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Ultrasonic tomographic velocimeter for visualization of axial flow fields in pipes

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A B S T R A C T

An ultrasonic tomographic velocimeter to provide quantitative images of axial flow fields in pipes is developed and presented in this work. To detect the flow in various directions and positions, a novel transducer configuration strategy is proposed. All-in-one transducers are mounted in two sectional planes of the pipe. In each plane, N transducers are equally spaced along the circumference. Overlapped propagation paths are introduced by the configuration strategy, and the influence of the vortex flow can be eliminated theoretically by averaging the line velocities of the overlapped paths. To achieve a fast detection speed, the projection data is collected via an electrical scan in a fan-beam mode. After rearrangement and interpolation of the projection data, the parallel beam filtered back projection (FBP) algorithm is implemented to reconstruct the axial flow field. Numerical simulations with the theoretical velocity profiles were performed. The compensation method for the vortex flow is proved to be effective and necessary, and the number of transducers required for reconstruction of common flow profiles was estimated. Accordingly, an ultrasonic tomographic velocimeter consisting of 2×12 transducers was fabricated. Experiments were conducted in the straight pipe and downstream of a single bend pipe and compared with the computational fluid dynamics (CFD) simulation results. As demonstrated, the ultrasonic tomographic velocimeter was capable of visualizing both symmetric and asymmetric axial flow fields with high reliability.

1. Introduction

Visualization of axial flow fields in pipelines is of significant interest in scientific researches and industrial applications. The measurement results can help promote fluid dynamical theories and modify computational models. In process control and custody transfer, the knowledge of fluid velocity distributions can be used to optimize process equipment design and provide more accurate calculation of the volumetric flow rate.

In the past decades, many techniques have been developed to obtain the distribution of flow fields. Most of them, such as the hot-wire anemometry, laser Doppler velocimetry and ultrasonic Doppler velocimetry, are point-based techniques [1, 2]. Particle image velocimetry is an optical technique capable of measuring two-dimensional flow fields with high spatial resolution [3, 4]. However, it requires tracing particles to indicate the flow motion and optical access to the measurement plane. Unfortunately, these requirements may not be achieved in many applications, such the cases as opaque pipe walls or fluids.

Ultrasonic transmission-mode tomography provides a non-intrusive method to obtain the inner characteristic distribution of an object, such as the temperature field [5], multi-phase flow distributions [6, 7], and horizontal flow [8–10]. Some researchers have implemented its principle to measure axial flow fields in pipelines. Teerawatanachai et al. [11, 12] fabricated an ultrasonic tomographic velocimeter and visualized the axial flow field in straight pipes. The velocimeter consisted of one emitting transducer and seven receiving transducers, and was rotated mechanically to obtain all projection data. In Refs. [13–15], the axial flow field was detected via rotating commercial multi-path ultrasonic flowmeters. To accelerate the detection speed and avoid perturbances to the pipe flow, an electronic scan was employed as a substitute for the mechanical rotation in Ref. [16]. Current research works have demonstrated that ultrasonic tomographic velocimetry provides an alternative access to two-dimensional visualization of axial flow fields in pipelines. Since it is based on the ultrasonic transit-time principle, ultrasonic tomographic velocimetry has the advantages of being insensible to fluid properties, easy setup and high working temperature. However, current ultrasonic tomographic velocimeters still need improvements in spatial resolution, response speed and robustness to vortex flow.

In our present work, an ultrasonic tomographic velocimeter was developed and special considerations were taken of the above

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three problems. The process of flow field imaging comprises two major stages. The first stage is the detection of the pipe flow, i.e. the forward problem. The second stage is the reconstruction of the axial flow field, i.e. the inverse problem. For the first stage, a novel transducer configuration strategy is proposed, which can realize compensation for vortex flow by introducing overlapped chords. And with this configuration, the flow can be electronically scanned to ensure fast detection speed. In the second stage, the axial flow field was reconstructed with the filtered back projection (FBP) algorithm. To improve the spatial resolution of the reconstructed flow field, the projection data was interpolated with a cubic spline method. Numerical simulations were conducted to investigate the reconstruction performance with respect to the number of transducers and verify the robustness to vortex flow. On this basis, a 2×12 transducers ultrasonic tomographic velocimeter with a diameter of $D=500$ mm was fabricated. Experiments were performed to measure the axial flow fields in straight pipelines and downstream of a 90° single bend pipe. Finally, comparisons with the computational fluid dynamics (CFD) simulation results were made for validation.

