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Approach for Acoustic Transit Time flow measurement in sections of varying shape: Theoretical fundamentals and implementation in practice

S. Marushchenko [a,*], P. Gruber [b], T. Staubli [b]

[a] Aircraft Manufacturing Technology Department, National Aerospace University, Kharkiv, Ukraine
[b] Lucerne University of Applied Science and Arts, School of Engineering and Architecture, Switzerland

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ABSTRACT

This paper focuses on the generalization of the Acoustic Transit Time (ATT) flow measurement method currently embodied in ultrasonic flow meters. First, the existing theoretical fundamentals that cover flow measurement in regular conduits are presented and relevant design features of typical ultrasonic flow meters are described. A detailed derivation of a measurement method for the generalized theoretical fundamentals of multipath ATT flow is then presented. This generalization consists of extending the existing theoretical background in the case of an irregular section, which is defined as a section that has a non-standard shape and/or a varying shape and size, e.g. one that has transition from a rectangular to a circular section. On the basis of the derived generalized theory, the approach for flow measurement in such irregular sections is developed. This approach is then tested numerically using an example of a converging measurement section that represents the water intake of the Kaplan unit. During the test of the new approach, the flow rate and flow profile at the inlet were varied to investigate the effect of such variations on the accuracy of flow rate determination. Results for a significant flow profile and flow rate variations show that the overall error dispersion of the flow rate evaluation is of the order of 0.5%.

1. Introduction

The Acoustic Transit Time (ATT) method is a well-accepted technique used to continuously measure the flow rate in hydraulic power plant applications with a permanently installed flow meter. ATT flow meters have many advantages such as no moving parts, high reliability and measurement performance stability, all of which are related to low maintenance costs. In addition, there is no associated pressure loss, they have a wide measurement range and the ability to measure in large sections. These advantages, and particularly the latter, frequently make the ATT flow meter the most suitable choice for use in the flow measurement of the water intake of hydraulic power plants, where cross sectional dimensions are large. However, in some types of hydraulic turbines (e.g. Kaplan-type turbines), there is usually no available straight conduit section and measurements can only be performed in the intake section. In such cases, therefore, the meter can be only installed in a section that has a varying shape.

Standards such as IEC60041 [1] and ASME PTC 18 [2] regulate performance testing of hydraulic turbines. Among other issues, the standards introduce procedures for ATT flow measurement in the conventional case of regular, straight measuring sections. However, for irregular sections or sections with a varying shape, the aforementioned standards contain neither practical recommendations nor a theoretical background. In addition, Standard [3] recommends avoiding sections that have irregular cross-sections. Although an example of ATT method realizations in irregular sections with varying shapes can be found in [4,5] and [6], these papers do not provide a theoretical background for flow measurement in such sections. However, one study [7] proposes a governing equation to enable ATT flow measurement in irregular sections and contains a brief description of the idea underlying implementation of this equation, but does not present a detailed theoretical background for using the ATT method under conditions where there are irregular measuring sections. The conventional theoretical basis, as described in [8], cannot be used with the ATT method in irregular measuring sections.

The 'area flow function', $F(z)$, which is discussed in Section 2.3, is the central element of the ATT flow measurement because flow rate integration is actually the numerical quadrature of discrete F (z) values. However, the area flow function in an irregular section cannot be uniquely determined as it is dependent on the cross-section shape, which means that certain prerequisites of the

* Corresponding author.
E-mail address: marushchenkos@yandex.ru (S. Marushchenko).

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method, such as weighting and positioning procedures (see Section 2.4), are not applicable in such cases. There is thus no theoretical work that describes the issues involved in using the ATT method in irregular sections, nor how to deal with such issues.

This paper therefore aims to fill this gap by developing a theoretical background for application of the ATT method for measurements of both irregular sections and sections with varying shapes. The goal is to adapt the developed theory to provide a method for practice and thus open prospects for significant extension of the ATT method application field.

2. ATT flow measurement in regular conduits

2.1. Basic principles of ATT method

The operational principle of an ATT flow meter lies in its ability to measure the acoustic pulse propagation time between a pair of transducers in both a downstream, t_{12}, and upstream, t_{21}, direction (Fig. 1).

According to Fig. 1, the projection of mean velocity on the acoustic path is $\bar{v}_p = L/(1/t_{12} - 1/t_{21})/2$, where L, t_{12} and t_{21} denote the acoustic path length and the acoustic pulse transit times from transducer 1 to transducer 2 and back, respectively.

The mean axial velocity, $\bar{v}_{ax}$, is then given by Eq. (1),

$$\bar{v}_{ax} = \bar{v}_p / \cos\varphi, \tag{1}$$

where φ is the acoustic path inclination angle.

The flow rate through a cross section is $Q = A \cdot v_{bulk}$, where A and v_{bulk} denote the area of the cross section and the bulk velocity in the cross section, respectively. Therefore, to calculate the flow rate using the ATT method it is necessary to evaluate the factor $k = v_{bulk}/\bar{v}_{ax}$ that relates v_{bulk} with $\bar{v}_{ax}$. This can be evaluated experimentally on the basis of an analytically described velocity distribution (e.g. the velocity distribution for turbulent flows described by Gersten, Herwig [9]) or from numerically determined flow fields. The flow rate can then be calculated as $Q = A \cdot k \cdot \bar{v}_{ax}$.

