Ultrasonic Sensors in Air

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Abstract - Ultrasonic Sensors in Air are Intelligent Sensors, which use wave-propagation phenomena in air to measure physical or chemical variables. With accordance to the influence principle, two main types of ultrasonic sensors can be differentiated.

Propagation-Path Sensors decode changes on propagation to get a fast measurement of temperature, pressure variations or gas concentration. Most important are ultrasonic flow sensor e.g. for engine intake air or for air/gas measurement.

Distance-Sensors detect echoes from objects and evaluate their propagation time and amplitude. Examples are distance meters and presence detectors. By intelligent algorithms based on signal theory models or heuristic approaches (synthetic aperture, pulse holography, fuzzy or neural network etc.) the resolution and detection range were increased, the radial and lateral resolution significantly enhanced and objects recognized.

With piezoelectric PVDF-foils efficient and versatile transducers arrays were relized. Robust transducers for operation in adverse environment (dirt, moisture, abrasion) were developed using rugged matching layers or a special composite-transducer technology.

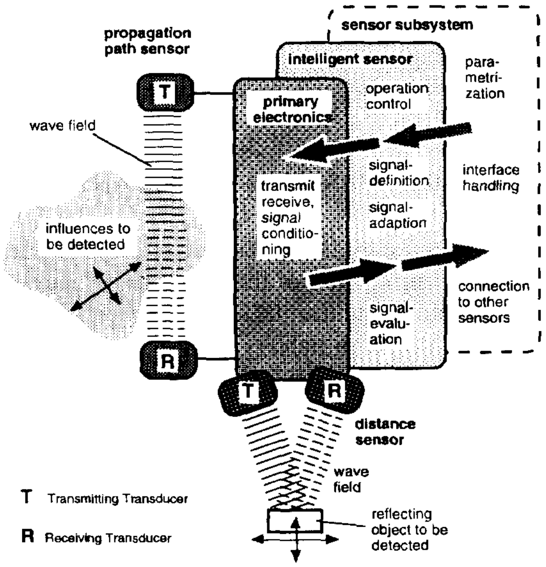

Fig. 1: Architecture of Ultrasonic Sensor Systems

INTRODUCTION

Sensors are the sensing organs of technical systems. They collect information about variables in the environment as well as on non-electrical system parameters, and provide the results as electrical signals. Sensors are an essential part of power generation and distribution systems, automated industrial processes, traffic management systems, as well as environmental and health maintenance systems. The development of sensors was stimulated by modern microelectronics. Even relative complex sensors, which previously could be realized only as scientific instruments [1], are now feasible as compact devices at low costs. Further, the proliferation of control systems opened a high application potential [2] for ultrasonic sensors .

Ultrasonic sensors in air are based on the medium which is always present everywhere men are, and without which human life is impossible. These sensors measure quantities, which often are immediately relevant for humans, such as the flow of air or short distances within a man´s reach. Moreover, these sensors imply generic approaches which could be used for other gases and even for liquids.

INTELLIGENT SENSOR SYSTEMS

Ultrasonic *sonar sensors* actively transmit acoustic waves and receive them later. This is done by ultrasonic transducers, which transform an electrical signal into an ultrasonic wave and vice versa. Often it is possible to use the same transducer for both transmitting and receiving. On its path from the transmitter to the receiver, the wave becomes modified by the situation under investigation (Fig. 1). The ultrasound signal carries the information about the variables to be measured. The task for the ultrasonic sensors is not merely to detect ultrasound. As *intelligent sensors* they have to extract the information carried by the ultrasonic signals efficiently and with high accuracy. To achieve this performance, the signals are processed, demodulated and evaluated by dedicated hardware. Algorithms based on models for the ultrasonic signal propagation and the interaction between the physical or

Ultrasonic Direct Sensors	Contact to transmitting transducers	**Contact of objects** **Acoustic Impedance, density**
	Reception of acoustic emissions	**Leak detection** **Orientation by correlation**
Ultrasonic Sonar Sensors Influence on ultrasonic transmission, transceiver system	**Ultrasonic Propagation Path Sensors** Influence on propagation time, phase and attenuation	**Volume and mass flow velocity in gases (drift effect), heat** **Determination/plausibility check of type and concentration of gases** **Transmission (ultrasonic barrier)** **Fast temperature measurement** **Dynamic pressure measurement** **Turbulence in Flow (Vortex-Meter)** **Density (r = Z/c)**
	Ultrasonic Distance Sensors Changing transmission configuration by reflecting objects	**Presence of stationary/moving objects** **Distance, position, level** **Characteristic object structure by partial echo separation, inverse filter, Fuzzy-classification, Neural network** **Lateral structure by correlation, synthetic apertur, holography** **Multi dimensional recognition** **Doppler: Motion, speed, flow velocity, path and speed over gound**

Fig. 2: Classification of Ultrasonic Sensors

chemical variables of interest are employed [3]. Furthermore, techniques of a *sensor specific signal evaluation* [4] are being applied. Previously known knowledge or experience, which is automatically "learned" by the sensor system, is used, including *fuzzy* or *neural network* techniques. Ultrasonic sensors can be embedded into a control system that accesses additional sensors, combines information of the different sensors, handles the bus protocols and initiates actions.

Depending on how an ultrasonic signal has been changed on its path from transmitting transducer to receiving transducer, *sonar sensors* can be divided into two types (Fig.2):

- the *distance sensor* (reflection) and
- the *propagation path sensor*

There are also *direct ultrasonic* sensors, which detect the *acoustic emission* of objects. Others are sensitive to the change of the properties of an oscillating transducer by the contact of different media. Even though important in some areas, those sensors will not be discussed here.

