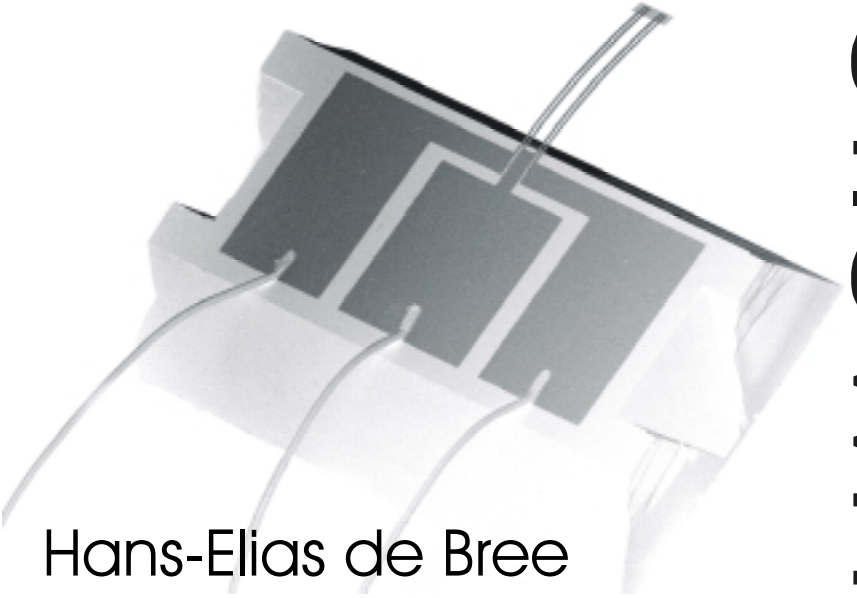
The Microflown



Hans-Elias de Bree

Report 1996-2001

ISBN: 9036515793
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Version 1.0, April 2001

Preface

A good idea is defined by its environment: did other people thought of it before and what are people doing with it now. Those people that are working with the Microflown and making it a success I want to thank here.

The concept “Microflown” is born at the University of Twente and it developed in to a working device at the science group “Micromechanical Transducers” what is a part of the Micro Electronics Material Engineering Sensors and Actuators, or MESA research institute. I would like to thank all the students and co-workers that helped me developing.

The Microflown became mature due to the commercialisation. Clients from all over the world demanded a “product” in stead of “a working device” and real-live questions were blend in the research making it more constructive. For this I would like to thank ir. Alex Koers MBA who founded the Microflown Technologies BV. I want to thank Doekle Yntema for the product development, Tjeerd Hans Terpstra for our face to the world: the Internet pages and ir. Philip Ekkels for the cleanroom technology based developments. With the efforts of the company, a reliable supply of Microflowns is established.

Not only products are needed to make the Microflown a success. Well-described applications are needed to demonstrate the use of the device. The most investigated application is the sound intensity measurement. For many years now prof. dr. ir. Erik Druyvesteyn is investigating this application and with nowadays also drs. ing. Ron Raangs working as Ph.D. on the subject, the sound intensity probe is becoming really mature. Their help is well appreciated.

The application to measure the acoustic properties of matter is investigated by prof. dr. ir. Henk Tijdeman and dr. ir. Frits van der Eerden. Their work on this application and help with understanding our calibration tubes is also well appreciated.

P.hD. student ir. Joost van Honschoten was the first person that could explain to me how the Microflown operated and I would thank hem for that. I would like to thank Meint de Boer and ing. Erwin Berenschot for the technology advises they gave and Henk van Wolveren for his general support. Furthermore I would like to thank dr. ir. Gijs Krijnen and prof. dr. Miko Elwenspoek for allowing the Microflown to grow in their science group.

For six years I worked on the development of the Microflown and now it is time for me to stop for a little while. In years much work has been done. Many wrong paths were followed however also much good came out and I am proud to name three products we developed.

The half-inch ICP probe was the first product that has been developed. It is designed as a general-purpose particle velocity microphone. It is commercially available since 1998 and it has proven itself in many applications. It is the simplest particle velocity probe that is commercially available.

The half-inch p**u** sound (intensity) probe is developed to have a far better price performance than the normally so expensive sound intensity measurements. It became a serious product due to the powerful software and calibration possibilities. Apart from the intensity, sound energy and acoustic impedance can easily be measured with this probe.

The last product, just developed, is the half-inch three-dimensional wide-band (20Hz-20kHz) ultra-miniature (5×5×5mm) sound probe consisting on three Microflowns and one miniature microphone. It is capable of measuring 3D particle velocity, sound pressure, 3D sound intensity, 3D sound energy and 3D acoustic impedance at once. No wonder it is named “the ultimate sound probe”.

Is the Microflown fully grown now? No not at all! My feeling is that the developments just are starting. First steps are taken in to the professional audio market (studio microphones) with the add-on Microflown that enables low frequency directivity and much effort is spent to create a low-noise, wide-band Microflown. Two possible routes are followed: less noise due to more power dissipation (the Megaflown) and more signal due to improved sensing materials. If these materials are mastered the Microflown becomes a true competitive acoustic sensor with various applications from high-end audio to mass market applications like ultra miniature microphones for e.g. smart cards or mobile phones.

Array techniques, underwater applications and constant temperature principles are still waiting to be explored. I hope that this book inspires more researchers to explore the numerous applications that the Microflown may offer.

Hans-Elias de Bree, April 2001

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INTRODUCTION

Purpose of this book

The purpose of this book is to provide an overview on the Microflown technologies, i.e. knowledge and skills that one should have to work with Microflowns. My goal is to write down the most essential matters that are known to me now. This book is a snapshot of the ongoing research: there is a lot to tell about the subject but, since the Microflown is investigated for only six years now, there is also a lot to be discovered. At this moment (spring 2001) a Ph.D. student and a post-doc are working full-time on this subject and several science groups and companies are investigating various Microflown based applications. A small (six persons) company "Microflown Technologies" is responsible for manufacturing and sales of Microflown based products.

Organisation of the book

The book is divided into two parts. The aim of the first part, containing four chapters, is to present a general theory and background information. This chapter will reveal how the Microflown was discovered and what happened since then (in the form of a scrapbook). Furthermore a general idea will be sketched on the capabilities of the Microflown. Chapter two deals with only the very basics of acoustic theory. These basics should be known to be able to understand the possibilities and applications of the Microflown. In chapter three the fabrication methods and packaging of the Microflown are presented. In the last chapter of the first section, preamplifiers, theory on selfnoise and figures that quantify the acoustical performance of the Microflown will be presented.

The second part of the book consists of a quantity of small chapters, each treating a subject briefly. These chapters can be read at random order. Some of these chapters are articles published previously that are altered so that they fit in; introductions are left out and relations with other chapters and subjects are made. Other chapters treat subjects that are necessary to get the overall picture complete. Since this book is a

report of the ongoing research, some of these chapters contain a discussion with the latest results and ideas of the work that has been done. These small chapters in the second part of the book are divided into five parts.

In the first part, "*The Microflown as a particle velocity sensor*", all the aspects of the Microflown itself are presented. Subjects like acoustic features, actual realisations of preamplifiers, specifics about packaging and calibration methods will be treated.

The second part is "*The sound intensity application*". The Microflown, used as an instrument to measure sound intensity is the most investigated subject until now. Here sound intensity measurement methods, several realisations of (3D) intensity probes and a comparison with a traditional probe will be presented.

The third part "The acoustic impedance application" focuses on the measurement of the acoustic impedance. Only a few months after its invention, the Microflown was used to measure the acoustic impedance. This impedance measurement is nowadays also a main subject of investigation.

The fourth part is about the Microflown used for sound reinforcement applications and in the last part various applications are treated.

A CD-ROM with lots of extra information, like scientific articles, press cuttings, photos, sound fragments and video fragments will be included.

The Microflown

The function of an acoustic transducer is simple to explain: it has to convert an audio signal from one form to another. Loudspeakers for example, convert electrical signals into acoustic sound waves by vibrating a diaphragm in response to an alternating current. Similarly, microphones convert acoustic sound waves into an electrical signal when a diaphragm vibrates in response to fluctuating air pressure. The design of these transducers hasn't changed much since their development decades ago. Most microphones still operate with a membrane.

