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Film Sensors for the Harsh Environment Application

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***Abstract*—**A capacitance level sensor with a segmented film electrode and a thin-film volume flow sensor with an innovative by-pass sleeve is presented as industrial products for the application in a harsh environment. The working principle of such sensors is well known; however, the traditional sensors show some limitations for certain industrial measurements. The two sensors presented in this paper overcome this limitation and enlarge the application spectrum. The problem is analyzed, and the solution is given. The emphasis of the paper is on developing the problem-solving concepts and the realization of the corresponding measuring circuits. These should give advice and encouragement, how we can still develop electronic measuring products in an almost saturated market.

***Keywords*—**By-pass sleeve, charge transfer circuit, fixed **ΔT** circuit, harsh environment, industrial application, segmented electrode.

I. INTRODUCTION

IN this paper, the development of two competitive sensor products for the “harsh environment” application in industry are presented. The first sensor is related to level measurement. Capacitive measuring principle has been used for a long time by determining the levels for wide variety of solids, aqueous and organic liquids, as well as slurries [1]. Nowadays there are as many capacitance level sensors on the market as there is sand at the sea. Nevertheless, we can still do something new here to enlarge the product spectrum, like the presented capacitance level sensor with segmented electrodes for the application in harsh environment [2]. The second example, also for the application in harsh environment, is a thermal volume flow senor with an innovative bypass sleeve [3]. The sleeve directs a partial laminar volume flow from the main volume flow, ensuring an accurate measurement and at the same time enlarging the measurement range. In addition, a fluid temperature independent ΔT measuring circuit is developed to measure the partial volume flow. The two sensor developments are presented in the order working principle, the problem and the solution, with emphasis on developing the problem-solving concepts and the measuring circuits.

II. A CAPACITANCE LEVEL SENSOR WITH SEGMENTED ELECTRODES

A. Working Principle

The principle of capacitance level sensor is based on measuring the change of capacitance of a plate capacitor. Such a capacitor is formed when a level sensing electrode is installed in a tank. The metal rod of the electrode acts as one plate of the capacitor and the tank wall (or reference electrode in a non-metallic tank) acts as the other plate.

As level of the medium in tank rises, the air surrounding the electrode is displaced by medium. A change in the value of the capacitance takes place. As all the materials have a larger dielectric constant than air, the value of the capacitance increases with the level of the medium in tank. By measuring the capacitance, the level of the medium in tank can be determined.

B. The Problem

When the capacitance level sensor is used in a so-called “harsh environment”, for example, measuring the lubricating oil in "off shore" wind power turbine, errors could occur due to the influence of the environment:

a) In the nights of cold winter, the temperature can drop to minus 20 ~ 30 ˚C, under such a low temperature the oil in tank becomes as thick as honey and sticks to the electrode rod (Fig. 1).
b) The dielectric constant of oil (normally 2 ~ 4) could be increased due to penetrated moisture, as water has a much larger dielectric constant (80) than oil.

Both influences lead to an increase in the dielectric constant of the capacitor physically (a) and chemically (b), as a result the measured capacitance is larger and the corresponding oil level is higher than what it is in reality.

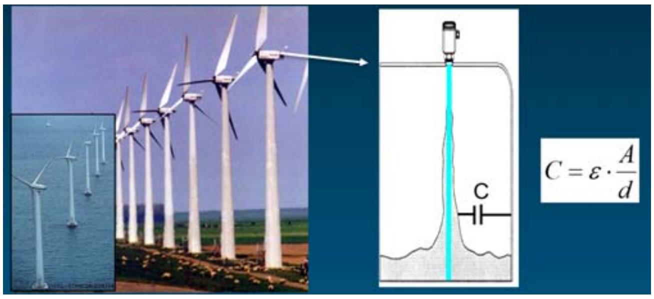

Fig. 1 Problem occurring of capacitance level sensor applied in wind power turbine

C. The Solution

This problem can be solved with an innovative design of the level sensor, namely the capacitance level sensor with segmented electrode. In this design, the sensor electrode is divided into a plurality of in the immersion direction equidistantly arranged small rectangle sections (the segmented electrode). Each section works as an individual electrode. The segmented electrode is screen printed on a flexible polyimide film support (Fig. 2 (a)); the film support is then clamped onto an internal tube which is elastically deformable and inserted into the sensor tube. After filling the internal tube with foam, the segmented electrode is stably in contact with the inner side

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of the sensor tube (Fig. 2 (b)).

