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ANECHOIC MEASUREMENTS OF PARTICLE-VELOCITY PROBES COMPARED TO PRESSURE GRADIENT AND PRESSURE MICROPHONES

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The Microflown is an acoustic particle velocity sensor invented at the University of Twente in Holland in 1994 and commercialized in 1997 [1, 9]. The sensor directly measures particle velocity rather than pressure-gradient as do most unidirectional and bidirectional microphones. The sensor has several interesting operational characteristics however few measurements of the Microflown have been published until now making it difficult for a potential user to assess the merits of this transducer in comparison to high quality condenser microphones commonly used in music and speech recording. This paper offers some insight by presenting anechoic measurements of particle velocity probes compared to the measurements of pressure-gradient and pressure microphones (of condenser type) made under identical acoustical conditions at varying distances from a point source having a wide frequency range. Detailed frequency response measurements show how the characteristics of these transducer types are dependent on their distance to the source, and highlight the need of transducer calibration with respect to distance. Very few microphone manufacturers publish frequency response data for more than one reference distance to the source although distance is often used to modify the applied response of the microphone. An additional goal for making these measurements is to establish the relationship between particle velocity and pressure gradient values using the same acoustical conditions. The measurements were made in the large anechoic chamber of the NHK Science and Technical Research Laboratories (STRL) in Tokyo during the April-May of 2006.

Keywords: microphone measurements, anechoic microphone response, Microflown sensor, particle velocity, pressure gradient, pressure transducer, proximity effect, distance dependent measurement, small acoustic source.

1. The Microflown sensor

1.1. Transducer type and operation

The Microflown acoustic particle velocity sensor does not have a membrane and the associated mechanical suspension; therefore it is not subject to system resonances and frequency response equalization due to energy being stored in moving mass and compliance. The sensor measures the temperature difference between two closely spaced and heated wire resistors, and quantifies particle velocity from the temperature measurement. The wires are heated with a DC current to target temperature of 300°C with typical operational temperature ranging between 200°C – 400°C. The wires are composed of the silicon nitride carrier covered with an electrically conductive platinum layer used as the temperature sensor and heater. When exposed to airflow, the temperature of the two wires changes asymmetrically due to the differential effect of heat flowing between the upstream and downstream wire. The resulting temperature difference causes resistance difference that is measured with a bridge circuit to produce a signal proportional to particle velocity. The relationship between the temperature difference among the wires and the measured particle velocity is linear. When there is no particle velocity present, the heat is transferred into the surrounding air and the sensor output signal is self-noise.

Particle velocity is closely related to pressure gradient, however, the exact measure of this relationship has not been experimentally established. One of the objectives of these measurements is to determine this relationship.

1.2. Directivity

The Microflown has a cosine shaped figure-of-eight bidirectional sensitivity because the two-wire system can sense the positive and negative velocity direction. The cosine pattern is uniform across all frequencies due to small 350 μm spacing between the wire sensors compared to virtually any audio wavelength. A single-wire sensor (a hot wire anemometer) can also be used as a velocity transducer but unlike the Microflown it does not have directional selectivity, it is not linear, and has low sensitivity in the audio range.

1.3. Frequency response

The low frequency response of this particle velocity sensor is extended to DC because the Microflown can measure DC-flow, which is particle velocity with frequency of 0 Hz. Unlike membrane-type transducers, the Microflown response it is not bound by band-limiting resonances or other restrictions of the mechanical vibrating system.

The Microflown has an overall low-pass frequency characteristic with a 6 dB/oct. roll-off above 1 kHz due to heat diffusion, and an additional roll-off above 8 kHz caused by the thermal mass of the sensor. These are both first-order effects, each providing 6 dB/oct attenuation [2].

1.4. Low frequency sensitivity

The Microflown, which directly measures particle velocity as transfer of heat, uses an extremely close spacing of sensor elements achieving a high sensitivity at low frequencies and a coherent measure of velocity at high frequencies. The point of measurement is also well defined.

To achieve a high sensitivity and signal-to-noise ratio at low frequencies using the pressure-gradient principle, two pressure transducers must have a large spacing in the direction of wave propagation to record a reasonable pressure gradient on long wavelengths. However, pressure-gradient microphones typically measure the wave's pressure at two points that are closely spaced in order to record a coherent gradient up to the highest workable audio frequency.

1.5. Sensitivity to wind noise

The Microflown probe is sensitive to wind velocity and DC flow of acoustic energy such as air turbulence from moving objects and people, and from air conditioning. A windscreen could be used to filter out DC velocity components but the windscreen should not affect the heat transfer properties between the two wires. The additional benefit of the windscreen is to protect the probe's fragile sensor from coming into contact with human hair or clothing fibers, which could easily break the delicate wires and make the sensor unable to operate.

1.6. Self-noise

The Microflown fitted with the Titan sensor element (used since 2003) has low self-noise compared to the 1/2″ pressure microphones showing an improvement of 20–25 dB at frequencies below 100 Hz once both transducers' output levels are adjusted to be equal at 1 kHz [3]. De Bree [10] measured the A-weighted low-pass filtered self-noise of the Microflown sensor and of the Schoeps MK8 pressure-gradient microphone up to 250 Hz (-3 dB point) bandwidth. The output signals were filtered using an external third-order low-pass filter, and the preamplifier gains were adjusted to achieve equal 0 dBV per Pascal sensitivity for each transducer in an anechoic chamber. The Microflown provided 6.2 dB(A) self-noise while the Schoeps MK8 provided 18.9 dB(A). The theoretical 2 dB(A) value predicted for the Microflown could not be achieved due to the presence of hum and background noise in the chamber.

