Sensors & Transducers, Vol. 158, Issue 11, November 2013, pp. 249-254

Sensors & Transducers

© 2013 by IFSA

http://www.sensorsportal.com

Development of Noise Measurements. Part 7. Coriolis Mass Flowmeter and its Errors

Pylyp SKOROPAD, Bohdan STADNYK, Svyatoslav YATSYSHYN, Halyna POL'OVA
Institute of Computer Technologies, Automation and Metrology,
National University Lviv Polytechnic,
Bandera str.12, Lviv, 79013, Ukraine
Tel.: +38-0322-37-50-89,
E-mail: slav.yat@gmail.com

Received: 9 September 2013 /Accepted: 25 October 2013 /Published: 30 November 2013

Abstract: Coriolis mass flowmeter instrumental and dynamic errors are studied. They can be decreased by the thermocouple usage of *R* or *S* types instead of *Pt100* sensors. The dynamic error analysis shows that it is able to improve the operation accuracy in the dynamic regime and eliminate the initial period of the flowmeter exploitation in the error compensation absence regime. In consequence of the instrumental error consideration the expediency of the differential thermocouples installation with the reduced performance dispersion, lowered by taking into account of local and extensive inhomogeneities as result of technological deviations of wire production. *Copyright © 2013 IFSA.*

Keywords: Coriolis mass flowmeter, Instrumental error, Dynamic error, Differential thermocouple, *Pt100* sensor.

1. Introduction

In the case of engineering on Coriolis effect basis quite spread flowmeters – Coriolis mass flowmeters (farther – CMF) [1] the transformation function (TF) is the dependence of the liquid mass or volume on its flowing velocity through the specified cut. It is determined by the comparison of the time characteristics of two identical sensors in the CMF input and output. More phase difference of mentioned characteristics corresponds to faster controlled environment flowing. So there is a dependence on the hydrodynamic regime of the current environment flowing through the CMF, its viscosity, the temperature etc.

The measurement error is determined mostly by the determination error of phase shift performance and is, for instance, ±0.5 % in the common usage L series CMF of "Emerson" company [2]. This is viscous component of the instrumental error. The firm Oval Corp. presents the CMF Ultra Mass MK 2 [3] with its 1.0 % of the readout error under the nonessential zero-shit error as an outstanding achievement in the branch of liquid and gas flow metrology. The process of liquid pouring from one vessel to another one or gas pumping is the transitional process accordingly to aero-, hydrodynamic and heat engineering conceptions. Therefore Maersk Oil Trading Company within flowmeters mounting on tank barges is proud of the next achievement: the CMF error doesn't exceed ±0.5 % [4].

2. Error Estimate and CMF Accuracy Problems

In the metrological conception [5] the CMF consists of transducers with appropriate sensors and peripheral devices and the microprocessor unit of received signals processing. The CMF sensors determines the flow velocity, temperature and provide information in form of output signals to the microprocessor that carries out the function of the brain of the measurement device and system in total providing access to the display, main menu and output device of processed information for the interaction with other systems, for instance, the filling system. Peripheral devices provide monitoring, warning signalization and other functions, for instance, periodic processes management and the function of liquid density more accurate determination etc.

It is important to understand the correlation or non-correlation of viscous and temperature components of the CMF instrumental error. Let's consider for this moment referring to [6] that the CMF instrumental error mentioned components are non-correlated. The same is exposed in [7] where there is a presence of an instrumental error correcting means for correcting an instrumental error according to a sum of respective compensative instrumental-error values determined by the temperature correcting means, the temperature difference correcting means and the resonant frequency correcting means. The elasticity of metal tubes changes with temperature; they become more elastic as they get warmer. To eliminate the corresponding measurement error, the tube temperature is continuously measured by temperature sensor and is used to continuously compensate for variations in tube elasticity.