In order to measure the very small capacity with a high resolution, a measuring circuit is developed based on “charge transfer” principle [4]. Fig. 3 illustrates the working principle of the charge transfer measuring circuit. The measuring capacity C_X is first charged to a fixed voltage with the switch S_1. This creates a charge Q_X on the capacitor. Then the capacitor is discharged via the switch S_2. The charge Q_X is completely transferred into the collecting capacitor C_S. By repeating this transfer process several times, the charge to be measured accumulates on the collecting capacitor C_S.

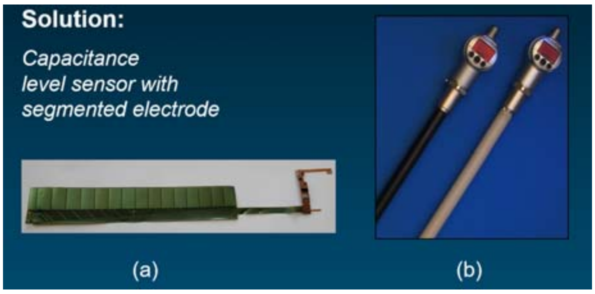


Fig. 2 Capacitance level sensor with segmented electrode: electrode arrangement on flexible film with charge transfer measuring circuit (a) and photo of the finished sensors (b)

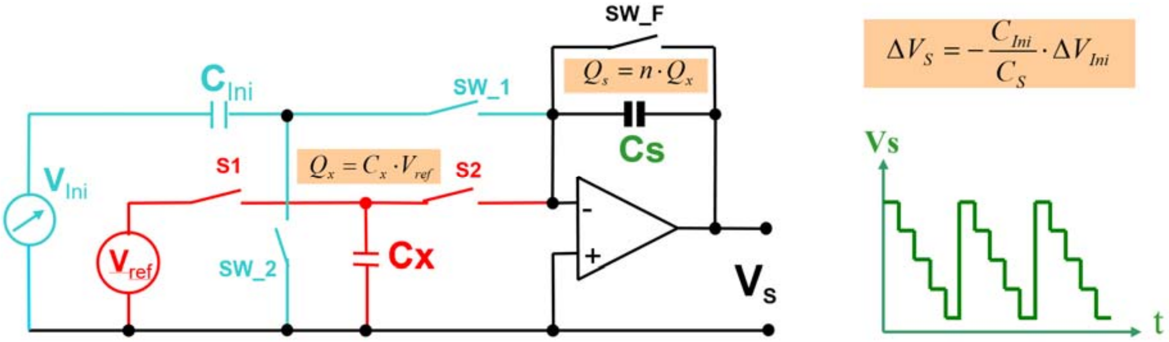


Fig. 3 Charge transfer principle for measuring the small capacitance of segmented electrode

During the evaluation, a suitable offset value can be determined for the entire load and only the deviation from this offset value will be considered. In this way, the resolution is increased.

Another capacitor C_{ini} is used to initially set the output voltage to a positive value. Every charge transfer causes a negative voltage swing. The output voltage thus gradually decreases. The levels of the output voltage are counted by the microcontroller and used to calculate the capacity.

The charge transfer measuring circuits are realized with only few electronic components, as shown in Fig. 3 (b). The switch S_1 is implemented per software by the microcontroller; the voltages on the capacitors C_X and C_{ini} are also given from microcontroller via D/A converter.

By the measurement, the individual electrodes will be switched in alternation to the charge transfer measuring circuit as measurement electrode. All other electrodes which are not switched as the measurement electrode are counter electrodes and switched to the ground potential. Fig. 4 shows the measured capacitance of each individual electrode with the increasing level of hydraulic oil in a tank. The characteristic change of capacitance in all electrodes due to the symmetrical arrangement is essentially identical. The difference of the capacitance value between the “not immersed” and the “immersed” state of the electrode E1 to E5 is approximately 2 pF at a base capacitance of approximately 150 pF. This capacitance difference is mainly dependent on the dielectric constant of the liquid. In polar liquids, such as water, it is greater than in nonpolar liquids, such as oil.