2. Measurements of the Microflown compared with the measurements of the pressure and pressure-gradient condenser microphones

2.1. Measurement conditions

Three types of transducers were measured in a large anechoic chamber of the NHK STRL under identical acoustical conditions at varying distances from a small sound source having a wide frequency range:

- Microflown Particle Velocity Sensor with a custom built 48 V Phantom-powered preamplifier,

- Schoeps CMC68 Pressure Gradient Microphone, a true dipole transducer operating with a single diaphragm (CCU6 preamplifier plus MK8 capsule),
- Bruel & Kjaer 1/2″ Free-Field Pressure Condenser Microphone type 4191 with type 2669 preamplifier.

2.2. Distances to the sound source

Fourteen distances were chosen between the source and the microphone: 2 cm, 3 cm, 5 cm, 8 cm, 10 cm, 20 cm, 30 cm, 50 cm, 1 m, 1.2 m, 1.5 m, 2.0 m, 2.5 m, and 3.0 m.

2.3. Automated microphone positioning

The NHK anechoic chamber is equipped with a laser guided transport system that automatically positions the microphone at a correct distance to the source for each measurement.

2.4. Frequency range

The magnitude frequency response of the transducers was measured at 0° angle on-axis within the frequency range 50 Hz to 2 kHz.

2.5. Source signal level

The reference Sound Pressure Level was 53 dB SPL/1 kHz/1 m. The sound pressure level was as much as 50 dB higher near the microphone at 2 cm distance from the source due to the proximity boost achieving 103 dB SPL at 80 Hz. In some cases, the sound pressure was adjusted to 70 dB SPL(1 kHz) for each distance from the microphone to the source in order to retain constant signal to noise ratio for each measurement.

2.6. Monopole sound source

The ideal monopole radiation would have been achieved with a source similar to B&K Mouth Simulator Type 4227 as it can generate 110 dB SPL in the range 200 Hz – 2 kHz at 2.5 cm distance from the lip ring. However, the limited response of this source at low frequencies was considered to be a major disadvantage.

Instead, Genelec 1029A active monitor was selected as the best approximation of a small size broadband source (Fig. 1). Its low harmonic distortion and a wide frequency response from 68 Hz to 20 kHz (± 2.5 dB) are produced from a 5″ woofer and 3/4″ hard-domed tweeter powered by a pair of 40 Watt amplifiers. The crossover frequency of 1.7 kHz (visible as a small dip in all frequency response plots) achieves a single-source performance to above 1 kHz. The monitor measures $10'' \times 6'' \times 7.125''$ and is housed in a die-cast low-resonance aluminum enclosure. The two rectangular reflex ports have been blocked off packed with dense sound absorbing foam to change the loudspeaker into a closed box with a monopole radiation characteristic for all frequencies of interest up to 1 kHz.

Fig. 1. Genelec 1029A active monitor serving as a broadband monopole source within 50 Hz – 2 kHz frequency range next to the Microflown particle velocity sensor.

2.7. Dependence of transducer response on distance to the source

The frequency response of pressure gradient and particle velocity microphones is a function of spherical wave "proximity effect"; the bass response rises considerably when these microphones are used in close distance to a small sound source. For low frequencies and/or small distances, the particle velocity is inversely proportional to frequency and pressure, and inversely proportional to radial distance from the source. At high frequencies and/or relatively large distances from the source (in plane wave conditions) the particle velocity is proportional to the pressure and largely in phase with it. It was expected that the output signals of the Microflown sensor and the Schoeps CMC68 pressure gradient microphone would increase with decreasing frequency and distance to the source.

The frequency response of the pressure microphone is theoretically not a function of its distance from a sound source in a free field. It was expected that in the anechoic chamber the B&K 1/2″ free-field condenser microphone type 4191 would produce a constant frequency response at each distance from the source, its output level dependent only on the inverse square law.

3. Measurement results

3.1. Frequency response curves

Figure 2 shows the raw measured frequency response data of B&K4191 and of Schoeps CMC68 for the fourteen distances from 2 cm to 300 cm. As expected, the pressure microphone curves are parallel to each other indicating no substantial effect of distance on frequency response. The curves are offset in level according to the inverse square law, shifted by 6 dB per doubling of distance. The ripple visible in the bottom curves indicates lower values of signal to noise ratio when the microphone is further away than 1 m from the source calibrated to 53 dB SPL/1 kHz/1 m.