The Microflown does not measure fluctuating air pressure, it measures the so called particle velocity. Basically, the Microflown is the acoustical equivalent of an ampere meter. Instead, the Microflown measures the velocity of air particles across two tiny, resistive strips of platinum that are heated to about 200°C. In fluid dynamics, the motion of gas or liquid

particles is called a flow, hence the name Microflown, which is sensitive to the movement of air rather than pressure.

When air flows across the strips, due to heat transfer the first wire cools down a little, and the air picks up some heat. Hence, the second wire is cooled down with the heated air and cools down less than the first wire. A temperature difference occurs, which alters their electrical resistance. This generates a voltage difference that is proportional to the airflow (particle velocity) and is directional: when the direction of the airflow reverses, the temperature difference will reverse too. In the case of a sound wave, the airflow across the strips alternates according to the waveform and this result in a corresponding alternating voltage.

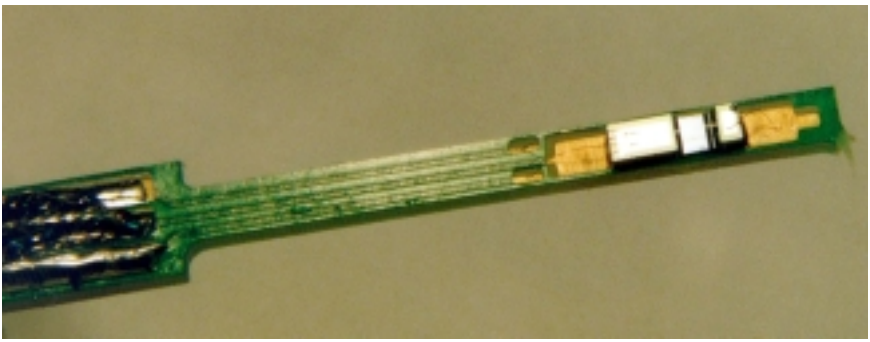

Fig. 1.1: A bridge type of Microflown, wirebonded and glued on a printed circuit board. It is the half-product for several applications.

High tones can not be sensed as good as low tones, this is because of the thermal mass (the temperature of a sensor can not vary at infinite velocity) and due to diffusion effects (it takes time for heat to travel from one wire to another). See further chapter 2 "*Acoustics*" and chapter A1 "*Model of the Microflown*".

When a sound wave passes through a region of air, the particles don't move through the region with it; they vibrate in place, in a pattern determined by the sound's waveform. As they do, the Microflown detects their velocity.

As might be imagined, the amplitude of particle motion within a sound wave is extremely small, in the region 50nm/s (fifty divided by a billion meters per second) up to 1m/s. Fortunately, this amplitude can be increased at the sensors, by a proper packaging. If packaged correctly, the

amplitude of the alternating flow can be increased dramatically; this effect is called package gain.

Regular sound levels (conversation, face-to-face) have sound levels of about 60dB. At these levels the temperature difference of the two sensors of the Microflown will vary only ten milli-Degrees Celsius.

The entire Microflown (sensors and electrical connections) measures a mere 1mm wide, 2mm long, and 0.3mm thick (see Fig. 1.1)[1]. The sensor strips themselves are 200nm thin (about 600 atoms) and 10μm wide, making them almost impossible to see with the naked eye (the diameter of a human hair is 80μm).

In addition, the Microflown has no moving parts, which means it's highly reliable and exhibits no resonances. It's also resistant to extreme ambient conditions, such as a high moisture, and dirt and high temperatures.

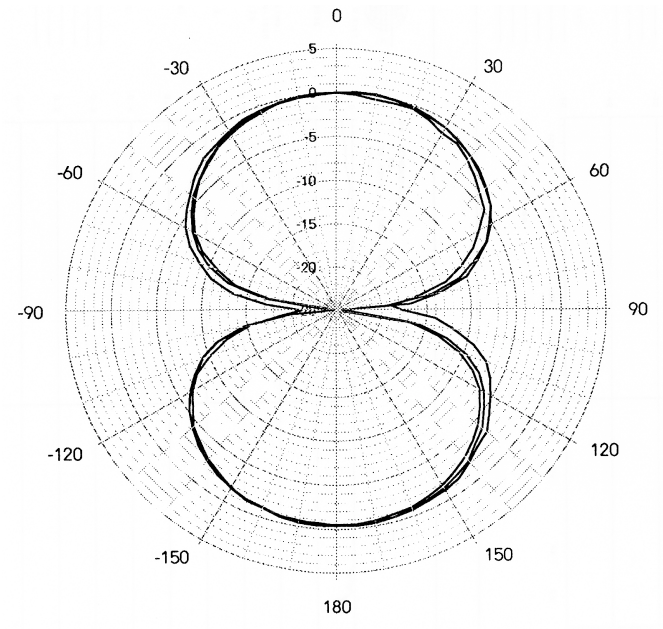

Fig. 1.2: The figure of eight type of polar pattern of the Microflown measured at 150Hz, 2kHz and 4kHz (measured by Brüel & Kjær, 1995).

[1] 1meter = 1m = 1.000mm = 1.000.000μm =1.000.000.000nm

Because of their tiny size, Microflowns are fabricated in a cleanroom environment using similar techniques to those used in semiconductor manufacturing. As a result, their acoustic performance characteristics fall within very tight limits compared to traditional microphones.

The Microflown is directional, see Fig. 1.2 (the polar pattern is figure of eight), and because it measures air velocity instead of pressure, it is sensitive to nearfield sources while effectively rejecting far field sources. This can be exploited in telecom applications. With a low power dissipation (lower than 10mW) and a limited frequency bandwidth (100Hz to 3.4kHz) the selfnoise is competitive.

Since nowadays apart from the sound pressure, particle velocity can be determined instantly (this is a unique feature of the Microflown) acoustic quantities as sound intensity, acoustic impedance and sound energy density can be measured three dimensional, instantaneous, broad band (10Hz-20kHz) and at one position in space.

Sound intensity is associated with the product of sound pressure and particle velocity and quantifies the amount of sound. The specific acoustic impedance is related with the ratio of both, and is a useful quantity to determine for example the reflection or absorption of matter. Sound energy density quantifies how much energy is stored in an acoustic wave, sound intensity quantifies how much sound energy is transported and specific acoustic impedance quantifies the possibility for sound energy to be transported.

If the power dissipation is of less concern the Microflown can theoretically also be a technology that has high-end applications, such as studio mikes and music instrument transducers. The selfnoise of the Microflown improves linear with the square root of the power dissipation, so the sound quality improves twice if the operating power is increased four times. First efforts are presented in chapter D, *"the audio application"*.

Microphones & Microflowns

This paragraph deals with the differences and similarities of both types of sound transducers. Just as a microphone, the Microflown is sensitive for sound waves. But sound waves consist of two parts, the (well-known) sound pressure and the relative unknown particle velocity.

Fig. 1.3: Symbols of a Microflown and a microphone. The two lines in the Microflown symbol represent the two wires (sensors) of a Microflown, the one line in the microphone symbol represents the membrane.

Sound can be understood as variations of the static air pressure and particle velocity. The following can explain this. Pressure is defined as force per unit area. This force is caused by an amount of air particles at a certain position. So variations in sound pressure are influenced by variations in the number of air particles. If the number of particles in a certain volume changes during time, there must be a particle motion towards that volume and backwards. The velocity of the movement of these particles is called particle velocity. Sound therefore consist always of two parts: sound pressure and particle velocity.

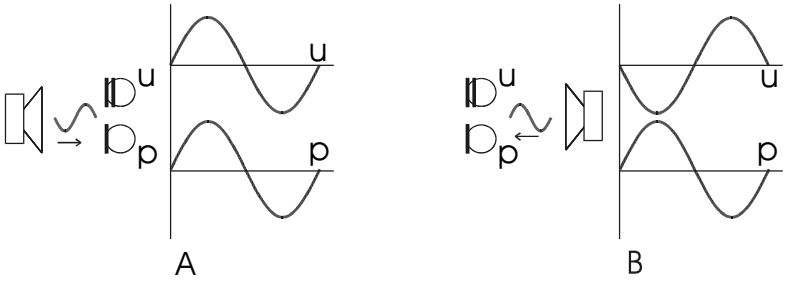

Fig. 1.4: Symbol and response of a sound pressure microphone (p) and a Microflown (u) for two directions.

