by input amplifiers can often be found. Having arrived in the digital age an AD-converter with an appropriate analog anti-aliasing-filter comes next. Depending on the digital output, voltage and data-format additional logic may be needed before entering the processor.

2.2 Digital microphones

Due to timing constraints and higher frequencies cable length limitations are tighter and impedance adjustment cannot be ignored. Sometimes tristate buffers are needed to deal with increased cable lengths along with higher capacities. Just like in the analog case EMC filters and ESD protectors are often needed to meet all requirements.

2.2.1 Digital microphone with PDM output

Most of the digital MEMS microphones use PDM output. PDM stands for pulse-density-modulation and is also known as SDM which stands for sigma-delta-modulation. The output is a high frequency (same as clock input) stream of 0s and 1s where high input pressure is translated in many 1s, low input pressure in many 0s and average input pressure in as much 0s as 1s (5). PDM-MEMS have a clock (CLK) input and a tristate output (DATA). Two microphones can share a data line. One has it when clock is low and the other one when clock is high – this can be determined by the channel select input.

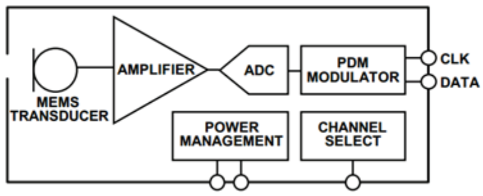

Figure 4 – digital MEMS microphone with PDM output

Before being processed the PDM data has to be translated to PCM (pulse-code-modulation) by filtering and downsampling. Most processors are unable to do this real-time, but some CODECs (coding- decoding-circuits) can do the job or it can be implemented into a field-programmable-gate-array (FPGA).

2.2.2 Digital microphone with I2S output

Very few digital MEMS microphones have an I2S output. I2S (inter-IC sound) is an electrical serial bus interface standard used for connecting digital audio devices together. It is used to communicate PCM audio data between integrated circuits in an electronic device (6). I2S MEMS have two clock inputs (Serial Data Clock and Word Clock) and a tristate output (Serial Data Output). Just like PDM pairs two I2S microphones can share a data line too. One transmits when word clock is low and the other one when word clock is high.

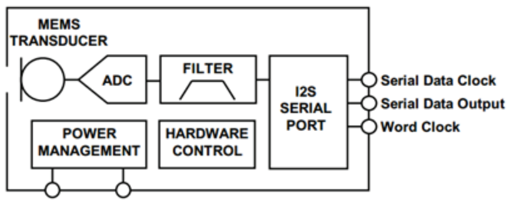

Figure 5 – digital MEMS microphone with I2S output

Filters are included and the serial PCM data needs no further treatment to be processed.

2.2.3 Digital microphone with TDM output

One digital MEMS microphone has a TDM (time-division-multiplex) output. This is similar to I2S but instead of 2 microphones up to 16 can share a data line (SD). The serial data word select (WS) is an input that controls when data output is active. Serial data word select output (WSO) puts out a delayed word select to be connected to the WS of the next microphone. Up to 16 microphones can be chained up that way. The serial data clock inputs (SCK) of all microphones must be tied together.

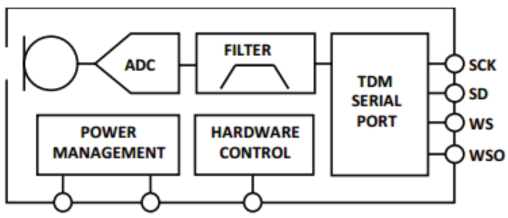

Figure 6 – digital MEMS microphone with TDM output

Filters are included too and data is ready to be processed. Cables must be short since the frequencies on the clock and data lines are up to 8 times higher.

3. KEY PARAMETERS AND DATASHEET ANALYSIS

3.1 Parameters found inside microphone datasheets

Mechanical specifications like **weight** and **dimensions** are often supported by drawings and information how to contact the terminals or pads. **Soldering profiles**, **environmental values** and **absolute maximum ratings** appear in many datasheets. Electrical properties like **operating voltage**, **current consumption**, **logic voltage definitions**, **power supply rejection**, **output impedance**, **output polarity**, **input clock frequency** and **turn on time** are always there but rarely all of them. Most important for microphones are of course the acoustical attributes. **Directional characteristic**, **sensitivity**, **dynamic range**, **signal to noise ratio**, **equivalent input noise**, **maximum sound**

pressure level, **acoustic overload point**, **full scale acoustic level**, **frequency response**, **distortion** and **clipping characteristics** are among these.