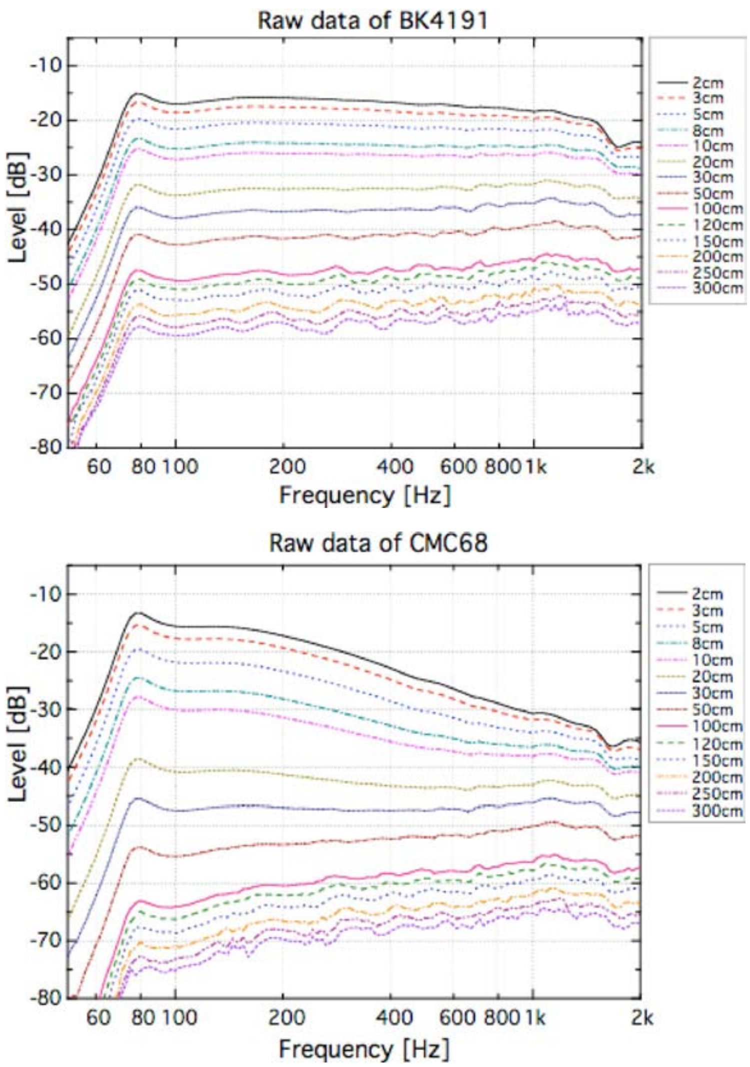

Fig. 2. Frequency response of the pressure (top) and pressure-gradient (bottom) microphones at 14 distances to the small broadband source in anechoic chamber.

The pressure-gradient microphone shows a substantial magnitude level increase at low frequencies for distances less than 30 cm, and a low-frequency attenuation for distances larger than 30 cm. The microphone is clearly calibrated to have a flat response at 30 cm distance from the source. For far away sources, the pressure gradient microphone attenuates low frequencies at the rate of nearly 3 dB/oct below 1 kHz.

Figure 3 shows the raw frequency response data of two Microflown sensors showing a close matching between them. It can be observed that the proximity boost is operating at all distances smaller than 1 m. At distances of 1 m or more the output remains flat regardless of distance. We can conclude that the particle velocity sensor provides a flat frequency response for distant sources (1 m away and beyond) without the low-frequency roll off which characterizes pressure gradient microphones.

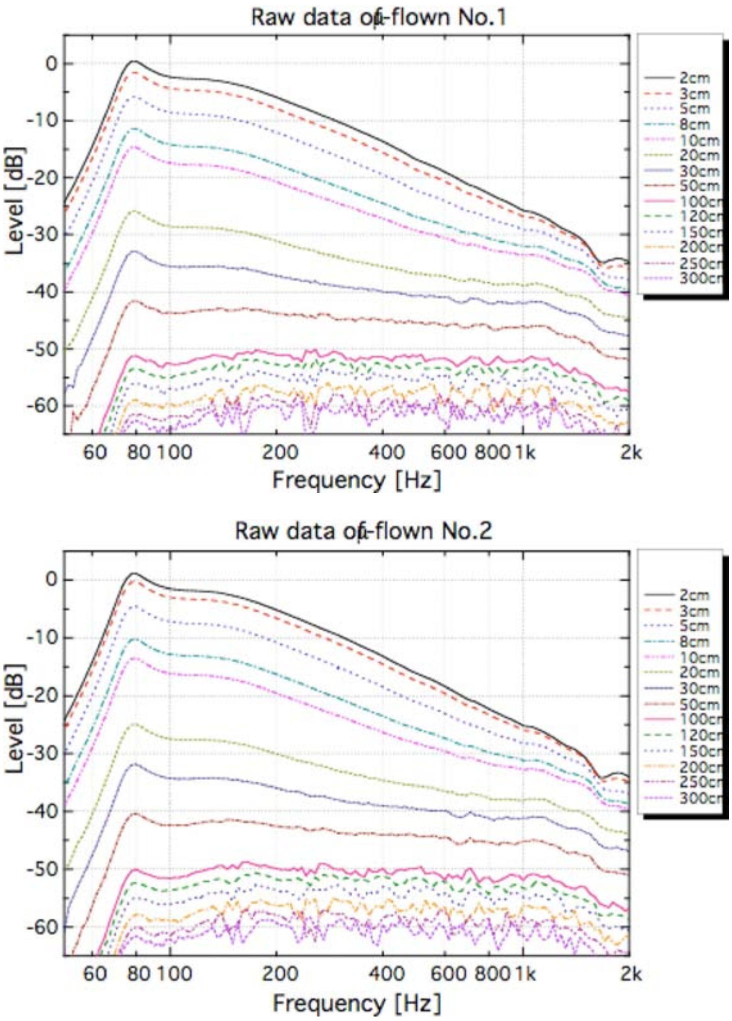

Fig. 3. Frequency response of two Microflown sensors measured at 14 distances to the small broadband source in anechoic chamber.

