P2.24: Determination of the Sensitivity Behaviour of an Acoustic and Thermal Flow Sensor By Electronic Characterisation

J.W. van Honschoten, V.B. Svetovoy*, T.S.J. Lammerink, G.J.M. Krijnen, M.C. Elwenspoek
Transducers Science and Technology Group, University of Twente, The Netherlands
*Institute of Microelectronics, RAS, Yaroslavl, Russia
email j.w.vanhonschoten@el.utwente.nl

Abstract
The Microflown is an acoustic and thermal flow sensor that measures the sound particle velocity instead of sound pressure. For most applications the Microflown should be calibrated [1-2], which is usually performed acoustically in a standing-wave-tube [1,3]. Here it is shown that the sensor's sensitivity and frequency behaviour can be determined electronically as well, and an electronic method for determination of the device output response, which is more convenient, is therefore presented. The method is not only less complicated, it also makes it possible to cover with easily the entire acoustic frequency spectrum.

Keywords
Acoustic sensors, flow sensors, MEMS, electronic characterisation

INTRODUCTION

The Microflown consists of two closely spaced thin wires (1500×2.5×0.4 μm) of silicon nitride with an electrically conducting platinum pattern on top. See Fig.1. These wires act as temperature sensor *and* as heater. The wires are electrically powered and heated to about 600K. When a particle velocity is present, the temperature distribution around the resistors is asymmetrically altered due to convection, and a temperature difference between the two wires occurs. Because of the temperature dependence of the resistance of the wires, their resistance difference thus quantifies the particle velocity.
In this paper an electronic method, instead of the usual acoustic method, for determination of the device sensitivity function is described. From physical principles and similarities between the governing equations [4,6], it can be proven that from electronic measurements only, the acoustic behaviour can be deduced.

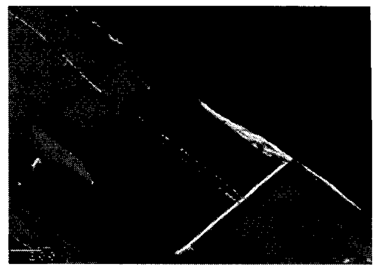


Fig.1: SEM Photo of a bridge type Microflown

THEORY

In this paper it will be shown that the sensitivity of the Microflown to acoustic signals can be found using only electrical measurements. The relationship between its sensitivity and the impedances of the two wires exists for very general conditions of the system. There are only two, very genaral, assumptions. The first one is that the heat transfer in the device can be described by the linear heat equation. Since the heat conductivity of air depends on temperature, this assumption restricts the power dissipated in the wires to about 10 mW [1]. The second assumption is that the wire width and thickness are much smaller then all the other geometrical parameters characterizing the Microflown. This is typically true for all Microflowns used in applications.
Devices of different design are in practical use. The channel can be closed, half-open (Fig.1), or open (free standing wires). One can find an analytical solution for the temperature distribution for a rectangular channel [1] or for free standing wires [2]. In the general case of arbitrary channel cross section one can find the solution of the heat equation in terms of unknown eigenvalues and eigenfunctions describing the temperature distribution in the channel cross section.
The statement to be proven here is that the relation between the acoustic sensitivity and the impedances of the wires does *not* depend on the unknown eigenvalues and eigenfunctions and so it has a very general character. It will be proven that the background temperature, the correction to it due to time-dependent particle velocity (sound wave) and

that due to a time varying power in a wire, all can be expressed via the same Green's function. This property is true if the wires can be considered as thin. The reason is that all these values are the solution of the same heat equation with the same boundary conditions. In this way one can deduce a relationship between the acoustic sensitivity and the wires' impedances as a function of the wires' positions. Such a relation is not very helpful in practical sense but the specific symmetry of the heat equation allows one to relate the change of the Green's function with sensor position with the integral over frequency from this function. In this way the acoustic sensitivity is connected with the electrical transfer function of the device averaged over the frequency band from 0 to a given frequency f.