The CMF transfer function error temperature component is the error specified by the temperature regime of liquid/gas flowing. It depends on the temperature of the control environment (on temperature dependence of the liquid flowing regime through the CMF); on the CMF body outlet temperature that is provided by [7] with the help of temperature detecting means for detecting a temperature of the inner tube, and temperature detecting means for detecting a temperature of the outer tube; temperature correcting means for compensating an instrumental error according to a change of temperature of the inner tube; temperature difference correcting means for compensating an instrumental error according to a difference between a temperature of the inner tube and a temperature of the outer tube.

The main problems of the CMF accuracy improvement lie in that hydrodynamic, thermal, electrical and other processes in the CMF are not studied completely that specifies an unsatisfied TF reproducibility. Four platinum film resistance thermometers mounted in the CMF for the instrumental error maximum decrease are more accurate than thermocouples [8] in the measurement stationary mode thanks to good accuracy (better than thermocouples), good interchangeability and long-term stability.

The accurate measurements of thermometers electrical resistance predict the usage of 3 or 4 wires measurement systems (Last one is unaffected by extension wires resistance). However resistance thermometers demand the preliminary warming up from power sources in the measurement process that leads to the some new additional errors appearance. Under the presence of 4 resistance thermometers with 4 wires measurement scheme at face value of every resistance and the necessity of the thermometer preliminary warming before measurement to every thermometer should be supplied to 6 wires and to the device microprocessor switchboard – to 24 wires just from the resistance thermometers. Consequently the construction is being unwarrantedly complicated. The resistances measurement duration which is provided alternately because of the preliminary heating necessity will increase. The additional component appears not only of instrumental error but also of dynamic one specified by the possible control environment parameters change for full measurement period and results processing by the microcontroller. As a result some questions appear regarding such CMF usage in short-term measurements, for instance, under bear bottling as heterogeneous liquid-gas environment for which the CMF is ideal.

3. Work Goal

The research of appearing causes and the possibility of the Coriolis mass flowmeter instrumental and dynamic errors values decrease specified by the reasonable choice and energy-generating temperature sensors mounting with calibration characteristics reduce dispersion as a result of taken into account peculiarities of their production technology.

4. Accuracy Measurement Problems on the Example of the CMF with Straight Tube

4.1. The Flowmeter Construction

Let's consider in details the straight tube CMF construction (Fig. 1) assembled of the measuring and reference tubes. The special reference frequency generator creates one tube vibrations relative to another one. These tubes reciprocal position will change on the condition of liquid movement through the CMF. Then the effect of tubes "beating" appears proportionally with the velocity of liquid movement (quantity) that passes through the CMF.

The CMF has two separate contours for temperature measurement. The first contour is in the form of the resistance thermometer which has a thermal contact with the measuring tube and it gauges the liquid temperature passing through the CMF measuring tube. The second contour (for the temperature measurement) consists of three analogical sensors: two are located on the reference tube and the third is on the body. These sensors are used for temperatures difference correction between the body, the reference tube and the measuring tube. Such CMF provides highly accurate value measurement of the flow and the liquid density under conditions of the changeable surrounding temperature that is mainly different from the liquid storage temperature in a reservoir.

The impact factors analysis shows that there is viscosity values scatter of the control flow under the nominal measurement temperature, and the flow viscosity changes during the measurement on account of its selection mainly from some storage layers where the velocity value is extreme because of the durable terrestrial gravity effect. As result the viscosity component of the CMF instrumental error measurement appears which is specified by the control liquid. It is determined by TF changes appearing, for instance, in case of the volume reservoir emptying and getting into the CMF of the control liquid with changeable viscosity relative to time. So far as this instrumental error component is partly specified by the selection conditions of the control environment therefore it isn't often mentioned by the CMF producer.