Distance sensors based on ultrasonic principles use the travel time and amplitude of the received signal (e.g. the echo) to derive the presence, distance, and type of a sound reflecting object. Intelligent evaluation methods allow target objects to be recognized and classified. Furthermore, lateral details can be recognized by introducing defined relative movements between the sensor and the object.

In the case of *ultrasonic propagation sensors*, the effect of the tested variables on the transmission is evaluated. Here, the parameters that are affected are the speed of propagation, local changes of propagation (diffraction and refraction), directional and frequency dependency (anisotropy and dispersion), propagation attenuation, acoustic impedance, scattering and wave guiding coefficients.

ADVANTAGES AND DISADVANTAGES

The main advantages of ultrasonic sensors are due to the continuous interrogation of the quantities of interest by a wave field and the immaterial sensing principle. These are

- Excellent long term stability,
- low power consumption and low cost realization.

In particular, the advantages of ultrasonic distance sensors are:

- directional sensitivity,
- high structural resolution due to large bandwidth,
- remote measurement, low interference with objects to be detected, sensitivity to virtually all kinds of objects,
- imperviousness to wetness, contamination or wear.

Ultrasound has the property, that its velocity is strongly affected by the flow velocity of the fluids in which it propagates. This drift effect is the basis for high resolution flow sensors, the most important propagation path sensors which have a number of advantages:

- high accuracy, high linearity, rapid response,
- applicable for a wide variety of gases and liquids
- integration along the entire sound path,
- proper recognition of the flow direction,
- high sensitivity to temperature and to properties of fluids.

Deficiencies of ultrasound systems are often associated with properties that are advantageous at other times, such as the effect of temperature and material composition on the speed of sound. The effect that ultrasound attenuation increases with frequency, limits the measurement distance compared with optical or microwave based sensors. However, in these cases lower frequencies can be selected, at the expense of reduced structural resolution, and higher sensitivity to acoustic interference noise. On the other hand, interference noise can be effectively suppressed by the high propagation attenuation in air.

ULTRASONIC FLOW SENSORS

The measurement of the volume flow velocity and of the mass flow velocity is of high importance for a variety of applications. In the industrial process technology, for instance, flow is the most important parameter after temperature and pressure. Further examples where flow plays an essential role, are the human respiration, the intake air of internal combustion engines, the gas for heating homes and for cooking. For all these application, there is a trend to robust and accurate electronic measuring devices without moving parts and with minimum obstruction of the flow. Besides ultrasonic flowmeters only thermal methods, i.e. hot wire meters or hot film meters, and vortex meters are in accordance with this trend.

For ultrasonic flow meters, various methods have been realized. The *aberration* of a transversal ultrasonic beam by the flow and the use of correlations techniques [5] are useful only for special cases, rather than being applied generally. When Doppler methods are used, it is difficult to determine in which partial volume of the measuring tube the actual measurement takes place. For this reason, Doppler flow measuring methods normally suffer from a limited accuracy apart from being dependent on scattering particles in the fluid, such as impurities. Also, the vortices which are shedded from a disturbing rod in the measuring tube like from singing telegraph wires and whose frequency is proportional to the flow velocity, can be detected and counted by ultrasound. Problems are that there is only a unidirectional measurement possible, and, that the vortex frequency can be severly disturbed by locking to the frequency of pulsations in the pipe [6].

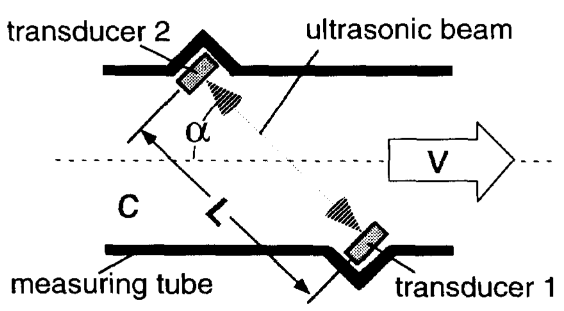

Fig. 3: Principle of ultrasonic flow measurement.

High accuracy results, however, are achieved by the drift-effect, which makes the direct ultrasonic measurement of the flow velocity possible [7]. This means that the ultrasonic waves are transported by the flowing medium. The principle for the measurement of the flow in a pipe by ultrasound is shown in Fig. 3. The time required for sound to travel between two ultrasonic transducers set at the distance L from one another depends on flow velocity v, the speed of sound c, and the angle α between the direction of flow and the direction of sound propagation.

$$v = \frac{L}{2\cos\alpha}\cdot\left(\frac{1}{t_2}-\frac{1}{t_1}\right) = \frac{L}{2\cos\alpha}\cdot\left(\frac{t_1-t_2}{t_1 t_2}\right)$$

For the calculation of the mean value of the flow velocity, besides the known constants of the measuring tube, only the difference of the reciprocals of the propagation time in the both directions is required. These reciprocal times can be measurable directly as repetition frequencies of the so called "Sing-Around-Method". In the moment of reception of an ultrasonic pulse the transmission of a further pulse becomes triggered and so on, thus the repetition frequency $1/t_1$, or $1/t_2$, depending on the direction of transmission, is achieved. This repetition rate can be stabilized by a so called "electronic flying wheel", which triggers the transmission, if occasionally a pulse fails to be received. This is done by an oscillator, which is locked to the repetition frequency by a phase lock loop. Presently those methods are obsolete, as the travelling time of the ultrasonic signal is measured directly and the appropriate calculations can be done easily by a microcomputer. The flow velocity measured by the ultrasound, however, is the *volume flow* velocity, i.e. the transported volume per unit time, rather than the *mass flow* velocity.

