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A Modified Design of an Anemometric Flow Transducer

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Abstract: In an anemometric flow transducer, the effect of flow rate of a fluid on the heat transfer from a heated surface in contact with the flowing fluid is utilized in order to measure the mass flow rate of the fluid. In the present paper a modified approach of design of an anemometric flow transducer has been described. In this transducer the temperature sensing IC AD590 has been used as a flow sensing element and the effect of fluid temperature has been eliminated by using four identical IC units. The performance of this transducer has been theoretically analyzed. Experiment has been performed to verify the theoretical characteristic equations. The results of experimental study are presented in the paper. A linear characteristic in the laminar condition and a nonlinear characteristic in the turbulent condition with very good repeatability have been observed. *Copyright © 2008 IFSA.*

Keywords: Anemometer, Flow transducer, Heat transfer co-efficient, Temperature sensing IC.

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1. Introduction

Flow rate is one of the most important process variables, which are required to be measured and controlled in any process plant in order to obtain better quality product at a lesser cost with better safety of operation. There are various types of flow transducers [1-3, 22] well accepted in process industry. The orifice plates with DP transmitters [1-3, 22] are still being used as the volume flow rate sensor of a process fluid through a pipeline. The electromagnetic flow meters are used for accurate measurement of flow rate of a conducting liquid. Turbine flow meters are used for flow measurement of a clean fluid. The ultrasonic and vortex flow meters [1-3, 22] are also common in volume flow rate measurement. Development of smart and intelligent flow meters like coriolis mass flow meters, multi variable flow meters [2, 3] have also become popular in industry. For the last few decades attempts are being made by various workers to design flow sensors by intelligent application of different physical phenomena. Various works on anemometer technique of flow measurement of a fluid in a pipeline are being reported in recent times. In hot wire anemometer [3-4] mass flow rate of a fluid is measured by measuring the change in resistance of a constant current hot resistance wire immersed in the fluid. In a self-balancing bridge technique [1, 3] the temperature of the fluid velocity sensor is kept at a constant value and the feedback current to restore equilibrium is taken as the measure of the index of the fluid velocity. Both the methods are well established and have numerous applications in hot wire anemometers. Turbulent eddies may cause random variations in the rate of heat exchange with a heated temperature detector. In thermistor type anemometric flow sensor [1-3, 22], the effect of these eddies on flow rate measurement is detected by running the sensing element at constant voltage or current. H Fujita *et al*, [12] have used thermistor for low flow rate measurement. M. S. Beck *et al* [18] have utilized the cross-correlation of temperature fluctuation for liquid flow measurement whereas P. G. Bently *et al* [19] have reported the application of transit time fluctuation analysis for fluid flow measurement. G. A. Sokolov *et al* [14] have used the microprocessor based computation for a thermal type flow meter. L Spassov, *et al* [15] have used thermo-sensitive quartz resonator for liquid flow rate measurement where the change of frequency of the sensor is taken as a measure of flow rate. S G Joshi *et al* [17] have reported a new technique of flow measurement using surface acoustic wave, where the frequency of the device changes with flow velocity as an effect of heat transfer. Application of semiconductor diodes as thermo-anemometric flow sensor has been reported by M.M. Ismailov *et al* [16]. Using anemometric technique a digital flow meter has been developed by K. Oktamoto *et al* [13]. A highly accurate flow measurement technique using alternative direction method for thermal flow sensors has been developed by J. A. M. Michael *et al* [11]. A new technique of temperature compensation of hot wire anemometer has been reported by R. P. C. Ferreira *et al* [10] and the same group has reported the performance evaluation [8] of that sensor. A hot film anemometer in high pressure application has been studied by U. Schmid [9]. A surface micro machined out of plane hot wire anemometer has been developed by J. Chen *et al* [7]. W. R. M. Almeida *et al* [5] have utilized sigma delta modulation technique to develop an accurate thermo resistive anemometer. All these anemometric flow sensors work on the principle of heat transfer [20-21] from the heated surface of the sensor into the flowing fluid.

