Measuring Set including a Virtual Standards® Technology-Based Superimposed Ultrasonic Flow Meter

S.M.Yermishin (syermishin@virtualstandard.ru)
A.V.Lopatin (alopatin@virtualstandard.ru)
V.A. Dulev (vdulev@virtualstandard.ru)
N.A. Khoteev (nkhoteev@virtualstandard.ru)
P.G. Shabanov (shabanov@virtualstandard.ru)
A.B. Menshikov (menshikov@virtualstandard.ru)
A.V. Startsev (avstar@virtualstandard.ru)

(20, Dayev per., Moscow, 107045, Russia, phone: +7 (095) 204-8286,
fax: +7 (095) 204-8285 Virtual Standard Inc., Madison Technologies Ltd.)

Abstract

A Virtual Standard® technology-based flow measuring set has been developed for liquid media. Virtual Standard® technology is a universal technology for determining and introducing corrections in measuring device readings to reduce their errors. The set consists of a measuring module implemented as Vzliot-PR superimposed ultrasonic flow meter (basic accuracy = 1.3% to 2%) and a processing module i.e., digital computing device. The resulting accuracy of the flow measuring set is 0.25% to 0.5%.

Key words: superimposed ultrasonic flow meter, reading corrections, measurement result ambiguity, virtual standard.

1. Introduction

The problem of finding means of and methods for improving measurement accuracy often arises in measurements conducted using superimposed ultrasonic flow meters. An individual adjustment of superimposed ultrasonic flow meters often provides an opportunity for solving this problem, in particular when one does not want to pay extra money for precise measuring devices. An appropriate standard and adjusting devices are required to achieve that. The Virtual Standard® technology has been developed to adjust measuring devices so that measurements could be conducted with a higher class of accuracy, but without using standards or adjusting devices.

Virtual Standard® technology is a universal technology for determining and introducing corrections in measuring device readings to reduce their errors. The measuring device for which reading corrections are determined is called 'Virtual Standard® system measurement module'. The digital computing device where reading corrections are determined is called 'Virtual Standard® system processing module'. The Virtual Standards® system is a functional implementation of the Virtual Standards® technology and some corresponding additional service functions: exchanging data between measuring module and processing module, establishing an interface between measuring module and processing module, establishing an interface between the Virtual Standards® system and users, automating measurements and the document management, and supporting accounting payment operations.

Present-day flow meters consist of transducers in both hardware and software implementations. A higher measurement accuracy is achieved through increasingly correct and precise measurements. Software has traditionally been used in flow metering to improve measurement accuracy through improving precision i.e., to reduce the random error component. The most popular processing methods used for that purpose are various statistical processing and filtering algorithms. However, the question whether software can be used to increase flow meter correctness i.e., to take into account the systematic error component, and what processing methods should underlie such software, remains open. This work is designed to answer this question in particular technical application to superimposed ultrasonic flow meters for liquid media.

2. Target setting

The measured flow of liquid medium in a pipeline and a superimposed ultrasonic flow meter interact in a field created by radiators, which is accompanied by transformation of the radiated energy on measurement object into other forms of energy in sensors. The measured liquid medium disturbs the field of the radiated energy and introduces errors in measurement results.

The principal meaning of the measurement procedure is converting an interacting, and thus closed reciprocal 'measured flow of liquid medium in the pipeline – superimposed ultrasonic flow meter' system that is isomorphic in terms of abstract algebra, into a one-way (homomorphous) system. The true value of the measured quantity corresponds to this ideal state with one-way (homomorphous) 'measured flow of liquid medium in the pipeline – superimposed ultrasonic flow meter' links. The actual value of the measured quantity differs from the true value by the measurement error.

Assume that a set of states S is observed on ultrasonic flow meter radiators over measurement time t_i, and a set of measurement results J is registered at sensor outputs. Assume that

$$S = \begin{vmatrix} s_{12} & s_{12} \\ s_{21} & s_{22} \end{vmatrix} \qquad (1)$$

where s_{11} and s_{21} are values of the measured quantity in the measurement plane (measuring beam) on the measurement object to the left of axis of symmetry φ_1 at moments of time t_1 and t_2, respectively;

s_{12} and s_{22} are values of the measured quantity in the measurement plane (measuring beam) on the measurement object to the right of axis of symmetry $-\varphi_1$ at moments of time t_1 and t_2, respectively.

