A New Velocity Algorithm for Sing-Around-Type Flow Meters

JERKER DELSING

Abstract—**In many flow metering applications the fluid temperature can change rapidly during the measurements. An example is flow metering in district heating systems. These temperature changes will cause fast, large changes of the speed of sound in the fluid. If not recognized, this phenomenon can introduce severe errors in sing-around-type flow meters. The sing-around flow meters used today handle this problem with varying success. Therefore, the algorithm used to calculate the flow velocity from the sing-around frequencies has been modified. This new algorithm compensates for fast changes of fluid temperature during the sing-around measurement cycle. A complete derivation is given for both laminar and turbulent flow. Test measurements comparing the new algorithm and the conventional one showed a superior performance of the new algorithm, especially in the case of rapidly changing fluid temperature.**

I. Introduction

ULTRASONIC flow meters using the sing-around method are well known. Normally they are considered to be independent of the temperature and type of flowing fluid. This is correct as long as the speed of sound does not vary between the measurement of the downstream sing-around frequency f_1 (axial interrogation path assumed, cf. Fig. 1 and [1])

$$f_1 = \frac{c_1 + v}{L} \tag{1}$$

and the upstream frequency f_2

$$f_2 = \frac{c_2 - v}{L} \tag{2}$$

where c_1 and c_2 are the speed of sound and v is the fluid velocity during the time of the measurement and, further, L is the ultrasound transducer distance. Thus the fluid velocity becomes

$$v = \frac{L}{2}(f_1 - f_2) - \frac{c_1 - c_2}{2}. \tag{3}$$

From this it is obvious that an error is introduced if c_1 is not equal to c_2.

Today two major variations of sing-around technique flowmeters are in frequent use. Both techniques measure the sing-around frequency over many successive sound burst transmissions, i.e., sing-around loops, as opposed to the transit time method where only the time for a single sound burst transit is determined.

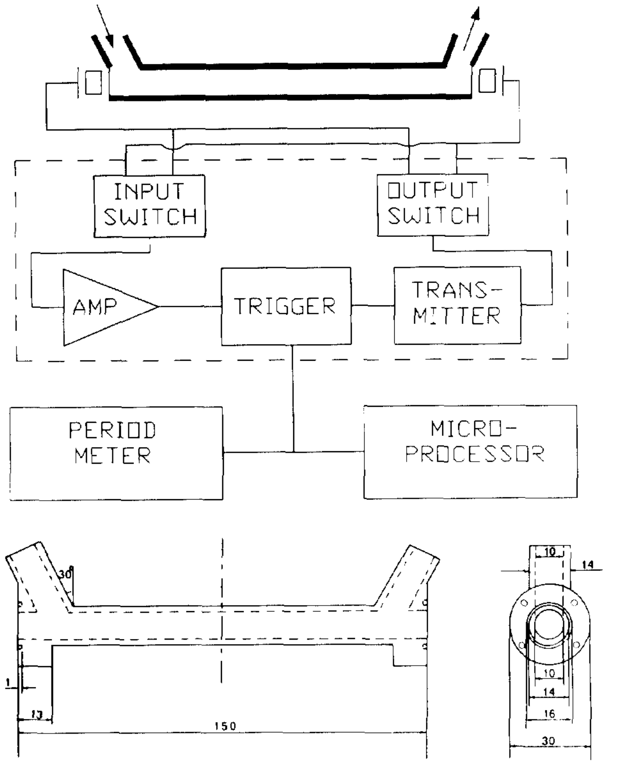

Fig. 1. Block diagram and flow cell geometry of sing-around flow meter of axial interrogation type used in this paper.

The dual path sing-around flow meter measures the sing-around frequency simultaneously in the up- and downstream path, cf. Fig. 2 and [2]. Thus the speed of sound term in (3) will be zero. However, for accurate measurements of low flow velocities (1 cm/s ± 1 percent) extremely accurate matching of the electronic delay time in the two paths is required since the frequencies have to be measured with an accuracy of better than $1:10^7$, [3]. Unfortunately, such matching will drastically raise the meter price.