In the present paper a modified anemometer technique of flow measurement has been developed. In this technique the anemometer effect i.e. cooling effect of flowing fluid on the heat sink metallic surface of a temperature sensing IC unit like AD590 is utilized to measure the mass flow rate of the fluid. In order to compensate the temperature effect of the fluid, four identical IC units are used and mounted in the same diametrical plane along two perpendicular diametrical directions. The flow tube is mounted in the horizontal position in such a way that it is always filled up with flowing fluid. Four identical temperature sensing units (AD590) are mounted at equidistance apart in the same diametrical plane of the flow tube, of which two sensing IC's are mounted along a horizontal diameter and the other two IC's are mounted along the vertical diameter in the same plane. As a result the cooling effect of the fluid on the IC's along horizontal diametrical positions may be assumed to be different from that on the IC's along vertical diametrical position. All the IC units are supplied from the same stabilized 5 Volts dc source so that their heat supply rate is identical. The output of each IC is a current signal passing through a load resistance and is not dependent on the value of load resistance up to a certain limiting value. The dc voltage developed across each load resistance has been found to be related with fluid flow rate. Sum of the voltage signals developed for two horizontal IC's has been subtracted from that of the voltage signals for two vertical IC's. As a result the effect of temperature of the fluid is nullified and the resultant after this subtraction may be assumed to be a function of fluid flow rate only. This function of the flow sensor has been theoretically analyzed and its characteristic equations for streamline and turbulent flow conditions have been derived. Experiment has been carried out to find these characteristics of the flow sensor in both streamline and turbulence conditions. Experimental results are reported in the paper. It has been observed that these experimental characteristics almost follow the theoretical ones. A linear characteristic under laminar condition and a nonlinear characteristic with an appreciable linear region under turbulent condition have been observed. Hence using a suitable linearization technique in the turbulent region the proposed sensor may be used as a detecting device for measuring the flow rate of a fluid through a pipeline. Moreover these characteristics can be utilized to determine the transition between streamline and turbulent condition of a flowing fluid through a pipeline.

2. Method of Approach

Let us assume that the metal cap of a temperature sensing IC (AD590) is mounted on an insulating pipeline section of a flow head so that the outside surface of the metal cap is in contact with the fluid flowing through the pipeline as shown in Fig. 1. For a metallic pipeline section the IC may be mounted with proper thermal insulation between pipeline and its metallic cap so that the heat loss or gain through the surface of metal cap may only be convected into the fluid in contact.

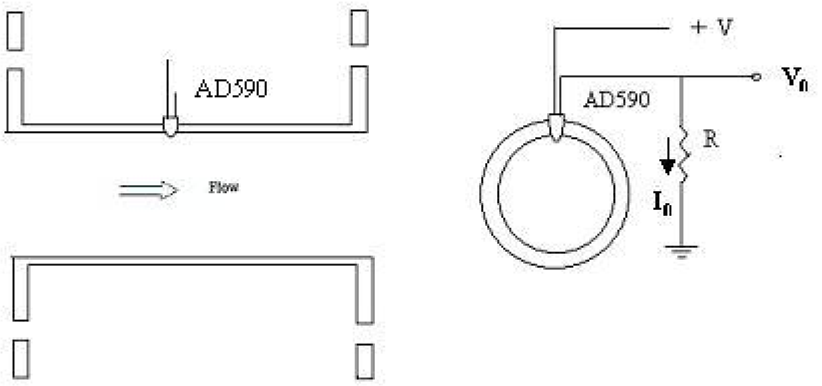


Fig. 1. Mounting of AD590 in the flow head.

Let us assume that at no flow condition, the temperature of the fluid and that of the metallic cap of AD590 directly in contact with the fluid is T_F and T_0 respectively. Let the output current of the IC through a load resistance R be I_0 . Hence the energy balance equation may be assumed to be given by

$$I_0 (V-I_0R) = h_q A (T_0-T_F), \tag{1}$$

where V is the supply voltage, h_0 is the heat transfer co-efficient of the metallic heat sink of the IC unit and A is the effective area of its metallic surface in contact with the fluid.

Now due to flow of fluid, the heat transfer coefficient changes [20, 21] with mass flow rate (q) of the fluid. Let the Taylor's series expansion equation for this heat transfer co-efficient be given by,

$$h_q = h_0 + (\delta h_q / \delta q)_{q,} \Delta q + (1/ 2 !) (\delta^2 h_q / \delta q^2)_{q,} \Delta q^2 + \ldots\ldots, \tag{2}$$

where h_0 is the heat transfer coefficient at no flow condition and h_q is its value at a flow rate q and fluid temperature T_F.