2. Principle of ultrasonic tomographic velocimetry

Ultrasonic tomographic velocimetry accomplishes imaging of axial flow fields by combining the transit-time ultrasonic flowmeter and the computerized tomography (CT) technique. As shown in Fig. 1, the transit-time ultrasonic flowmeter operates by transmitting a pulse forward from an upstream transducer A to a downstream transducer B and back again. Regardless of the vortex flow, the transit time of the upstream pulse, t_u, and the downstream pulse, t_d, can be expressed by Eqs. (1) and (2) respectively [17].

$$t_u=\int_0^L \frac{dl}{c-v_z(l)\cos\ \alpha} \tag{1}$$

$$t_d=\int_0^L \frac{dl}{c+v_z(l)\cos\ \alpha} \tag{2}$$

where α is the inclination angle, c is the sound velocity, L is the length of the propagation path, and $v_z(l)$ is the axial flow velocity at point dl. With the line velocity of the propagation path defined as $V_{path}=1/L\int_0^L v_z(l)dl$, it can be calculated as

$$V_{path}=\frac{L(t_u-t_d)}{2t_ut_d\ \cos\ \alpha} \tag{3}$$

Ultrasonic tomographic velocimetry assumes that flow fields remain constant between the two cross-sections where transducer A and B are mounted. With the projection of the propagation path onto the cross-section referred to as a projection chord, the line integral P_L of the axial flow field $v_z(x,y)$ along the projection chord can be obtained as

$$P_L=\int_0^{L_p} v_z(x,y)dl=V_{path}\times L_p \tag{4}$$

where $L_p=L\sin\alpha$ is the length of the projection chord. The principle of CT indicates that a two-dimensional image $f(x,y)$ can be reconstructed from its projection data in different orientations and positions [11]. In fact, the projection data is exactly the line integral of the image along a projection path. Therefore, with the axial flow field perceived as an image, it can be reconstructed from the line integrals along various projection chords.

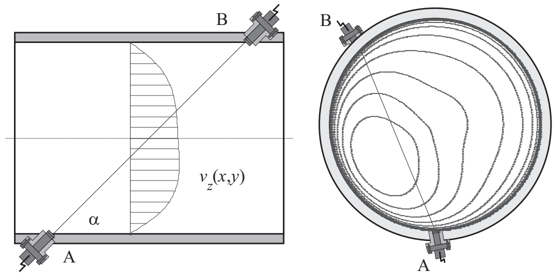

Fig. 1. Schematic of the transit-time ultrasonic flowmeter.

3. Flow detection

3.1. Transducer configuration

To obtain the projection data in various directions and distances, transducers are configured in a specific tomographic strategy in this work. As shown in Fig. 2(a), $2\times N$ all-in-one piezoelectric transducers are installed in two sectional planes of the pipe, whose distance equals the pipe diameter D. In each plane, N transducers are equally distributed along the pipe circumference. Each transducer can propagate ultrasonic pulses to all transducers in the opposite plane. Fig. 2(b) depicts the chord network formed by the propagation paths.

3.2. Scanning procedure

To achieve a fast detection of the pipe flow, projection data are collected via an electrical scan in the fan-beam mode, as shown in Fig. 3. First, all-in-one transducers in the upstream plane operate as transmitters and those in downstream plane operate as receivers to measure the transit time of downstream signals. Upstream transducers are sequentially excited from the first to the last and propagate ultrasonic pulses to all downstream transducers. Then, the transit time of upstream signals is measured in the same way. Since most flow fields are time-varied, the electronic scan is of practical significance.

3.3. Compensation for vortex flow

In reality, the transit time of ultrasonic pulses is influenced by the transverse velocities as well as the axial velocities. For flow rate measurement using ultrasonic flowmeters, flow regimes are well developed by installing straight pipes upstream the detecting section. The transverse velocities are ignorable against the axial velocities. However, this is not suitable for flow field imaging, where flow regimes can be either developed or undeveloped. For undeveloped cases, vortex flow phenomenon will cause significant disturbance to the measurement of axial flow fields. With the consideration of the transverse velocities, the transit time of downstream and upstream ultrasonic pulses propagating between transducer A_i and transducer B_j ($i, j=1,2,3, \ldots, N$) can be obtained as

$$t_d(i,j)=\int_{L_{i,j}} \frac{dl}{c+\vec{e}(i,j)\cdot\vec{V}(l)} \tag{5}$$

$$t_u(i,j)=\int_{L_{i,j}} \frac{dl}{c-\vec{e}(i,j)\cdot\vec{V}(l)} \tag{6}$$

where $L_{i,j}$ is defined as the propagation path between transducer A_i and transducer B_j, $\vec{V}(l)=(v_x(l),v_y(l),v_z(l))$ is the flow velocity vector, $\vec{e}(i,j)=(e_x(i,j),e_y(i,j),e_z(i,j))$ is the direction vector of the downstream pulse along propagation path $L_{i,j}$, and $e_z(i,j)=\cos\alpha_{ij}$ in particular. With substitution of Eqs. (5) and (6) into Eq. (3), the