4.2. Instrumental Error Temperature Component of the Measurement by the Means of *Pt100* Film Sensors

The error temperature component value in the gas flow control by the means of the CMF is underlined by the [9], where, for instance, it is tempting to answer that the temperature tripled (60/20), but the ratio of the absolute temperatures is important for flow measurement (60+273)/(20+273) = 1.137, we notice the 13.7 % error-increase. As a result of producing peculiarities the CMF transfer function of one lot is characterized by some spread. In turn the producer takes into account that during 2 sensors mounting in the fuel quantification scheme and 4 temperature sensors in the scheme of amendment introduction the TF CMF maximum identity cannot be attained. It leads to the necessity of the individual calibration of every CMF. It enables to minimize [10] the instrumental error to ± 0.1 % in the most accurate CMF types. It is absolutely obviously the calibration is effective only in some before prescribed in very short temperature range of the CMF operation that includes beforehand indicated temperatures of the control environment and the CMF etc. Though most likely firms don't mention but the calibration is done in one TF point under fixed impact factors the number of which is quite significant. Besides that the control environment can considerably change its own viscosity under the measurement. So the CMF with instrumental error which is under the calibration has producer guaranteed dispersion or coverage interval under the operation will spread its own coverage interval demonstrated in the Fig. 1.

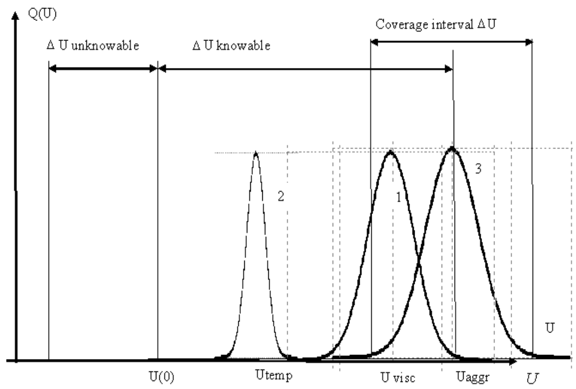

Fig. 1. CMF instrumental error (3) as amount of two components with the fixed uncertainty: viscosity one (1) and temperature one (2) that is expressed by the coverage interval.

Moreover in the usage practice the dynamic error appears [11] specified by the resistance sensor essential inertness, and the methodical error as result of the sensor heating from the power supply [12] and the dynamic error additional component caused by its internal self-heating. Because a current must be passed through the sensor to obtain a voltage signal for the electronics there is a small amount of power generated which causes the sensor to warm up and thereby changing its resistance. A large current will give a nice big signal for the electronics but also a larger self-heating error. A small current reduces this error but lower drift electronics is required to minimize errors from the circuit. The best trade off depends on the application however generally currents of the order of 1mA or less are typically used. Self-heating errors are larger when measuring gas temperatures because of the poorer heat dissipation from the sensor [13]. Simultaneously the heating alternation of each of 4 resistance sensors increases the CMF dynamic error more than in 4 times.

As the resistance sensors in industrial applications are commonly used the film sensors that at first had their market in white-ware applications. Film sensors have a platinum pattern fixed onto its surface that gives 100 or 1000 ohms resistance at 0°C. They are known as *Pt100* and *Pt1000* respectively. Industrial *Pt100* detectors are divided into four tolerance classes under [15]: *AA, A, B* and *C*. The new standard makes a difference between wire-wound and film sensors. Experience shows that film sensors can't handle as wide temperature ranges as wire wound sensors under the different tolerance classes. Film sensors are gradually used more often in industrial applications. Closer tolerances at other temperatures can only be achieved through calibration that determines the specific properties of the individual sensor. This is because the quality of platinum specified in IEC 60751 is reduced by the material being an alloy with added palladium – done for compliance with the traditional DIN standard. The alloy gives rise to departures from the ideal curve, necessitating a safety margin corresponding to the slope of curve A or, at worst, of curve B.

Tolerances for assembled *Pt100* sensors including film sensors are shown in IEC 60751:2008. For example, film sensor type *B* has performance tolerance ± 0.5 °C at 50 °C or ±1 %. Though [12] informs about typical accuracies 0.2 %, 0.1 % of such sensors. It should notice that accuracy and performance tolerance are absolutely different in effect. The last one concerns the sensors interchangeability and it is especially important in case of identical sensors usage in one CMF.