For streamline flow Δq^2 and higher order term are negligible

Hence

$$h_q = h_0 + \alpha\, \Delta q, \tag{3}$$

where

$$\alpha = (\delta h_q / \delta q)_q \tag{4}$$

As a result, more heat will be transferred to the fluid and temp of AD590 will decrease from T_0 to $T_0 - \Delta T$ and output current will decrease from I_0 to $I_0 - \Delta I$. Hence energy balance equation at steady state will be given by

$$\{V - (I_0 - \delta I_0) R\}(I_0 - \delta I_0) = (h_0 + \alpha\, \Delta q) A(T_0 - \Delta T - T_F) \tag{5}$$

or,

$$h_0 A (T_0 - T_F) + A\alpha (T_0 - T_F) \Delta q - h_0 A \Delta T = I_0\{V - I_0 R\} - \{V - I_0 R\}\delta I_0 + R I_0 \delta I_0 \tag{6}$$

Combining the equation nos. (1) and (6), we have,

$$A\alpha (T_0 - T_F) \Delta q - h_0 A \Delta T = -\{V - I_0 R\}\delta I_0 + R I_0 \delta I_0$$

or

$$A\alpha (T_0 - T_F) \Delta q - h_0 A \Delta T = (2R I_0 - V)\delta I_0 \tag{7}$$

Now I_0 is proportional to T and hence we have,

$$\delta I_0 = k\, \Delta T, \tag{8}$$

where k is the constant of proportionality.

Hence the equation (7) is reduced to

$$(2R I_0 - V + h_0 A K)\delta I_0 = A\alpha(T_0 - T_F)\Delta q, \tag{9}$$

where K = 1/k

or

$$\delta I_0 = \frac{- A\alpha(T_0 - T_F)\Delta q}{(V - h_0 A K - 2R I_0)} \tag{10}$$

So the change of output signal across the resistance R due to a change of flow rate by Δq is given by,

$$\delta V_0 = R\, \delta I_0 = \frac{- RA\alpha(T_0 - T_F)\Delta q}{(V - h_0 A K - 2R I_0)} \tag{11}$$

Integrating both sides, we have the output signal under laminar condition given by

$$V_0 = - K_1\, \alpha\, q + K_2, \tag{12}$$

where

$$K_1 = \frac{RA(T_0-T_F)}{(V- h_0A\ K-2R\ I_0)} \tag{13}$$

and K_2 is the constant of integration.

So under streamline flow condition, the output voltage across the resistance R is linearly related with flow rate.

Now under turbulent condition the heat transfer co-efficient given by the equation no. (2) may be approximately given by,

$$h_q = h_0 +(\delta h_q / \delta q)_q\ \Delta q + (\delta^2 h_q / \delta q^2)_q\ \Delta q^{\,2} \tag{14}$$

or

$$h_q = h_0 + \alpha\ \Delta q + \beta\ \Delta q^{\,2}, \tag{15}$$

where

$$\beta = (\delta^2 h_q / \delta q^2)_q \tag{16}$$

Hence putting $\alpha\ \Delta q + \beta\ \Delta q^{\,2}$ in place of $\alpha\ \Delta q$ in equation (11) it is reduced to

$$\delta V_0 = - \frac{RA(T_0-T_F)(\alpha\ \Delta q + \beta\ \Delta q^{\,2})}{(V+ h_0A\ K_1-2R\ I_0)} \tag{17}$$

or

$$(\delta V_0 / \delta q) = - K_1\{\alpha + \beta\ \Delta q\} \tag{18}$$

Now if we assume Δq as a small deviation of flow rate from an initial flow rate q_0 then the above equation is reduced to

$$(\delta V_0 / \delta q) = - K_1[\alpha + \beta\ (q -q_0)] \tag{19}$$

Integrating both sides we have the output signal under turbulent condition given by