The Microflown theory has been developed in details in Ref.[1]. The problem was solved there for a rectangular channel but the proposed method is still valid for more general geometries. Here we will follow the description given in that paper and adopt the same notations.

Stationary temperature distribution

Let us consider first the temperature distribution in the channel of the Microflown (Fig. 1) when the gas inside does not move. Chose the coordinate system as shown in Fig.2 with the x-axis along the channel.

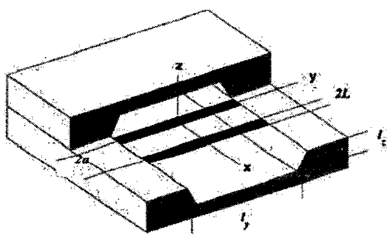


Fig.2: Geometry of the sensor used in the analysis

The wires, of length l_y, are directed along the y-direction. The distance between the wires is $2a$; one of them is located at $x=a$ and the other one at $x=-a$. If both of them are heated with a constant power P and there is no gas flow, then the temperature distribution $T(x,y,z)$ is found from the stationary heat equation:

$$-k\nabla^2 T = \frac{P}{l_y}[\delta(x-a)+\delta(x+a)]\delta(z). \qquad (1)$$

According to our assumptions in (1) the heat conductivity k was supposed not to depend on temperature and because the wires are thin and narrow the heat sources on the right-hand side can be described by δ-functions. Note that the power is distributed homogeneously along y and the temperature is determined by the power per unit wire length.

It is convenient to introduce the dimensionless coordinates and parameters

$$\xi = \frac{x}{l},\quad \eta = \frac{y}{l},\quad \zeta = \frac{z}{l},\quad \xi_1 = \frac{a}{l},\quad \xi_0 = \frac{L}{l}, \qquad (2)$$

where l is any characteristic size of the channel cross section and L is half the width of the wire. In the dimensionless coordinates the equation (1) will get the form

$$\left(\partial_\xi^2 + \nabla_\perp^2\right) T = -\frac{P}{kl_y}[\delta(\xi-\xi_1)+\delta(\xi+\xi_1)]\delta(\zeta), \qquad (3)$$

where $\nabla^2_\perp = \partial^2_\eta + \partial^2_\zeta$ is the transverse Laplace operator.

At the channel walls, the temperature obeys homogeneous boundary conditions, for example, $T=T_0$. Because the device walls are made of silicon, which has a heat conductivity k_{Si} much larger then the air conductivity k, we can take the walls to be at the environment temperature T_r (room temperature). Even in the situation that the wire is in contact with the silicon substrate it was proven [1] that only a small part of the heat flux escapes via this contact and that the main heat flux goes via the air. Therefore, even in the contact points the same boundary conditions hold. The situation that there are no walls in any direction can be considered as a wall at infinity where the same condition ($T=T_0$) is true. Eq.(3) is linear and one can redefine the temperature $T \rightarrow T-T_0$ in such a way that the boundary condition is reduced to $T=0$ at the channel walls.

One can define the set of functions $\psi_n(\eta,\zeta)$ which obey the boundary conditions and are the eigenfunctions of the transverse Laplace operator:

$$\nabla_\perp^2 \psi_n(\eta,\zeta) = -\lambda_n^2 \psi_n(\eta,\zeta) \qquad (4)$$

with corresponding eigenvalues λ^2_n. Here the index n is actually a multi-index comprising two numbers (n,m) since Eq.(4) is two dimensional. These numbers do not need to be integer; one or both of them can be continuous if the problem of Eq.(4) has a continuous spectrum. There is no necessity to have explicit expressions for the functions $\psi_n(\eta,\zeta)$ and the values λ^2_n, it is quite sufficient to know that the functions can be chosen orthogonal:

$$\int d\eta d\zeta \psi_n \psi_m = \delta_{nm}. \qquad (5)$$

Here δ_{nm} is the product of Kronecker symbols if both components of the multi index are integer; one or both of the symbols have to be changed by the δ-function if one or both of these components are continuous. Additionally, one can prove that for the problem (4) with the boundary conditions $\psi_n=0$ at the channel boundaries all λ^2_n are positively defined.