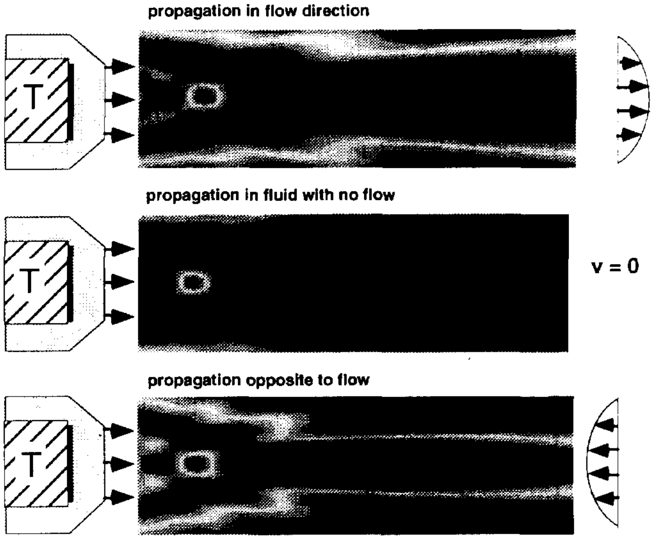

Fig. 4 : Simulation of sound pressure distribution in an ultrasonic flow measuring tube, with flow in different directions and without. Coaxial sound radiation (T ultrasonic transducers).

PROBLEMS OF FLOW MEASUREMENT

In spite of many important advantages, ultrasonic flow measurement is often considered as unreliable and of less accuracy. A reason for this underestimation is that people often do not differentiate between the different methods and for example transfere difficulties of the Doppler method to ultrasonic methods in general. Furthermore, meters with non satisfying properties were built in the past due to the insufficient knowledge of the physical effects which are relevant for the ultrasonic flow measurement.

In pipes, the flow velocity can differ locally as a result of turbulence. The measured value is a mean of the local speeds occurring along the path of the ultrasound signal. It is generally different from the actual mean speed in the pipe, particularly in the case of low flow velocities with laminar flow profiles.

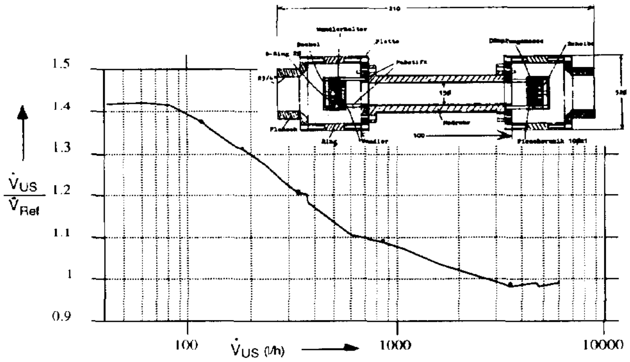

Fig. 5: Error curve of flow meter with a coaxial arrangement of the ultrasound propagation.

Additional causes for an improper function are refractive effects of the flow profile, which affect the ultrasound like lenses. Combined with wave guiding properties of the measuring tube, these refractions give improper results particularly when a coaxial sound radiation us used. As an illustration (Fig. 4) the results of a simulation are presented in which the sound pressure distribution in a coaxial measuring tube was calculated as a function of the flow direction. Figure 5 shows the calibration curve with air in an ultrasonic flow meter with a coaxial arrangement of flow an ultrasound propagation.

A further effect, which reduces the accuracy, is the so called "Zero Flow" error. Due to unsymmetries between the two directions of the ultrasonic path even at non flow there are measured slightly different values t_1 and t_2 of the propagation time. This fictitious small flow superimposes the actual flow causing at low flow velocity with decreasing flow a drastically increasing error.

Namely, for low fluid flow velocities the typical propagation time differences are of the order 10 - 100 ns. To achieve the required accuracy of 1%, these differences must be determined up to an accuracy in the subnanosecond range (50 ps - 1 ns). For operating frequencies between 100 kHz and 2 MHz this is an inherently ambitious task. Zero flow errors are brought about by deviations between the propagation time in different direction mainly caused by nonsymmetric properties of transducers and electric circuits on the

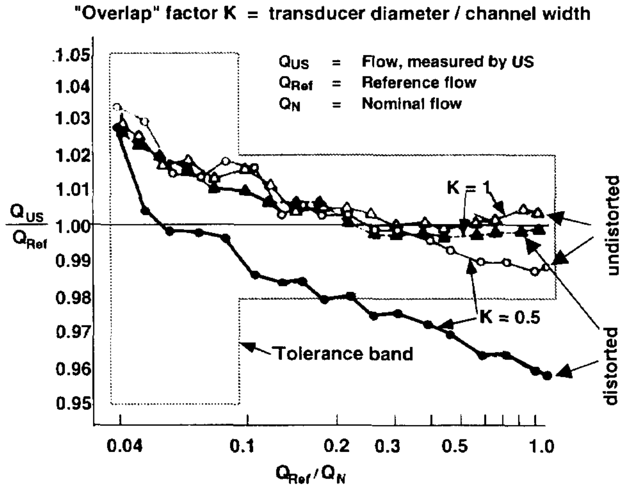

Fig. 6: Characteristics for an ultrasonic flow measuring tube, with normal transducer arrangement (k=1) and with apodized transducer (k=0,5), at undistorted and heavily distorted flow

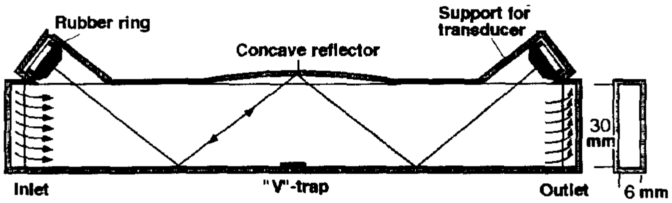

Fig. 7: Measuring tube configuration for an ultrasonic gas meter

transmitting and receiving side. Strict requirements for the uniformity of transducers raise costs and cannot be maintained for long periods of time due to different aging. In principle, the symmetry of the transducers would be of minor importance, if the design of the whole measurement arrangement is in accordance with the reciprocity theorem (Helmholtz 1860):

"If in a region, which is partly bounded by extended solid walls and partly unbounded, sound is generated in point A, the velocity potential in point B is equal to that potential, which would occur in A, if the same sound excitation is applied at B".