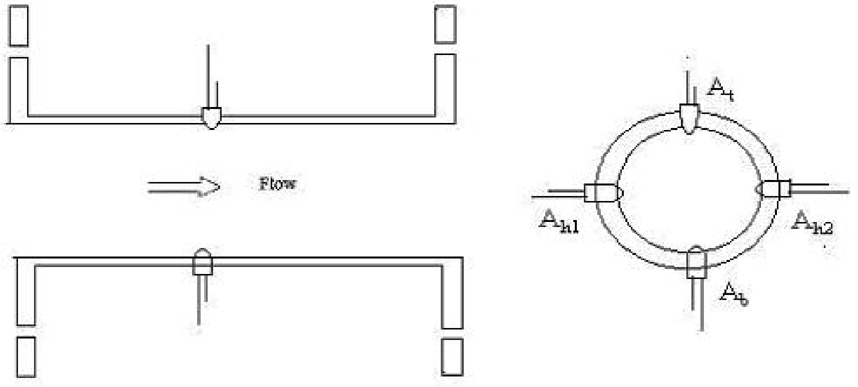
$$V_0 = - K_1\alpha\ q - K_1\ \beta\ q^2 /2 + K_1\ \beta\ q_0\, q + K_{3,} \tag{20}$$

where K_3 is the integration constant

or

$$V_0 = - K_1\ \beta\ q^2 /2 - K_1(\alpha - \beta\ q_0)q + K_3 \tag{21}$$

Now if a single IC sensor is used then the above equation nos. (12) and (21) will depend on fluid temperature (T_F). So with the change of fluid temperature the output will change. In order to eliminate this effect four identical IC sensors are used in the present design. These IC sensor units (AD590 with metal cap) are mounted in a cylindrical pipeline in the same diametrical plane equidistant apart of which two IC units are mounted along vertical diameter and two other IC units are mounted along horizontal diameter of the pipeline as shown in Fig. 2.



(a) Flow head

(b) Cross-section of flow head with IC units

Fig. 2. Mounting of four IC units on the PVC pipeline section of the proposed flow head.

Now the heat loss by the IC units is transferred to the fluid and the hot fluid particles always move in the upward direction due to convection process. So for the top IC unit only the upper portion of the fluid in the diametrical plane take part in the heat transfer process. For the bottom IC unit whole liquid in the diametrical plane take part in the heat transfer process. For each of the IC units along horizontal diameter, the upper semicircular part of the fluid takes part in the heat transfer process. Hence heat transfer co-efficient for the four identical IC units mounted in different locations may be assumed to be different.

Let under no flow condition of the fluid, the heat transfer co-efficient for the top IC unit A_t, bottom IC unit A_b, and horizontal IC units A_{h1} and A_{h2} be respectively h_{0t}, h_{0b}, h_{0h1} and h_{0h2} and the values of heat transfer parameters α and β under flow condition of the fluid for these IC units be (α_t, β_t); (α_b, β_b); (α_{h1}, β_{h1}) and (α_{h2}, β_{h2}) respectively.

Hence from equation (12), the sensor output across a load resistance R under streamline condition, for the IC units A_t, A_b, A_{h1} and A_{h2} will be given by the following set of equations (22)

$$\left.\begin{array}{c} V_{ots} = -K_1\,\alpha_t\,q + K_2 \\ V_{obs} = -K_1\alpha_b\,q + K_2 \\ V_{oh1s} = -K_1\,\alpha_{h1}\,q + K_2 \\ V_{oh2s} = -K_1\alpha_{h2}\,q + K_2 \end{array}\right\} \qquad (22)$$

From equation no. (21), these equations will be modified under turbulent condition, by the following set of equations.

$$\left.\begin{array}{c} V_{ott} = -K_1(\alpha_t - \beta_t\,q_0)\,q - (K_1\,\beta_t\,q^2)/2 + K_3 \\ V_{obt} = -K_1(\alpha_b - \beta_b\,q_0)\,q - (K_1\,\beta_b\,q^2)/2 + K_3 \\ V_{oh1t} = -K_1(\alpha_{h1} - \beta_{h1}\,q_0)\,q - (K_1\,\beta_{h1}\,q^2)/2 + K_3 \\ V_{oh2t} = -K_1(\alpha_{h2} - \beta_{h2}\,q_0)\,q - (K_1\,\beta_{h2}\,q^2)/2 + K_3 \end{array}\right\} \qquad (23)$$