3.2 Key parameters and how to compare them

All parameters can be important from time to time. For example one cannot easily replace a microphone that accepts 12V and consumes only 100µA by one that needs 250µA and has an absolute maximum rating of 3.63V.

Focusing on the development of a new phased array system one usually starts from the other side. Depending on the scope of applications there is a range of amplitudes that has to be measured. On the quiet end there is the **equivalent input noise** (EIN) of the microphones that must be equal to or lower than the minimum sound-pressure-level (SPL) to be measured. On the loud end the **maximum sound pressure level** (maxSPL) must be high enough to measure the highest applicable levels. The preferred **frequency response** is flat and ranging from the lowest to the highest frequencies that have to be measured. Filters can be implemented to compensate for a non-flat **frequency response**, but the more peaks there are the more complex it gets. Amplifying everything below average adds noise and damping everything above average reduces the **maximum sound pressure level** of that range. Sometimes **environmental values** like operating/storing temperatures and humidity have to be considered too. Other attributes are less important or taken as they are and the new system is developed consistent to them. **Sensitivity** by the way can sometimes be relevant when designing an adequate amplifier for analog microphones, but nothing to worry about for digital microphones.

The first key parameter EIN is missing in most datasheets but it can be calculated from the almost always present **signal to noise ratio** (SNR) as follows:

$$EIN = 94dB - SNR \quad (1)$$

The second key parameter is maxSPL and often difficult to compare because it is not specified at the same level of distortion or even worse with no measurement condition at all. Datasheets of conventional electret capsules are usually conservatively specified at 1% distortion but the makers of MEMS microphones invented new phrases like **acoustic overload point** or **full scale acoustic level** to make their products look better at first sight. For example a look inside the InvenSense INMP621 datasheet reveals only 105dB SPL at 1% distortion along an **acoustic overload point** of 133dB SPL at 10% distortion and a **full scale acoustic level** of 140dB SPL (7) – what a difference!

The third key parameter is **frequency response**; it is easier to compare and often available as a diagram (dB/Hz). Sometimes the diagram looks pretty good but is limited to for example 100Hz…10kHz and you can read something like "flat frequency response up to 20 kHz", whatever that means.

3.3 Analyzing the datasheets

An investigation from the year 2015 covered datasheets of the conventional analog electret capsules Sennheiser KE4-211-2, Panasonic WM-61A, PUI POM-3535L-3-R and Primo EM158N, the analog MEMS microphones EPCOS C928 and InvenSense INMP510, the digital PDM MEMS microphones ST MP34DT01 and InvenSense INMP621 and the I2S MEMS microphone InvenSense INMP441.

The KE4-211-2 has EIN=27dB (A weighted), maxSPL=130dB and the **frequency response** is within ±3dB from 20Hz...20kHz (8).

The WM-61A has EIN=<32dB (A weighted) calculated from SNR=>62dB (A weighted), the maxSPL is missing and there is no other information it can be calculated from and the **frequency response** is within ±4dB from 20Hz...20kHz (9).

The POM-3535L-3-R has EIN=26dB (A weighted) calculated from SNR=68dB (A weighted), the maxSPL is missing and there is no other information it can be calculated from and the **frequency response** is missing too (10).

The EM158N has EIN=20dB (A weighted) calculated from SNR=74dB (A weighted), maxSPL=115dB and the **frequency response** is within -6dB and +2dB from 50Hz...20kHz (11).

The C928 has EIN=28dB (A weighted) calculated from SNR=66dB (A weighted), maxSPL=131dB and the **frequency response** is from 20Hz...20kHz with no tolerance and diagram given (12).

The INMP510 has EIN=29dB (A weighted), maxSPL=105dB and the **frequency response** starts from -3dB at 60Hz, stays below +3dB up to 10kHz and has a peak of +13dB at 20kHz (13).

The MP34DT01 has EIN=31dB (A weighted) calculated from SNR=63dB (A weighted), maxSPL=100dB and the **frequency response** is within -2dB and +3dB from 100Hz...10kHz (14).

The INMP621 has EIN=29dB (A weighted), maxSPL=105dB and the **frequency response** starts from -3dB at 45Hz, stays below +3dB up to 10kHz and has a peak of +17dB at 20kHz (7).

The INMP441 has EIN=33dB (A weighted), maxSPL=105dB and the **frequency response** is within -3dB and +2dB from 60Hz...15kHz (15).