In practice, however, strict reciprocity is difficult to maintain.

INDEPENDENCE FROM FLOW PROFILE

To eliminate the influence of the velocity profile, for measurement tubes of large nominal diameter several sound paths can be placed in such a way that the influences of flow profile differences and of flow disturbations are suppressed [7]. The problem is posed by the fact that sound paths near the middle of the tube measure too much flow in the case of a laminar profile, while paths near the walls measure too little. The sensitivity of other paths lies in between.

For small diameters, it is hardly possible to arrange several soundpaths side by side, because of lack of space for the ultrasonic transducers and above all, because wall reflections and waveguide effects prevent the formation of line-shaped paths. For small measuring tube diameters, a broad sound beam can be generated instead, which fully fills the width of the retangular measurement tube. Goal is to let all parts of the flow profile contribute to the result of the measurement according to their part of the cross-sectional area. This integration over the complete flow profile maintains the ultrasonic flow measurement independent of the flow profile and flow disturbances.

The efficiency of such an arrangement was demonstrated experimentally using an ultrasonic measuring tube with a broad sound beam which was designed for a heat meter [8]. A highly disturbed flow was generated by a half-closed stop valve directly at the inlet side of the measurement section. For well-installed ultrasonic transducers, hardly a deviation was observed compared to undisturbed operation. For transducers with a partly shaded surface, flow disturbations caused evident measurement errors (Fig. 6).

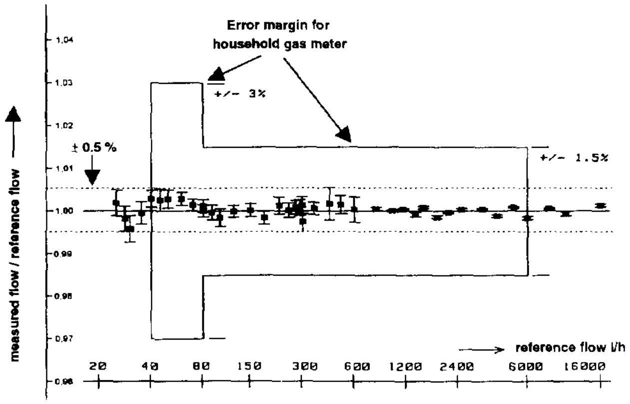

Fig. 8: Corrected calibration curve of a laboratory prototype of an ultrasonic gas meter

HIGH ACCURACY OVER A WIDE RANGE

While developing an ultrasonic gas meter for the measurement of gas consumption in households, first the previously mentioned coaxial measurement arrangement with a cylindrical tube was investigated (Fig. 5). With this arrangement, the waveguide properties of the tube and diffraction by the flow profile turned out to yield strong nonlinearities, which depend on the type and temperature of the gas and therefore cannot be corrected. For a W-shaped sound path in a measurement tube with a slim retangular cross section very good results were achieved (Fig. 7). In this case the diameter of the transducer exceeds the width of the rectangle and the sound beam fills up the cross section very well [9].

Selection of the intended sound path is achieved by using short sound pulses with high initial slope. Parasitic sound paths, which contribute disturbing signals, were suppressed by a special design of the measuring tube. By use of ultrasonic transducers of high quality and uniformity and by a strong effort to design electric circuits conforming to reciprocity, the zero flow error was kept small.

The procedure described led to excellent results. Fig 9 shows the measured characteristic curves for six combustible gases, which in some cases differ extremely with respect to sound velocity and absorbtion. Practically the same calibration curve is achieved with air. These results proved that air can be used for calibration without

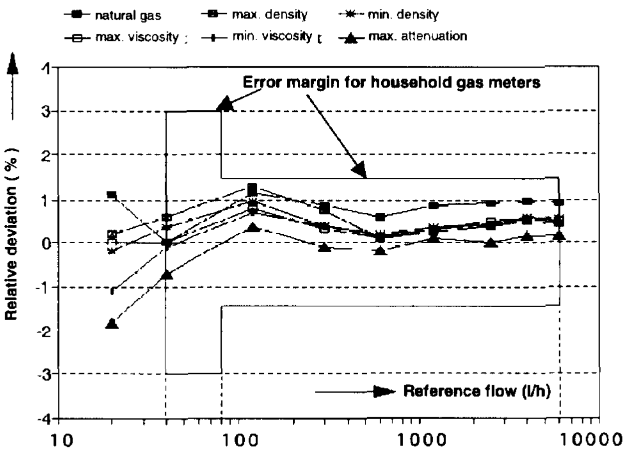

Fig. 9: Calibration curves of the ultrasonic household gas Meter for different gases

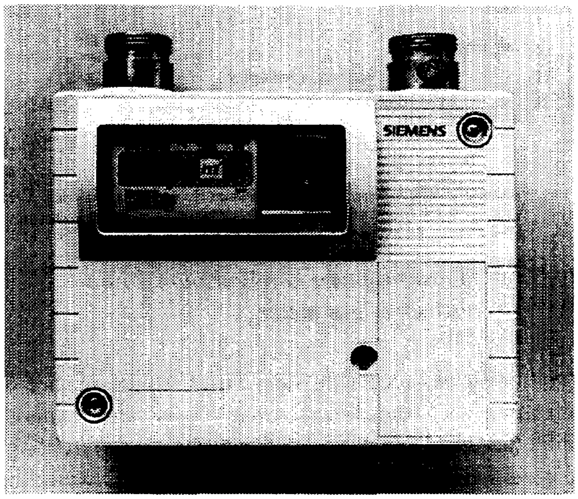

Fig. 10: Ultrasonic household gas meter

the necessity for expensive test stands operating with combustible gases. Fig. 8 shows the corrected calibration curve of a laboratory prototype constructed and adjusted carefully. Data was measured for nitrogen using a precision volume displacement flow testbench as a reference. Within a range of 1:1000 i.e. from 20 l/h to 20000 l/h the error of the measuring tube is less than 0.5 % compared to the reference value. The pressure loss at the upper end of the specified measurement range (6 m^3/h) is less than 2 mbar.

