SELFNOISE REDUCTION IN ACOUSTIC MEASUREMENTS WITH A PARTICLE VELOCITY SENSOR BY MEANS OF A CROSS-CORRELATION TECHNIQUE

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ABSTRACT

The Microflown is a thermal acoustic sensor which does not measure sound pressure but the accompanying *particle velocity* (see [1-5]). This particle velocity is deduced from a temperature difference between two heated wires. A drawback is the sensor's lower signal-to-noise (S/N-) ratio at higher frequencies compared to pressure microphones.

A method is presented to reduce the noise by utilisation of cross- instead of auto-correlation spectra of two Microflowns. Dependent on the number of data points used, improvements of the signal-to-noise-ratio as high as 30 dB have be attained. The bandwidth in which the sensor's noise characteristics are comparable to those of current microphones, thus increases from about 2 to 10 kHz.

INTRODUCTION

The Microflown is an acoustic sensor that measures particle velocity instead of pressure, the quantity that is usually measured by conventional microphones [2, 3, 4, 14]. It consists of two heaters that act simultaneously as sensors. These two closely spaced (ca. 300 µm) thin wires of silicon nitride, similar to [16], have an electrically conducting platinum pattern on top of them. A SEM photograph of a Microflown is depicted in Fig.1. Dimensions of the two wires are $1000\times10\times0.5$ µm (*l´w´h*). The metal pattern can be used as heater *and* as temperature sensor, by using its temperature dependent resistance. The silicon nitride layer is used as a mechanical carrier for the platinum resistor patterns. The sensors are powered by an electrical current, and heated to an operational temperature between 200ºC and 600ºC.

Since the invention of the Microflown (in 1994, [2]) it is mostly used for measurement purposes: 1D- and 3D-sound intensity measurement [3, 4, 5, 6], measurement of acoustic impedances [7, 8] and of pressure [9]. Besides the sensor can be used in combination with a microphone for professional recording purposes [19]. This is because the Microflown is, contrary to pressure gradient microphones, comparitively sensitive to low frequency sound waves. A particle velocity sensor with a wide measurable frequency spectrum can be obtained by a combination of a Microflown and a so-called 'pressure gradient' microphone and has a 'figure-of-eight' polar pattern of the sensitivity.

Forced convection by an acoustic wave causes a small, asymmetrical, perturbation to the temperature profile around the heated wires, so that a temperature difference between the two sensors occurs. This temperature difference, to which the sensitivity is proportional, can be calculated with perturbation theory [12,13]. Subsequently the frequency dependent behaviour of the sensitivity can be analysed; it is found that two important characteristic frequencies occur in this frequency dependence.

In [12] a rigorous description is given for a realisation of the Microflown in a channel, i.e. with fixed walls acting as heat sinks near both heaters. A model for its sensitivity when the wires are in free space, was developed as well ([13,14]).

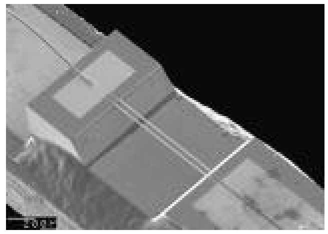


Fig.1 SEM Photo of a bridge type Microflown. At the top of the sample a wire-bond is visible. The sample is glued on a printed circuit board; the glue is seen at the lower left side of the picture.

THEORETICAL DESCRIPTION OF NOISE AND SIGNAL-TO-NOISE RATIO

So far, most research and modelling has concentrated on the frequency characteristics and the sensitivity of the sensor. Purpose in the descriptions and modelling was, besides the understanding of the behaviour, the optimisation of the sensitivity. However, a more relevant parameter than the sensitivity only, is the signal-to-noise (S/N) ratio, particularly in comparing the sensor to pressure microphones.