Figure 4 shows this more clearly by separating the curves into two groups based on distance (2 cm – 1 m and 1 m – 3 m) and adjusting the source signal to measure 70 dB SPL @ 1 kHz at each microphone distance. The ripple due to the poor signal to noise ratio is now completely gone, and the gain from the proximity to the spherical wave source reaches 25 dB for the lowest frequencies at 2 cm distance, compared to the gain at 1 m distance.

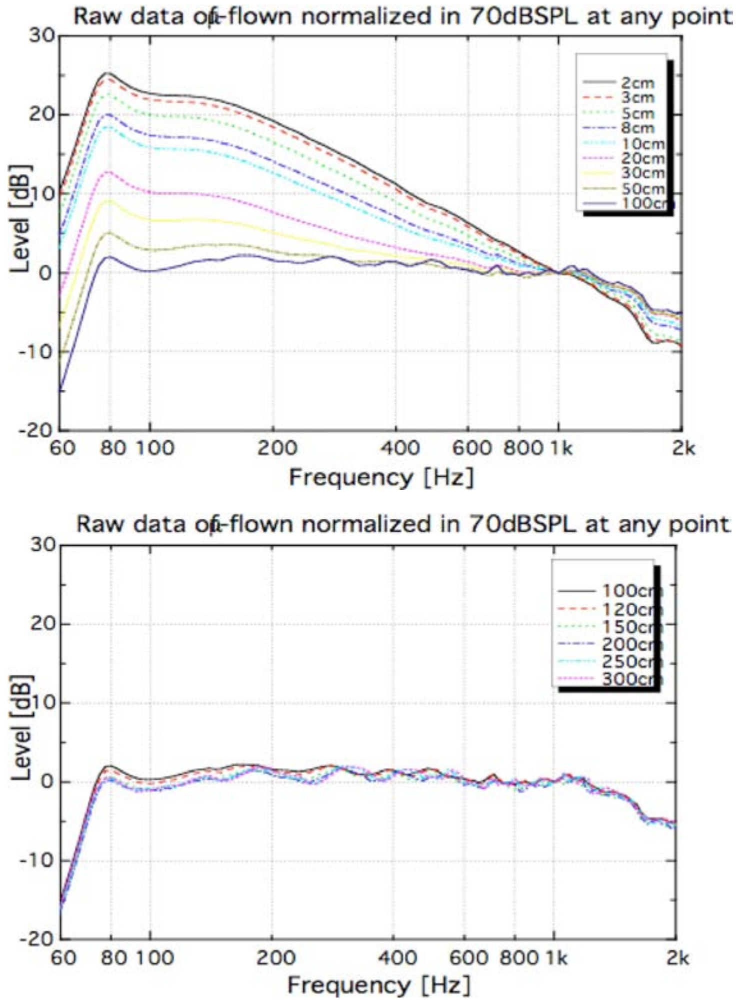

Fig. 4. Frequency response of the Microflown sensor measured using constant 70 dB SPL@1 kHz at each distance, and separated into two graphs according to distance: 2 cm – 1 m (top), and 1 m – 3 m (bottom).

Figure 5 presents the measurements after they have been normalized (equalized) by the curve measured at 1 m. The equalization removes frequency response characteristics of the loudspeaker and the microphone focusing only on gain changes due to distance. The reference curve at 1 m is a straight line and other curves show the relative boost at each distance due to the proximity effect. At source distances larger than 1 m, there are no level changes due to the proximity effect.