The solution of Eq.(3) can be found by expanding the temperature on these functions ψ_n:

$$T(\xi,\eta,\zeta) = \sum_n T_n(\xi)\psi_n(\eta,\zeta) \qquad (6)$$

If one or both components of the multi-index are continuous then the corresponding summation has to be changed by an integral. Using then the orthogonality condition (5) one can find the equation for the components $T_n(\xi)$:

$$\partial_\xi^2 T_n - \lambda_n^2 T_n = -\frac{P}{kl_y} A_n[\delta(\xi-\xi_1)+\delta(\xi+\xi_1)], \qquad (7)$$

where the constants A_n are $A_n = \int d\eta \psi_n(\eta,0)$.

The solution of Eq.(7) should obey the boundary conditions at both ends of the channel $T_n \to 0$ when $\xi \to \pm$. This solution can be easily found as

$$T_n(\xi) = \frac{P}{kl_y}\frac{A_n}{2\lambda_n}\left[\exp(-\lambda_n|\xi - \xi_1| + \exp(-\lambda_n|\xi + \xi_1|)\right). \quad (8)$$

One can substitute it into Eq.(6) to get the final result for the temperature distribution. Note that actually we have not solved the heat equation because the functions ψ_n and the values of λ_n have not been specified. However, Eq.(8) is everything that is needed to connect the acoustical sensitivity of the sensor with the electrical measurements.

One important detail should now be mentioned. If one would like to find the heater temperature, for example at $\xi = \xi_1$, one fails because the sum in (6) will diverge. This is because at large n the eigenvalues λ_n are proportional to n but the coefficients A_n can be n-independent. Then the sum in (6) will be logarithmically diverging. It is quite clear why this divergence appeares. It results from the approximation that the wire can be considered as infinitely thin. There is an easy way to avoid this problem without significant complication of mathematics. One should average the temperature over the heater width in the place where it is located. For example, if one intends to calculate the heater temperature at $\xi = \xi_1$ one can average only the first term in (8) in the range $\xi_1 - \xi_0 < \xi < \xi_1 + \xi_0$ because the second term does not bring any trouble and is safely converging due to the presence of the exponent. The averaging then gives us

$$\overline{T}_n(\xi_1) = \frac{P}{kl_y}A_n\left[\frac{1-\exp(-\lambda_n\xi_0)}{2\lambda_n^2\xi_0} + \frac{\exp(-\lambda_n|\xi + \xi_1|}{2\lambda_n}\right].$$

Comparing it with (8) at $\xi = \xi_1$ a simple rule to avoid the divergence problem can be deduced. In the place where the divergence is possible the following substitution has to be made:

$$\frac{1}{\lambda_n} \to \frac{1-\exp(-\lambda_n\xi_0)}{\lambda_n^2\xi_0}. \quad (9)$$

This change allows taking into account the final width of the wire and makes the sum in (6) convergent. Indeed, at $\lambda_n\xi_0 << 1$ the right hand side of (9) coincides with the left hand side but at large n it behaves as $1/\lambda_n^2$ providing the sum in (6) to be convergent.

Analogy between acoustically and electrically induced disturbance

Now one can consider the situation that the gas in the channel is flowing along the channel with some velocity $v(t)$ defined by a sound wave. This movement breaks the symmetry in the temperature distribution due to the convection process. The sound velocity is typically small in comparison with the heat diffusion velocity $D/l \sim 0.1$ m/s, where $D = k/\rho c_p \approx 1.9 \cdot 10^{-5}$ m^2/s is the heat diffusion coefficient for air. For this reason the convection introduces only a small correction δT^a to the temperature distribution. This correction can be found from the nonstationary heat equation when the convective term is considered as a perturbation [1]

$$\partial_t \delta T^a - D\nabla^2 \delta T^a = -v(t)\partial_x T. \quad (10)$$

For the electrical characterization of the device suppose that both wires are heated by constant power P, but that one of the heaters, for example at $x=a$, is powered additionally by a small AC component $\delta P(t) < \;\; P$.