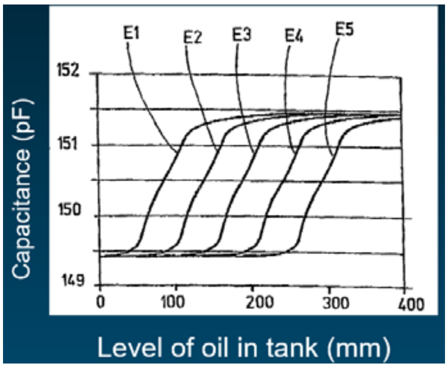
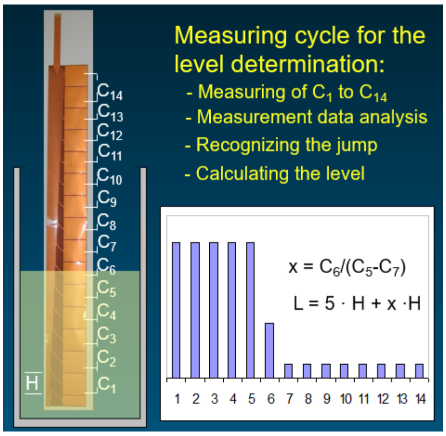


Fig. 4 Characteristic of the measured capacitance of five section electrodes

The level is determined in four steps, as shown in Fig. 5. In the first step, the capacitances of all the individual electrodes are successively measured. In the second step, the individual electrodes are classified into “immersed”, “not immersed” and “partially immersed” using the stored reference values for different mediums. In the third step, a linear interpolation takes place for determining the level in the area of partially immersed electrode. The accuracy attainable in this more or less analogous determination step depends on the height of the individual electrodes in the immersion direction. In the last step, the level will be mathematically determined by adding the total length of the immersed electrodes (here 5 x H) and the height of the in the immersion direction partially immersed electrode (a fraction of H).



Measuring cycle for the level determination:
- Measuring of C_1 to C_{14}
- Measurement data analysis
- Recognizing the jump
- Calculating the level

$x = C_6/(C_5 - C_7)$

$L = 5 \cdot H + x \cdot H$

Fig. 5 Algorithm for level determination of the sensor with segmented electrodes

III. A THERMAL VOLUME FLOW SENSOR WITH A BY-PASS SLEEVE

A. Working Principle

The hot-wire anemometry has been widely used in measuring the velocity of gas and liquid flow. The sensor, in form of a thin wire (typically 2.5–5 µm in diameter) or a film, is soldered between prongs and inserted into the flow [5], [6]. The measurement principle is to control the current to the hot-wire, so that its resistance – and hence the temperature – is kept constant, independent of cooling imposed by the fluid. The required heating power is a measure of the velocity. Alternatively, two temperature sensors can be arranged spaced apart, preferably one behind the other in the flow direction, in this case the occurring temperature difference is a measure of the flow velocity.

B. The Problem

By application in “harsh environment”, for example, for volume flow measurement in hydraulic systems, the wire sensor could be damaged due to the very high pressured, quick and strong inflow in hydraulic oil pipes [7], [8].

C. The Solution

A thin-film sensor chip with an innovative sleeve for a by-pass measurement is developed for the application in hydraulic systems (Fig. 6). The sensor chip consists of two CrNi thin-film resistors fabricated as a half-bridge circuit on an Al_2O_3-substrate; the 500 Ω resistor works as a heater and the 15 kΩ resistor works as a temperature sensor. The large value difference between the two resistors has the advantage that at a given voltage supply, only very little current flows through the sensor element, hence preventing the self-warming effect of the sensor element. After a passivation, the sensor chip is soldered onto a connector with an innovative bypass sleeve.

The sleeve has several inflow openings distributed evenly in the circumferential direction and an outflow opening on the end face of the sleeve. In addition to protecting the sensor chip from direct powerful inflow by the fluid, the sleeve directs at the same time a constant proportion of the volume flow to the sensor chip for measurement. After being screwed into the measuring block, the inflow openings of the sleeve are located in a flow-calmed area while the outflow opening is laterally flowed by the main volume flow. A stagnation pressure is thereby formed between the inflow and outflow opening. As a result, a partial fluid volume flows through the cavity of the sleeve and thus through the sensor chip, as shown in Fig. 7 (a). The partial volume flow in the sleeve is laminar, as shown by the simulation in Fig 7 (b). The relationship between main volume flow in pipe and partial volume flow in sleeve is from a value of about 10 l/min essentially linear, as given in Fig. 8.

