Stereo and time-resolved PIV for measuring pulsatile exhaust flow from a motorized engine

Junichi OKI*, Yukika KUGA*, Yoichi OGATA*, Keiya NISHIDA*, Ryo YAMAMOTO**, Kazuhiro NAKAMURA***, Haruna YANAGIDA** and Hideaki YOKOHATA**

*Department of Mechanical Systems Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashihiroshima, Hiroshima 739-8527, Japan
E-mail: d161484@hiroshima-u.ac.jp
**Mazda Motor Corporation, 3-1 Shinchi, Fuchu-cho, Aki-gun, Hiroshima 730-8670, Japan

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Abstract
The present experimental study deals with a pulsatile turbulent flow simulating the exhaust flow of an automotive engine. In the experiments, a four-cylinder engine is used as an exhaust-flow generator to realize flow conditions close to those in an engine environment. Particle image velocimetry (PIV) measurements visualize the flow field in an S-shaped double-bend duct at a Reynolds number of 48,000 and a Womersley number of 70.9. Stereo PIV, which is classified as a two-dimensional three-component measurement, is conducted in the duct cross sections located downstream of the bends. The stereo PIV system is synchronized with the engine operation to enable phase-locked measurements at particular phases, and the phase-averaged results show the large-scale vortical structures and the duct axial velocity distribution. Downstream of the first bend, the secondary flow consists of vortices that circulate as Dean-type vortices. Downstream of the second bend, by contrast, vortices that circulate in opposite directions to the Dean-type vortices, so-called Lyne-type vortices, form in the core of the cross section. These secondary flows persist without significant changes in their large-scale vortical structures over time. Time-resolved PIV is conducted to track the temporal evolution of the flow in the bend planes. The results show that the flow reverses locally along the inner wall of the bends during flow deceleration. Snapshot proper orthogonal decomposition (POD) is used on the time-resolved PIV data to extract the significant flow structure from the instantaneous field. We propose POD as a good post-processing tool for the instantaneous data of pulsatile cases.

Keywords: Exhaust flow, Pulsatile flow, Turbulent flow, Secondary flow, Reversed flow, Flow separation, Particle image velocimetry, Proper orthogonal decomposition

1. Introduction

Automotive engines today must be designed to comply with increasingly stringent exhaust emission regulations while continuing to improve engine performance. The velocity distribution inside an exhaust manifold influences the conversion efficiency and durability of the catalytic converter mounted close to the exhaust ports. Previous studies have investigated the velocity characteristics of the pulsatile exhaust flow. Benjamin et al. (2002) and Persoons et al. (2004) measured the velocity distribution within the catalyst systems. Jeong (2014) carried out a computational fluid dynamics (CFD) analysis to investigate the effect of exhaust gas pulsation on the thermal response and conversion performance of the catalytic converter. An important component is the oxygen sensor mounted in the exhaust manifold to detect the air/fuel mixture ratio. For proper detection, the exhaust gas coming through each of the exhaust runners must be blown to this oxygen sensor. Knowledge about the velocity field in the exhaust manifold would help in finding the optimum location for the oxygen sensor (Merati et al., 2017).

The fluid motion in the exhaust manifold tends to be spatially complicated because of the pipe geometry with its multiple bends. To optimize the manifold geometry, it is crucial to know how such bends affect the flow dynamics. Flow around bends is encountered in many engineering applications and hemodynamic problems (i.e., blood flow) and
has been studied by many researchers. The pioneering work in this area is due to Dean (1927), who solved the steady problem theoretically and showed a secondary vortical structure comprising two symmetrical counter-rotating vortices known as Dean vortices. This secondary flow arises because the centrifugal force, which is always present at a bend, is not balanced by the pressure gradient in the pipe cross section.