Table 1 – microphone key parameters from the 2015 investigation

microphone	**EIN (A weighted)**	**maxSPL**	**frequency response**
KE4-211-2	27dB	130dB	20Hz...20kHz ±3dB
WM-61A	<32dB	unknown	20Hz...20kHz ±4dB
POM-3535L-3-R	26dB	unknown	unknown
EM158N	20dB	115dB	50Hz...20kHz -6...+2dB
C928	28dB	131dB	20Hz...20kHz
INMP510	29dB	105dB	60Hz...20kHz -3...+13dB
MP34DT01	31dB	100dB	100Hz...10kHz -2...+3dB
INMP621	29dB	105dB	45Hz...20kHz -3...+17dB
INMP441	33dB	105dB	60Hz...15kHz -3...+2dB

According to the datasheets analyzed in 2015 the I2S microphone that would have been the easiest to implement (in terms of downstream processing) was the one with the highest EIN of 33dB. Best PDM microphone had 29dB, best analog MEMS had 28dB and the best conventional electret capsule had 20dB. Analog microphones have 115...131dB maxSPL, digital MEMS reach the 1% distortion limit at 100...105dB maxSPL but can go much higher with the drawback of higher distortion. The **frequency response** of the MEMS microphones is worse than that of the conventional electret capsules and needs to be equalized using digital filters to meet the demands of a measurement system.

4. MEASUREMENT RESULTS OF 2015

In the meantime microphone preamplifiers for the analog microphones were prepared and experimental arrays for the MEMS microphones as well as a prototype I2S measurement card were designed.

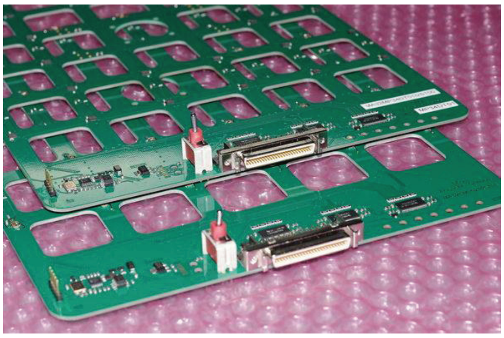

Figure 7 – MEMS microphone arrays

From 26 to 28 October 2015 microphone measurements have been carried out in the anechoic chamber at the Berlin University TU-Berlin. The measurements were done with 10 to 32 microphones of each type and by comparison to a G.R.A.S. 46AE measurement microphone. That microphone was also good enough to measure the noise floor inside the anechoic chamber. The sound source for the **frequency response** measurements was a KSdigital C8-COAX active 2-way coaxial Loudspeaker driven by a Tektronix AFG3102 frequency generator. Evaluation of the measurement results revealed that the far sound field (11 meter distance) was only homogenous from 50…500Hz and from 1kHz upwards its homogeneity started to fade. After that the reference frequency was changed from 1kHz to 500Hz and the calculations were done again leading to better looking frequency response diagrams. More information on this can be found in the DAGA 2017 manuscript (16).

4.1 Equivalent input noise results

The analog microphone preamplifiers are good but still contribute up to 1dB of noise; the noise of the digital microphones can be directly compared.

Table 2 – **equivalent input noise** from the 2015 measurements

microphone	measured EIN (A weighted)	noise floor (G.R.A.S. 46AE)
KE4-211-2	27.8dB average (26.1…30.6dB)	16.5dB (A weighted)
WM-61A	31.6dB average (30.6…32.3dB)	16.4dB (A weighted)
POM-3535L-3-R	30.3dB average (28.2…32.1dB)	16.4dB (A weighted)
EM158N	27.2dB average (24.6…31.3dB)	16.4dB (A weighted)
C928	29.4dB average (28.9…29.7dB)	16.3dB (A weighted)
INMP510	30.0dB average (29.7…30.3dB)	16.4dB (A weighted)
MP34DT01	36.7dB average (33.0…49.0dB)	16.1dB (A weighted)
INMP621	30.8dB average (30.4…31.5dB)	16.3dB (A weighted)
INMP441	36.4dB average (33.3…41.3dB)	16.0dB (A weighted)

EINs of KE4-211-2, WM-61A, C928 and INMP510 are within specification, EIN of INMP621 is slightly higher than specified and EINs of POM3535L-3-R, EM158N, MP34DT01 and INMP441 are well above specification.

4.2 Frequency response results

Reduced measurement accuracy between 1kHz and 20kHz as mentioned above should be paid attention to. The KE4-211-2 microphone preamplifiers contain an analog low-cut filter with -3dB at 100Hz.