2.2. Application of ATT in non-ideal velocity distributions and cross flow

An axial velocity profile in a conduit can be influenced by elements located upstream or downstream. Cross-flow may also be induced (Fig. 2), and because of the acoustic path inclination, this cross flow velocity component also contributes to the mean axial velocity, $\bar{v}_{ax}$, derived from the mean projected velocity, $\bar{v}_p$. Fig. 2 shows the relation between axial and transverse velocity components.

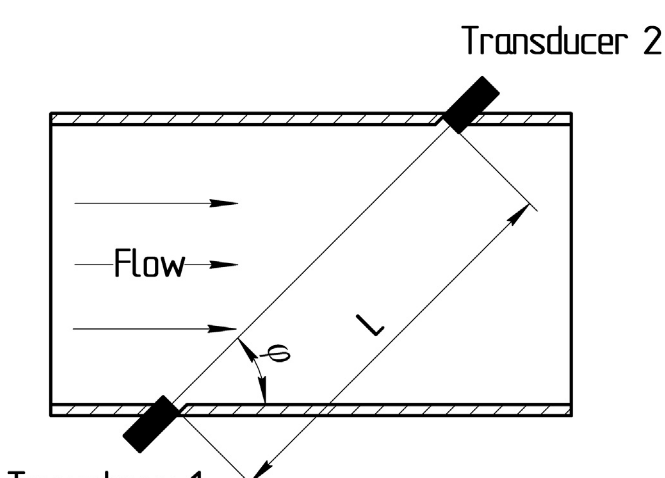

Fig. 1. Schematic of dual sensor ATT meter.

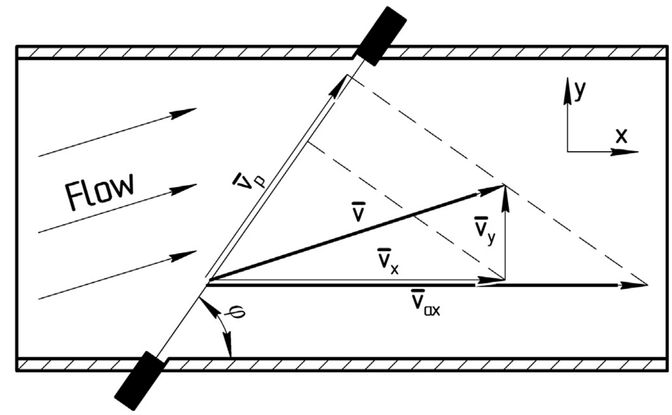

Fig. 2. Relation between velocity components: mean projected $\bar{v}_p$, mean transverse $\bar{v}_y$, true mean axial $\bar{v}_x$ and indicated mean axial $\bar{v}_{ax}$ in cross flow conditions[1].

According to Fig. 2, the indicated mean axial velocity, $\bar{v}_{ax}$, is related to the true mean axial velocity, $\bar{v}_x$, as $\bar{v}_{ax} = \bar{v}_x + \bar{v}_y \cdot \tan\varphi$. To reduce the contribution of cross flow, the double measuring plane design is commonly used (Fig. 3).

The $\bar{v}_y$ component contributes equally in magnitude, but is opposite in sign to the indicated mean axial velocities in planes A and B: $\bar{v}^A_{ax} = \bar{v}_x + \bar{v}_y \cdot \tan\varphi$, $\bar{v}^B_{ax} = \bar{v}_x - \bar{v}_y \cdot \tan\varphi$. The resulting indicated mean axial velocity, $\bar{v}_{ax}$, is therefore free of the cross flow component contribution under the condition of identical cross flow in A and B: $\bar{v}_{ax} = (\bar{v}^A_{ax} + \bar{v}^B_{ax})/2 = \bar{v}_x$.

A typical commercial ATT meter consists of a number, N, of crossing path pairs that form two identical measuring planes, A and B (Fig. 4). Multipath configurations decrease the influence of non-ideal velocity distribution on the flow rate integration.

The approach used for flow rate integration in the case of a multipath flow meter is described in the following section.

2.3. The area flow function

The total flow rate through a conduit of a cross section with a general shape (Fig. 5) can be calculated according to Eq. (2),

$$Q = \int_{z_1}^{z_2} F(z)\mathrm{d}z. \tag{2}$$

The function $F(z)$ is the so-called 'area flow function' and it describes the flow rate per unit width through a conduit as a function of the z-coordinate. It can be calculated as $F(z) = \bar{v}_x(z) \cdot l(z)$, where $\bar{v}_x(z)$ and $l(z)$ denote the true mean axial velocity and the width of the cross section as a function of the z-coordinate, respectively.

A real flow meter has a finite number, N, of measuring layers (i.e. $2N$ measuring paths for a double plane arrangement), so the integral of Eq. (2) needs to be replaced by a finite sum of discrete values $F(z_i)$, and in this respect, the Gaussian quadrature method is conventionally used. According to Weierstrass's theorem, each continuous function at an interval $[a; b]$ can be closely approximated by an algebraic polynomial (by an increase of the polynomial degree). Consequently, it is expected that the accuracy of the approximation increases with the number of the polynomial degree, and thus, the term known as the 'polynomial degree of quadrature' is used, which is the maximum degree of a polynomial, which can be integrated by this quadrature with zero error. Among all existing quadrature methods, the Gaussian quadrature has the highest polynomial degree equaling to $2N-1$, and it

[1] To emphasize the fact that the mean axial velocity, $\bar{v}_{ax}$, evaluated according to Eq. (1) may differ from the true one, it is hereafter referred to as the indicated mean axial velocity.