Then

$$J = \begin{vmatrix} j_{11} \\ j_{12} \end{vmatrix} \qquad (2)$$

where j_{11} and j_{12} are DC values at moments of time t_1 and t_2.

Let us use an ultrasonic flow meter described by linear operator T:

$$T = \begin{vmatrix} 1 & 0 \\ 0 & -1 \end{vmatrix} \qquad (3)$$

$$J = T \cdot S \cdot D \qquad (4)$$

$$D = \begin{vmatrix} d_1 \\ d_2 \end{vmatrix} \qquad (5)$$

where d_1, d_2 is an operator describing the nature of conversion (for example, voltage growth at the input amplifier or voltage reduction at the input divider, etc.) at the moment of time t_1, t_2.

It should be noted that in virtually all cases, measurements transform energy (poles relative to the axis of symmetry) received from the measurement object in the measuring device, therefore, the linear operator of type (1) is a general form used to present measurement information signal conversions in flow meters.

At the same time, (4) is actually a form of coordinate conversion that is most frequently used in the flow measurement process.

Linear operator T (3) perturbations due to external factors are present in the real technical measurement process:

$$T(\chi) = T + \chi \cdot T' \qquad (5)$$

where χ is a scalar parameter assumed to be sufficiently small, T' is a perturbation caused by external factors.

$T(\chi)$ type linear operators are known to be characterized by multi-valued eigenfunctions with two branches [1]. Article [1] also presents the result of an analytic study of eigenvalue perturbation for perturbed operator (3) of the form

$$T(\chi) = \begin{vmatrix} 1 & \chi \\ \chi & -1 \end{vmatrix} \qquad (6)$$

Eigenvalues

$$\lambda(\chi) = \pm(1+\chi 2)1/2 \qquad (7)$$

of type (6) operator $T(\chi)$ are branches of the single double-valued analytical function $\pm(1+\chi^2)^{1/2}$ that is, the operator definition domain contains so-called 'exclusive points' $\chi=\pm i$ where eigenvalue increments due to splitting are infinitely large quantities as compared with the change in the operator $T(\chi)$ proper. An estimate of the convergence radius is given in [1] for perturbation theory series. Convergence radius is $r_0=1$.

Fig. 1 illustrates the ambiguity of the set of measurement results.

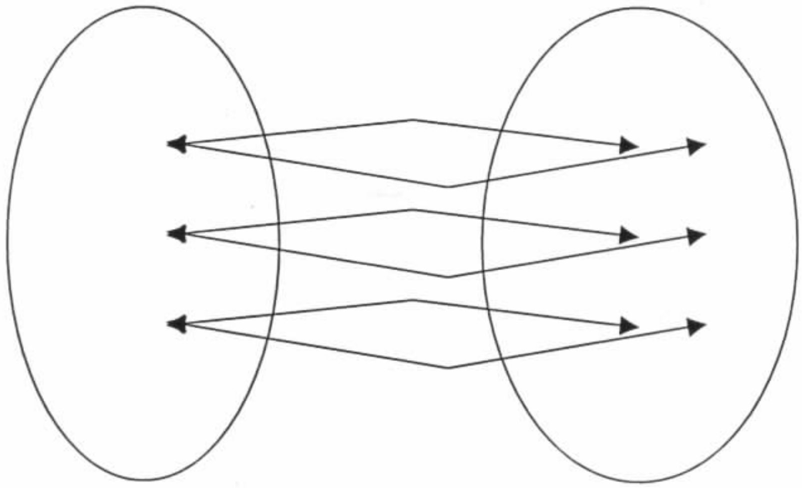

Fig. 1. Illustration of the lack of one-to-one correspondence between the true value of the measured quantity on the object and measurement results

Two possible sets of measurement results Ω^1 and Ω^2 correspond to a single set of true values of the measured quantity on object ϑ.