Sound pressure, affected by the number of air particles at a certain position, does not have a direction; sound pressure is a scalar quantity. Contrary, the velocity of air particles does have a direction: particle velocity is a vector quantity. The unit of sound pressure is Pascal, the unit of particle velocity is meters per second.

In an electrical analogy sound pressure corresponds to an electric voltage and particle velocity to electric current. The amount of power is quantified in Watts. Multiplication of voltage and current results in electrical power and analogously, sound pressure times particle velocity is associated with sound power (density) in the acoustical domain.

The construction of traditional microphones does have a great resemblance compared to the human ear and both detect sound pressure. Just as the human ear, microphones consist of a membrane. Sound pressure “pushes” a membrane forward and backwards and the deflection of the membrane is detected.

In case of the Microflown, particle velocity alters the temperature distribution of the heated sensors. This altered distribution causes a temperature change in both sensors and the temperature difference quantifies the particle velocity. Contradictory to traditional microphones, sound is perceived without any movement of a diaphragm, or something like this.

If one compares the acoustic quality of both types of microphones (its like comparing cats to dogs!), the traditional ones perform about ten to hundred times better nowadays (regarding S/N). Traditional microphones however are being developed more than hundred years already by many universities and companies and the limits of these transducers are well known. The development of the Microflown started in the end of 1994 and only a few persons have worked on the subject and in this six years the quality increased tremendously. In other words we just started and who knows where it ends?

History

The very nice thing about this project is that at all times it felt that it could be starting just in the following week. Since the beginning it was very exciting and that excitement did not stop.

Fig. 1.5: The Microflown logo as it was displayed in 1996.

Those were the times.

The Microflown was invented in 1994. I was just graduated from my masters study on low noise electronics, a self-biasing Wheatstone bridge so to say, and was working in the micro-mechanics lab at the University of Twente on liquid flow-sensors. The electronic circuit was one of the essential steps that lead to the invention, or better said the discovery of the Microflown. The liquid mass-flow sensor did not operate in the measurement set-up at all. When removed from the fluid the sensor was still operational because of the self-biasing electronics. When talking into the sensor, I saw to my surprise it reacted to speech. This is how I discovered that it could be used as a microphone apart from a mass flow sensor. I went to my professor and one thing lead to another.

A proposal was written to the Dutch Technology Foundation and they immediately filed for a patent. To get a grant, the normal procedure is that a panel of (international) experts is chosen, they comment on the proposal and an “non expert” (national) jury will judge the proposal on utilisation and scientific value. Unfortunately the experts were divided into two groups. One group said: “old news” and the other: “not possible”. Therefore, proposal was rejected.

Kleinste microfoon meet warmtestroom

In zijn debuut *Archibald Strohalm* beschreef Harry Mulisch een oeroud principe waarmee de windsnelheid is vast te stellen: verhit een spijker en meet hoe snel hij in de wind weer afkoelt. Aan de Technische Universiteit Twente gebruiken ze een verwant idee om de kleinste microfoon ter wereld te ontwerpen. Een microflown, noemen ze het ding van één bij een halve millimeter toepasselijk.

Klassieke microfoons bevatten een membraan dat geluidsgolven oppikt en via een magneet en een spoel in een stroom omzet. Dat heeft het nadeel dat lage frequenties nauwelijks te meten zijn. En bovendien moet het membraan een minimale omvang hebben om iets op te pikken.
De nieuwe microflowns uit Twente, onlangs gepresenteerd tijdens een Europese conferentie over sensoren, kan desnoods microscopisch klein worden gemaakt. Bovendien is er geluid tot extreem lage frequenties mee te meten.

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Dat kan doordat het micro-microfoontje is afgeleid van een stromingsmeter. Het systeem meet hoe in een chip opgewekte warmte zich verspreidt door de minieme luchtverplaatsingen waaruit geluid bestaat.

Op een siliciumchip worden daartoe over een groef drie brugjes gelegd, waarvan de middelste als een soort gloeidraad wordt verhit. Onder het bruggetje ontstaat een bel hete lucht die door geluidstrillingen wordt verplaatst en de naburige brugjes opwarmt. Daardoor treden meetbare veranderingen op in de elektrische eigenschappen van de brugjes.

Fig. 1.6: The first time it was published in a newspaper.

One has to understand that the “invention” of the Microflown was in fact nothing more than somebody talking into a relatively standard flow sensor (with a very noisy result). It was difficult to explain that this was something new and that it was important enough to put time and money in. In the beginning, important voices on the university said that it was nothing more than a flow sensor used as a very bad microphone, so “why the excitement?”

The first time that it was in the published in the newspaper showed that more people thought that it was indeed something new, see Fig. 1.6. The first scientific article we got published in Sensors and Actuators reinforced our confidence and on the way back of the convention in Stockholm (Sweden) we visited Brüel & Kjær in Denmark. Their response strengthened our feeling: we had something good in our hands.

Because the Dutch Technology Foundation and the University of Twente thought it was a very good idea, the proposal was filed again but now stronger, with a recommendation of a lot of Dutch companies who did see possible applications. Again the proposal was rejected.

Fig. 1.7: The (smallest) booth of Microflown Technologies B.V. on the 1998 AES convention in Amsterdam, 24 hours after its legal start.

This is why the first two years the Microflown project was completely unofficial. The work was done by a lot of students that did various assignments. This group of students named themselves “The Microflown Team”. I co-ordinated that group and waited for two years on the grant of the Dutch government to start my Ph.D. work.

After these two years of working the financial horizon was closing in, so according to Dutch law I defended my thesis in public and got my Ph.D. degree. Since the Dutch Technology Foundation was not able to start the project and nobody did know what to do with the Microflown, I obtained the patent rights. Just before my dissertation I went to the microphone manufacturer Sennheiser and they where willing to sponsor the research at the university for one year (1997). In return they got a two-years licence to exploit the Microflown for telecom purposes. After that one year the Dutch Technology Foundation granted a proposal for a Ph.D. student and a post-doc position. I became post-doc at the University of Twente.

A company by the name of Microflown Technologies B.V. was founded in 1998. They got the legal rights for the commercialisation of the various Microflown based products.

Technology History

As said, the history of the Microflown began when I took a mass flow sensor that could be found in the micro mechanics lab. It was normally used for liquid flow sensing (this was initially my reason to use it too). After I talked to the sensor and it even responded on an oscilloscope, the research was proceeded into getting better listening Microflowns. A photo of the first sensor plus a preamplifier (the Gadget) can be found at Fig 4.6.

The technology at that time (1994) was to use a mass flow sensor with golden temperature sensors and heater on a silicon nitride layer of 1 micrometer, see Fig. 1.8. Due to the materials choice, the operating temperature could not be chosen very high since gold has a relative low melting point. This resulted in a large number of burnt down Microflowns and a relative low sensitivity. The 1-micrometer silicon nitride carrier layer caused a very low corner frequency of about 10 Hertz.