Since the Microflown consists fundamentally of two electronically heated wires, an inevitable origin of noise is formed by the so-called resistance-noise, which is therefore a theoretical minimum of the noise from one wire. For a resistance *R* at absolute temperature *T*, these voltage variations in a frequency interval Δf are given by ([10]; *k* the Boltzmann-constant):

$$\langle V_{noise}^2 \rangle_{(f,\, f+\Delta f)} = (4kTR)\Delta f \qquad (1)$$

It is observed that the noise manifest in the sensor's output signal is often higher than this. Various effects may explain this; the noise may be of electronic, (thermo-)acoustic or purely thermal origin, and/or the noise may be mainly mechanical. One hypothesis describes the noise as originating from 'thermal agitation noise' due to 'Brownian motion'([10,11]) of air molecules and dust particles. First calculations on these processes show the thermal agitation noise to be not so likely for the Microflown. A possibly more adequate explanation is based on the fact that there are many resistance inhomogenities in the sputtered wire. These local resistance variations result in local temperature changes with corresponding voltage oscillations.

The noise occuring in the acoustic measurements manifests itself in the form of small, stochastic voltage fluctuations in the output signal of the sensor. For the mean value μ of these voltage fluctuations *v(t)* yields

$$\mu = E\{v(t)\} = < v(t) > = 0 \qquad (2)$$

where $E\{x(t)\} = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t)dt$ represents the expectation value of a stationary stochastic time function *x(t).* Defining the corresponding autocorrelation function as

$$\varphi_{vv}(t) = E\{v(\tau)v(t+\tau)\} = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} v(\tau)v(t+\tau)d\tau \qquad (3)$$

it is seen that the dimension of $\varphi_{vv}(t)$ is V^2, so that it can be interpretated as a power P, in particular $\varphi_{vv}(0) = E\{v^2(t)\} = P_{average} = v_{eff}^2$. [10]

The Fourier transform of the autocorrelation function, $\Phi_{vv}(\omega) = F(\varphi_{vv}(t))$, represents the power density spectrum and shows how the power of the stochastic signal is distributed over the frequency domain. Furthermore, a cross correlation function $\varphi_{v_1 v_2}(t)$ can be defined, which function indicates the mutual correlation between two signals $v_1(t)$ and $v_2(t)$ [11]. If $v_1(t)$ and $v_2(t)$ are two statistically independent variables, and if one of or both of the signals have expectation value zero (i.e. there is no DC-component), then

$$f_{v_1v_2}(t) = E\{v_1(\boldsymbol{t})v_2(t+\boldsymbol{t})\} = E\{v_1(\boldsymbol{t})\}E\{v_2(t+\boldsymbol{t})\} = \\ = E\{v_1(t)\}E\{v_2(t)\} = 0 \tag{4}$$

The autocorrelation function of the sum of two signals $v(t)=v_1(t)+v_2(t)$ follows from

$$f_{vv}(t) = \lim_{T\to\infty} \int_{-T/2}^{T/2} \{v_1(t)+v_2(t)\}\{v_1(t+t)+v_2(t+t)\}dt = \\ = f_{v_1v_1}(t) + f_{v_1v_2}(t) + f_{v_2v_1}(t) + f_{v_2v_2}(t) \tag{5}$$

If $v_1(t)$ and $v_2(t)$ are statistically independent, $f_{v_1v_2}(t) = f_{v_2v_1}(t) = 0$, so that $f_{v\,v}(t) = f_{v_1v_1}(t) + f_{v_2v_2}(t)$, and therefore for the Fouriertransforms yields analogously: $\Phi_{vv}(w) = \Phi_{v_1v_1}(w) + \Phi_{v_2v_2}(w)$.

In measurement techniques, the statistical independence of different noise sources in the cross correlation functions can be applied to reduce the noise.[e.g.15].

The output signal of the Microflown is proportional to the inproduct $\vec{v}\cdot\vec{n}$, with $\vec{v}$ the local particle velocity and $\vec{n}$ the unit vector in the plane d, and perpendicular to the wires. If now two similar Microflowns are placed parallel and closely to each other and if the distances between both wires of a sensor and between two different sensors are small compared to the acoustic wavelength, then both output signals are in good approximation equal, or fully correlated. On the other hand, it seems justified to assume that both noise sources of the sensors, are uncorrelated. These noise sources are mainly determined by the resistance noise of the resistors, which are independent. If furthermore both sensors are independently powered, the noise associated with the electrical powering should be uncorrelated as well. Other noise sources that occur in the noise spectrum of a Microflown, that manifest themselves particularly in the low-frequency region, are likely to be mutually independent. Of course, possible noisy acoustic fluctuations may have correlated influences on both sensors. Besides, electrical interferences (frequency components of the electrical powering frequency) may cause disturbances.