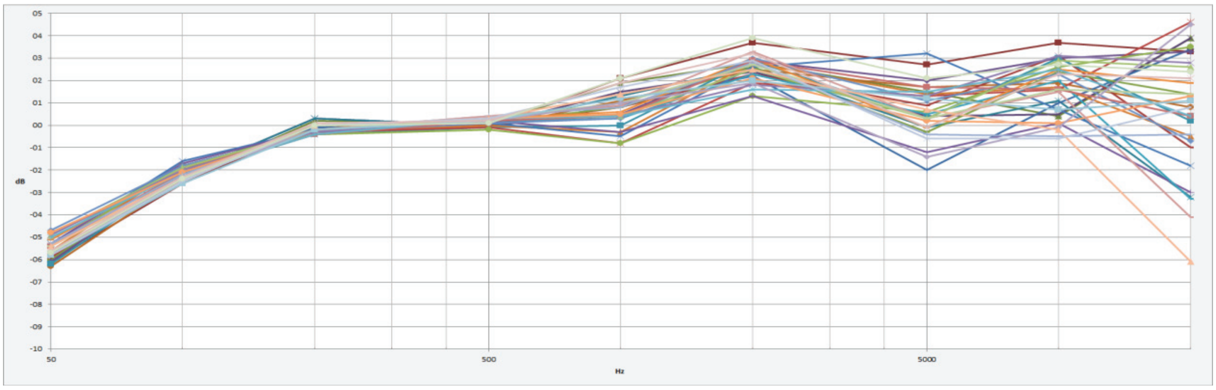

Figure 8 – frequency responses of KE4-211-2 analog microphones with preamplifiers