One is interested in the correction to the sensor's temperature δT^e due to this additional AC power. It can be found from the equation

$$\partial_t \delta T^e - D\nabla^2 \delta T^e = \frac{\delta P(t)}{l_y}\frac{1}{\rho c_p}\delta(x-a)\delta(z). \quad (11)$$

Of course, the equations (10) and (11) are the same but the sources on the right hand side, which define the solutions, are quite different. In the acoustic case a source is distributed along the channel axis but in the electric case the source is located on the wire. When the sources are different the solutions also will be. However, because the unperturbed temperature T obeys the heat equation as well it is possible to connect δT^a and δT^e.

Now consider the case of a sound wave, harmonically varying in time, and an AC power

$$v(t) = v\exp(i\omega t), \quad \delta P(t) = \delta P \exp(i\omega t) \quad (12)$$

with the corresponding frequency $f = \omega/2\pi$. Introducing the dimensionless coordinates and frequency

$$\overline{f} = \frac{\omega l^2}{D} \quad (13)$$

one gets instead of (10) and (11)

$$\nabla^2 \delta T^a - i\overline{f}\delta T^a = -\frac{v}{v_0}\partial_\xi T,$$

$$\nabla^2 \delta T^e - i\overline{f}\delta T^e = \frac{\delta P}{kl_y}\delta(\xi - \xi_1)\delta(\zeta),$$

where $v_0 = D/l$ represents the diffusion velocity. The temperature correction obeys the same boundary conditions as the temperature itself: it disappears on the channel walls and is going to zero at $\xi \to \pm\infty$. Therefore, we can expand δT (acoustic or electric) in the same eigenfunctions ψ_n:

$$\delta T(\xi, \eta, \zeta) = \sum_n \delta T_n(\xi)\psi_n(\eta, \zeta). \quad (14)$$

Substituting it into the equations above one finds

$$\begin{aligned} \partial_\xi^2 \delta T_n^a - K_n^2 \delta T_n^a &= \frac{v}{v_0}A_n \partial_\xi T_n, \\ \partial_\xi^2 \delta T_n^e - K_n^2 \delta T_n^e &= -\frac{\delta P}{kl_y}A_n\delta(\xi - \xi_1), \end{aligned} \quad (15)$$

where $K_n^2 = \lambda_n^2 + i\overline{f}$.

To see the correspondence between δT^a and δT^e it will be convenient to write the solutions via the same Green's function $G_n(f, \xi - \xi')$ which, by definition, obeys the equation

$$\partial_\xi^2 G_n(f, \xi - \xi') - K_n^2 G_n(f, \xi - \xi') = \delta(\xi - \xi'). \quad (16)$$

It has a well known solution

$$G_n(f,\xi-\xi') = -\frac{1}{2K_n}\exp\left(-K_n|\xi-\xi'|\right). \tag{17}$$

Using this function the solution of the equations (15) can be written then as follows

$$\begin{aligned}\delta T_n^a &= \frac{v}{v_0}A_n\int_{-\infty}^{\infty} d\xi' G_n(f,\xi-\xi')\partial_{\xi'}T_n(\xi'),\\ \delta T_n^e &= -\frac{\delta P}{kl_y}A_n G_n(f,\xi-\xi_1).\end{aligned} \tag{18}$$

The unperturbed temperature distribution $T_n(\xi)$ given by (8) can also be represented via the same Green's function but then taken at zero frequency:

$$T_n(\xi) = -\frac{P}{kl_y}A_n\left[G_n(0,\xi-\xi_1)+G_n(0,\xi+\xi_1)\right]. \tag{19}$$

Using only general properties of the Green's function one can transform the integral in (18) to the form:

$$if\,\delta T_n^a = \frac{v}{v_0}\frac{P}{kl_y}A_n\partial_\xi\left[\begin{matrix}G_n(0,\xi-\xi_1)+G_n(0,\xi+\xi_1)\\ -G_n(f,\xi-\xi_1)-G_n(f,\xi+\xi_1)\end{matrix}\right] \tag{20}$$