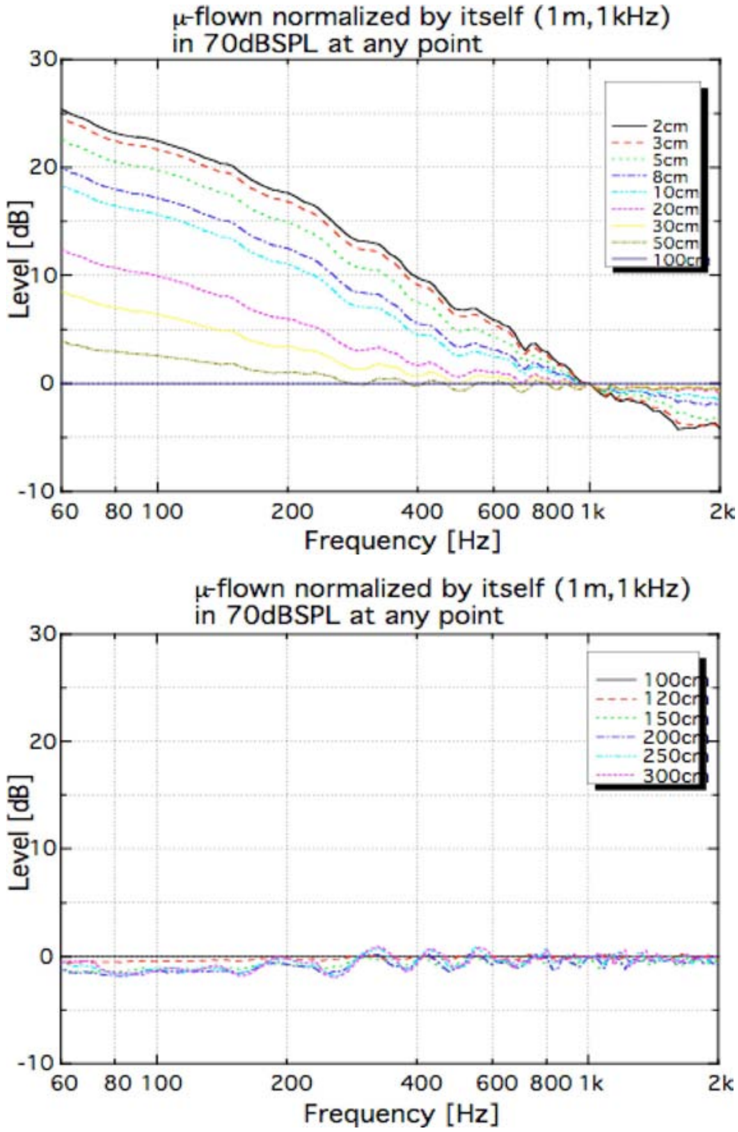

Fig. 5. Frequency response of the Microflown sensor normalized (equalized) with the curve measured at 1 m, and separated into two graphs according to distance: 2 cm – 1 m (top), and 1 m – 3 m (bottom). All curves are calibrated with 70 dB SPL at 1 kHz.

Figure 6 shows the results of the same normalization for the pressure gradient microphone Schoeps CMC68. Comparing this graph with the previous one reveals that the proximity boost is virtually the same for the particle velocity sensor and the pressure gradient microphone. Once the response is matched at 1 kHz and 70 dB SPL for all dis-

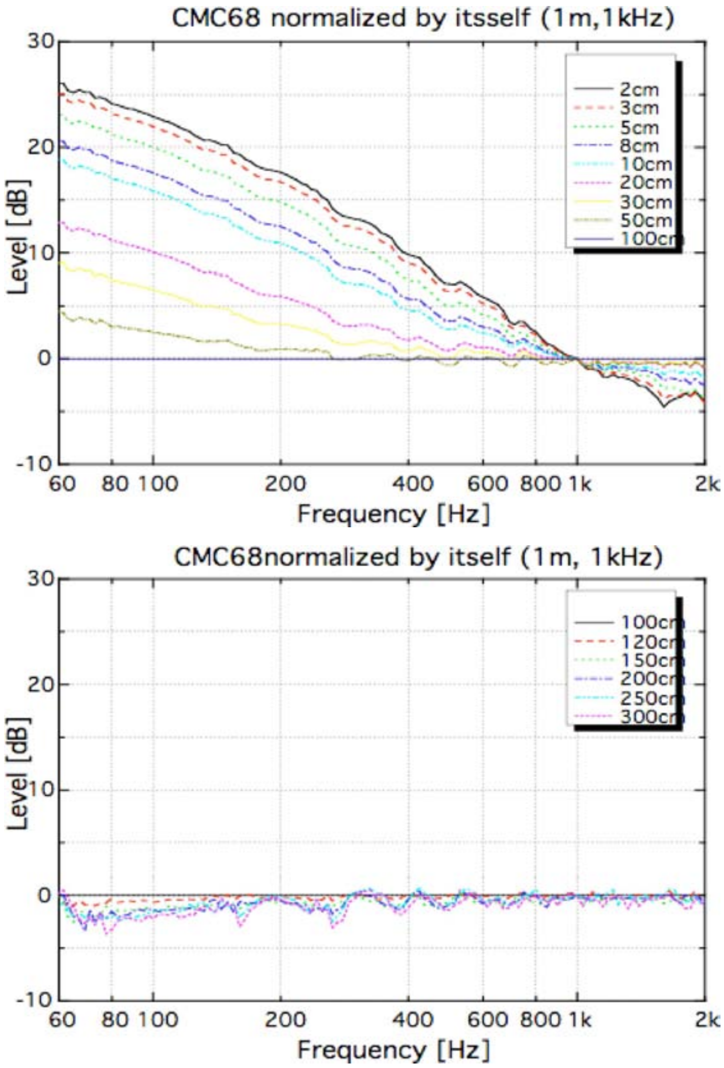

Fig. 6. Frequency response of the Schoeps CMC68 microphone normalized (equalized) with the curve measured at 1 m, and separated into two graphs: 2 cm – 1 m (top) and 1 m – 3 m (bottom). All curves are calibrated with 70 dB SPL at 1 kHz.

tances, the proximity boost due to distance and frequency is exactly the same for both transducers.

Figure 7 shows the output of the Schoeps CMC68 when all response curves have been equalized with the flat reference response measured at 30 cm, and are made coincident at 1 kHz. The 30 cm curve becomes a straight line while the curves at distances less than 30 cm show low-frequency boost, and the curves at distances larger than 30 cm show low frequency cut. This group of curves shows how the spectral balance of the source changes when the microphone capturing it is moved closer or further away from the 30 cm reference distance, where the response is flat.