Based on the measuring tube described above an ultrasonic gas meter [9] was developed which has the ability to replace the conventional gas meter in the future (Fig. 10). In Great Britain, the ultrasonic gas meter has already been approved to be used as a household gas meter. The ultrasonic gas meter is battery-operated. A single lithium cell (D-size) has sufficient capacity for ten years of operation. This impressively illustrates the extremly low energy consumption of the ultrasonic flow meter principle.

FAST RESPONSE TO PARAMETERS OF AIR

The rapid response time and the flow direction recognition of ultrasonic flow measurement methods are important for *air mass meters* [10] which are to measure the intake air flow of internal combustion engines (Fig. 11). In pulsating and reversible flows, ultrasonic sensors prove to have a faster response time than hot-wire and hot film sensors. Fig. 12 demonstrates this by comparing the results obtained with an automotive hot wire sensor, a fast hot wire sensor (too delicate to be used permanently in engines) and the ultrasonic sensor. Both, the laboratory type hot wire and the ultrasonic sensor show a considerably faster response. In addition, the ultrasonic sensor correctly evaluates the reversed flow, whereas the thermic sensors respond only to the absolute value of the flow. These advantages open a new technical potential for improved fuel injection systems that can manage individual cylinders and transient loads. By fast injection valves an air acompanying fuel injection can be done in accordance with the air actually passing the injection valve. Thus, a predetermined distribution of the gasoline/air mixture (homogeneous or stratified charge, cylinder and cycle specific) at the moment of ignition, becomes feasible as a key factor to lower consumption and cleaner exhaust.

The measured volume air flow can be transformed to a mass flow of the air by the multiplication with the density. For this calculation the temperature and the pressure must

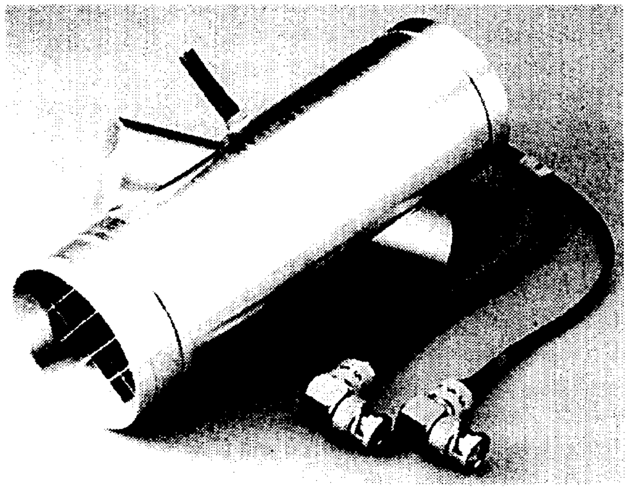

Fig. 11: Ultrasonic intake air flow meter for internal combustion engines (laboratory prototype)

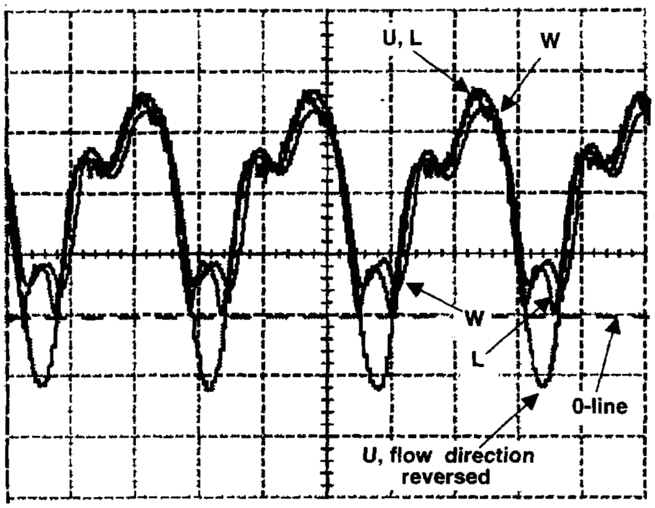

Fig. 12: Response to pulsations of different air flow meters U = ultrasonic meter, W = hot wire meter, L = lab type hot wire meter

be known. Wheras the temperatur can be got from the ultrasonic flow measurement, as discussed later, the pressure could be measured by an additional pressure sensor. However, as the atmospheric pressure varies very slowly, in an engine management system the air density can be estimated from the atmospheric pressure based on a large time constant evaluation of the exhaust sensor results. As an advantage this method will work also with changing gasoline quality. Such ultrasonic air mass meters have intrinsicly an excellent long term stability, are inexpensive to build and do not require an individual calibration.

Ultrasonic flow meters can be used not only to measure the flow velocity, but also to obain information about additional quantities. For example, an important quantitiy is the sound velocity of the flowing medium. During ultrasonic flow measurement, it can be determined with high precision from the sum of the propagation times. The speed of sound is a characteristic parameter for the type and status of the medium in the measuring tube. Plausibility considerations, whether the measuring tube contains the right type of medium, are thereby supported efficiently. For mixtures of gases with different speeds of sound, e.g. gasoline vapour in the air of an intake air flow meter for an internal combustion engine, the concentration of the vapour can be determined (Fig. 13). The sensitivity of this method increases with larger variations of the speed of sound in the various media. An ultrasonic concentration sensor was successfully employed as a key component in a laser printer with a novel method for fixing the toner particles to the paper using the vapour of an organic solvent.