Now it is seen that the acoustic and electric corrections to the temperature are really related to each other. However, there is no direct proportionality between δT^a and δT^e. Moreover, δT^a depends on the derivative on ξ, which we are not able to control. The actual precise relation comes from a specific property of the Green's function for the heat equation

$$\partial_\xi\left[G_n(f,\xi-\xi') - G_n(0,\xi-\xi')\right] = \frac{i}{2}(\xi-\xi')\int_0^f d\tilde{f}\,G_n(\tilde{f},\xi-\xi') \tag{21}$$

which can be checked directly with the help of (17). In this way a general relation can be deduced, connecting the temperature response of the Microflown to an acoustic wave with the Green's function, which, in its turn, is proportional to the temperature response to the electric signal:

$$\delta T_n^a = -\frac{v}{2v_0}\frac{P}{kl_y}A_n\frac{1}{f}\int_0^f d\tilde{f}\left[(\xi-\xi_1)G_n(\tilde{f},\xi-\xi_1)+(\xi+\xi_1)G_n(\tilde{f},\xi+\xi_1)\right]. \tag{22}$$

This relation is true for any point along the channel.

For practical purposes one is interested in the temperatures of the sensors, that are located at $z=0$ and $x=a$ or $x=-a$. Additionally, since the sensor resistances are really important, the temperatures have to be averaged over the wire length. Now these averaged temperatures are denoted as ΔT_1 and ΔT_2 for the sensors located at $x=a$ and $x=-a$, respectively. Using (14), (18), and (22) for the mean wire temperatures characterized electrically or acoustically one finds

$$\begin{aligned}\Delta T_1^e &= -\frac{\delta P}{kl_y}\sum_n\frac{l}{l_y}A_n^2G_n(f,0), \quad \Delta T_2^e = -\frac{\delta P}{kl_y}\sum_n\frac{l}{l_y}A_n^2G_n(f,2\xi_1),\\ \Delta T_1^a &= -\Delta T_2^a = -\frac{v}{v_0}\frac{P}{kl_y}\frac{\xi_1}{f}\int_0^f df\sum_n\frac{l}{l_y}A_n^2G_n(f,2\xi_1).\end{aligned} \tag{23}$$

Therefore the final relation between the averaged sensor temperatures in the acoustical and electrical characterization becomes obvious

$$\Delta T_1^a = \frac{v}{v_0}\frac{P}{\delta P}\frac{\xi_1}{f}\int_0^f df\,\Delta T_2^e. \tag{24}$$

It shows that the acoustical response at a frequency f is proportional to the electrical response averaged over the frequency range from 0 to f. This is a nontrivial and unobvious relation that will be true for any device as long as the wires are thin and the temperature dependence of the heat conductivity can be neglected (linear heat equation). For thin wires it was natural to suppose that their heat capacity is not important, but in reality the finite heat capacity of even thin wires becomes still important at high frequencies. The method to take this finite heat capacity into account has been proposed in Ref. [1] and can also be applied to the problem of electrical characterization of the device. It will be discussed elsewhere but for the moment one should notice that the main equation (24) will be true as long as the frequency remains small in comparison with the characteristic frequency f_1 describing the heat capacity of the sensors [1]

$$f_1 = \frac{kl_y}{V_w(\rho c_p)_w}, \tag{25}$$

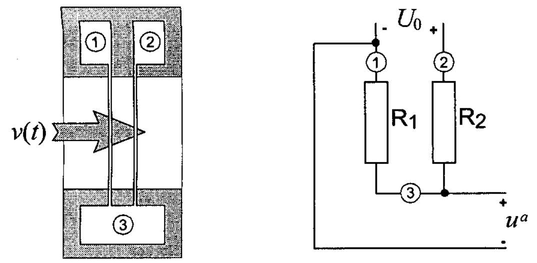
where the volume and heat capacity have the subscript w of the wire. For the devices in use this frequency is about *1800 Hz*.