The conventional single path sing-around flowmeter, cf. Fig. 1, measures the sing-around frequency in one direction first and thereafter in the other direction. Here it is assumed that the same electronics is used for both directions. Therefore no matching of electronic delays is required as in the dual path sing-around method. However, if a high accuracy (1 cm/s ± 1 percent) is required, the

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The author is with the Department of Electrical Measurements, Lund Institute of Technology, P.O. Box 118, 221 00 Lund, Sweden.
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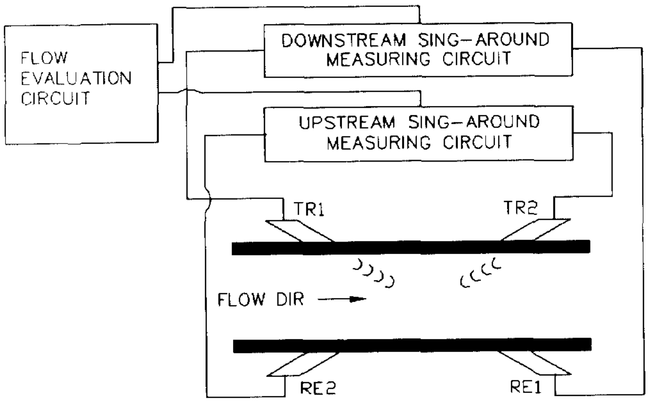

Fig. 2. Sing-around flow meter with dual sing-around path.

measuring time becomes relatively long, about 0.1 s. Therefore, changes in the speed of sound during the measuring time will introduce severe errors in the measurements as previously indicated.

In this paper a method to improve this deficiency of the single path sing-around flow meter will be given. This kind of flow meter is especially useful in heat meters used in district heating systems, where meter accuracy of ± 1 percent at flow rates of 1 cm/s are required, calling for a sing-around frequency measuring accuracy of $1:10^7$. This is most readily obtained by multiple period averaging measurements. From these sing-around period measurements a microprocessor can easily calculate the flow velocity using the conventional sing-around velocity algorithm.

It is this algorithm which has been modified, resulting in a clearly improved meter accuracy for flow situations with rapidly changing fluid temperature. In this modified algorithm the velocity is calculated from four consecutive sing-around period measurements, as opposed to the use of only two consecutive measurements in the conventional algorithm. As a result of this, errors introduced by variations of the speed of sound during the measurement cycle can be eliminated. This is correct under the condition that the flow velocity and speed vary linearly with time during four consecutive sing-around period measurements.

The new algorithm is derived for fully developed turbulent and laminar flow. Control measurements have been performed comparing the modified and the conventional sing-around algorithm. The meter used for these tests features a single path axial interrogation configuration. The sing-around frequencies are measured by the multiple period averaging technique. This flow meter is extensively described in [3]. A comparison of the two algorithms shows clearly that the modified algorithm improves the flow meter accuracy for systems where the fluid temperature is drastically changed during short time intervals. Such temperature changes are common in, for example, district heating systems.

II. Notations Used for the Evaluation

Throughout this paper the following notations will be used. These notations are also explained in Fig. 3.