4.3. Temperature Component of CMF Instrumental Error of Measurement by Means of Thermocouples

To replace *Pt* resistance sensors is proposed to use well studied *Pt-Rh* thermocouples [16]. For temperature range 243 ... 1000 K thermocouples type *S* (*Pt*-10 % *Rd* / *Pt*) are used. At first sight they are worse than mentioned resistance sensors. They have much worse the calibration characteristics reproducibility that for second class thermocouples is ±1.5°C in the temperature range 0–600 °C [17] against ± 0.1 % in platinum resistance sensors. But film sensors are characterized by reproducibility of ± 1 % that slightly worse compared to characteristics of mentioned thermocouples.

Table 1 [14] describes briefly the main differences between thermocouples and *Pt100*s in general terms.

Table 1. Comparison thermocouple vs. resistance sensor.

Property	Thermocouple (TC)	Pt100 Sensor
Measuring range	Large: -200 < T < + 1000 °C	Limited: -200 < T < + 600 °C
Stability	Not good, especially in high temperature	Excellent. annual drift < 0.01°C
Measuring location	From hot junction to reference location	Across entire *Pt*-wire length
Ageing	Significant in high temperature	Insignificant, see Stability.
Response time	Very short possible < 1 s	Not as short as corresponding TC
Excitation power	None	Significant < 1 mW
Physical strength	Very good	Limited
Pricing	Slightly lower than corresponding *Pt100 s*	Slightly higher than corresponding TC

Let's pay attention that in 90 % cases the CMF operates under room temperatures where thermocouple instability and ageing affect are very low. It is provided significant advantage to thermocouples. They have other essential advantages: the method error absence from measurement current warming; this mentioned procedure time is economized and the dynamic error is considerably lesser; the CMF electrical structure is significantly simplified because of leading-in wires amount from temperature control means decreases. The sensors signals measurement is more simple and accurate so far as the thermocouple signal measurement compensation method has better accuracy than the resistance sensors signal measurement potentiometric method. Then the additional resistance sensors power supply is unnecessary.

4.4. Thermal Response Time

The response time of platinum resistance sensors is 60 s. It means the following. During the first minute the thermometer is warming up to the temperature 63.2 % of the applied temperature drop value. After 3 minutes it reaches 95 % of the temperature spring and after 5 minutes it reaches 99 %. Very small and quick *Pt100* film sensors type *TF101N* thermal response time refer to manufacturer data [18]: $t_{0,9}$ in the air – 10 s, in water < 1 s. Because it takes longer for the components of a *Pt100* sensor to warm up, *Pt100* sensors generally have a longer response time than thermocouples. The last one under the unprotected junction which as result of two 0.125 mm diameter thermoelectrodes welding has similar form to a sphere of 0.2 mm diameter is characterized by the thermal response time on the level 1.0 s in the air and 0.04 s in the water (Table 2) [19]. Otherwise it is characterized by the significantly lesser inertia in comparison to the film resistance sensor.

Table 2. Response time * of thermocouples.

Wire size, (mm)	Still air 427°C/38°C	60 ft./sec air 427°C/38°C	Still H_2O 93°C/38°C
0.025	0.05 sec	0.004 sec	0.002 sec
0.125	1.0 sec	0.08 sec	0.04 sec
0.381	10.0 sec	0.80 sec	0.40 sec
0.75	40.0 sec	3.2 sec	1.6 sec

*The time constant is defined as the time required reaching 63.2 % of an instantaneous temperature drop.

The measurement resistance procedure of every of 4 sensors includes the following steps: the current is consecutively led to every of them, after the sensor warming the voltage drop is measured on it. It takes usually 7-10 minutes for *Pt100* sensors produced of the bobbin wound wires. Only in this case the taken platinum resistance sensors readings can be taken into account by the microprocessor. At the same time the additional method error appears from the measurement current warming and additional time for this warming that is equivalent to thermal response time additional increase.