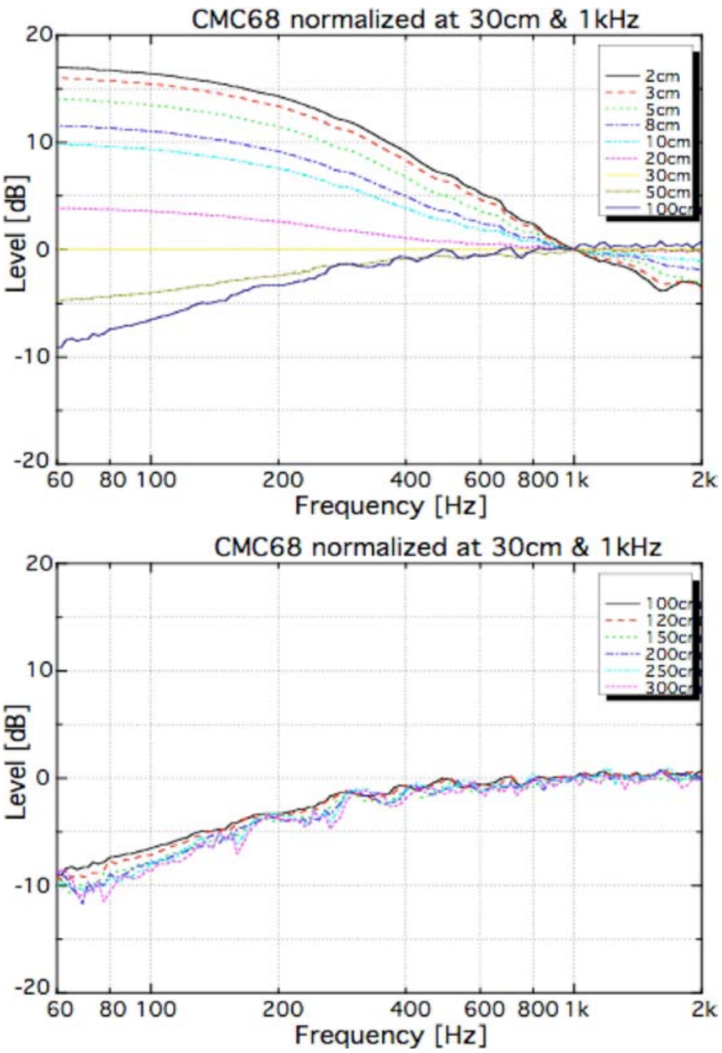

Fig. 7. Frequency response of the Schoeps CMC68 when all response curves are equalized with the flat reference response measured at 30 cm, and matched at 1 kHz. Distances separated into graphs: 2 cm – 1 m (top) and 1 m – 3 m (bottom). Low-frequency roll off affects sources being further away than 30 cm.

Previously, we have seen in Figs. 2 and 3 that the pressure gradient microphone is calibrated to have a flat response at 30 cm and the particle velocity sensor is calibrated for a flat response at 1 m.

Figure 8 shows the difference between the particle velocity and the pressure gradient transducer response at each distance to the source. The relative response of the particle velocity probe when compared to the pressure gradient response displays a uniform -2.6 dB/oct slope increasing in gain towards low frequencies regardless of the distance to the source. The corresponding timbre difference between the particle velocity and the pressure gradient transducer could be simplistically compared to the sonic difference