In the case of unsteady laminar flow around a bend, Lyne (1970) showed theoretically that two additional vortices (each circulating in the opposite direction to its associated Dean vortex) appear in the core of the cross section. The study of unsteady laminar flow around a bend is motivated mainly by physiological applications, especially in human vasculature. Under pulsatile (physiological) inflow conditions, Chang and Tarbell (1985) observed secondary vortices similar to those found by Lyne. According to more-recent fluid dynamical studies of physiological flows (van Wyk et al., 2015; Najjari and Plesniak, 2016), the secondary flow consists of multiple vortices as well as the Dean and Lyne types with the temporal evolution of vortical structures. Furthermore, in unsteady laminar flow, as well as the secondary radial flow, the axial flow (in the axial direction of the pipe) also exhibits behavior that differs from the steady case, even if the pipe geometry does not vary axially. Chandran and Yearwood (1981) made three-dimensional hot-film measurements of the velocity pulsatility of pulsatile flow around a bend and found reverse flow along the inner wall of the bend during the deceleration phase. Similar phenomena have been reported in other studies on pulsatile flows around bends (Chang and Tarbell, 1985; Hamakiotes and Berger, 1990; Qiao et al., 2004; Timité et al., 2010). Common among these studies is that the reverse flow is initiated from the inner wall during the deceleration phase. Talbot and Gong (1983) observed flow separation from the inner wall during the deceleration phase, and this is inherently the same as the aforementioned reverse flow.

Turbulent flows often occur in various engineering applications, not to mention an engine exhaust system. Sudo et al. (1998) used a rotating hot-wire probe to measure the turbulent flow velocity in a 90° pipe bend. They showed experimentally that the acceleration of flow along the inner wall of the bend was caused by a favorable axial pressure gradient. Tunstall and Harvey (1968) found that turbulent flow downstream of a sharp bend was dominated by an alternating clockwise/anticlockwise streamwise vortex instead of the steady Dean motion. This phenomenon, now known as “swirl switching,” has been investigated recently through particle image velocimetry (PIV) (Hellström et al., 2013; Kalpakli et al., 2015) and large-eddy simulation (LES) (Carlsson et al., 2015). To identify the switching motion of the vortical structures, those studies used proper orthogonal decomposition (POD) as an inhomogeneous spatial filter for the PIV and LES data.

Turbulent flow in an S-shaped duct is of interest because combinations of multiple bends are commonly used to redirect flows in situations such as the intake of an aircraft engine (Taylor et al., 1982). Ng et al. (2008) and Mazhar et al. (2016) observed secondary flow in the second bend of an S-shaped duct travelling away from the outer wall, opposite to the case with Dean vortices.

Some studies have looked at pipe-bend flows that were both turbulent and pulsatile. Kalpakli et al. (2013) used stereo PIV to measure three velocity components of the pulsatile turbulent flow around a 90° bend. A previous study by the present authors (Oki et al., 2017) showed secondary vortical structures developing through an S-shaped duct but did not describe their temporal evolution sufficiently.

The objective of the present study is to investigate experimentally the pulsatile flow structures that develop in an S-shaped test section simulating an exhaust pipe. In the experiments, to simulate engine conditions as closely as possible, we used a real automotive engine driven by a motor to generate the pulsatile inflow waveform. The velocity fields presented herein were obtained from phase-locked stereo PIV and time-resolved PIV. Although the time-resolved PIV data can show the evolution of flow structures with high temporal resolution, the limited camera memory meant that there were too few engine cycles to perform a statistical calculation such as phase averaging. To address this problem, we introduce snapshot POD analysis as a way to filter the time-resolved PIV data. The present study extends our collective understanding of pulsatile turbulent flows in bends to allow better design of exhaust systems.

2. Experimental Methods

As a model exhaust pipe, we used an S-shaped test section made of transparent acrylic to enable optical access. As shown in Fig. 1, the test section has two 57.7° bends (hereinafter referred to as the first bend (upstream) and second bend (downstream)) each with a 50-mm radius of curvature and connected by a 200-mm-long straight duct. The test section has square cross section (32-mm hydraulic diameter). During PIV, we could obtain the particle images without
image distortion by photographing through the perfectly flat surface.