5. CMF Performance Improvement under the *S*-type Thermocouples Usage

Some CMF types operation theory shown in [1] is based on the difference temperature measurement of two points. It can be successfully done by one thermocouple which hot and cold junctions control the mentioned points. The standard thermoelectric inhomogeneity of *S*-type thermocouple in accordance with [17] is ±1.5°C. The inhomogeneity is estimated [20] as difference between maximum and minimum values of the thermo-EMF concerning comparison certified reference material on every 5 m length of wire in the bobbin under the temperature 900±20°C ... 1300±20°C. It is specified by the real imperfect technology of the wire producing. So tolerance classes of calibration characteristics have been proposed. They are intended to ensure interchangeability of thermocouples without special calibration testing. A unique advantage of thermocouples is that 'bobbin calibration tests' may be made of samples from a given bobbin of wire, and those test results will apply to all thermoelectrodes made from that same bobbin. In this way significantly closer control of tolerance variations may be gained without incurring the high cost of testing a large number of individual thermoelectrodes and therefore the thermocouples [21].

The necessity of the electric signal output from the thermocouple demands the double compensation wires usage that leads to a number of other problems appearing. That's why the better decision is considered to measure the temperatures difference of 2 points by the means of the differential thermocouple that consists of 2 towards switched thermocouples. Then leading-in wires are done of the same thermoelectrodes. Naturally such wire is the best one of two by the thermoelectric inhomogeneity, in our case – *Pt* wire.

However the thermoelectric inhomogeneity of 2 already connected thermocouples increases in $\sqrt{2}$ times, so to ±2.12°C (the thermoelectric inhomogeneity of 4 thermocouples used in the construction will reach $\pm 1.5 \times 2 = \pm 3$°C) that cannot meet technical demands.

Scientific and technological solutions are based on the technology knowledge of thermocouple wires production of platinum and platinum group alloys. Taking into account that in the bobbin of thermocouple wire there are equal by their impact local and extensive inhomogeneities, the action of the last inhomogeneities can be practically eliminated by the significant decreasing of thermoelectrodes length [21]. Especially it concerns the next cases: a) the usage of small parts of thermoelectrodes, for instance, the length about 0.05 m that is less than 1 % of length under which the thermoelectric inhomogeneity is studied; b) the usage in two and more thermocouples of thermoelectrodes from neighboring piece of bobbin. Then for the wire of *Pt*-10 % *Rd* the thermoelectric inhomogeneity of such wire length mounted in small CMFs can be decreased in some times: from ≤ ± 8 μV to ≤ ± 2 μV.

Thus the differential thermocouple is produced for the CMF in Π-shape where 2 vertical thermoelectrodes are made from *Pt* wire with thermoelectric inhomogeneity ≤ ± 2 μV and between them there is a short horizontal section of *Pt* – 10 % *Rd* wire with inhomogeneity ≤ ± 2 μV. As result the *S*-type thermocouple inhomogeneity that is determined as root-mean-square deviation of non-correlated values of 2 different wires inhomogeneity is ± 2√2 μV or ±0.52°C. This is the reproducibility of temperatures difference measurement in 2 CMF neighboring points by the means of replaceable differential *S*-type thermocouples.

Totally the CMF is equipped by 4 ordinary or better by 2 differential thermocouples. The first differential thermocouple consists of two towards switched thermocouples that measure correspondingly the temperatures of input and output of reference tube. In the second pair other 2 thermocouples are switched towards – for temperatures difference measurement on the CMF measuring tube and on its body, so one more differential thermocouple is realized. This fulfillment enables to introduce temperature corrections: for the first thermocouple – on control liquid temperature changes within the tube as result of the thermal-hydrodynamical flowing regime change; for the second thermocouple – on control environment temperature changes as a result of passing through the CMF.

6. Conclusions

1. The metrological characteristics of Coriolis mass flowmeter which is equipped with 2 phase sensors and 4 temperature sensors have been studied. They can be improved by the replacement of *Pt100* resistance sensors with *S*-type thermocouples.