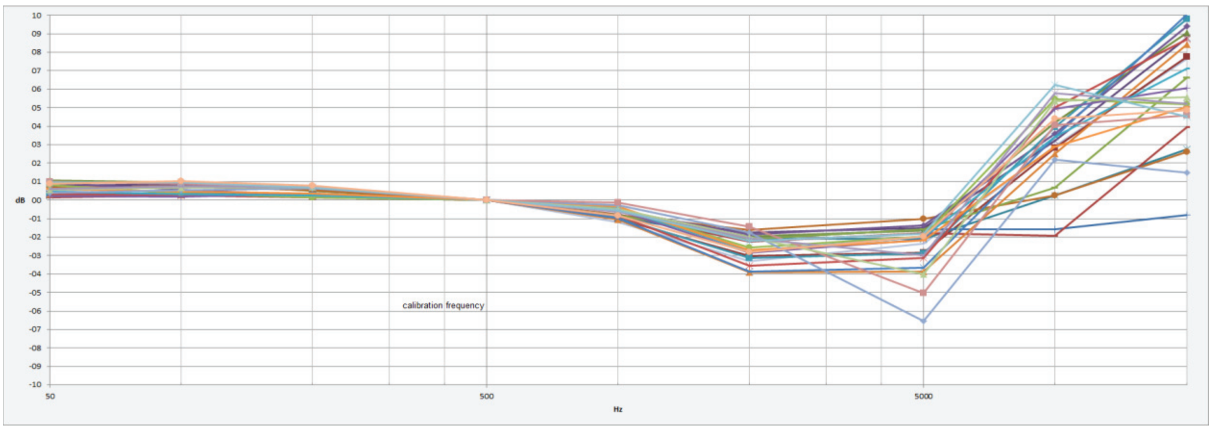

Figure 9 – frequency responses of WM-61A analog microphones with preamplifiers

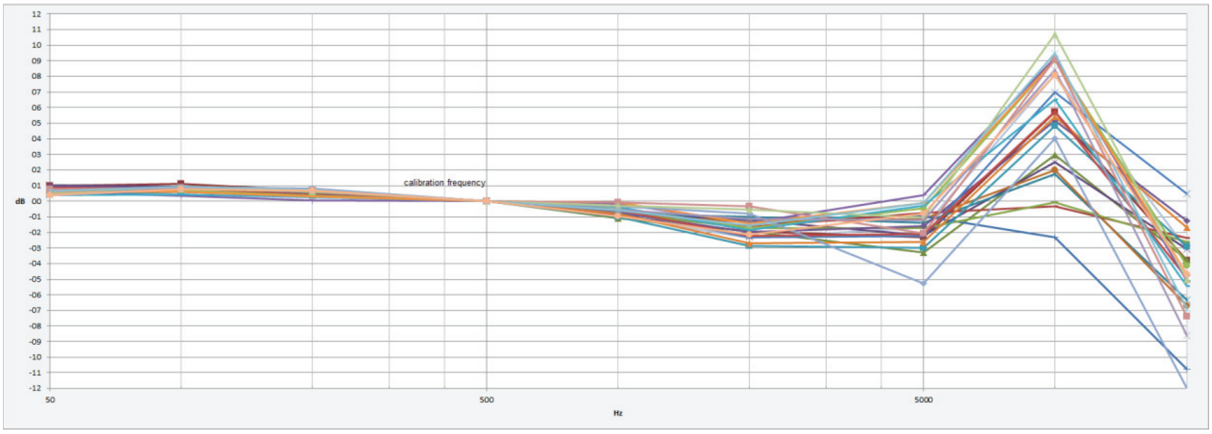

Figure 10 – frequency responses of POM-3535L-3-R analog microphones with preamplifiers

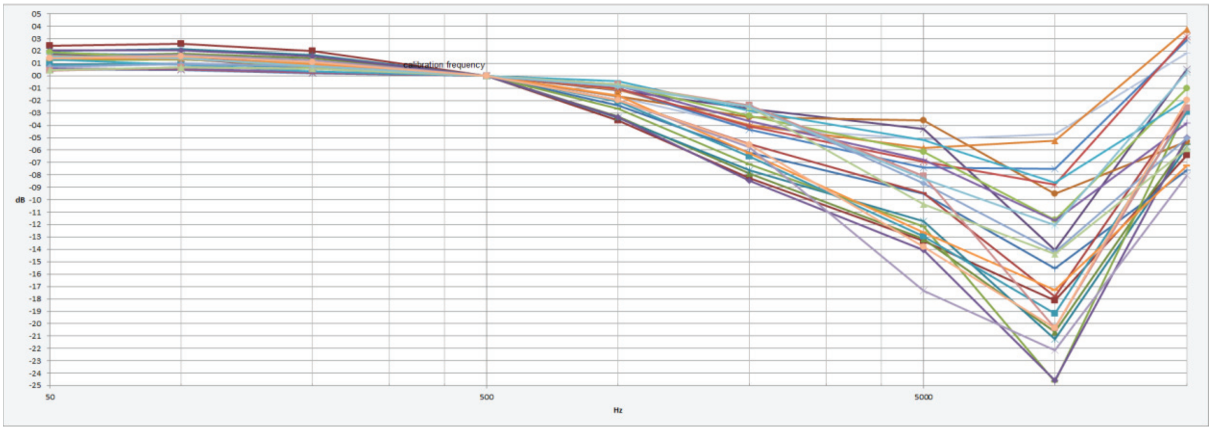

Figure 11 – frequency responses of EM158N analog microphones with preamplifiers

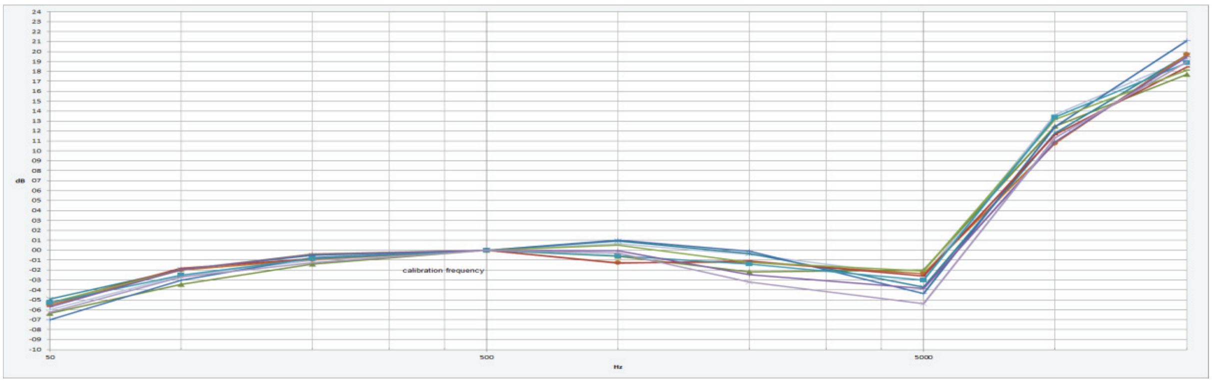

Figure 12 – frequency responses of C928 analog MEMS microphones with preamplifiers