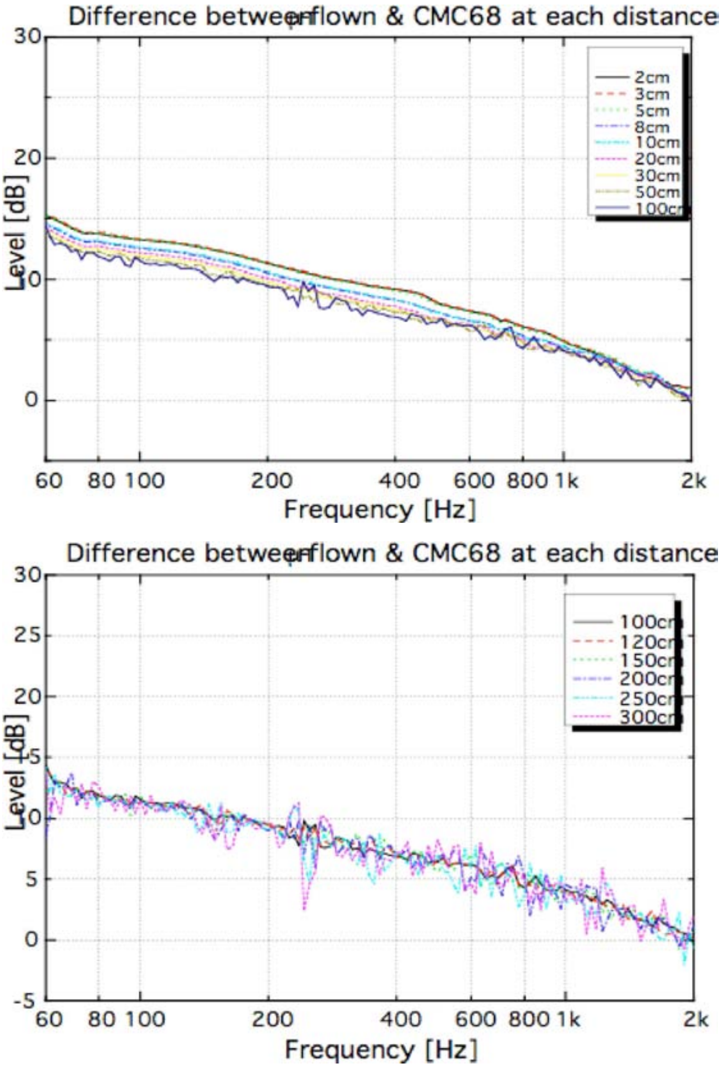

Fig. 8. The difference between the particle velocity and the pressure gradient transducer response at each distance to the source. Distances separated into two graphs: 2 cm – 1 m (top) and 1 m – 3 m (bottom). The average slope is -2.6 dB/oct.

between pink and white noise. At all distances to the source, a particle velocity probe has more bass than a pressure gradient microphone. The reader may refer to a similar sonic difference between a dynamic ribbon microphone and a condenser pressure gradient microphone.

The authors believe that the cause of the measured 2.6 dB difference between the output of the particle velocity and the pressure gradient sensor, verified under identical acoustical field conditions, may be due to an inequality between the values of pressure gradient and particle velocity. While particle velocity is proportional to pressure gradient, it is not equal to it.

Unlike a typical condenser or dynamic microphone, the Microflown sensor does not employ equalization from a mass or stiffness controlled mechanical operation to adjust its frequency response because it does not have a resonant mechanical system of a membrane and a suspension. We believe that the Microflown sensor measures the true value of particle velocity.

At each distance to the source, from 2 cm to 300 cm, this measured difference remains the same therefore it cannot be caused by proximity. We have determined (see Fig. 6) that the two transducers, particle velocity and pressure gradient, exhibit the same

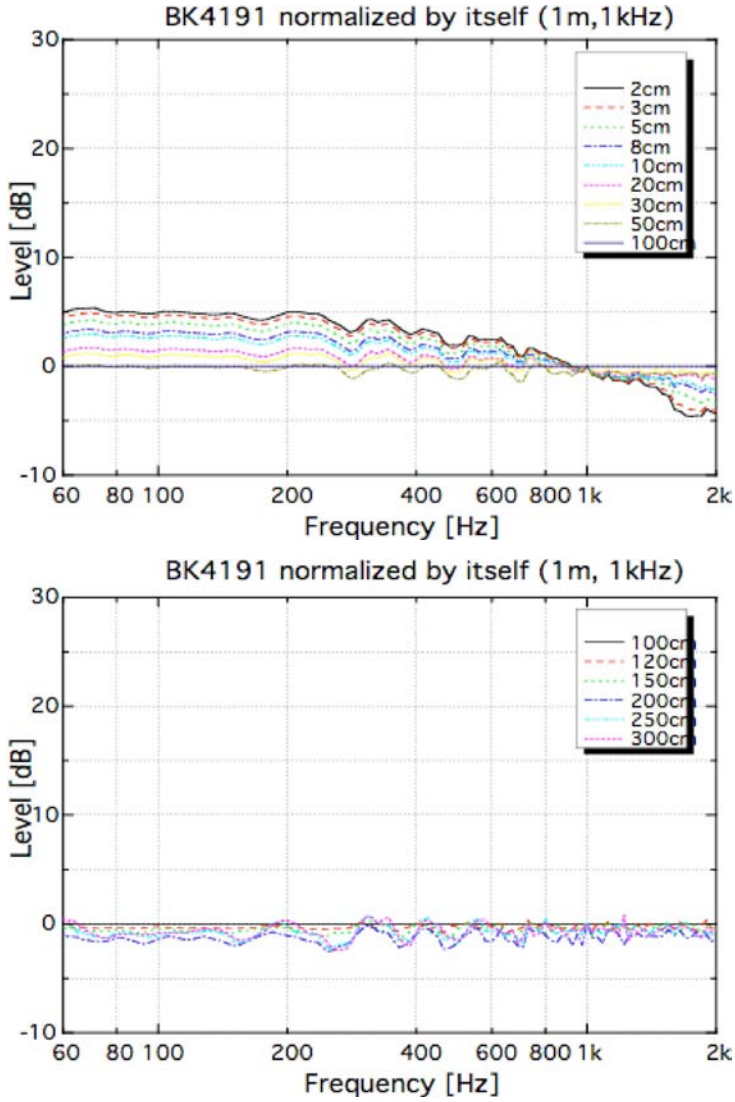

Fig. 9. The frequency response curves of the 1/2″ diameter B&K 4191 microphone measured at various distances to the small sound source and normalized (equalized) with the curve measured at 1 m. Measurements are separated into two graphs: 2 cm – 1 m (top) and 1 m – 3 m (bottom).

relative proximity boost. The high frequency roll off above 1kHz in the response of the Microflown has a 6 dB/oct slope, more than the 2.6 dB average, so it is also unlikely to be the cause of this difference. However, another possible explanation for the measured difference could be that the heat to voltage signal conversion of the Microflown transducer might provide an inherent frequency dependent response slope caused by the characteristic of the heat sensing system.