2. The dynamic error analysis shows that the operation accuracy in dynamic regime can be improved and initial non-compensation flowmeter exploitation period can be removed by the means of thermocouples with unprotected junction usage. Then the flow measurement process can be conducted in the real time regime avoiding the dynamic error since 1 second of the measurement despite of the CMF with film/bobbin – wound resistance sensors where values become reliable since 60/500 second correspondingly.

3. In consequence the CMF instrumental error consideration the expediency of differential

thermocouples mounting is demonstrated. They have reduced dispersion of calibration characteristics by taking into account the thermoelectrodes manufacturing peculiarities and by the usage of more thermoelectrically homogeneous thermoelectrode as cross-cut one in the Π-shape construction of the differential thermocouple.

References

[1]. Flow and level measurements (www.omega.com/literature).

[2]. Emerson Process Management – Coriolis Flow and Density Measurement (http://www2.emersonprocess.com/en-us/brands/micromotion/pages/coriolis-flow-density-measurement.aspx).

[3]. OVAL Corporation (http://www.oval.co.jp).

[4]. J. Rosenkrans, Bunkering in the 21-st century: the case for Coriolis flowmeters and experiences thus far, in *Proceedings of the Wilhelmsen Premier Marine Fuels Bunker Seminar*, Oslo, October 14, 2010.

[5]. M. Kazahaya, A mathematical model and error analysis of Coriolis mass flowmeters, *IEEE Transactions on Instrumentations and Measurement,* Vol. 60, Issue 4, 2011, pp. 1163–1174.

[6]. V. Voytov, Diagnostics of hydraulic machines running gear, *Transactions of National Forestry Engineering University,* Lviv, Ukraine, Vol. 20, Issue 3, 2010, pp. 74-77. (in Ukrainian)

[7]. T. Endo et al., Error correcting Coriolis flowmeters, G01F1/84, *Patent* US 5796012 A.

[8]. Hyper Sense Technology Co. Ltd (http://www.hyper-sense.com.tw/front/bin/ptdetail).

[9]. D. Spitzer, The consumer guide to Coriolis mass flowmeters, Seminar, *Spitzer and Boyes, LLC*, 2004.

[10]. Micro motion Coriolis flow & density measurement (http://www.micromotion.com).

[11]. N. Yaryshev, Theoretical basis of measurement of nonstationary temperature, Leningrad, USSR, *Energy-Atom Publishing House,* 1990. (in Russian).

[12]. F. Philpott, The Pt100 sensor, I.Q.Instruments, (http://www.iqinstruments.com/iqshop/technical/pt100.html).

[13]. Ya. Lutsyk et al., Temperature measurements: theory and practice, Lviv, Ukraine: *Beskyd Bit,* 2006. (in Ukrainian).

[14]. Resistance thermometer theory (http://indutrade.Episerverhosting.com/en/Business-areas/Special-roducts/Pentronic/)

[15]. IEC 60751:2008, Usage limitations and accuracies, *WIKA Data Sheet IN 00.17*, April 2013.

[16]. O. Gerashchenko et al., Temperature measurements, Handbook, Kyiv, Ukraine, *Naukova Dumka,* 1986. (in Russian).

[17]. IEC Tolerance Class EN60584-2. Thermocouple type, *WIKA Data Sheet TE 67.26*, April 2011.

[18]. ZIEHL industrie-elektronik GmbH + Co KG (http://www.ziehl.de/ziehl/englisch/temperature_monitoring/5pt100sensoren_e).

[19]. OMEGA Engineering (http://www.omega.com/pptst/IRCO_CHAL_P13R).

[20]. I. Levin, I. Rogelberg, Thermoelectric inhomogeneity of the wires and the methods of its measurement, *Investigation of Thermocouple Alloys*, Moscow, USSR, 1977, pp. 93-106. (in Russian)

[21]. R. Park, Thermocouple fundamentals, Course Tech., Temp. 2-1 (http://www.advindsys.com/ApNotes/tcfund).

2013 Copyright ©, International Frequency Sensor Association (IFSA). All rights reserved.
(http://www.sensorsportal.com)