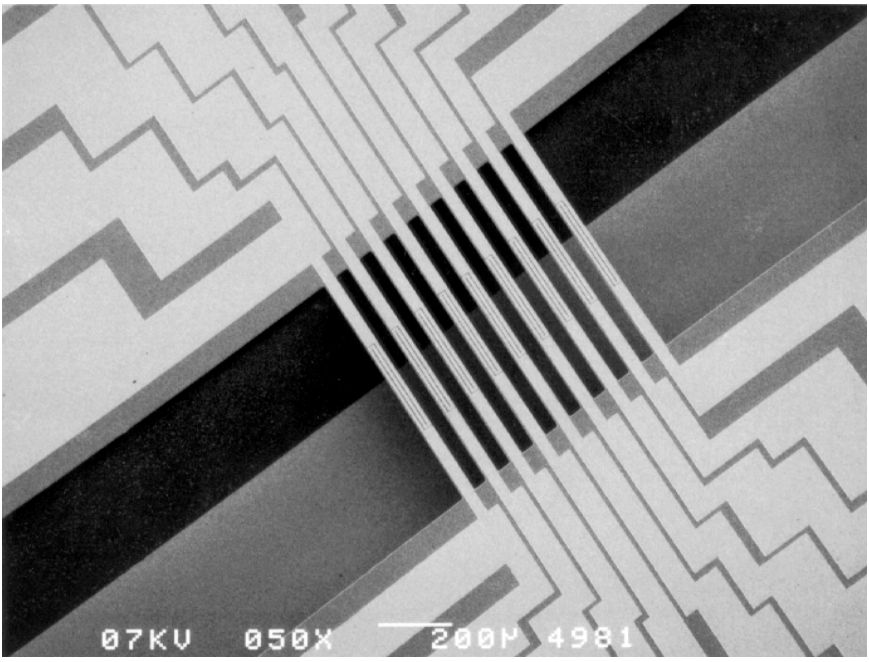

Fig. 1.8: First bridge type of Microflown. It was used as a mass flow sensor and it had, for research purposes, several elements over a channel that could be used as a sensor or heater (Theo Lammerink).

The acoustic quality of a Microflown increases if either the corner frequency or sensitivity increases. The corner frequency is a figure that expresses how high tones the Microflown can hear and the sensitivity how good the Microflown can hear. The frequency of sound is between 20 Hertz (very low tone) and 20,000 Hertz (very high tone).

The ohmic impedance of the sensors was very low and the electronic noise of the preamplifier was not completely understood (the Gadget, see chapter 4). Due to this the noise performance was far from optimal.

One could say that the first Microflown could only hear very low frequencies, it was quite deaf and that the electronics made a lot of noise too. But it showed that it was possible to detect sound with a mass flow sensor.

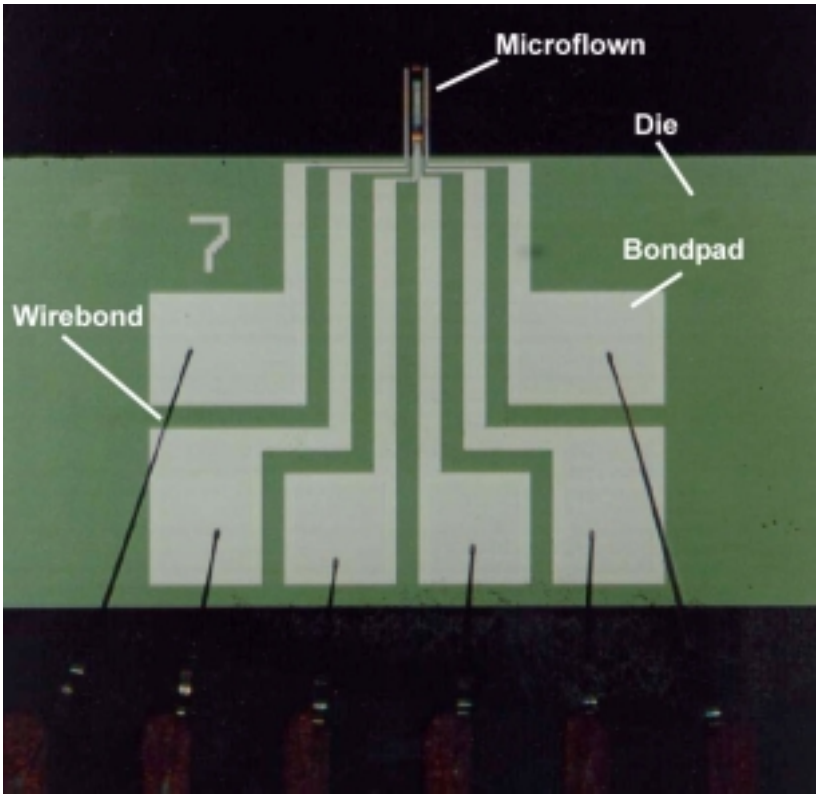

Fig. 1.9: First cantilever type of Microflown. It had a heater and two sensors. Note the enormous die compared to the sensor element. The (aluminium) wirebonds are used for making the electrical connections, they are "bonded" on the bondpads. The die is silicon bulk material.

The next sensor that was made was a cantilever type of Microflown, see Fig. 1.9. At that time we thought that it would perform better when the sensors where free in the sound wave and not close to a rigid wall (the bottom of the channel).

In those days we discovered that it is quite difficult to compare one Microflown with another. We had to invent acoustic measurement set-ups and find out what parameters of the Microflown should be compared. Now it is all quite obvious but at that time we had a lot to think about.

Fig. 1.10: Measuring the quality of a Microflown on the roof of the university building.

Questions like “is it a scientific proof that the Microflown is sensitive for particle velocity, only by proving that it is not sensitive for sound pressure?” where at that time subjects of long discussions.

First we had to understand that the Microflown was sensitive for particle velocity instead of sound pressure. We discovered that no other particle velocity sensors did exist and that of course was a nice thing to find out; it meant that we had something special. Consequent was that we could not simply buy a reference particle velocity microphone for calibrating the Microflown.

We understood that we had to find environments that had a special acoustic impedance (this is the ratio of sound pressure and particle velocity). We heard that free-field measurements should be performed. In first experiments we took the “free-field” very literally, we measured on the roof of our building, see Fig. 1.10. That was not very comfortable, especially in winter times.

The first measurement set up where we could determine the quality of a Microflown indoors was a long tube (forty meters). A short acoustic burst was generated into the tube made of simple rain pipe. Sound pressure and particle velocity were measured before the sound travelled to the end of the tube, reflected and returned. This calibration principle worked quite well but measurements took a lot of time (about half an hour) and place (40 meters).

We tried a lot of acoustic set-ups. Nowadays a short standing wave tube is used most commonly, see chapter A5 *"calibration methods"*.

After we made acoustic set-ups, learned about corner frequencies, differential resistor variations, operating power, selfnoise and corner frequencies we could start comparing various types of Microflowns.

We discovered that the corner frequency rises if the silicon nitride carrier layer of the sensors was made thinner and that the sensitivity rises if the operating temperature was increased. After we burned down a lot of golden sensors we started to use platinum as sensor material. This metal can be heated so much that it starts to glow, for us a sign that we should be careful not to put more power into it.

The "normal" mass flow sensor of which the Microflown is originated, consists on one heater and two sensors located closely around it. At an early stage we discovered that for proper operation this heater is not necessary. From 1996 we started to use a Microflown with only two sensors and no heater. We found out that if the heater is omitted the power in the sensors can be increased and that due to this the selfnoise was reduced. It was also easier to make, see Fig. 2.15.

The cantilever Microflown that was made of platinum had a corner frequency of 300Hz and the sensitivity improved a factor five. In total the sound reproduction quality improved about 50 times. A major improvement but we needed much more to be competitive with normal microphones.

A factor ten was what the microphone manufacturer Sennheiser requested. They sponsored the university research for one year in 1997. In that year it was discovered that if the Microflown was packaged properly, the sensitivity could rise a factor 7. We had to study on packaging methods and as a first step I did put the Microflown under the clip of a pencil and to my surprise the sensitivity went up! This way of packaging did us realise that the sensors should be placed near a wall in stead of free in the sound wave. We returned to the bridge type of Microflowns and due to the increased mechanical stability we could

make the silicon nitride sensor support thinner again. The corner frequency increased to 750Hz.

This type, a bridge with platinum sensors and 100nm silicon-nitride carrier layer was ready in 1998, too late for Sennheiser. The intrinsic sensitivity of this bridge type of Microflown was increased just a little bit, the corner frequency had increased a factor 2.5 but main improvement was the package gain, resulting in a 7 times improvement of the overall sensitivity. The total improvement was a factor 20.