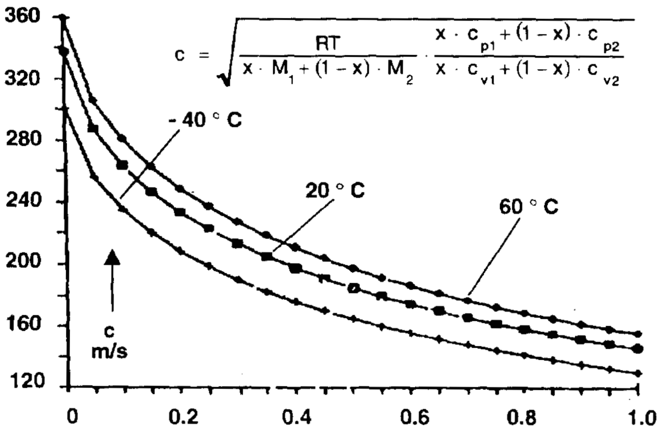

Fig. 13: Speed of sound as a function of gasoline vapour concentration

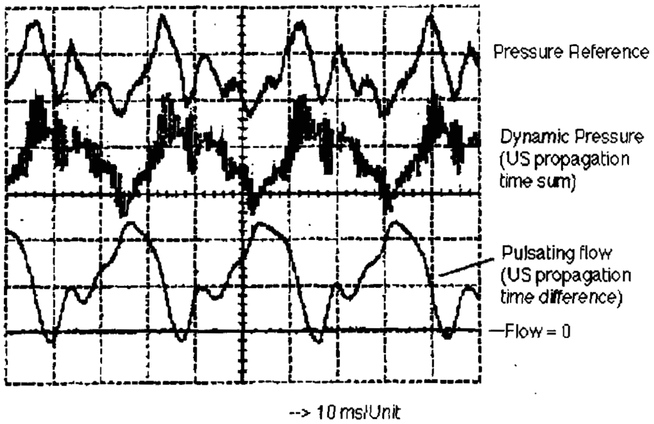

Fig. 14: Measurement of fast pressure variation in the ultrasonic air flow meter

In media with a known relationship between the speed of sound and temperature, particularly in gases or gas mixtures with known composition, the determination of the actual speed of sound makes a precise and fast temperature measurement possible (typical risetime 1 ms or less). Thus, even at a distance of about 10 cm from the outlet valve, the the temperature variations of hot exhaust gases (mainly nitrogen) of an internal combustion engine were measured with high time resolution. However, for the intake airflow sensor and other gas measuring devices, it can be useful to deploy an additional low cost temperature sensor in the measuring tube. This can increase the accuracy of the above mentioned estimation of the type of medium or the composition of mixtures. Given the knowledge of the type of medium and its thermal capacity it is possible to determine the heat transfer which is associated with the volume flow. By deploying an additional temperature sensor at a different position in the same tube system the heat loss between the two temperature sensors can be determined, for example in the previously mentioned heat meter.

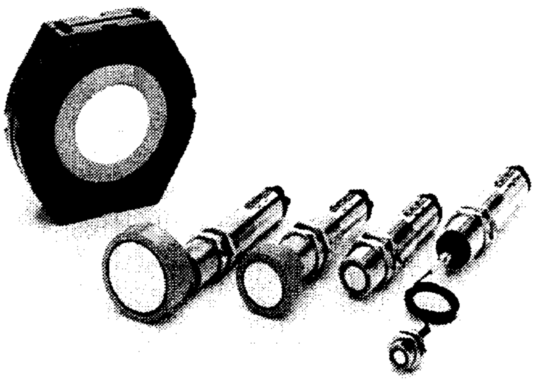

Fig. 15: Ultrasonic presence detectors for operation frequencies of 60-400 kHz

In gases, pressure has very little influence on the speed of sound. However, fast adiabatic pressure variations are associated with temperature variations and therefore accessible for the ultrasonic measurement. Fig. 14 shows the results of such a measurement of pulsating air flow in an ultrasonic air mass sensor compared to a conventional pressure sensor.

INTELLIGENT DISTANCE SENSORS

Ultrasonic Distance sensors are used to detect the presence and distance of objects. They do so by evaluating the echo of a transmitted pulse with concern to its travel time. Time dependent control of sensitivity is used to compensate the distance dependency of the echo amplitude, while different reflection properties are compensated by an automatic gain control, which holds the average echo amplitude constant. Echo amplitude therefore has very little influence on the accuracy of the distance measurement, provided the signal to noise ratio is not very low.

By considering whether the echo has been received within a time window, i.e. a time interval, which can be preset by the user, the distance range is given in which the sensor responds to the presence of an object [11]. Accordingly, two or more different time windows can be defined and their results, i.e. whether an object is present (logical high state H) or not (logical low state L), can be analyzed by Boolean operations. Using this technique, interference can be supressed and relevant objects are monitored more reliably. Fig. 15 shows a variety of such ultrasonic presence sensors with different operation frequencies, which are designed for different distance range and different local resolution. Such sensors are employed in the automation of industrial processes as well as in traffic control systems; for example, to monitor, whether car parking places are occupied. Ultrasonic distance meters are used for the measurement of the filling level in containers or

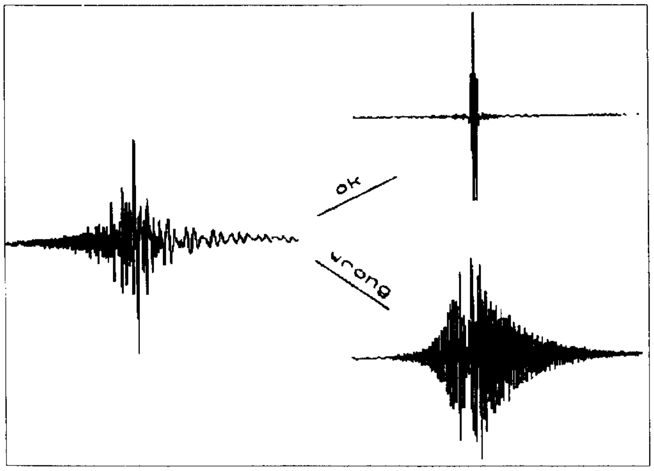

Fig. 16: Fast object recognition with inverse fitered ultrasonic signals. a) transmitted signal, b) response from right object, c) reponse from wrong object.