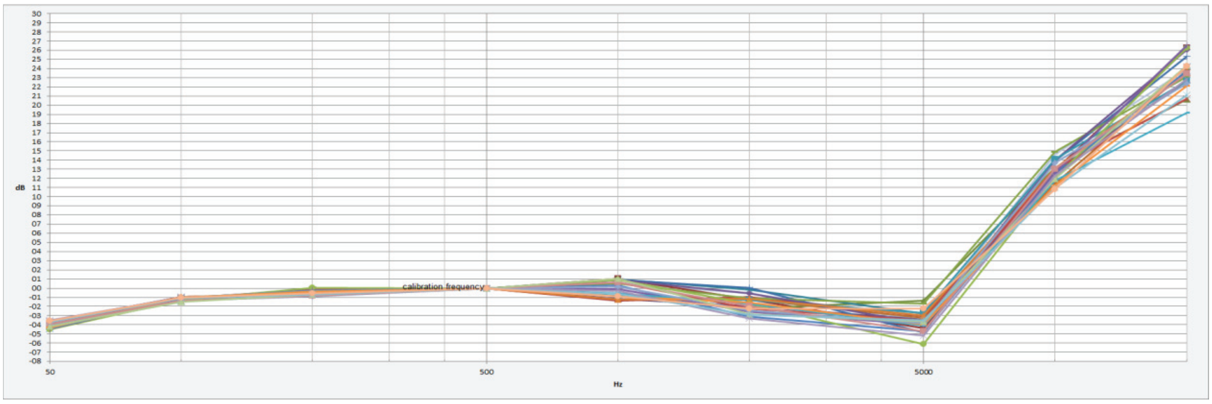

Figure 13 – frequency responses of INMP510 analog MEMS microphones with preamplifiers