A nice story can be told on interpretation of measurement results that where performed in an anechoic room. Various Microflowns where tested and to our surprise one of them, nr. 183 had a significantly higher sensitivity (+6,7dB or 2.2 times). The number 183 Microflowns was called “mit Bügel”. The operator of the anechoic room had written this on the results. The “mit Bügel” referred to the metal wire that was made around the Microflown to protect the cantilevers, see Fig. 1.12. In our quest to find an answer why this nr. 183 Microflown was better I removed the wire to be able to study the sensor under a microscope. We could not find a reason. All this happened early 1996 and at the end of 1997 I “discovered” the package gain and found at the same time the answer to the “mit Bügel” question. The metal wire that I removed to find out why nr. 183 had a better sensitivity was in fact the answer: the metal wire was acting as a package that caused a gain of 6.7dB. One needs an open mind to find answers!

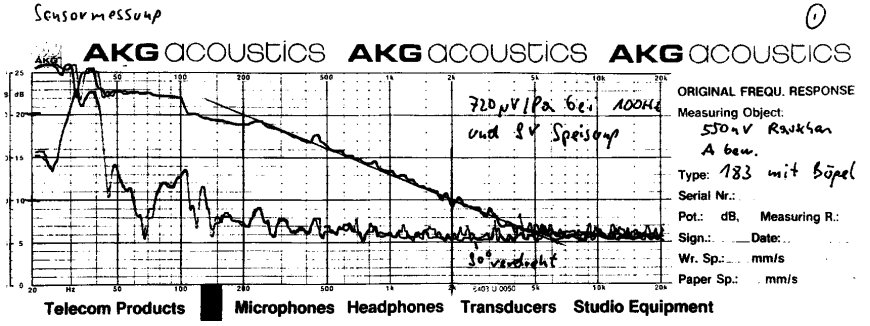

Fig. 1.11: Anechoic measurement results (March 1996; 720uV/Pa bei 100Hz und 9V speisung. 550nV Raussen, A bew. 183 mit Bügel; Curve measured by AKG acoustics).

Another story of an open mind: during cost price discussions with a Japanese firm on mass marked applications (toys and telecom), the subject was “the economy of scale”. The more one makes the lower the price per unit. So we discussed on other mass applications. One of the Japanese researchers had an idea to use the Microflown as a fuse! These elements will possibly be needed in all toys and cellular telephones in the future. In this way the each toy and cellular phone could need two instead of one Microflown.

The Microflown that was used in 1999 was made of single platinum (no support layer) this resulted in a corner frequency of about 1kHz and 2.5 times higher sensitivity. The overall performance of that Microflown increased 3.4 times.

In total the quality of the Microflown was improved a factor 30,000 over the past five years. The corner frequency improved from 10Hz to 1kHz (a factor 100) the intrinsic sensitivity a factor 15 plus a sensitivity improvement of 7 times due to package gain. The noise performance of the electronics improved a factor 3. This is quite an achievement but we still need at least a factor ten (20dB) to reach a selfnoise that is competitive to a studio microphone.

Fig. 1.12: A cantilever Microflown with protection wire mounted into a m5 bolt. This realisation is used in the impedance tube. The protection wire caused a package gain of 6dB (Theo Veenstra, 1996).

If one keeps in mind that the selfnoise has improved 30,000 times and it still needs at least 10 times to reach high quality one can imagine how loud I had to shout in the beginning to demonstrate the working of the Microflown.

The selfnoise of a properly packaged Microflown in 2000 is more than 40dB(A), a good studio microphone has a selfnoise of 15dB(A) to 20dB(A). So a lot has to be done in order to create a high end Microflown. For measurement purposes the Microflown has proven itself many times now.

Apart from the sound quality improvement another development was going on the search for applications and, strongly related to that, the packaging and preamplifiers.

The first application that was examined was the particle velocity measurement for the determination of specific acoustic impedance. Already in 1995 the Microflown was used by Laboratory for Network Theory and VLSI Design of the University of Twente, to determine the quality of a horn loudspeaker, see chapter C1: *"Measuring the acoustic impedance of a horn loudspeaker"*. Later the faculty of Mechanical Engineering deployed the Microflown for Experiments in an impedance tube, see chapter C2: *"Acoustic impedance tube"*. The Microflown had to be mounted into a m5 bolt for this, see Fig. 1.12.

In early times the sound intensity application was investigated in co-operation with Philips Research Laboratories Eindhoven (Natlab). One of the first realisations is depicted in Fig. 1.13. The particle velocity probe has been developed into a half inch probe in which the sound pressure probe is incorporated, see chapter B1: *"P-U sound intensity probe"*. The sound intensity research has expanded over the years into one of the key subjects. Not only the realisation of a sound intensity probe is under investigation but also measuring methods, calibration methods and comparisons to other probes are investigated. See chapter B.

Connectivity is one of the major issues in acceptance of a product. The probe should be plugged in and ready to use. The 7-pins LEMO, the BNC and the Brüel & Kjær connector have become standard in the field of acoustic measurements. We choose the first two types of connectors because the latter connector is a bit bulky and outdated.

The BNC connector is a two-wire "signal and shield" connector only. It is a very simple and low cost connector. We use the (unofficial) standard ICP© protocol: a 4mA DC power source is powering the preamplifier and the AC voltage is used as output. Apart from the ICP

protocol we use a 7-pins LEMO connector. In this way it is possible to use the same cables and connectors to connect a Microflown to a microphone powering-module, see chapter A: *"The half-inch Microflown, electronics and performance"*. In 1998 the ICP probe became commercially available (Microflown Technologies B.V.).

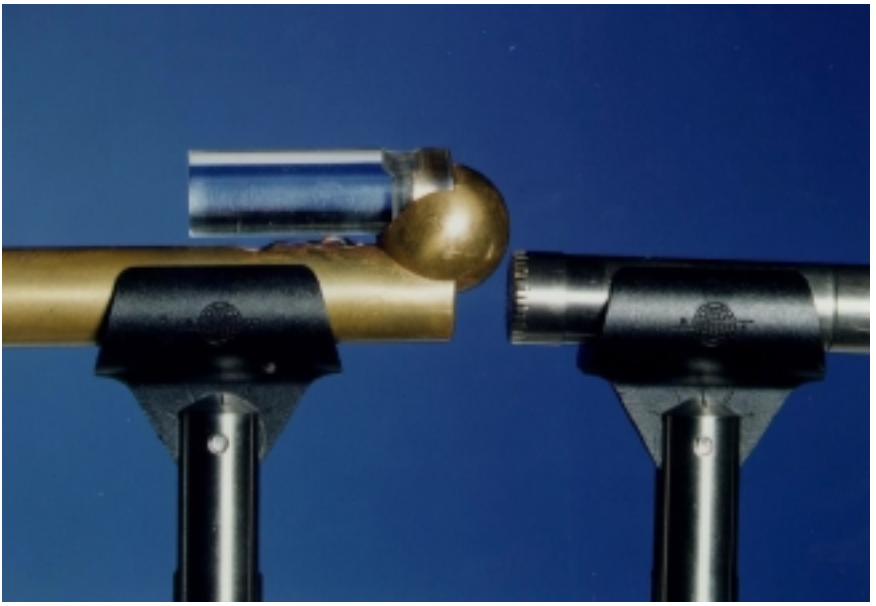

Fig. 1.13: One of the first p-u sound intensity probes (1997). The Plexiglas cylinder and the brass sphere are mounted to create package gain.

The connectivity forced us to design various types of preamplifiers. We started with "the Gadget", a circuit that was inherited from my master's study. This circuit has a lot of positive features for laboratory use however the disadvantage was that it needed a high operating voltage (about 25V) and the power dissipation of the preamplifier itself was quite high. This Gadget was therefore not very useful for battery powered applications. For these applications (especially telecom applications) the CE-Gadget was designed: a circuit that operated at very low supply voltages and needed just a few milli-Watts to operate. To comply to the (two-wire) ICP protocol a complete new preamplifier design was needed: powering and readout is accomplished on the same wire. Specifics of these circuits can be found in chapter 4: *"electronics and noise"*.

A complete other type of preamplifier that has been designed is the Phantom preamplifier. The Phantom protocol defines a differential output, for specifics on this circuit see chapter D2: "*Add-on Microflown for a high-end pressure gradient microphone*".