If we present measurement results as a function of an unknown random error component and of an unknown systematic error component, then the equation in a single set of measurement results is unsolvable (one equation in two unknown quantities). If we consider measurement results as multi-valued sets, we obtain a system of several (two) equations in two unknown quantities: the random and systematic measurement error components. Such system is solvable, which enables an estimate to be obtained of the true value of the measured quantity and corrections to be formed for the measuring module reading that increase measurement result correctness. The linear independence of system equations, similar to the formation of a multi-valued set, is ensured by the conclusions of the T.Kato perturbation theory for linear operators. These results underlie the Virtual Standard® functioning algorithm.

3. Mathematical algorithm of the Virtual Standard®

Fig. 2 shows a flow chart of mathematical algorithm operation. Once a physical quantity has been measured on the object, and the measurement results have been digitized, they are fed to the processing module where they are saved in a certain memory domain where Y_1, the first subset of the multi-valued set of measurement results, is formed. After that, coefficients $\{a_1, \ldots, a_n\}$ are formed with due regard to eigenvalues (7) which have been calculated by Kato for the multi-valued function linking the true value of the measured quantity on the measurement object to the elements of the multi-valued set of measurement results, which are used to calculate auxiliary set Y_2 of measurement results that is saved in the processing module memory. Thus, a series of multiple measurements is carried out as a function of the increasing/decreasing measured parameter, which results in the formation of two linearly independent subsets Y_1 and Y_2 of the multi-valued sets of measurement results. Then a target function is formed using the minimax criterion:

$$P(d(\bullet)) = \sup_{a \in X \times \Delta X} \min(\pi^{\alpha}(a_i) \mid l(d(a_i)) \qquad (8)$$

For example, minimum relative deviation $l(d(a_i))$ from the optimum value of the functional dependence $\pi^{\alpha}(a_i)$ sought with respect to its maximum possible value in this dimension and limit domain ΔX (for example, formed in the measuring device tolerance domain) can be used as such criterion for finding an unambiguously defined functional dependence of values Y_1 and Y_2 from the unknown systematic and random error components with the target function and limit domain being placed in the processing module memory. At the next stage, coefficients $\{a_i\}$ are calculated and determined as results of performing the task of using formula (8) to optimize an unambiguously defined functional dependence $Y_1, Y_2 = \Psi(\Delta_{random}, \Delta_{syst})$ of values Y_1 and Y_2 from the unknown systematic and random error components, and the calculated coefficient are saved in the digital module memory. After that, individual corrections are calculated for measurement results Y_1 with due regard to the real measuring device error using known coefficients of the unambiguously determined functional dependence from the digital module memory. The individual correction calculation results are used to determine the actual value of the measured quantity induced by the processing module as a measurement result.