If we subtract the sum of the output signals (V_{oh1s} , V_{oh2s}) for the horizontal IC units from the sum of the output signals (V_{ots} , V_{obs}) for the top and bottom IC units then the resultant output under laminar condition will be given by

$$V_{ors} = (V_{ots} + V_{obs}) - (V_{oh1s} + V_{oh2s}) \tag{24}$$

or,

$$V_{ors} = - K_1 (\alpha_t + \alpha_b - \alpha_{h1} - \alpha_{h2})q \tag{25}$$

or,

$$V_{ors} = K_1 (\alpha_{h1} + \alpha_{h2} - \alpha_t - \alpha_b)q \tag{26}$$

or,

$$V_{ors} = K_3 q, \tag{27}$$

where

$$K_4 = K_1 (\alpha_{h1} + \alpha_{h2} - \alpha_t - \alpha_b) \tag{28}$$

Now if the fluid temperature increases from T_F then the magnitude of each of V_{oh1s} , V_{oh2s}, V_{ots} and V_{obs} decreases by same amount and so the equation (24), (26) and (27) may be assume to be independent of fluid temperature.

Similarly from equation no. (23), the resultant output voltage under turbulent condition is given by

$$V_{ort} = K_1\{ (\alpha_{h1} + \alpha_{h2} - \alpha_t - \alpha_b) + (\beta_{h1} + \beta_{h2} -\beta_t - \beta_b)q_0 \}q + (K_1/2) (\beta_{h1} + \beta_{h2} -\beta_t - \beta_b)q^2 \tag{29}$$

or,

$$V_{ort} = K_5 q + K_6 q^2 \tag{30}$$

where

$$K_5 = K_1\{ (\alpha_{h1} + \alpha_{h2} - \alpha_t - \alpha_b) + (\beta_{h1} + \beta_{h2} -\beta_t - \beta_b)q_0 \} \tag{31}$$

and

$$K_6 = (\beta_{h1} + \beta_{h2} -\beta_t - \beta_b)q_0 \}q + (K_1/2) (\beta_{h1} + \beta_{h2} -\beta_t - \beta_b) \tag{32}$$

In this case also the effect of fluid temperature on the four IC units will be identical and will have no effect in the equation nos. (29) and (30).

3. Design

The flow head is designed with a PVC pipeline section of length 80cm, 30cm outside diameter and 25cm inside diameter with flange joints at both ends as shown in Fig. 2 (a). At the middle section of the flow head pipeline, four IC units are mounted at equidistant apart in the same diametrical plane as shown in Fig. 2(b). The outer surfaces of the metallic sinks of the IC units are just in contact with the flowing liquid and produce negligible obstruction to flow. Each IC unit is supplied from a stabilized 5V DC source through a load resistance of 1 kilo ohm. The DC voltage signals across the load resistances of the top and bottom ICs (A_t and $A_{b)}$ are added by an adder circuit consisting of op Amp A_1 as shown in Fig. 3. Similarly the voltage signals across the load resistances of two horizontal IC unit's (A_{h1} and A_{h2}) are added by another adder circuit consisting of op Amp A_2. The resultant output is obtained by subtracting the output of second adder circuit from that of the first one by the differential circuit consisting of op Amp A_3 as shown in the same figure. This electronic circuit is mounted on a PCB, which is again mounted inside the flow head box not shown in figure. Thus the four IC units and the electronic circuit together form the proposed head mounted flow transducer.