The Phantom powering that uses the XLR connector has become standard in the field of professional audio. The Microflown of 1999 had not reached the low noise properties to become a wide band, high quality microphone but could very good be used as an accessory microphone to cover only the lower frequencies. Early versions made use of additional powering but as mentioned, the modern versions use only the Phantom powering. In 2001 the add-on Microflown became commercially available (First Decade B.V.).

From the beginning the sound reinforcement application was investigated. Although the selfnoise was not very good we managed to broadcast some sentences on the BBC world service in November 1996.

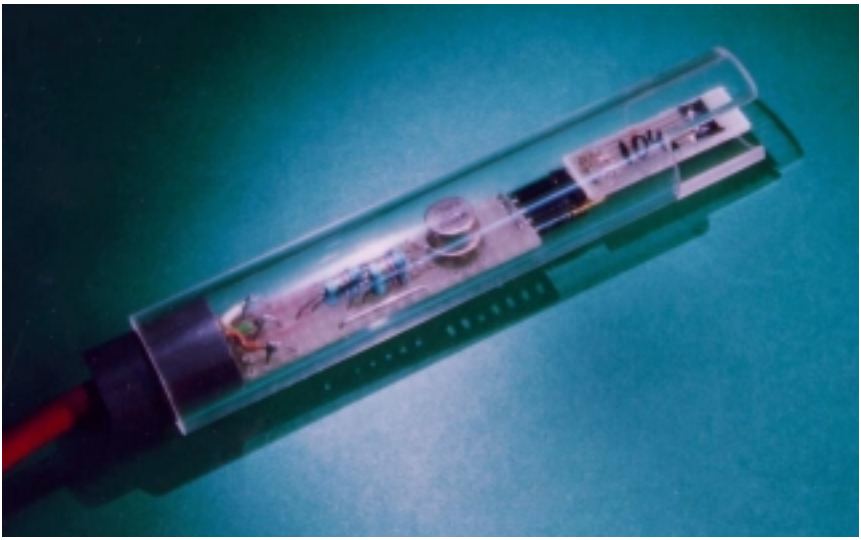

Fig. 1.14: One of the first Microflowns for speech reinforcement purposes (1996).

In the future two ways of improving the acoustic properties will be examined. The first way to improve the noise level is to make a Microflown that consists of 500 "normal" ones. In this way the power dissipation of the total device will increase 500 times (to 15W) and signal to noise ratio of this "high power Microflown (or Megaflown)" will

improve √500=22 times. Off course, all those 500 Microflowns don't have to be connected to each other by hand: these Microflowns and connections are made at once, on one wafer. This is done by trough-the-wafer-etching, see chapter D4: *"Megaflown"*. The final result of this technique is not certain since the package cannot be made in the similar to the normal way. So the signal to noise improvement is simply to calculate but the package gain is not known yet.

Another approach to improve the quality of the Microflowns is by using another sensor material. In 1999 the best sensor material that could be processed was platinum. New process schemes made it possible to use (doped) silicon or germanium. This material is ten times more sensitive to temperature variations than platinum. Since it is a thermal sensor, this improves the quality of the Microflown in a direct manner. The final outcome of this technology is not certain since the noise behaviour of the new sensor material is not known yet. It is not the sensitivity increase, which can be found in literature, but the signal to noise ratio that quantifies the quality of a Microflown and the noise of the hot semiconductor sensors is not known yet. For silicon or germanium the resistor value as function of the temperature is, contradictory to platinum, not linear. This could lead to linearity problems, i.e. relative high distortion figures. This could be solved by a constant temperature concept, see also chapter E3: *"DC flowsensor"*.

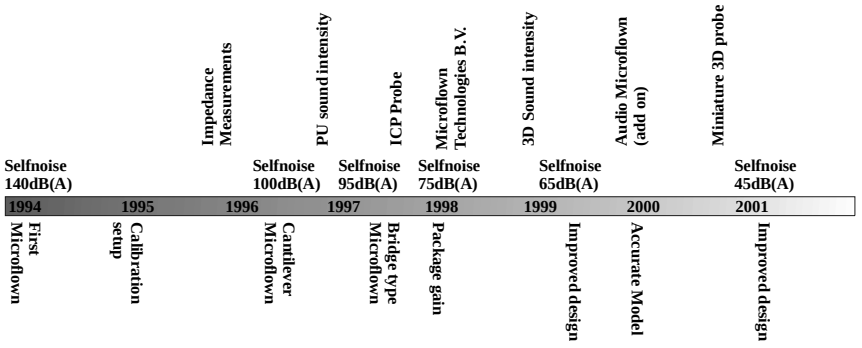

Fig. 1.15: Developments the Microflown. The selfnoise in dB(A) is an estimation based on the sensitivity of the Microflown at that time, 20kHz bandwidth and 40mW operating power. For telecom purposes the bandwidth is limited to 3.4kHz and the selfnoise is 20dB lower. For sound reinforcement the operating power may be chosen higher which leads to lower selfnoise.

In 2000 a more reliable model became available regarding the frequency dependence of the Microflown. Only then it became clear that a Microflown had instead of one, two corner frequencies. One due to diffusion effects (it takes time for heat to travel from one wire to another) and the other due to the heat capacity of the both wires.

Micro-mechanics

The Microflown is made using micro-mechanics, in a so-called clean room. The field of micro-mechanics is a logical follow-up of microelectronics. Microelectronics started its revolution after the invention of the transistor by Shockley in the Bell laboratories in 1947. In years, the size of transistors decreased and integrated circuits came onto the market. With the spin-off of the microelectronics it was found that it was possible to create micron sized mechanical structures and the micro-mechanics became an important field within the Sensors & Actuators groups.

Micro-mechanics techniques include firstly the basic processing steps of IC technology, namely thin film deposition, doping, lithography, and etching. In addition, they incorporate special etching and bonding processes that allow for the sculpturing of three-dimensional microstructures.

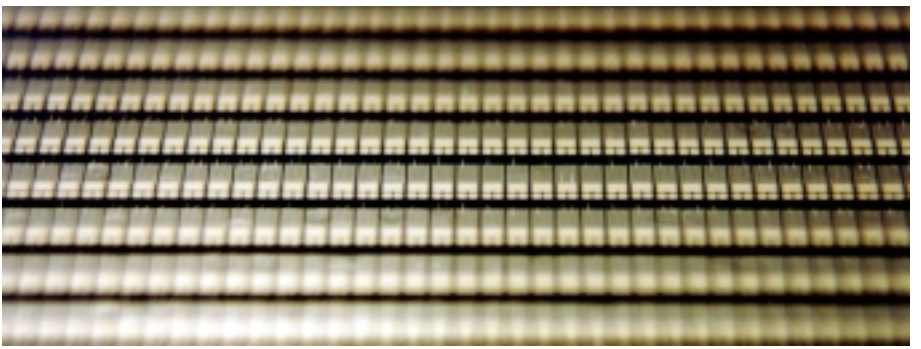

Fig. 1.16: Photograph of a lot of Microflowns, sawed but still in the wafer.

The fabrication of a Microflown in a cleanroom requires a certain number of standard process steps. Before any process is allowed to start, the (silicon) wafers need to be cleaned. This is to avoid contamination of

the equipment and also to be sure that the process is started with a fresh wafer. After the cleaning a 300nm silicon nitride layer is deposited on the waver. This layer is used as a mask for the wet chemical etching and as a carrier for the sensors. A 200nm metal platinum layer is deposited with a sputter technique. This layer will be the actual sensor layer and will be used as bond-pads to establish later electrical connections on the printed circuit board. The platinum layer is patterned with a lift off technique. When the patterned platinum layer is ready the silicon nitride layer is etched to create a path for the wet chemical etchand to create the channel. The wet chemical etching will create the channel and will set the sensors bridges free.

With the use of micro-mechanics thousands of similar Microflowns are made at once on one wafer.

Applications

The Microflown is a new type of sensor that can be used in many applications. Just to give a general idea some of the (possible) applications will be summed here.