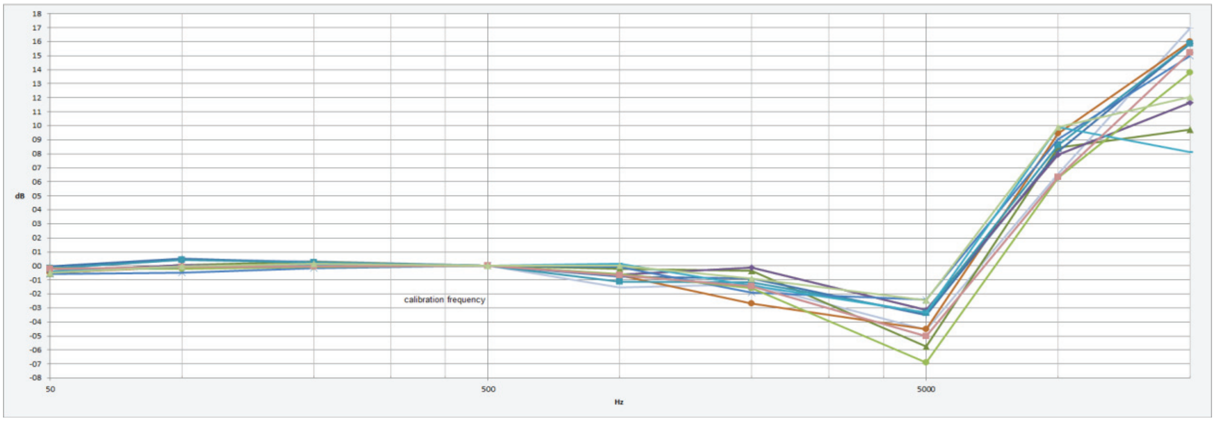

Figure 14 – frequency responses of MP34DT01 digital PDM MEMS microphones

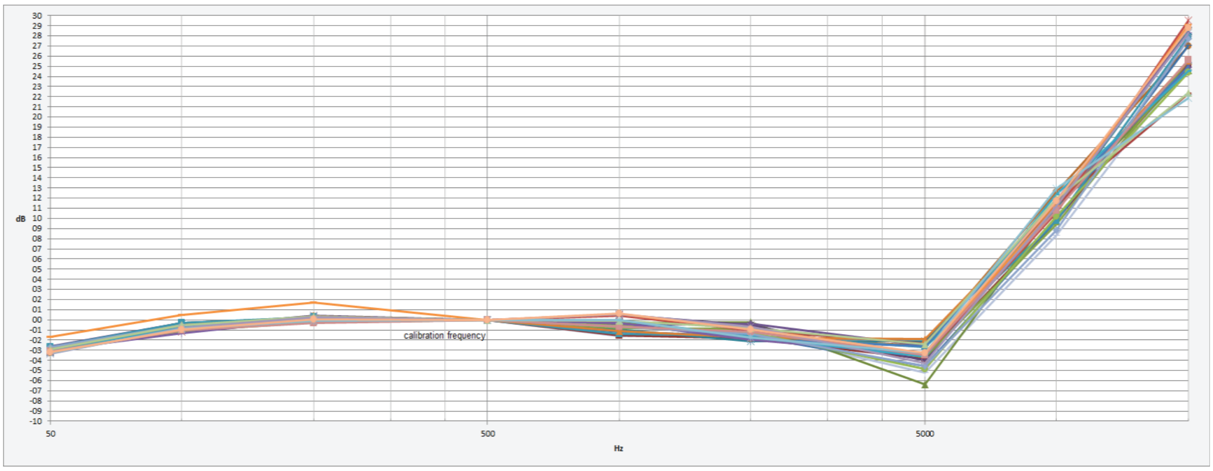

Figure 15 – frequency responses of INMP621 digital PDM MEMS microphones

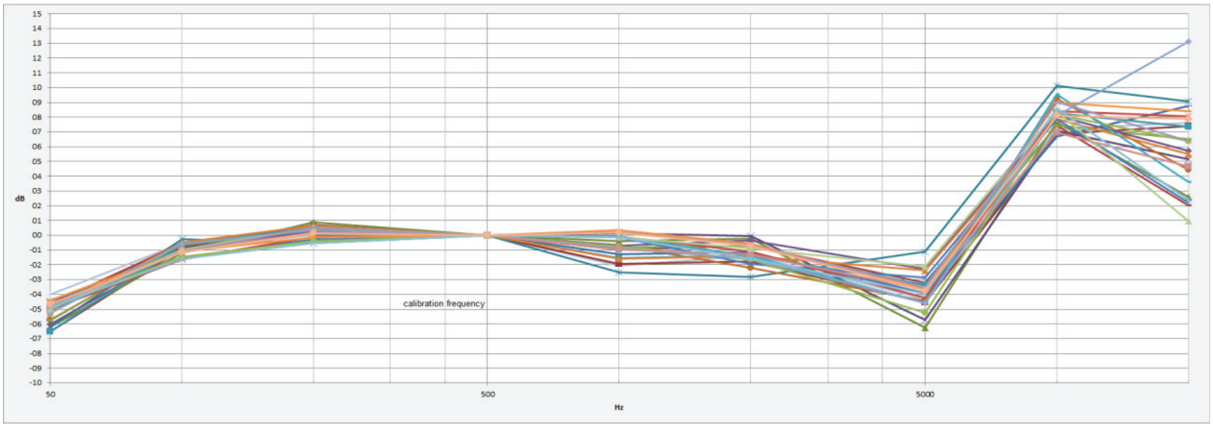

Figure 16 – frequency responses of INMP441 digital I2S MEMS microphones

Respecting the reduced measurement accuracy above 500Hz the measured frequency responses of the KE4-211-2, WM-61A, INMP510, MP34DT01, INMP621 and INMP441 seem to be within specification, EM158N response is falling too fast from 1kHz on and believed to be out of specification and the responses of POM-3535L-3-R and C928 are not bad but cannot be compared due to insufficient specification (no diagrams in the datasheets).

5. MEMS MICROPHONE IMPROVEMENTS BETWEEN 2015 AND 2017

MEMS makers have made improvements during the last 2 years. The latest investigation was done in May 2017. Among the analog MEMS the C928 was a prototype and did not make it into production, the INMP510 is still manufactured but with the InvenSense ICS-40720 there is already a better alternative. The top ported digital PDM MEMS microphone MP34DT01 is still available but has now a companion named MP34DT04 with lower EIN, the bottom ported PDM MEMS INMP621 is still made and InvenSense has not yet one with lower EIN but the Knowles SPH1668LM4H-1 is slightly ahead. The I2S MEMS microphone INMP441 is not recommended for new designs and has a superior successor called ICS-43434. The InvenSense ICS-52000 is the first TDM MEMS microphone already available.

The ICS-40720 has EIN=24dB (A weighted), maxSPL=105dB and the **frequency response** starts from -3dB at 75Hz, stays below +3dB up to 10kHz and has a peak of +17dB at 23kHz (17).

The MP34DT04 has EIN=30dB (A weighted) calculated from SNR=64dB (A weighted), maxSPL=100dB and the **frequency response** is within -2dB and +3dB from 100Hz...10kHz (18).

The SPH1668LM4H-1 has EIN=28.5dB (A weighted) calculated from SNR=65.5dB (A weighted), maxSPL=120dB and the **frequency response** is within ±2dB from 100Hz...10kHz (19).