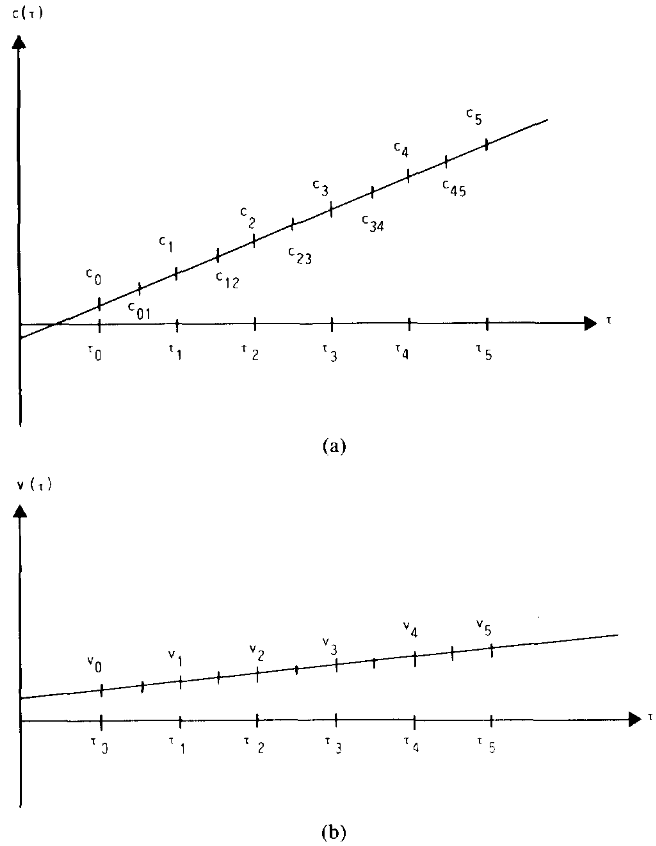

Fig. 3. Notations used in derivation of modified sing-around algorithm. Speed of sound c, flow velocity v, and time τ.

1) τ_i is the absolute time where i is denoting the serial number of the sing-around period measurements.
2) $t_{i,i+1}$ is the mean sing-around period averaged over N periods between τ_i and τ_{i+1}:

$$t_{i,i+1} = \frac{\tau_{i+1} + \tau_i}{N}.$$

   a) $t_{i,i+1}$ with odd i is measured for ultrasound transmitted downstream.
   b) $t_{i,i+1}$ with even i is measured for ultrasound transmitted upstream.

3) $v_{i,i+1}$ is the mean fluid velocity during the time between τ_{i+1} and τ_i.
4) v_{i+1} is the mean of $v_{i,i+1}$ and $v_{i+1,i+2}$.
5) $c_{i,i+1}$ is the mean speed of sound during the time between τ_{i+1} and τ_i.
6) c_{i+1} is the mean of $c_{i,i+1}$ and $c_{i+1,i+2}$.

III. Derivation of the New Algorithm

The improvement of the conventional sing-around algorithm is applicable only under the following two conditions.

1) The speed of sound c is assumed to vary linearly with time τ over short time intervals:

$$c = c_0 + A \cdot \tau. \tag{4}$$

2) The velocity of the fluid v is assumed to vary lin-

early with time τ over short time intervals:

$$v = v_0 + B \cdot \tau. \tag{5}$$

Here A and B are constants. By short time intervals we mean a few tenths of a second. These conditions are assumed throughout this section. Fortunately they can be considered fulfilled in most flow meter applications.

Using the notations introduced above, (3) can be rewritten as

$$v_2 = \frac{L}{2}\left(\frac{1}{t_{12}} - \frac{1}{t_{23}}\right) - \frac{c_{12} - c_{23}}{2} \tag{6}$$

where v_2 is the mean of v_{12} and v_{23}, and L is the distance between the ultrasonic transducers.

From this equation the mean velocity v_2 can be deduced if the temperature is constant and, therefore, the sound velocities c_{12} and c_{23} are equal. However, this is often not the case. Therefore, in the following, a new algorithm will be derived (in (30)) which allows the calculation of v_2 under the assumption that the speed of sound varies linearly (mainly due to temperature changes) during the time of four consecutive sing-around period measurements.