The exact verification of the cause of the measured difference is not the subject of this paper so we hope that an independent verification of these hypotheses will be published.

Figure 9 shows the response curves of the pressure microphone equalized by the reference response at 1 m. This is provided as a verification of the pressure values near the loudspeaker. There is only a negligible change in the output with varying distances and can be attributed to the non-ideal behavior of the Genelec loudspeaker in approximating a monopole. At distances close to the loudspeaker, 10 cm or less, free-field conditions no longer exist and are bound to affect wave propagation and increase in radiation resistance. The propagating waves have both planar and spherical shapes at very close distances to the loudspeaker.

3.2. Comparing Microflown with ribbon velocity microphones

Velocity transducers, such as dynamic ribbon microphones, operate on the pressure gradient corresponding to the air-particle velocity in the sound wave driving the velocity of the ribbon, which is typically made of a lightweight strip of aluminum. Listening tests conducted informally during music recording sessions at McGill University by students who used both Microflown probes and ribbon velocity microphones have shown a striking similarity in the sound quality of these two transducer types. Some advantages of the Microflown sensor were evident in the higher sensitivity and lower noise level at low frequencies. There was also a noticeably more extended low frequency response and less likelihood of transducer damage from wind and pop, both attributed to the lack of mechanical system of membrane and suspension. The disadvantage of the Microflown was a steeper high frequency roll-off compared to most ribbon microphones.

3.3. Random energy efficiency

The polar response of the Microflown is a bidirectional cosine or figure-of-eight patterns providing reduced reception of random reverberant sounds and background noise generated at a distance. This loss of ambient sound is 66% or 4.8 dB compared to the omnidirectional response and is known as the *random energy efficiency*. The directional characteristic and the *random energy efficiency* are independent of frequency for a true dipole. If the sensor is placed close to the source and the proximity boost is used to amplify the signal of that source, the resulting gain provides an additional increase in the ratio of signal to random noise and reverberation. A “close-talking” application of the Microflown can produce very high signal level and attenuation of ambient noise but requires adjustment of the preamplifier gain to accommodate a substantially higher signal level without distortion.

4. Applications of the Microflown sensor

4.1. Applications in measurements of sound intensity

The sensor is normally used to determine acoustic impedance and reflection index of materials [4], as a transducer providing an alternative to laser vibrometer for a non-contact near-field acoustic holography measurement of structural vibration [5], and for one-, two- and three-dimensional measurement of sound intensity [6, 7]. Proper calibration of Microflown for use in p-**u** intensity probes requires that velocity and pressure transducers have closely matched phase. Phase mismatch will strongly affect the accuracy of sound intensity measurements made in highly reactive sound fields, for example in the near field of a source. Near field, far field, and standing wave (for example in a standing wave tube) calibration methods have been developed and proposed for adoption but have not been standardized yet for the use in sound intensity measurements.

4.2. Applications in room acoustics

The Microflown two-wire thermal sensors can be used to capture directional room impulse response [8]. The probe's cosine directional selectivity is a property useful for changing the ratio between early reflections and the diffuse sound since only the 1/3 of the power in the diffuse sound field is measured with the particle velocity probe. This feature can correct for unfavorable room characteristics and be employed to optimize the presentation of virtual room in a multichannel environment. The flat frequency response of the Microflown for plane waves allows accurate recording of frequency characteristics of reflected waves.

5. Conclusions

Microflown^{TM}probes [9] are true figure-of-eight-pattern particle velocity transducers having extended response down to below the lowest audible frequency, low noise and high output. The Microflown sensor does not require a membrane and the associated mechanical vibration system and is free from various forms of mechanical system response limitations.

Unlike pressure-gradient microphones, velocity probes do not measure acoustic pressure at two points to derive a pressure gradient. When particle velocity is present, acoustical particle velocity sensors measure the temperature difference of the two closely spaced and heated platinum wire resistors, and quantify particle velocity from the temperature measurement. Both particle velocity and pressure gradient microphones show the same amount of relative proximity boost when moved closer than 1 meter to a small broadband source. The frequency response of the pressure-sensing microphone is in general independent of distance.

The particle velocity probe has flat frequency response for distant sources, from 1 meter on, while the sensitivity of pressure gradient microphone attenuates low frequencies at the rate of 2.6 dB/oct. We can assume that the rounded off value of 3 dB/oct represents the difference between particle velocity and pressure gradient components measured in the same sound field using these specific sensors tuned for each parameter. The explanation of the reasons why this measured relationship of 3 dB/oct exists is beyond the scope of this paper. In practical cases, electronic equalization may be used to correct for this difference. DE BREE [10] proposed an add-on Microflown to extend the low frequency response of the pressure gradient microphone.

Although dynamic ribbon microphones were not measured in this study, informal listening tests revealed similarities in sound quality between the Microflown sensor and a group of ribbon microphones. The advantage of the Microflown is lower noise level and a more extended response towards the lowest frequencies; the disadvantage is a more rapid loss of sensitivity at high frequencies.

The Microflown can be used to selectively capture room response at low frequencies. Its flat response for distant sources does not attenuate low frequencies of the ambient sound and reflections, as does the pressure gradient microphone. The uniform bidirectional pattern across all frequencies, and the 4.8 dB random energy efficiency, allow the user to selectively capture directional aspects of room response.

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