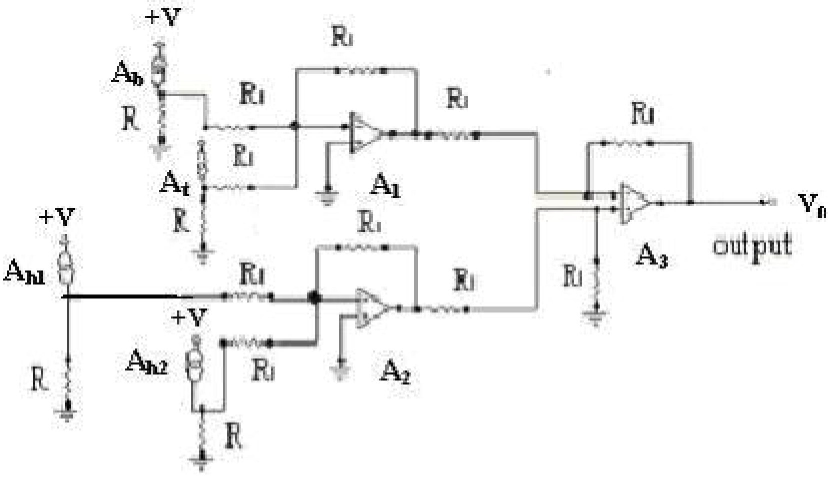


Fig. 3. Design of flow transducer using op Amps.

4. Experiment

The experiment was performed to find the static characteristic of the proposed flow transducer with the experimental setup as schematically shown in Fig. 4. In this experiment clean water was used as the experimental liquid. The water level of an overhead tank was maintained constant by feeding continuous water supply to the overhead water tank by a centrifugal water pump and allowing the excess water to discharge through an overflow line. Thus a fixed water head of about 5 meter was maintained throughout the experiment.

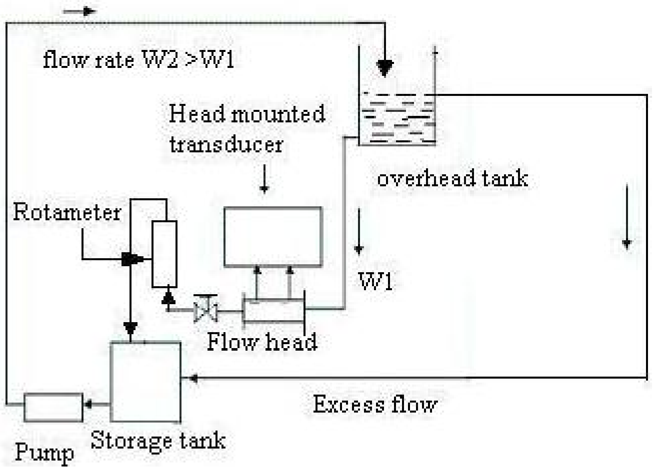


Fig. 4. Experimental setup.

The experimental flow head was installed horizontally in the discharge water line and the output was taken through a regulating valve and a rotameter. Now the mass flow rate through the flow head was increased in steps by observing the reading of the rotameter and at each step accurate volume flow rate was calculated from direct collection method and then it was converted into the mass flow rate by multiplying it with the density of water. In each of these steps, the output of the flow transducer is measured by a digital 4 and ½ digit multimeter. The static characteristic graph of the transducer was then drawn by plotting the transducer output against flow rate. The characteristic thus obtained is shown in Fig. 5.

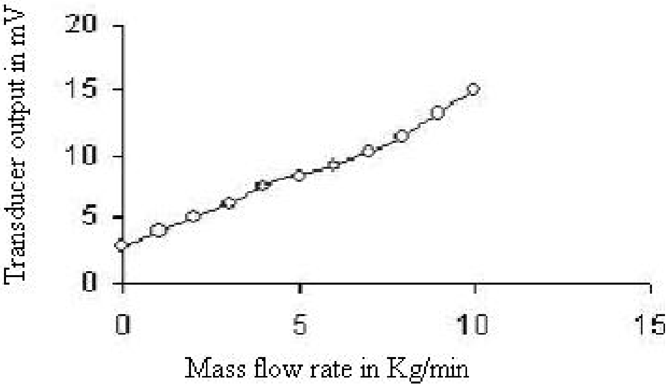


Fig. 5. Static characteristic graph of the proposed flow transducer.

5. Discussion

From Fig. 5, it is found that the static characteristic graph of the flow transducer is almost linear under streamline condition and it is nonlinear under turbulence condition of the liquid. Thus the transducer characteristic was found to follow approximately the theoretical equation nos. (26) and (27). The experiment was repeated for both increasing and decreasing flow rate and the same characteristic was obtained. The transducer characteristic was also found to be independent of liquid temperature by repeating the experiment with hot water.