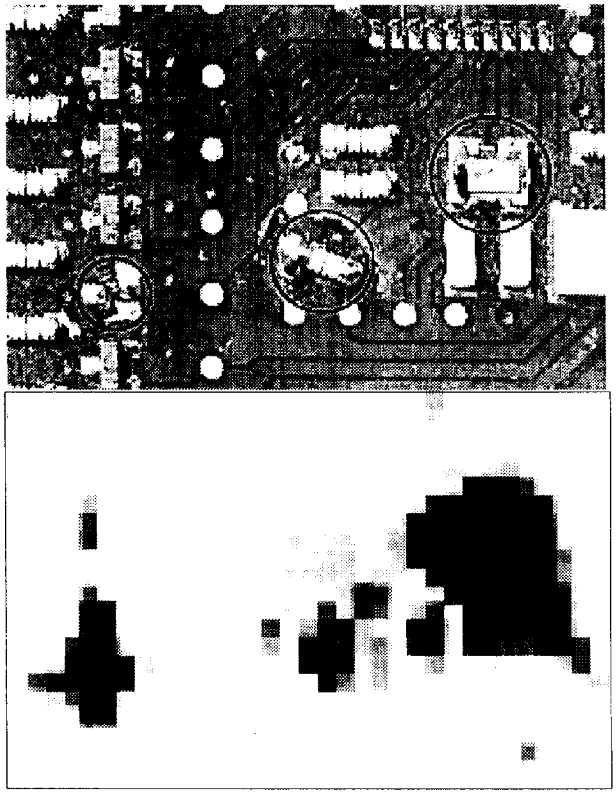

Fig. 17: Recognition of defects in a printed circuit by fuzzy evaluation of correlation functions.

the height of material on conveyor belts. To measure the level of liquids or bulk materials in containers, a high performance level meter was developed, which uses Fuzzy logic, rather than Boolean, to filter the echo for the content level from a large number of interfering echoes, which are caused by stationary or moving disturbing objects or by multiple reflections [12]. This was facilitated by a recently developed low cost fuzzy coprozessor (SAB 81C99, for 8051 microcontroller systems), which is able to evaluate a large number of rules in a short time [13]. In our level meter this coprocessor, which is based on an original concept from Siemens Research Department, was first used in intelligent sensor analysis, and now provides rapid and efficient processing of fuzzy algorithms. For future *personal robots*, which automatically do household work, e.g. vacuuming, intelligent ultrasonic distance sensors is the best choice for navigation and collision avoidance [14].

OBJECT RECOGNITION

Distance sensors operating in air and using broadband ultrasound transducers [15] achieve a high local resolution in the direction of sound propagation, which can be greatly enhanced by analog/digital conversion of the whole high frequency signal, which is received by the receiving transducer and storing this so called *echo profile* in the memory of a (micro)computer for further digital signal processing. By merely comparing the stored echo profiles of a reference situation and an actual situation, it can be determined, wether the actual situation corresponds to the reference. In the case of echo profiles, which are derived from the superposition of echoes of partial objects, digital signal processing allows partial echo separation [16]. The resulting pattern depends on the amplitude and relative positions of the objects and represents a kind of an acoustic fingerprint, based upon which objects consisting of partial objects can be recognized.

In order to achieve rapid object recognition, so called inverse filtered excitation signals are transmitted, which are adapted to a specific object as a key is to a lock [3] (Fig. 16). These signals are calculated using convolution integrals, from the echoes of test pulses, which are targeted at the object in a learning phase. When these signals are transmitted the correct object will produce a short pronounced echo pulse that can be rapidly identified by simple means without the need for further calculation and is easily differentiated from the echoes of "incorrect objects". This procedure has been implemented using optimized calculation routines on a standard 8-bit microcontroller. After a learning phase of only 3 seconds the object is reliably recognized within milliseconds.

By using transducer arrays or a moving transducer, lateral structures that would normally be indistinguishable to standard ultrasonic sensors can also be scanned [17]. The use of composite transducers characterized by broadband frequency properties, wide angle radiation and the employment of pulse holographic techniques, achieves structural resolutions of less than 1 mm in both axial and lateral directions [18] [19]. Frequency domain evaluation methods were successfully employed to obtain a position and orientation invariant object recognition and classification [20].

Ultrasonic echo profiles pertaining to different parameters can also be processed by fuzzy logic. By a fuzzy based evaluation of the correlation functions of reference signals and actual signals from a printed circuit board under test assembly defects can be recognized and classified [21] (Fig. 16). At the UFFC ´94 conference a paper will be presented which describes the application of a *neural network* technique for the position invariant recognition of small objects using a transducer array [22].