The second term in (6) depends on the speed of sound, which is unknown. However, since the speed of sound can be measured by means of the sum of the sing-around frequencies, this unknown term can be calculated. Utilizing the above assumption about linearity, the speed of sound c_2 is found to be

$$c_2 = \frac{c_{12} + c_{23}}{2} = \frac{L}{2}\left(\frac{1}{t_{12}} + \frac{1}{t_{23}}\right) - \frac{v_{12} - v_{23}}{2}. \tag{7}$$

Since c is assumed to vary linearly with time, c_{12} and c_{23} can be expressed as

$$c_{12} = \frac{c_1 + c_2}{2} \tag{8}$$

and

$$c_{23} = \frac{c_2 + c_3}{2} \tag{9}$$

where c_1 and c_3 are calculated in the same way as c_2, cf. (7). Then c_{12} and c_{23} can be expressed as

$$c_{12} = \frac{c_1 + c_2}{2} = \frac{L}{4}\left(\frac{1}{t_{01}} + \frac{2}{t_{12}} + \frac{1}{t_{23}}\right) - \frac{2v_{12} - v_{01} - v_{23}}{4} \tag{10}$$

and

$$c_{23} = \frac{c_2 + c_3}{2} = \frac{L}{4}\left(\frac{1}{t_{12}} + \frac{2}{t_{23}} + \frac{1}{t_{34}}\right) - \frac{v_{12} + v_{34} - 2v_{23}}{4}. \tag{11}$$

Introducing these two expressions for c_{12} and c_{23} into (6) yields

$$v_2 = \frac{L}{8}\left(\frac{3}{t_{12}} - \frac{3}{t_{23}} - \frac{1}{t_{01}} + \frac{1}{t_{34}}\right) - \frac{v_{01} - v_{12} - v_{23} + v_{34}}{8}. \tag{12}$$

Here an equation has emerged that is completely independent of the speed of sound c. However, a new term dependent on the fluid velocity has appeared. The following calculation will show that this term is small for both fully developed turbulent and laminar flow conditions.

In the following derivation a flow cell design of the axial interrogation type is assumed (cf. Fig. 1). Further, all end effects are assumed to be small. First the case of a turbulent flow profile will be discussed.

For turbulent flow the velocities v_{01}, v_{12}, v_{23}, and v_{34} are equal to the mean velocities in the pipe. Using the assumption that the velocity changes linearly with time, these velocities can be expressed as

$$v_{12} = v_{01} + \tfrac{1}{2}BN(t_{01} + t_{12}) \tag{13}$$

$$v_{23} = v_{12} + \tfrac{1}{2}BN(t_{12} + t_{23}) \tag{14}$$

$$v_{34} = v_{23} + \tfrac{1}{2}BN(t_{23} + t_{34}) \tag{15}$$

where B is a constant, cf. (5), N is the number of sing-around periods averaged and $N \cdot (t_{i,i+1} + t_{i+1,i+2})/2$ is the time between $v_{i,i+1}$ and $v_{i+1,i+2}$. Accordingly the last term in (12) is

$$\frac{BN[t_{34} + t_{23} - t_{12} - t_{01}]}{16}. \tag{16}$$

In the above expression it is of interest to determine the magnitude of the time difference $(t_{34} + t_{23} - t_{12} - t_{01})$. For fluid velocities not higher than one percent of the speed of sound, t_{01}, t_{12}, t_{23}, and t_{34} can be approximated as

$$t_{01} = \frac{L}{c_{01} - v_{01}} \approx \frac{L}{c_{01}} \tag{17}$$

$$t_{12} = \frac{L}{c_{12} + v_{12}} \approx \frac{L}{c_{12}} \tag{18}$$

$$t_{23} = \frac{L}{c_{23} - v_{23}} \approx \frac{L}{c_{23}} \tag{19}$$

$$t_{34} = \frac{L}{c_{34} + v_{34}} \approx \frac{L}{c_{34}}. \tag{20}$$

Since the speed of sound is assumed to be a linear function of time, cf. (4), the different speeds of sound c_{12}, c_{23}, and c_{34} can be written as