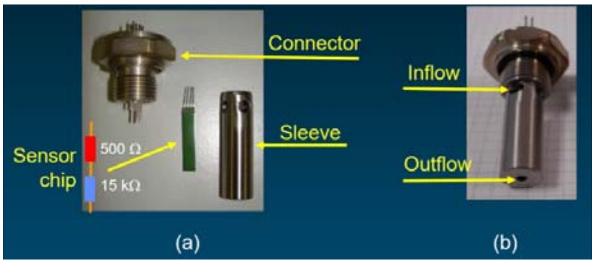


Fig. 6 Thin-film sensor chip, connector and sleeve (a) and assembly (b)

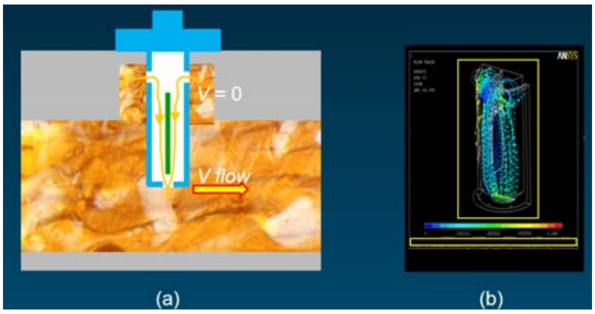


Fig. 7 Sensor in measuring block (a) simulated results of laminar flow in the sleeve (b)

For the partial volume flow measurement, a fluid-temperature independent fixed ΔT circuit is developed. With this circuit, a temperature difference (ΔT) between the sensor chip and the fluid is predetermined and kept constant.

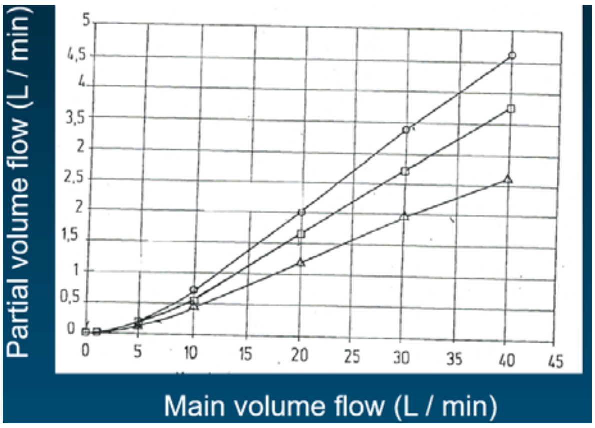


Fig. 8 The relationship between the partial volume flow in sleeve and the main volume flow in oil pipe

Fig. 9 illustrates the circuit: a Wheatstone bridge constructed with the temperature sensor, heating element and two matching resistors. An adjustable resistor R (ΔT) is added to the arm of the temperature sensor. The R (ΔT) determines the temperature difference (ΔT) between the sensor and the fluid.

The temperature sensor and heating element are fabricated using the same material, so the percentage change of the resistance with the temperature is the same, so that the ratio of their resistance remains constant, independent of the fluctuation of fluid temperature.

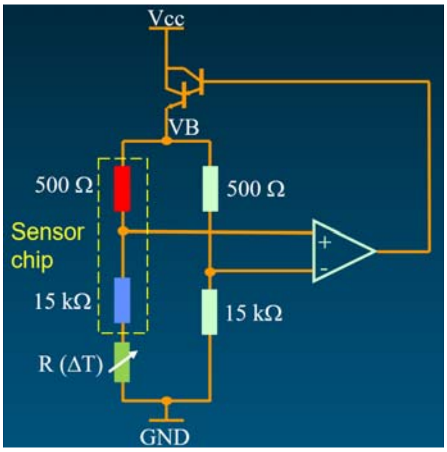


Fig. 9 Servo amplifier circuit for volume flow measurement with a ΔT constant method

A servo loop amplifier keeps the bridge in balance by controlling the voltage of the bridge (VB) and the current to the heating element, so that the temperature difference ΔT is kept constant. For example, if the fluid flowing speed increases, more heat is dissipated from the heating element and the resistance of the heating element becomes smaller. As a result, the bridge goes out of tune. The amplifier recognizes this and controls the Darlington transistor to increase the bridge voltage. Consequently, more current flows through the heating element, compensating the dissipated heat. The bridge voltage VB represents the heat transfer and is thus a direct measure of partial volume flow in the sleeve. The main volume flow can be determined by multiplying the partial volume flow with the bypass reduction factor.

IV. CONCLUSION

A capacitance level sensor with segmented electrode and a thin film volume flow sensor with an innovative by-pass sleeve are developed for the "harsh environment" application in industry. With the capacitance level sensor, the capacitances of each individual electrode will be measured successively by switching them in alternation to a charge transfer measuring circuit. The level will then be determined by adding the total length of the immersed electrodes and the height of the in the immersion direction partially immersed electrode. With the thin film volume flow sensor, the protecting sleeve directs a partial laminar volume flow from the main volume flow, ensuring an accurate measurement and at the same time enlarging the measurement range. A fixed ΔT measuring circuit enables a fluid temperature independent measurement. Through design with the associated measuring circuits, the two sensors overcome the application limitations of the traditional sensors.

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