Assume that a certain particle velocity leads to an output signal $v_1(t)$ of Microflown 1, that is contaminated by a noise spectrum $n_1(t)$. Microflown 2, located closely to the first sensor, then gives an output signal $v_2(t)$, with additional noise $n_2(t)$. The cross correlation of $x_1(t)=v_1(t)+n_1(t)$ and $x_2(t)=v_2(t)+n_2(t)$ thus becomes

$$f_{x_1x_2}(t) = \lim_{T\to\infty} \int_{-T/2}^{T/2} \{v_1(\boldsymbol{t}) + n_1(\boldsymbol{t})\}\{v_2(t+\boldsymbol{t}) + n_2(t+\boldsymbol{t})\}d\boldsymbol{t} = \\ = f_{v_1v_2}(t) + f_{v_1n_2}(t) + f_{v_2n_1}(t) + f_{n_1n_2}(t) = \\ = f_{v_1v_2}(t) \tag{6}$$

The last step in Eq. (6) follows from the fact that the noise of Microflown 1 and that of 2 have no mutual correlation (assuming for a moment there are no acoustic but only electrical or thermal noise sources) and are uncorrelated to the signals as well.

Therefore, the power spectrum of the measured output signals $x_1(t)$ and $x_2(t)$, that are contaminated by noise, is found from this cross correlation;

$$\Phi_{x_1x_2}(w) = \Phi_{v_1v_2}(w) \tag{7}$$

and if both sensors have the same sensitivity (i.e. same proportionality between particle velocity and output voltage),

$$\Phi_{x_1x_2}(w) = \Phi_{v_1v_1}(w) \tag{8}$$

in which noise is not present anymore.

According to this theory, the approach of the application of cross spectra leads ideally to a noise spectrum of zero. The two noise sources in the respective signals are assumed to be uncorrelated, so that, the larger the measuring time and therefore the number of data points stored, the more the calculated cross correlation spectrum of the noise can be reduced.

The mean value of this cross spectrum is zero, but since the integration time is finite, a more relevant parameter to characterise this quantity is its variance, σ^2. The larger the number of points in the time series of the signals, the smaller this variance (Lindeberg-Lévy Theorem, Central Limit Theorem, [18], see also the Appendix).

EXPERIMENTS

To determine the signal-to-noise ratio of the Microflown, both the sensitivity, i.e. the output response of the sensor to a certain particle velocity, and its noise behaviour had to be measured. The sensitivity of the sensor in a bandwidth of about 04.0 kHz was determined in a 'standing wave tube' [1,6,8], by placing the Microflown in the tube with at one side a loudspeaker generating a broad frequency spectrum and at the other side a reference microphone. From the ratio between the output signals of both acoustic sensors, the sensitivity of the Microflown could be obtained.

To measure the noise spectrum of one Microflown, consisting of two (equal) resistances R_1 and R_2, a simple set up as shown in Fig 2 was used.

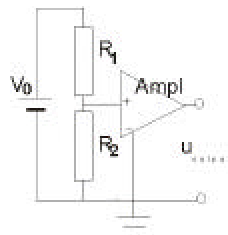
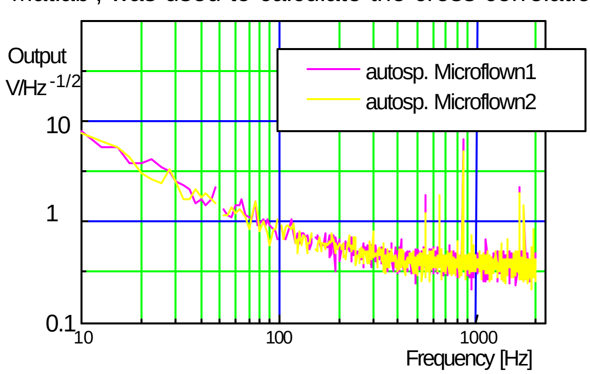