Implications for the electrical signals

In practical applications the voltage of a wire is often easily measured, and in the electrical characterisation one measures the voltage of the wire(s) as a function of frequency for a sensor. For this reason the relation (24) has to be expressed via directly measured values. The voltage is connected with the current I flowing via the sensor by Ohm's low:

$$U = IR_0\left[1+\alpha T(P)\right],$$

where R_0 is the sensor resistance at room temperature, α is the temperature coefficient, and $T(P)$ is the sensor temperature above the room temperature at a given power $P=U\cdot I$. When the device is operating as an acoustic sensor the stabilized voltage source U_0 is used and the signal u^a is recorded as indicated in Fig. 3.



a) b)

Fig.3 Electrical scheme of the Microflown, operating acoustically; $R_1=R_2=R$, u^a is the output signal.

In this case the temperature change of the sensor is related to the external influence: the acoustic wave. If the wave has a frequency *f* then the signal on this frequency can be written as

$$u^a = \frac{U_0}{2}\alpha\frac{R_0}{R}\Delta T_1^a, \qquad (26)$$

where ΔT^a_1 is defined at operating power $P=U_0^2/R$ and R is the sensor resistance at operating temperature.

In the case of the electrical characterization a stabilized DC current I_0 is flowing through each wire, while an additional AC component flows through wire 1 ($x=a$). The resulting current for the wire 1 can be written as $I = I_0 + \delta I\cos(\omega t)$.

The amplitude of the AC component δI can always be chosen small not to complicate the analysis. Neglecting then the higher order terms of AC components, the additional oscillating power in the wire can be represented as

$$\delta P = u_1^e I_0 + U_0\delta I, \qquad (27)$$

where $U_0=U(I_0)$ is the DC component of the voltage. The AC voltage measured on wire 1 can be written then using the Ohm law

$$u_1^e = R\delta I + \alpha R_0 I_0 \Delta T_1^e.$$

Since the sensor temperature is proportional to δP, we can express the AC voltage on the wire 1 as

$$u_1^e = \delta I R\cdot\frac{1+S_1}{1-S_1},\quad S_1 = -\alpha\frac{R_0}{R}\frac{P_0}{kl_y}\sum_n \frac{l}{l_y}A_n^2 G_n(f,0). \qquad (28)$$

Here P_0 represents the DC power. The wire 2 is powered with only a DC current and the AC voltage on this wire will be

$$u_2^e = \alpha I_0 R_0 \Delta T_2^e.$$

The temperature correction is again proportional to the amplitude of the oscillating δP, which can be found from (27). Thus one can find

$$u_2^e = \delta I R\cdot\frac{2S_2}{1-S_1},\quad S_2 = -\alpha\frac{R_0}{R}\frac{P_0}{kl_y}\sum_n \frac{l}{l_y}A_n^2 G_n(f,2\xi_1). \qquad (29)$$

Using the basic relation (24) one can express now the acoustic signal (26) via the electric signals (28) and (29)

$$u^a = \left(\frac{U_0}{2}\right)\frac{va}{D}\cdot\frac{1}{f}\int_0^f df\frac{u_2^e}{\delta IR + u_1^e}. \qquad (30)$$

This is the final relation one has been looking for. It contains the only geometrical parameter of the device, the mutual wire distance *a*, and only one medium parameter, the fluid characteristic *D*. All the other parameters are electrical, and well defined.