$$c_{12} = c_{01} + At_{m,n} \tag{21}$$

$$c_{23} = c_{01} + 2At_{m,n} \tag{22}$$

$$c_{34} = c_{01} + 3At_{m,n} \tag{23}$$

where $t_{m,n}$ is the time required for one period average measurement. By using these expressions (16) can be rewritten as

$$C \frac{4c_{01}^2 At_{m,n} + 12c_{01}A^2t_{m,n}^2 + 6A^3t_{m,n}^3}{c_{01}^4 + 6c_{01}^3 At_{m,n} + 6c_{01}^2 A^2t_{m,n}^2 + 6c_{01}A^3t_{m,n}^3} \tag{24}$$

where C is a constant equal to $L \cdot B \cdot N/4$. With $t_{m,n}$ equal to 0.1 s (flow meter sample rate of 10 Hz), the constant A not being greater than 10 m/s^2, and with a speed of sound in the range of 200–2000 m/s, which is appropriate for most fluids [4], the magnitude of the above expression only depends on the speed of sound. Since the terms including the speed of sound in the divisor are of power four and in the dividend of power two, it can be concluded that the above expression is very small and can be neglected.

For the laminar flow profile the situation is more complicated. The laminar velocity distribution is parabolic [5]. In the downstream direction the maximum velocity will determine the sing-around period. For similar reasons, the minimum velocity will determine the upstream sing-around period. Now the minimum velocity for a laminar flow profile is zero and the maximum here is denoted v_{max}. Since the velocity is allowed to vary linearly with time, v_{01}, v_{12}, v_{23}, and v_{34} become equal to

$$v_{01} = 0 \tag{25}$$

$$v_{12} = v_{max} \tag{26}$$

$$v_{23} = 0 \tag{27}$$

$$v_{34} = v_{12} + \tfrac{1}{2}BN(t_{12} + 2t_{23} + t_{34}). \tag{28}$$

Introducing these velocities into the last term of (12) yields

$$\frac{2v_{max} - 2v_{max} - BN(t_{12} + 2t_{23} + t_{34})}{16} \approx -\frac{B \cdot t_{m,n}}{8}. \tag{29}$$

To ensure that the temperature influence on the speed of sound will not impair the velocity measurement at laminar flow, the constant B, i.e., the fluid acceleration, must be less than or equal to

$$B \leq 8 \cdot \frac{\Delta v}{t_{m,n}} \; [\mathrm{m/s^2}]$$

where Δv is the absolute error acceptable in the flow measurement.

If the above condition is fulfilled, the improved sing-around algorithm will operate properly both for laminar and for turbulent flow.

For low velocities and high accuracy, requirement B becomes quite small. As long as laminar flow is present, the allowed value of B will increase proportionally to the acceptable flow velocity error Δv. Further, fast accelerations of the fluid will introduce turbulence in the meter body and thus the flow meter will give correct readings according to the above calculations for turbulent flow.

From the above we can conclude that the following modified sing-around algorithm is applicable both in the laminar and the turbulent case. According to the above reasoning (12) can be reduced to

$$v_2 = \frac{L}{8}\left(\frac{3}{t_{12}} - \frac{3}{t_{23}} - \frac{1}{t_{01}} + \frac{1}{t_{34}}\right). \tag{30}$$

IV. Tests

To verify the preceding algorithm the following tests were conducted. For this purpose a liquid sing-around flow meter was developed (see Fig. 1 and [3]). To obtain a correct comparison of the modified and the conventional sing-around algorithms, the calculation of velocity values was made with the same sing-around period data. The test system used is shown in Fig. 4. Here the sing-around periods are measured by a universal counter (Philips PM-6654) and transferred to a computer. Thus both the modified and the conventional sing-around algorithms could be evaluated using the same set of sing-around period data. As a reference flow meter a balance in conjunction with an electronic clock was used with an estimated error of better than 0.1 percent. The test measurement was performed during approximately 30 s with sample rates of 5 and 10 Hz. Thus 150 and 300 sing-around period values were obtained, respectively. From these values a mean velocity and standard deviation was calculated.