- It can be used as a **low quality microphone for speech, telecom, voice recognition systems or toys**. The silicon-based production technology makes mass production possible. Of course one could make Microflowns as single units but it is also possible to integrate them into the telephone chip. This will lead to reduced system cost, the acoustic sensor does not have to be mounted and soldered, and less components will be needed to compose a telephone. Leading to smaller and lighter telephone designs.
- Due to the silicon-based technology it is possible to make very much Microflowns with the same acoustic properties. This opens the way to **Array technology**, which allows for example faster and more accurate measuring features. This is important for techniques like acoustic holography. One could also think of an “acoustic camera”. Or a hands-free car phone system: a high directional microphone array that reduces the high level background noise that is present in cars.
- **High sound level microphone**. The Microflown can be put in to a small inlet of a backing chamber. Pressure variations will cause a particle motion through the inlet that is sensed by the Microflown. See chapter D1: *“The sound pressure Microflown”*.

- **Wind noise reducing system.** Wind noise is a low frequency rumble that is often encountered by outside measuring. Since the Microflown measures something completely different than a microphone and it is sensitive for low frequency sound waves, the combination of a sound pressure microphone and a Microflown can discriminate between wind induced rumble and real low frequency sound waves.
- **High temperature Microphone**. The Microflown can operate in circumstances with temperatures of several hundreds of degrees Celsius.
- **Chip card microphone**. Due to its small dimensions and its mass marked friendly production technique the Microflown could be used in smart cards.
- A Microflown can be used as a **level sensor**. The operation principle is still based on the temperature difference of two the identical heaters but now this difference is caused by buoyancy of air; no external flow is present. The sensor must therefore be packaged in a closed configuration.
- **Hydroflown,** i.e. underwater acoustics. The Microflown can also operate underwater. The applications can be found in the miltary (locating submarines or boats) but it can also be used in applications like fish finding.
- **Bass drum microphone**, the Microflown is especially sensitive for low frequency sound waves, which are produced by a bass drum.
- When a lot of Microflowns are coupled, a **high quality microphone** can be made. This Microflown will dissipate a lot more power (5W) but this would not be a problem for **studio microphones**.
- Due to the unique capability to measure particle velocity, a complete new range of acoustic measurements becomes possible: s**ound intensity, sound energy and acoustic impedance measurements.**
- The ability to measure the full sound vector in one spot, broad band (20Hz-20kHz) even in the near field. (**3D sound intensity, 3D sound energy and 3D acoustic impedance**)
- Due to the ability to withstand G-forces, the large temperature range of operation and directionality it can be used for **geophones**.

- **DC Flow sensor**. It is maybe evident to say that the Microflown can be used as a very sensitive and fast flow sensor. One charming application is an apparatus that is used to measure the quality of a singer. The sound intensity is measured to measure how loud somebody is singing and at the same time the amount of air-flow is measured to find out how "efficient" this singing is. In this way one can measure if the glottis (or vocal cords) is closing properly.
- **Fuse**. The Microflown consist on two tiny wires that will burn when the current is too high. This is exactly the same function that a fuse has.
- **Add on Microflown** for a pressure gradient or unidirectional (e.g. a cardioid) microphone to enable high signal-to-noise-ratio, directional sound-recordings at lower frequencies.
- Novel ways to measure the acoustic properties of damping materials in an **acoustic impedance tube.**
- Although the operation principle is not reversible, the Microflown can be used as a **thermal loudspeaker**.

Shortlist of features

To get an impression of the capabilities and properties of the Microflown, features will be summed here.

1. Unique: particle velocity sensitive.
2. New applications in sound intensity, acoustic impedance and sound energy density determination.
3. Directional: figure of eight response.
4. Smallest microphone.
5. No moving parts.
6. Sensitive from zero Hertz.
7. Thermal principle.
8. Sensitivity is independent of temperature.
9. Sensitivity can be improved considerably with proper packaging (package-gain).
10. Low pass behaviour, frequency response flat from 0Hz and –6dB/oct after about 500Hz to 1kHz and –12dB/oct after 2kHz to 8kHz (values are depending on geometry).
11. No ripples in the frequency and phase response.

12. Easy correction of frequency response for audio applications.
13. Bandwidth 1kHz without correction, 20kHz with correction.
14. Selfnoise dependant on power dissipation and bandwidth.
15. Selfnoise 45dB(A) at 60mW power dissipation and 20kHz bandwidth.
16. Selfnoise 30dB(A) at 10mW power dissipation and 3.4kHz bandwidth (telecom).
17. In a 1Hz bandwidth sound levels well below the threshold of hearing can be measured.
18. A p**u** sound intensity probe has in a 1Hz bandwidth a very low selfnoise (below the threshold of hearing).
19. Simple calibration techniques are available.
20. Resistant to moisture/water.
21. Resistant to high temperatures.
22. Cleanroom technology:
23. Made in thousands at the same time.
24. Suitable for array technology.
25. Silicon based sensor.
26. Transduction with platinum sensors.
27. In principle a modulator type of sensor (the transduction principle cannot be reversed) however, Microflowns can be used as a loudspeaker, see chapter E6: *"the Microflown loudspeaker"*.

Summary of articles

All articles can be found on the CDROM and www.Microflown.com

The Microflown, Ph.D. thesis, H-E de Bree, ISBN 9036509262, 7 February 1997.

A summary of the various research areas of the Microflown until 1996.

The Microflown; a novel device measuring acoustical flows, H-E. de Bree, P. Leussink, T. Korthorst, H. Jansen, T. Lammerink, M. Elwenspoek, Sensors and Actuators: A, Physical, volume SNA054/1-3, pp 552-557,1996)

The first article. Remarkable detail is that at that time we did not know about the proper terminology ("acoustical flow" in stead of "particle velocity") but we where already mentioning various applications like a unipolar microphone and sound intensity. Various types of Microflowns are described.

Use of a fluid flow-measuring device as a microphone and system comprising such a microphone, H-E. de Bree, Lammerink, Elwenspoek, Fluitman, Patent PCT/NL95/00220, 1995.

International patent on the working principle of the Microflown.

A new sound intensity probe; comparison to the Bruel & Kjaer p-p probe, W.F. Druyvesteyn, H-E. de Bree, J. audio Eng. Soc., Vol. 48, 2000 No. 1/2 January/February.

A comparison between the Bruel & Kjaer p-p probe and the Microflown-based pu probe. Critical experiments show that the behavior of the p-u probe is similar to the p-p probe. Advantages of the p-u probe above the p-p probe are that for different frequency ranges the same configuration can be used (no spacers), that no accurate matching of the sensors is necessary, the dimensions of the p-u probe can be smaller, so that also near-field measurements could be performed.

Add-on Microflown for a high-end pressure gradient microphone, H-E. de Bree, presented at the 109th LA AES September 2000 (no. 5181).

First steps of the Microflown in the professional audio. This is because the Microflown is, contradictory to pressure gradient microphones, very sensitive for low frequency sound waves. A combination of a Microflown and a pressure gradient microphone was realised to create a high-end wide band velocity microphone-pair with a figure of eight polar pattern.

Experiments with a new acoustic particle velocity sensor in an impedance tube, F.J.M. van der Eerden, H-E. de Bree, H. Tijdeman, Sensors and Actuators A69, (1998) 126-133.

As one of the first applications Microflowns are applied in an impedance tube to determine the impedance of an aluminium sample at the end of the tube. The sample has an orifice that accounts for the sound absorption. Comparing the results with theory and measurements with microphones leads to an excellent agreement. The characteristics of the Microflowns, like the simplicity and the small dimensions, make it a very attractive alternative to the microphones.

Optimisation of a two-wire thermal sensor for flow and sound measurements, J.W. van Honschoten, G.J.M. Krijnen, V.B. Svetovoy, H-E. de Bree, M.C. Elwenspoek, MEMS Interlagen 2001.

Paper on the model of the Microflown.

A novel technique for measuring the reflection coefficient of sound-absorbing materials, H-E. de Bree, F.J.M. van der Eerden, J.W. van Honschoten, ISMA25, International Conference on Noise and Vibration, September 13-15, 2000 - Leuven, Belgium.