Fig.2 Electrical scheme of the set-up to measure the output noise of theMicroflown, consisting of R_1 and R_2

The total amplification factor of the two amplifiers used (the output signal of the Microflown was amplified twice) was measured to be $3.00*10^7$, the applied voltage was 9.00 V, by DC-powering of a battery. It was checked that there was no significant contribution to the noise due to this powering. R_1 and R_2 were equal to 1.10 kΩ. The output voltage was stored by a 16 bits recorder, with an analog input (level 0.5Vpp to 10Vpp, impedance 20kΩ) and a sample frequency F_s=44.1 kHz, added to the PC.

The autospectrum of the noise of one Microflown thus measured, is plotted in Fig. 3. Then a second set-up, identical to the first (Fig. 2) with two perfectly similar amplifiers and an identical but independent voltage source, was used for the noise measurement on Microflown 2. Both Microflowns were placed into two different acoustically isolated boxes to reduce acoustic, and correlated, noise. The noise levels of these autospectra were compared to the Nyquist noise level of resistances of 1.10 kΩ. In Fig.3 it is seen that for frequencies above approx. 600 Hz, the noise spectrum is flat and corresponds indeed to the calculated value according to Eq.(1) with R=1.10 kΩ. The amplified (analog) output signals were thus recorded while the 50 Hz frequency component and its higher harmonics were filtered out. A mathematical software program, 'Matlab', was used to calculate the cross correlation function of these two data files. Both signals



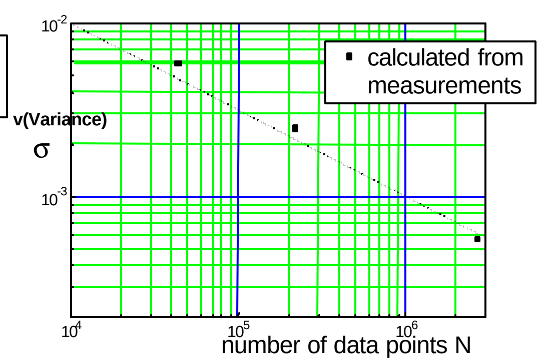


Fig 3. Measured autocorrelation spectra of the noise of Microflown 1 and 2 (Amplification factor: $3.00*10^7$). For frequencies above approx. 600 Hz the spectrum is flat and corresponds to the Nyquist noise level for normal resistances of 1.1kΩ.

Fig 4. Influence of the number of data points N on the variance of the calculated ratio (power in the cross correlation spectrum in the whole frequency range / the power in the auto spectrum) The variance σ^2 of this value is proportional to N^{-1}; the dotted line shows σ, prop. to 1/ N.

were high-pass filtered above F_{min}=600 Hz.The two signals were recorded and stored during 12 minutes. The time series therefore consisted of N=12*60*44100 $3.2\cdot10^7$ data points. The power in the cross spectrum in the total frequency range from F_{min}=600 Hz to F_s, devided by the power in the auto spectrum, was calculated from experimental data to be $2.25\cdot10^{-6}$; corresponding to a reduction of about 56 dB.
This value, however, cannot be considered as fully representative, since it is only one measurement point and one should be interested in its variance.
The time signal of 12 minutes was subsequently devided into 12 parts of 1 minute, parts of 5 secondes and parts of 1 second, corresponding to respectively $N=2.65\cdot10^6$; $N=2.2\cdot10^5$ and $N=4.4\cdot10^4$ points. For each N, the ratio (power in cross spectrum/power in auto spectrum) was determined, and since we could thus calculate several values for the same N, the variance of this ratio could be calculated, assuming a normal distribution of these values. The variances as a function of N are plotted in Fig.4.
With some mathematical statistics, (Lindeberg-Lévy Theorem, Central Limit Theorem, [18]), it can be shown that the variance in the ratio: power in cross spectrum/power in auto spectrum, is proportional to N^{1}, where N is the number of data points. An illumination is given in the Appendix. Comparing the experimentally found values in Fig.4 to the theoretical variance, they seem to behave as can be expected.