The electrical characterizations of the device gives the values $u^e_{1,2}$ as functions of frequency. To get the acoustic signal the integral in (30) should be calculated numerically. To do this one needs to extrapolate the integrand to smallest frequencies, which are not accessible in the measurements. The low frequency behavior of $u^e_{1,2}$ is easy to investigate analyzing the Green's function (17) in the limit $f\to 0$. This analysis gives

$$F(f) = \frac{u_2^e}{\delta IR + u_1^e} \to (A + iBf) \quad \text{at } f\to 0,$$

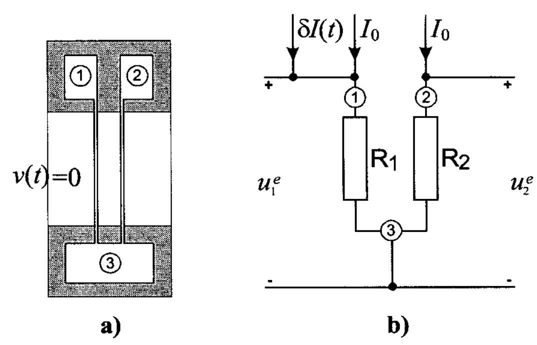
where *A* and *B* are some constants. If the experimental cut-off frequency is f_0, then

$$\int_0^f df\, F(f) = f_0\left[\operatorname{Re}F(f_0) + \frac{i}{2}\operatorname{Im}F(f_0)\right]. \qquad (31)$$

This relation defines the extrapolation procedure and so the problem can be considered as completely solved.

EXPERIMENTS

In the experimental set-up both wires of the sensor were connected as shown in Fig.4 ,together with a lock-in amplifier. The two wires were powered using a stabilized DC-current I_0. Using the current source, the frequency of the additional current δI was varied in a range from 10 to 4000 Hz while both the voltage of wire 1 and wire 2 were recorded. Using Eq.(30), the theoretical acoustic sensitivity as a function of frequency was calculated. The low experimental cut-off frequency was taken as 10 Hz. From this numerical procedure, the theoretic acoustic response of the sensor was found to be as the graph plotted in Fig.5.



a) b)

Fig. 4 Scheme of the set up used in the electrical characterisation. Now $v(t)=0$ (compare with fig.3) and the additional current is $\delta I(t)$.

Besides, the sensitivity was determined acoustically, i.e. in a 'standing wave tube' [1,3], an about 1m. long tube of approx. 10 cm diameter with at one side a loudspeker generating a broad frequency band signal, and at the other side a reference microphone. From the ratio between the output signals of both sensors, the sensitivity of the Microflown could be deduced.

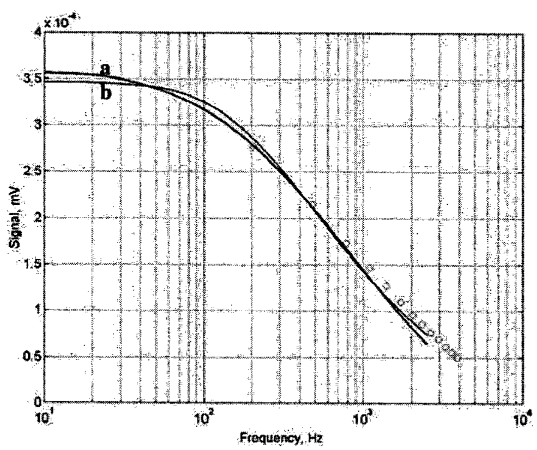


Fig.5 Electrically determined points (dots) of the sensitivity, the theoretical prediction for the acoustic sensitivity of the sensor, using the described calculations (line b) and the really acoustically determined (standing wave tube) response (line a).

From this figure it can be concluded that there is a satisfying correspondence between the electrically determined measurement points of the sensor sensitivity, and the theoretical prediction, which is model-independent, and the acoustically determined sensitivity (determined in the standing wave tube) as well.

CONCLUSIONS

An electrical characterisation method for the sensitivity of the Microflown was presented. It is shown to be a more convenient and less complicated method than the acoustic calibration of the Microflown using e.g. a standing wave tube. It is proven from physical principles and correspondences in physical equations that this method yields all the required information to deduce the sensor's acoustic response. Besides, the strength of the theoretical description and prediction of the acoustic response lies in the fact that it is very general and independent of the precise geometry of the sensor. The theory has been experimentally verified up to almost 4 kHz, and a good correspondence between measurements and theory was found.

ACKNOWLEDGMENTS

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