The ICS-43434 has EIN=29dB (A weighted), maxSPL=105dB and the **frequency response** starts from -3dB at 50Hz, stays below +3dB up to 10kHz and has a peak of +12dB at 20kHz (20).

The ICS-52000 has EIN=29dB (A weighted), maxSPL=105dB and the **frequency response** starts from -3dB at 40Hz, stays below +3dB up to 10kHz and has a peak of +18dB at 23kHz (21).

Table 3 – microphone key parameters from the 2017 investigation

microphone	**EIN (A weighted)**	**maxSPL**	**frequency response**
ICS-40720	24dB	105dB	75Hz...23kHz -3...+17dB
MP34DT04	30dB	100dB	100Hz...10kHz -2...+3dB
SPH1668LM4H-1	28.5dB	120dB	100Hz...10kHz ±2dB
ICS-43434	29dB	105dB	50Hz...20kHz -3...+12dB
ICS-52000	29dB	105dB	40Hz...23kHz -3...+18dB

6. PER CHANNEL COSTS OF CONVENTIONAL VS DIGITAL MEMS SYSTEMS

As described in chapter 2 the downstream processing for analog microphones is more complex than for digital MEMS. Buffers, cables, EMC filters, ESD protection and a little bit of logic are needed for analog and digital microphones. Digital PDM MEMS need downsampling-filters inside a CODEC or programmed into an FPGA for PCM conversion. Signals coming from analog microphones (MEMS or conventional) must pass anti-aliasing filters before being digitalized with AD-converters.

Table 4 – microphone prices from 05/24/2017 excluding taxes and estimated associated channel costs

microphone	**type**	**price**	**estimated channel costs (with microphone)**
KE4-211-2	analog	≈30$	80$
POM-3535L-3-R	analog	0.98$	51$
EM158N	analog	≈2$	52$
ICS-40720	analog	2.40$	52$
MP34DT04	PDM	1.10$	34$
SPH1668LM4H-1	PDM	0.94$	34$
ICS-43434	I2S	1.99$	32$
ICS-52000	TDM	2.63$	33$

Channel costs in the table above include electronic components and the PCBs from the microphone to the logic that connects to the main processing unit. The processing unit itself, the power supply, the enclosure and all the other things that belong to the individual phased array system are left out.

As expected omitting analog signal processing with AD-conversion can save time and money.

7. A WAY TO MAKE A GOOD DIGITAL MEMS MICROPHONE ARRAY

Comparing tables 1 and 3 shows that during the last years the noise performance of the analog MEMS became competitive with conventional electret capsules. Making the decision for MEMS, means soldering the microphones on a printed circuit board (PCB) together with other surface-mounted components and it also means having to add digital filters for frequency response equalization. In terms of EIN current digital MEMS are still worse than the analog ones but channel costs are lower and why not just take more of them to lower the noise?

Adding up the channels is part of beamforming algorithms. The signals resulting from the acoustical input are added regularly but microphone noise is uncorrelated and the sum of uncorrelated noises is their root sum square.

$$sum\_of\_noises = \sqrt{\sum_{i=1}^{n} noise_i^2} \tag{2}$$

$$attenuation\_of\_noise = 20 \log \sqrt{\text{number\_of\_channels}} \tag{3}$$

When the acoustical signals are in phase they are growing faster than noise that way. It is common to divide the results by the number_of_channels after summing the signals and equation (3) shows by how many dB the noise can be reduced. Doubling the number of microphone channels for example attenuates the noise by 3dB.

Figure 17 shows an Acoustic Camera with 96 digital MEMS microphones. According to the datasheet the microphones have EIN=30dB (A weighted) and the calculated acoustic-mapping-noise is 10dB (A weighted).

Figure 17 – Acoustic Camera with 96 digital MEMS microphones

8. FINAL REMARKS

Replacing conventional analog microphone capsules by digital MEMS microphones saves development time and until 2017 it can only save money when higher microphone noise is accepted. When low sound pressure levels have to be measured it is possible to lower the acoustic-mapping-noise by putting more digital MEMS microphones into the phased array system. Being honest, by 2017 a digital system on a par with an analog one would cost a little more than that.

For measuring high sound pressure levels the microphone's **maximum sound pressure level** (maxSPL) is of concern. Regarding this until 2017 conventional analog microphone capsules are still ahead. As written in chapter 3.2 maxSPL increases when higher distortions are accepted.

By 2017 the **frequency response** of the MEMS microphones is worse than that of good conventional analog electret capsules. It might be good enough for a troubleshooting system but to make an advanced measurement system digital filters for frequency response equalization have to be implemented.

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