ULTRASONIC TRANSDUCERS

The most important parts of any ultrasonic sensor are the transducers. The temporal (or spectral) and spatial radiation characteristics of these components are the prime determinants of sensor performance. Such transducers must have the following characteristics:

- robust design, full enclosure smooth and stable radiating surface, low sensitivity to contamination and wetness,
- high efficiency, high transmission level, high reliability, good receiving sensitivity,
- large bandwidth ensures rapid signal build-up and fast

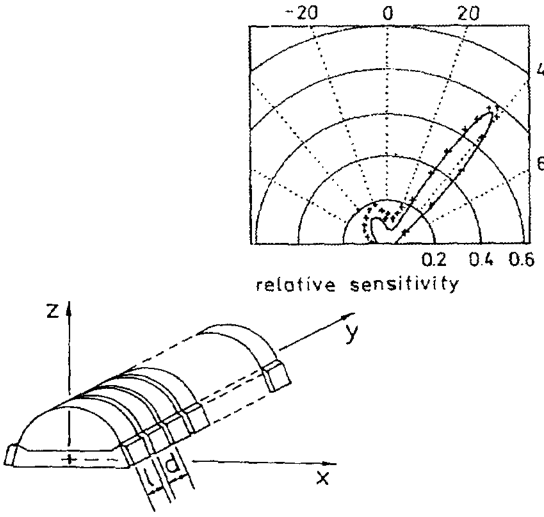

Fig. 18: PVDF-transducer array, design and radiation pattern, when operated as phased array

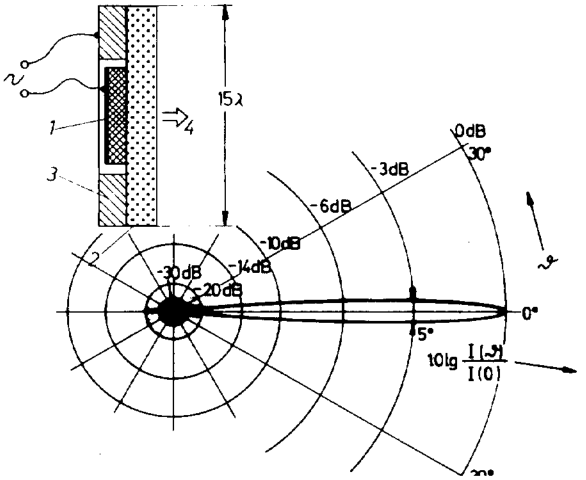

Fig.19: High directivity ultrasonic transducer: radiation pattern and design principle. 1) matching layer, 2) piezo-ceramic, 3) metal ring, 4) main lobe

decay after transmission stop and provids high local resolution,
- application specific directional characteristics with good suppression of side lobes.

For operation in air, no single transducer fulfills all of the above mentioned requirements optimally. Electrostatic foil transducers which have excellent acoustic properties in air, are of limited use because of their sensitivity to wetness and contamination. Transducer made from a piezoelectric PVDF-foil [23] have also a broad bandwidth and a lower impedance than electrostatic transducers. PVDF-transducers consist of a part of a cylindrical wall and transform vibrations which are excited by the transversal piezo-effect to a large area displacement. These can easily configurated as transducer arrays (Fig. 18) which can be operated as phased arrays with electronical steering of the radiation pattern.

Transducers made from solid piezoceramic or magnetostrictive materials are robust, but due to the high acoustic impedance of these materials are principally inefficient for the operation in gases. The acoustic matching of these solid materials to particular gasses can be substantially improved by applying transforming layers of materials with low acoustic impedance as in the case of the so-called RU transducers (Fig. 17). These transducers [24] have a high directivity and can be designed in the 30-500 kHz range and at a frequency, which is predetermined by their individual geometrical dimensions. They are ideal as high speed industrial sensors for measuring distances, level heights and similar parameters. Such transducers are also suitable for ultrasonic air or gas flow velocity measuring devices, for example in an automotive intake air mass meter. Transducers with rubber-like materials as matching layers are realized with good efficiency for airborne ultrasound in frequencies up to 1MHz [25].

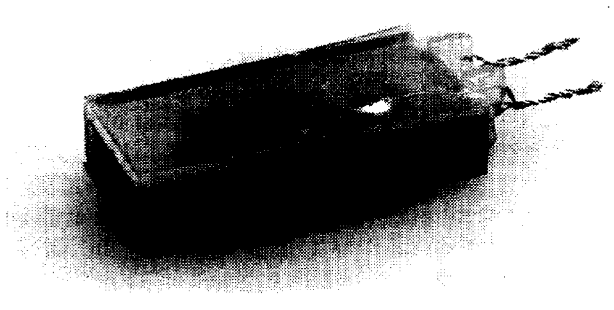

Fig. 20: L2QZ-Transducer

Promising materials for the acoustic matching to air and gases are *aerogels* which have a relatively low density (300 ... 2000 Kg/m^3). By the use of aerogels which can be described as gels in which air replaces the water as a second matching layer transducers of the previously described type were improved considerably in their efficiency/bandwidth-ratio. The instability of aerogels in the presence of water were successfully eliminated [26] but further research is to be done, to obtain aerogels which are also stable in the presence of organic solvents.

Using a stack of thin piezoceramic sheets and plastic material in between robust transducers for airborne ultrasound were constructed. These so called L2QZ-transducers (low Q-factor, low Z) show a relatively high bandwidth allowing short ultrasonic signals to be transmitted and received, providing a good local resolution [17].

CONCLUSIONS

Evidence has been given that a lot of different ultrasonic sensors can be developed for operation in air. By examples, it was shown that for many important applications these sensors are a good choice. Topics for future research and development work comprise:
- advanced physical models and algorithms to improve the sensor functionality and accuracy,
- application of digital signal processors to provide improved sensor signal evaluation at competitive costs,
- extension of the intelligent ultrasonic sensor concept forming a decentralized multiple sensor system with bus communication capabilities.

The application potential for ultrasonic sensors is apparent in many areas, for example in private housing, health care, environment protection, traffic and automotive control or industrial process control. In the future, ultrasonic sensors with improved functionality will continue to expand their applications.

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