From the figures 3 and 4 it can be concluded that the use of calculating the cross correlation spectrum, can reduce the noise level of the sensors considerably; if for example $N=10^6$ points are used, a reduction of 30 *dBV/ Hz* compared to the autospectra can be attained. This becomes therefore considerably lower than the Nyquist noise level for the resistances, 4kTR, approx.–160 *dBV/ Hz* (without amplification). It was experimentally verified that the sensitivity of the two Microflowns did not change when the sensors were applied simultaneously.
The sensitivity of the Microflowns, determined in the standing-wave-tube as described above, was used to calculate the noise floor, or the selfnoise, of the sensor in *Pa/ Hz*. The noise spectrum (in *V/ Hz*) devided by the sensitivity gives the equivalent noise 'pressure'level in *Pa/ Hz* The selfnoise in *Pa/ Hz* of the autospectrum of one Microflown, and that of the cross correlation spectrum of two identical Microflowns, can then be compared to the noise level of a representative current microphone, a calibrated condenser microphone. Doing so, it might be concluded that in a broad frequency range, from 100 to even above 10 *kHz*, the noise characteristics of the Microflown are better than that of a general microphone.

It should be stated, that in the application of cross correlation spectra, time averages are involved. Therefore, this method of noise reduction is useful for measurement of stationary signals; stationary sound intensity or particle velocity measurements. However, for instantaneous measurements or applications as sound recording, this method cannot be applied.

CONCLUSIONS

In this paper it was shown that a large reduction of the noise of the Microflown in its application as a sensor for stationary sound intensity measurements could be attained. This is achieved by the simultaneous use of two Microflowns closely spaced to each other and recording the cross spectrum of the output signals of both. Since in this cross correlation spectrum the relevant signals add but all the uncorrelated noise sources are eliminated, a significant improvement of the signal-to-noise ratio can be reached. The larger the number of data points used (the larger the measuring time), the larger this reduction becomes. The selfnoise level then becomes even lower than that of current microphones.

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APPENDIX

Assume that in the calculation of the auto correlation spectrum and the cross correlation spectrum, a time signal consisting of a series of N data points is used. To get some insight into the behaviour of the calculated quotient of power in cross spectrum and power in auto spectrum as a function of *N*, the two time signals are simplified to two uncorrelated arbitrary binary series of N points. They are modeled by two time series of which each data point represents a 1 or a –1 (like throwing a coin).
Define therefore the series as p_i and q_i, consisting only of values 1 and –1. So p_1, p_2, p_3,..=-1,-1,1,..etc.

The total power in the autospectrum of the first signal will therefore be proportional to $\sum_{i=1}^{N} p_i^2 = N$, the power in the autospectrum of the other also N, and the power in the cross spectrum of both will be proportional to $\sum_{i=1}^{N} p_i q_i$. Define $p_i q_i \equiv a_i$, so that the expected or mean value ([18]) of a_i, $E(a_i)=0$, and its variance σ^2, is $Var(a_i)=1$. Now the Lindeberg-Lévy Theorem, or Central Limit Theorem states that for a random variable $\overline{a} = \frac{1}{N}(a_1 + a_2 + ... + a_N)$ that converges in probability to $E(a_i)$, (here therefore equal to 0), for which the common variance σ^2 of a_i exist, $\overline{a}$ is asymptotically normal with mean $E(a_i)$ and with a variance σ^2/N. In our calculations we are interested in the ratio (power in cross spectrum/power in auto spectrum), so one should calculate the variance of $\frac{\sum_{i=1}^{N} a_i}{\sqrt{\sum_{i=1}^{N} p_i^2 \sum_{i=1}^{N} q_i^2}} = \frac{1}{N}\sum_{i=1}^{N} a_i = \overline{a}$. One sees therefore that the variance of this ratio behaves as σ^2/N; inversely proportional to the number of points N.