*A new method to measure the acoustic behaviour of sound absorbing material in an impedance tube is presented. The method makes use of the Microflown, and a microphone. The so-called p**u** method is compared to three other methods of which the two microphone technique is well known. It is shown that the combination of a microphone and a Microflown provides direct information on the acoustic impedance, the sound intensity and the sound energy density. The experimental results are compared to the results obtained with the conventional impedance tube measurements.*

Model of the μ-flown microphone, V.B. Svetovoy, I.A.Winter, Sensors &Actuators 86 (2000), 171-181.

Two Russian scientists made a mathematical model of the Microflown.

A low cost Intensity Probe, R. Raangs, W.F. Druyvesteyn and H-E. de Bree, AES Amsterdam 2001.

Paper about a low cost intensity probe that combines a sound particle velocity sensor and a microphone. Since the intensity is calculated from the cross-correlation of the velocity and pressure, a very accurate phase matching, as for the p-p method, is not necessary; and its signal to noise ratio (SNR) is higher than for the separate sensors. The data-acquisition and processing is implemented on a standard personal computer, combined with a simple calibration, and thus creating a very powerful intensity measuring device.

A method to measure apparent acoustic pressure, Flow gradient and acoustic intensity using two micromachined flow microphones, H-E. de Bree, T. Korthorst, P. Leussink, H. Jansen, M. Elwenspoek. Eurosensors X, Leuven, 1996.

First report on u-u sound intensity method. (It is the method complementary to the p-p method).

Realisation and calibration of a novel half-inch p-u sound intensity probe, H-E. de Bree, W.F. Druyvesteyn, M. Elwenspoek, 106th AES Munchen, 1999.

About a Microflown and a microphone in one housing, and a report of the standing wave tube calibration method.

A New acoustic measurement probe; the Microflown, W.F. Druyvesteyn, H-E de Bree, M. Elwenspoek, IOA London, 1999.

Several new measurement possibilities are presented (3D sound intensity measurements and the $u_{//}$-$u_{\perp}$ method, a sort of sound intensity like measurement technique where Microflowns are placed perpendicular to each other).

The Microflown, a true particle velocity microphone; Sound intensity application, H-E de Bree, NAG Journal, March 1998.

Overview of the research at that time. Focus is on the sound intensity.

Comparison of two methods for measurement of horn input impedance, H. Schurer, P. Annema, H.–E. de Bree, C. H. Slump and O. E. Herrmann, Published in the Proceedings of the 100th AES convention, Copenhagen, 1996.

Two methods to measure the acoustic input impedance of a horn are compared. First use of a Microflown, only a few months after its invention.

Intensity measurements in various rooms / a new intensity probe, W.F. Druyvesteyn, H.-E de Bree, 16th ICA and 135th ASA meeting; Seattle June 1998, Vol. 4, pp. 2827-2828.

Short paper about early reflections.

Sound intensity probes based on Microflown Technology, H-E. de Bree, presented at the ASA Berlin, 1999.

Overview of the research at that time. Focus is on the sound intensity.

Nieuwe intensiteitsmetingen; de Microflown technologie, H.-E. de Bree G. Krijnen, SWOT, Rotterdam, 1999.

Overview of the research at that time (in Dutch).

Er is meer geluid dan je hoort, H.-E. de Bree, Natuur en Techniek, 1998.

Overview of the research at that time (in Dutch). Focus is on the sound intensity.

The sound pressure Microflown; a novel way of transducing sound pressure, H.E. de Bree, Philip Ekkels, Dick Ekkelkamp, Gijs Krijnen, presented at the MME convention in Sweden 2000.

A Microflown has been realised that is able to detect sound pressure instead of particle velocity. This Microflown is packaged in such way that the usable bandwidth is 3.4kHz.

The two sensor Microflown; an improved flow sensing principle, H.E. de Bree, P. Leussink, T. Korthorst, M. Elwenspoek, Eurosensors X, Leuven, 1996.

Explanation of the two-sensor Microflown, the one that is used nowadays.

Three-dimensional sound intensity measurements using microflown particle velocity sensors, H-E. de Bree, W.F. Druyvesteyn, E. Berenschot, M. Elwenspoek, MEMS ’99, Orlando.

Realisation of a three dimensional Microflown.

The Wheatstone Gadget; a simple circuit for measuring differential resistance variations, H-E. de Bree, P. Leussink, T. Korthorst, Y. Backlund, H. Jansen, MME, Copenhagen ’95.

Explanation about a preamplifier.

Improving the signal to noise ratio of resistive sensors, H-E. de Bree and Miko Elwenspoek, MME, France ’99.

About the signal to noise ratio of resistive sensors.

The influence of viscothermal effects on calibration measurements in a tube, J.W.van Honschoten, H-E. de Bree, F.J.M. van der Eerden, G.J.M. Krijnen, presented at the LA AES 2000.

More information on the standing wave tube calibration method.

Bi-directional fast flow sensor with a large dynamic range, Hans-Elias de Bree, Henri V. Jansen, Theo S.J. Lammerink, Gijs J.M. Krijnen and Miko Elwenspoek. MME, 1998.

Paper about a Microflown use as a DC flow sensor.

The Microflown, from die to product, H.E. de Bree, M. Elwenspoek, presented at Eurosensors, Den Haag, 1999.

Paper about the production path.

The Deelen infrasound array for recording sonic booms and events of CTBT interest, L.G. Evers, H-E de Bree, H.W. Haak , A.A Koers, Proceedings of the 9th International Meeting on Low Frequency Noise and Vibration, May 17-19, 2000, Aalborg, Denmark.

Paper with The Seismology Division of the Royal Netherlands Meteorological Institute (KNMI) about infrasound measurements. Here the Microflown was successfully used in a field test to detect sonic booms.

Application of a Microflown as a low-cost level-meter, J. van Honschoten, J. van Baar, H.E. de Bree, T. Lammerink, G. Krijnen, M. Elwenspoek, MME, France 1999.

Paper about the Microflown used as a level meter.

An electronical characterisation method for an acoustic and thermal flow sensor, J.W. van Honschoten**,** T.S.J. Lammerink, H.-E. de Bree, G.J.M. Krijnen, M.C.Elwenspoek, Transducers 2001.

Students that worked on the Microflown project

Bram Jansens (music) production, Herman Wirtz (marketing research), Vincent Kruijver (marketing research), André te Stroet (Add on Microflown), Marcel (anti noise automotive), Michiel Schubbe (anti noise automotive), Maik Meurs (Megaflown), Erik Dobbelstein (antinoise room acoustics), Phillip Ekkels (Germanium Microflown), Richard Gerrits (Low Frequency Noise), Mathijs ten Berg (mechanical engineering), Anton Oostveen (mechanical engineering), Sietse waanders (mechanical engineering), Teis Coenen (arrays), Dick de Gelder (arrays), Lodewijk van Hoesel (arrays), Boudewijn de Jong (arrays), Joost van Honschoten (Ph.D. student modelling), Istwaan Knijff (low frequency sound intensity), Doekle Yntema (low frequency sound intensity), Tjeerd Hans Terpstra (internet sales), Goswin de Boer (low frequency sound intensity), Gerard Rauwerda (low frequency sound intensity), Bob Hendriks (hearing aids market research), Pascal Dijkstra (sound intensity marketing research), Mathijs Kip (marketing research), Peter Leusink, Erwin van Klinken (electronics), Twan Korthorst (cleanroom techniques), Marc van Doornik (mechanical engineering), Martin van Es (fabrication of sensors), Niels Olij (acoustic measurements), Niels Moseley (DSP programming), Oene de Vegt (analogue filtering), Ke Chun Ma (research on sensing materials), Theo Veenstra (calibration and measurements), Vincent Pol (electronics), Huy Van Nguyen (mechanical engineering), Daniel den Arend (electronics), Sjoerd Oosterbaan (constant temperature principle), Jeroen Kruiver (constant temperature principle), Arnoud van der Wel (analogue filtering), Wilfred Beckers (mechanical engineering), Lude Bakema (electronics), Albert Wessel (electronics), Hanneke Vreugdenhil (simulations and modeling), Edwin Potman (DSP programming), Pedro Roodenburg (first measurements).