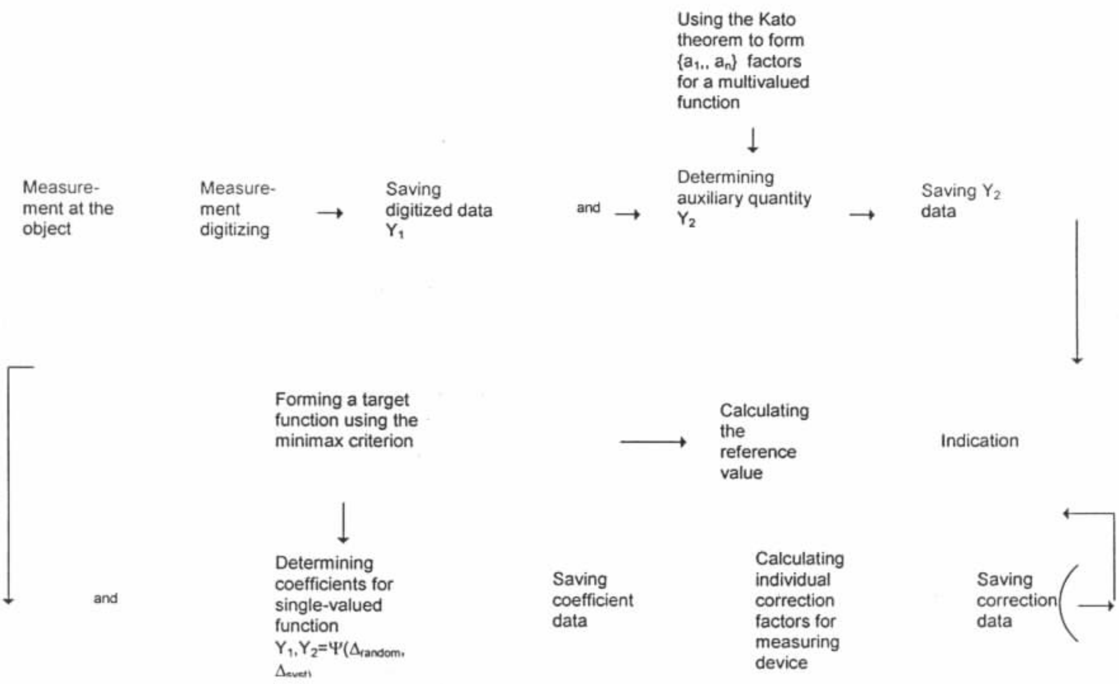

Fig.2. Virtual Standard algorithm

4. Experimental results

The above-described algorithm has been implemented in the form of a software package and tested in over 50 series of various designer's tests and tests performed to approve the type. Some Virtual Standard® test results are given in this work as an illustration. Vzliot-PR (1.3% to 2%) was used as a measuring module, and UROKS-400 precise flow metering plant (0.15%) was used as a working standard.

Virtual Standard® accuracy amounted to 0.25% - 0.5% in these experiments. The result observed was accuracy improved by a factor of 3 or more (Figs. 3&4).

The y-coordinate is Virtual Standard® system's relative error obtained on the UROKS-400 plant in measurements performed on a pipe 150 mm in these figures. The x-coordinate is numbers of measurements of the accumulated volume of liquid carried out by the measuring module i.e., the Vzliot-PR ultrasonic flow meter, at 15 second intervals. Figures 2&3 show two different series of measurements carried out in different flow rate ranges (37.3 m^3/s, 122.6 m^3/s) at different moment of time.

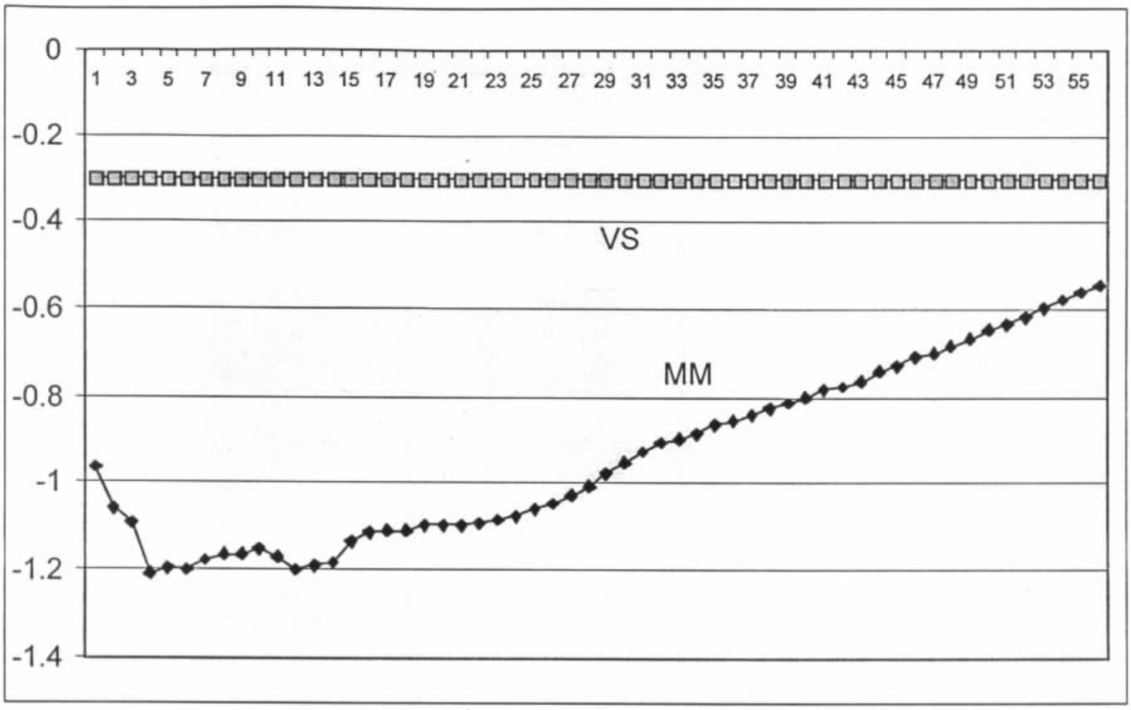

Fig. 3. Liquid flow measured using Virtual Standard® system with the Vzliot-PR flow meter as a measuring module at a standard flow rate of 37.3 m^3/s: MM = Measuring Module; VS = Virtual Standard