To confirm the function of the new algorithm, a set of measurements with a sample rate of 10 Hz and water velocities of 0–140 cm/s were made. In Fig. 5 the fluid velocity measured by the sing-around flow meter is plotted against the velocity measured by the reference meter.

To investigate the temperature dependence of the conventional and the modified sing-around algorithms the following test was performed. Flow measurements at constant water velocity but varying water temperature were made. Here the starting temperature was 30°C, from which the temperature was raised to 70°C within 30 s. Thus a strong variation of the water temperature was introduced during the measurement. The measuring time was 30 s and the sample rate 5 Hz. Thereby 150 velocity values to be used with both the conventional and the modified sing-around algorithms were obtained.

A good measure of the temperature dependence of the two algorithms is the standard deviation for the velocity values obtained by each algorithm. Therefore, the mean value and the standard deviation were calculated for both algorithms. In Table I the mean velocity and related standard deviation for both the conventional and the modified algorithms are shown.

The standard deviations for the conventional sing-around algorithm show that each velocity value can have errors of more than several hundred percent. The standard deviation for the modified algorithm, on the other hand,

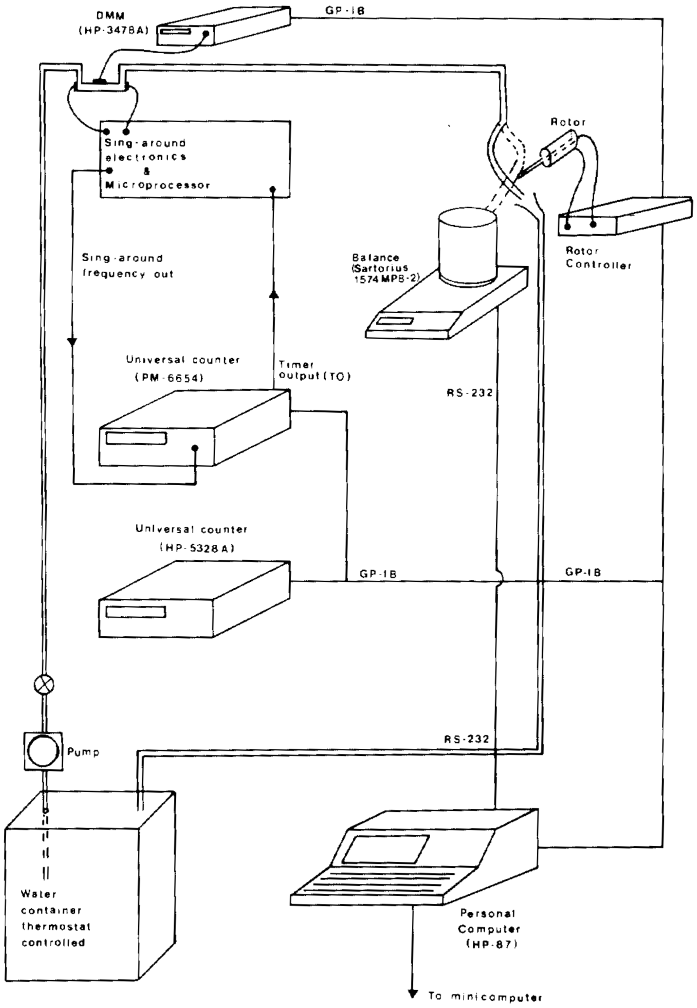

Fig. 4. Test system.