The working fluid was room-temperature exhaust delivered from a four-cylinder four-stroke engine through its exhaust manifold and catalytic converter. We connected the drive shaft of the engine to an inverter-driven induction motor capable of running at constant speed without firing. Both the inlet and outlet ends of the test section were connected to circular-sectioned exhaust pipes as depicted in Fig. 2.

Here, the Reynolds number is \( Re = \frac{W_m D}{\nu} \), where \( W_m \) is the time-averaged bulk velocity in the duct axial direction, \( D \) is the hydraulic diameter, and \( \nu \) is the kinematic viscosity. We determined \( W_m \) based on the time-resolved PIV results. All the measurements were made at \( Re = 48,000 \). The engine was driven at 1,500 rpm, corresponding to a Womersley number of \( \alpha = 70.9 \). Here, the Womersley number (also known as the frequency parameter) is \( \alpha = (D/2)\sqrt{\omega/\nu} \) (Womersley, 1955), where \( \omega \) is the angular frequency of the pulsation. In determining \( \omega \), we regarded the exhaust from each cylinder as one pulsation; that is, the engine used in the measurements produced four pulsations per engine cycle.

![Schematic of S-shaped test section](image)

**Fig. 1** Schematic of S-shaped test section. All lengths are in millimeters. Stereo PIV and time-resolved PIV were conducted where indicated by solid and dashed lines, respectively.

### 2.1 Stereo PIV

We used stereo PIV to measure the in-plane and axial velocity components in the duct cross section a distance 1\( D \) downstream of each bend exit (Fig. 1). A schematic of the stereo PIV setup with the test section is shown in Fig. 2 (left). We used a Laskin nozzle-based oil mist generator (FTR Oil Mist Generator; Flowtech Research Inc.) to atomize olive oil, with the resulting seeding particles entering the pipe between the engine and the test section. The stereo PIV setup consisted of a light source and two cameras. We passed the beam of an Nd:YAG double-pulsed laser (LS-2132 PIV; LOTIS TII) through a cylindrical lens to produce a 2-mm-thick light sheet. We positioned the two 1600 × 1200-pixel CCD cameras (AM-200GE; JAI) on either side of the test section to capture the light scattered from the seeding particles. The camera lenses ( Nikon; 50-mm focal length) were tilted against the image sensors so as to satisfy the Scheimpflug condition.

We applied phase-locked image acquisition to the stereo PIV measurements. For this purpose, we inputted the ignition signal from the engine cylinder to a delay pulse generator (FtrVSD2000; Flowtech Research Inc.) that externally triggered the laser and the cameras. This synchronization enabled the acquisition of an image pair once per the particular phase of interest in the engine cycle. We could adjust this phase by changing the setting of the ignition timing. To examine the measuring timing over the velocity waveform of the flow, we recorded the velocity data from a hot-wire probe (0251R-T5; KANOMAX) and the Q-switch signal of the laser simultaneously at a sampling frequency of 10 kHz in advance of the PIV measurements. We positioned the hot-wire probe at the center of the cross section of the entrance to the first bend. In the present study, we took 1,000 image pairs (corresponding to 1,000 cycles) at each of four different phases and used them to calculate the phase-averaged velocity fields.

We used the commercial software FtrPIV (Flowtech Research Inc.) for the PIV post-processing. The image pairs were correlated using a direct cross-correlation algorithm with an interrogation window comprising 33 × 33 pixels and 50% overlap. The resulting spatial resolution of the velocity vector was 0.534 mm. The calculation grid was not
specified in the wall vicinity within 0.804-mm distance from the wall surface to avoid taking the scattered light intensity from the wall surface into the correlation of moving particles. We set the time interval between image pairs as 8 μs when measuring at the highest flow rate and 10 μs otherwise.