Using a suitable linearization technique such as microprocessor based or analog electronic circuit based piece-wise technique can make the characteristic linear easily. Moreover from Fig.5, it is also observed that there is a distinct change of slope of the characteristic graph in the streamline and turbulent regions. Thus the transducer may be utilized to determine the transition between laminar and turbulent conditions of a flowing fluid through a pipeline.

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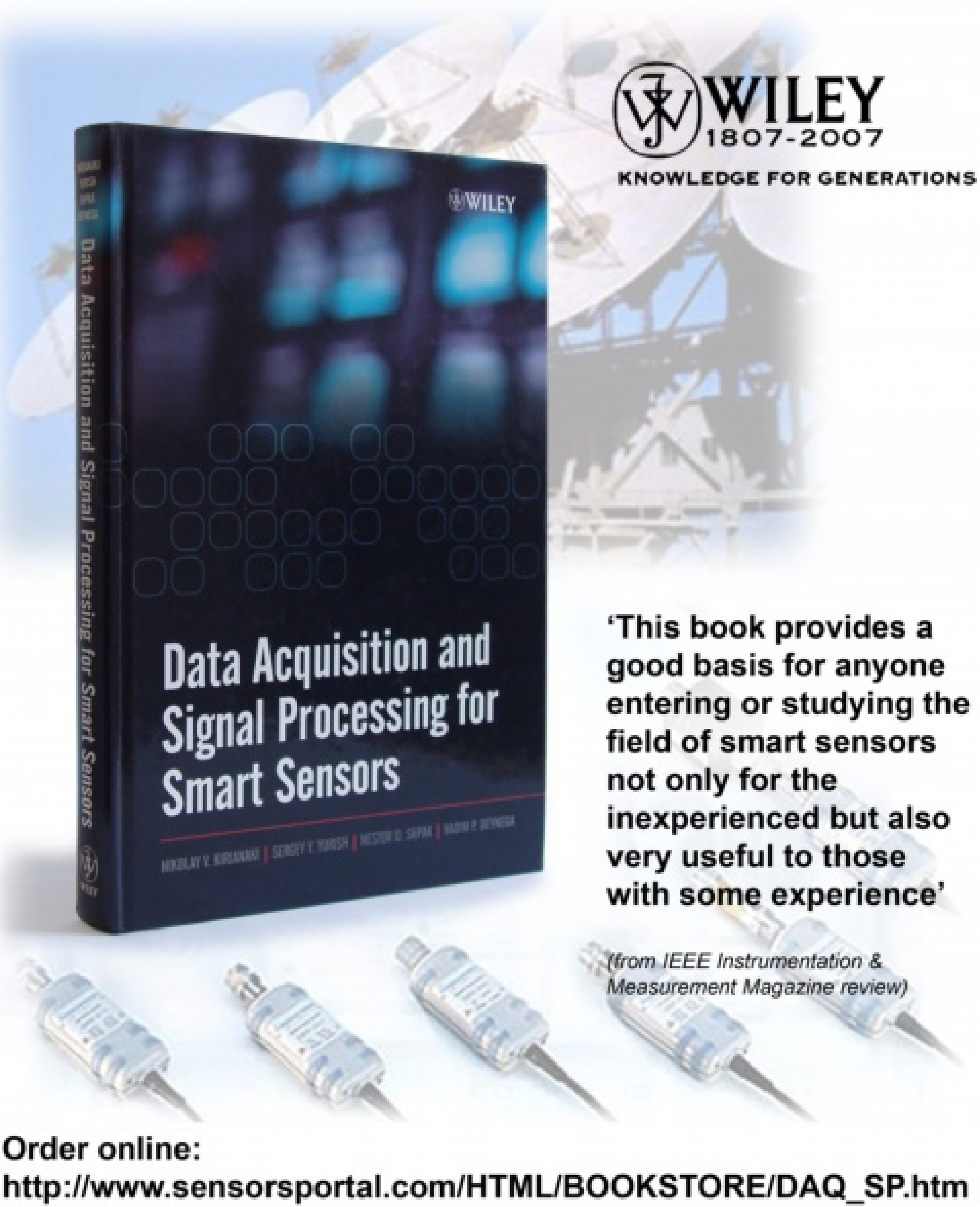
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