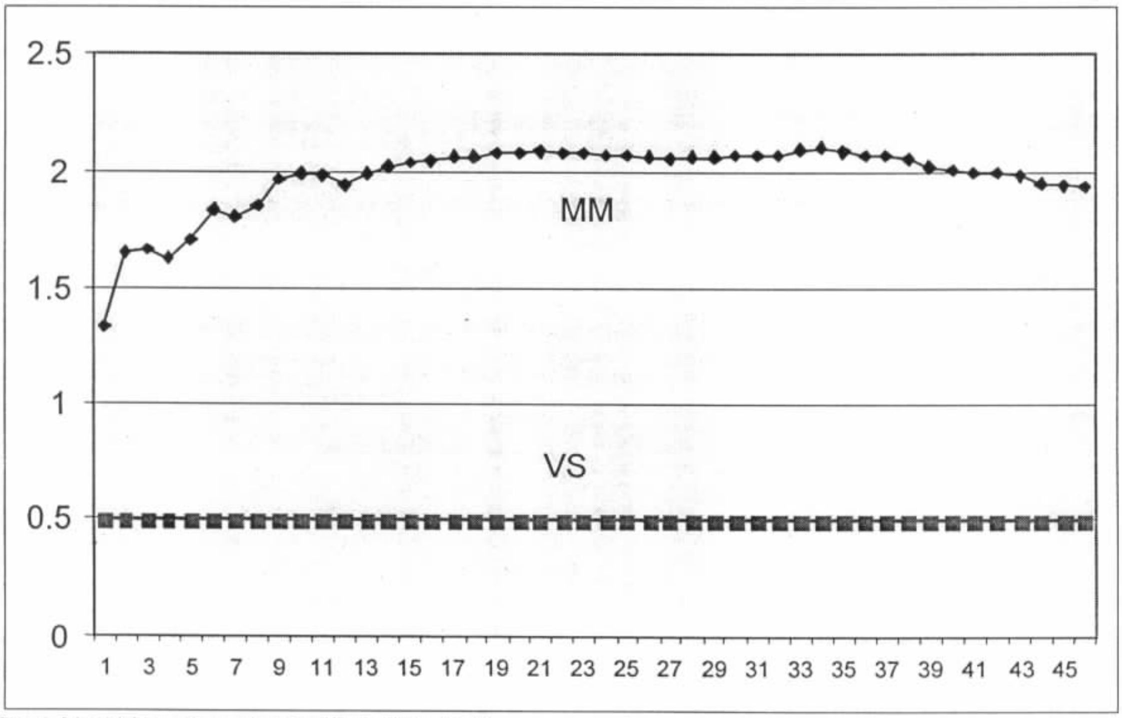

Fig. 4. Liquid flow measured using Virtual Standard® system with the Vzliot-PR flow meter as a measuring module at a standard flow rate of 122.6 m^3/s: MM = Measuring Module: VS = Virtual Standard

5. Conclusions

The theoretical and experimental results presented suggest that measurement accuracy can be fundamentally improved in a series of various measurements using the Virtual Standard® technology. What are the principal technical measurement tasks that can be performed using the Virtual Standard® system? We are of the opinion that this will be calibration/self-calibration of measuring devices and transducers in the first place. The use of the Virtual Standard® system reduces costs and improves the functionality of calibration operations so much that they can be carried out as frequently as required to use calibration as an efficient tool for improving measurement accuracy. Thus, an opportunity arises to implement a wider range of liquid flow measurements on the basis of Virtual Standard® technology using flow meters of other types to measure various ranges and accuracies.

Acknowledgment

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Reference

[1] Tosio Kato. Perturbation Theory for Linear Operators.//*Springer-Verlag, Feb. 1995.*