2.2 Time-resolved PIV

We captured the transient behavior of the flow by using time-resolved PIV capable of velocity measurements with high temporal resolution. A schematic of the time-resolved PIV setup with the test section is shown in Fig. 2 (right). We measured two velocity components of the flow field in the bend plane located at the center of the duct; measurements were conducted in the first and second bends separately (Fig. 1). The seeding particles were introduced into the test section in the same way as for the stereo PIV, and the measurement plane was formed by a 1-mm-thick light sheet emitted from an Nd:YAG double-pulsed laser (Mesa PIV, Continuum). We used a high-speed CMOS camera (FASTCAM SA-Z; Photron) with 1024 × 1024 pixels and equipped with a lens (Nikon) with a focal length of 50 mm.

The time-resolved PIV was conducted at a constant sampling rate of 10 kHz. To fulfill this, the laser and the camera were operated at a repetition rate of 10 kHz and at 20,000 fps, respectively. The start of photographing was triggered by the ignition signal. The camera and the laser were synchronized through the delay pulse generator to which the output signal from the camera was inputted. We took 1,000 image pairs at a corresponding measurement time interval of 100 ms. Incidentally, the period of the engine cycle is 80 ms when operating at 1,500 rpm.

The FtrPIV software calculated the two velocity components of the instantaneous velocity fields. During the post-processing, 20 × 20-pixel interrogation windows were specified with a 50% overlap, resulting in a spatial resolution of 1.34 mm. The calculation grid was not specified in the region within 1.89-mm distance from the wall surface for the reason stated in section 2.1. The time interval between image pairs was 25.1 μs.

![Fig. 2](image)

Fig. 2 Arrangements of PIV systems relative to test section. Left: stereo PIV; right: time-resolved PIV. A connection part between the test section and the pipe is illustrated in an enlarged view.

3. Results and Discussion

3.1 Flow field in duct cross section

Figure 3 shows the three instantaneous velocity components in the cross-sectional plane 1D downstream of the first bend. The presented data come from stereo PIV measurements at the phase in which the flow was accelerating (Fig. 3(c)). As shown in Fig. 3(a), the centrifugal force directs the in-plane (secondary) flow toward the outer wall along the core of the cross section, where the axial velocity is large. At the same phase but in the next cycle (Fig. 3(b)), the strong secondary flow in the direction of the centrifugal force appears closer to the right-hand wall. The secondary and axial velocities exhibit the different patterns depending on the cycle, even at the same phase. We attribute this velocity fluctuation directly to the turbulence and the cycle-to-cycle variation. In general, the time scale of the cycle-to-cycle variation is larger than that of the turbulence, but it is difficult to extract each part separately. Hence, the present study does not deal with the turbulent characteristics.
Phase averaging can be useful for capturing large-scale flow structures. The phase-averaged velocity fields were computed by ensemble-averaging 1,000 instantaneous fields at a specific phase. We tested the convergence of the averaged field in a manner similar to the approach of Bücker et al. (2012). We defined the convergence by \( \frac{\| \phi^N - \phi^{N-1} \|}{\| \phi^N \|} \), where \( \phi^N \) contains averaged variables from all grid points of \( N \) fields and is computed for each velocity component. With \( N = 1,000 \), the convergence was less than 0.4% for every position and phase. Furthermore, the theoretical uncertainty based on a 95% confidence interval was at most ±0.9 m/s for an averaged velocity component of 13.9 m/s among all the measured data. It is clear that \( N = 1,000 \) is a sufficient number of cycles from which to obtain well-converged averaged fields. Figure 4 shows the duct axial component of the vorticity calculated from both the instantaneous and phase-averaged velocity data at the second bend. In the instantaneous vorticity, multiple vortices are observed, while large-scale vortical structures, such as Dean and Lyne types, cannot be found. By phase-averaging the data, only four vortices could be captured clearly.