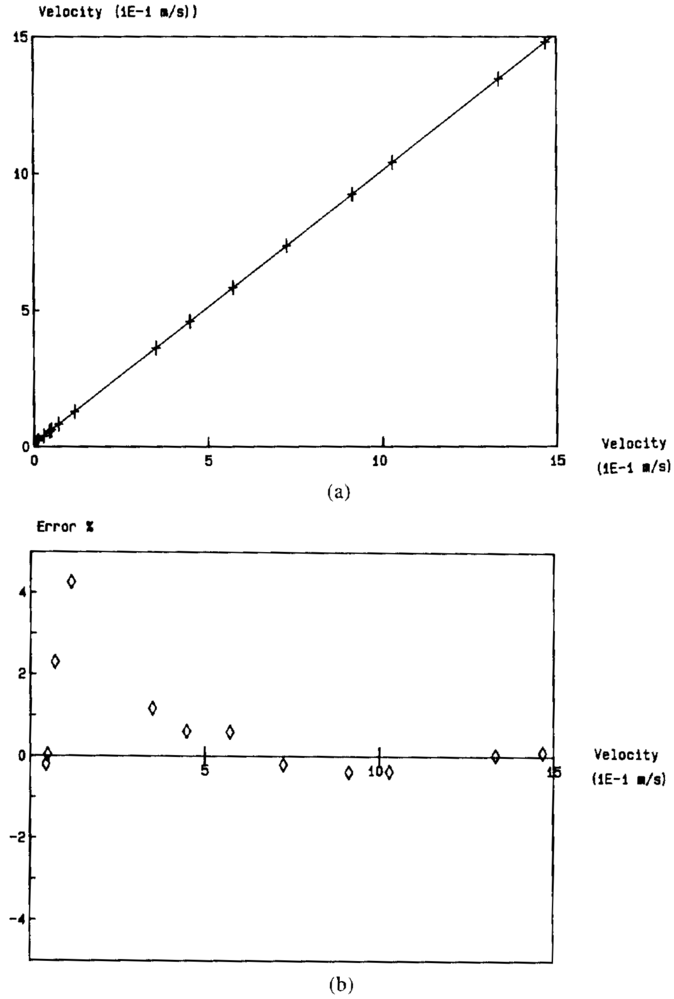

Fig. 5. Flow measurements using modified sing-around algorithm plotted against reference flow meter measurements along with associated error diagram.

shows values of not more than about 10 percent of the mean fluid velocity. Thus the modified sing-around algorithm has a superior performance over that of the conventional one for flows with changing fluid temperature.

V. Conclusion

From these calculations and tests it can be concluded that the modified sing-around algorithm is a clear improvement over the conventional algorithm for fluid flow with strongly changing temperature. It should also be noted that the modified algorithm performs as well as the conventional one for flows at constant temperature.

The general equation for the velocity is

$$v_i = (-1)^i \frac{L}{2}\left[\frac{3}{t_{i-1\cdot i}} - \frac{3}{t_{i\cdot i+1}} - \frac{1}{t_{i-2\cdot i-1}} + \frac{1}{t_{i+1\cdot i+2}}\right]$$

under the assumption that

1) the speed of sound varies linearly during four consecutive period measurements, and
2) the velocity of the fluid varies linearly during four consecutive period measurements.

TABLE I

Conventional Sing-Around		Modified Sing-Around	
Mean Velocity (cm/s)	Standard Deviation (cm/s)	Mean Velocity (cm/s)	Standard Deviation (cm/s)
10.68	20	10.38	1.1
13.97	20	13.66	1.3
14.90	28	14.87	1.8
36.25	36	35.59	2.5

Since this can be safely assumed in most cases, the new sing-around flow meter algorithm is independent of temperature variations in the fluid.

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Jerker Delsing was born in Umeå, Sweden, on June 3, 1957. He received the M.Sc. degree in engineering physics from the Lund Institute of Technology, Sweden, in 1982. He is currently a Ph.D. candidate at the Department of Electrical Measurements at the Lund Institute of Technology, where he is working on ultrasonic flow meters.

Since 1985 he has been employed by Alfa-Laval Automation, Inc., where he is currently working on sensors for the process industry.