Figure 5 shows the phase-averaged fields with three velocity components at four different phases. At the cross section 1D downstream of the first bend, the secondary flow direction corresponds to the centrifugal force over a wide region of the cross section, while the flows close to the left- and right-hand side walls are in opposite directions, resulting in a Dean-type circulation. This feature of the secondary flow structure is not dependent on the phase. The large axial velocity along the outer wall is due to advection of the fluid by the secondary flow. At the minimum phase, reverse flow appears along the inner wall; we consider this in detail later (sections 3.2 and 3.3).
Fig. 5  Phase-averaged velocity fields from stereo PIV data for the first bend (1st column) and second bend (2nd column) at the acceleration, maximum, deceleration, and minimum phases (from top to bottom). Hot-wire results showing the measurement timings (3rd column) are also presented, as in Figs. 3 and 4.
At the cross section 1D downstream of the second bend, the Dean-type vortices are localized to the side walls and the corners of the outer wall. Additional vortices, the circulation of which corresponds to the Lyne type, are formed in the core of the cross section at every phase, as also seen from the phase-averaged vorticity contour of Fig. 4(b). This is because the non-uniform axial flow caused by the secondary flow developed in the first bend enters the second bend, and the centrifugal effect is localized to the wall sides. We have previously discussed the formation of Lyne-type vortices in the second bend (Oki et al., 2017). As the flow decelerates, the axial flow starts to reverse on the inner-wall side; at the minimum phase, the entire cross section is dominated by this reverse flow, reaching ~20 m/s in the duct axial direction along the inner wall. The reverse flow along the inner wall leads to a centrifugal effect that is enough to direct the secondary flow toward the outer wall. Thus, at the deceleration and minimum phases, a wider region on the inner-wall side is occupied by Dean-type vortices than in the case at the other phases.

Fig. 6  Time-resolved PIV results in first bend (1st column) and second bend (2nd column). Instantaneous fields at three different times (from top to bottom) are shown. The vectors are plotted at half the full resolution (same hereinafter for all bend planes). The bulk velocity waveform (3rd column) was calculated from the PIV data obtained in the uppermost location (1.4D upstream of the first-bend inlet). In an enlarged view of the reverse-flow region at the minimum phase (bottom), full-resolution vectors are shown in the contours colored according to vorticity in the direction perpendicular to the plane.
3.2 Flow field in bend plane

Figure 6 shows the instantaneous fields with two velocity components obtained from the time-resolved PIV in the bend planes from the start of the deceleration until the end. Note that the graphs presented in Fig. 6 differ from those in Figs. 3–5 because the velocity waveforms in Fig. 6 were obtained from the time-resolved PIV data whereas those in Figs. 3–5 shows the hot-wire results and the time axes of the two types of PIV measurement do not coincide with each other.

In the first bend at time \( t = 4 \text{ ms} \), the velocity vectors are in the duct axial direction. During the deceleration phase \( (t = 7 \text{ ms}) \), the flow starts to reverse in the vicinity of the inner wall. We see that at the end of the deceleration \( (t = 10 \text{ ms}) \) the region of reverse flow spreads toward the inner wall at the first-bend entrance and the middle of the duct downstream of the first bend. The reverse flow develops from the straight duct wall downstream of the first bend toward the upstream as the flow decelerates. This reverse flow can also be regarded as separated flow. Talbot and Gong (1983) explained that the adverse pressure gradient during the deceleration phase is combined with the curvature effect, leading to flow separation. This perspective is applicable to the present reverse flow. In the pulsatile exhaust flow, the pressure gradient in the duct axial direction, which is produced by the periodic motion of the pistons and the exhaust valves, induces the change in the flow speed. In other words, it is reasonable to suppose that the favorable and adverse pressure gradients occur during acceleration and deceleration, respectively. The adverse pressure gradient during the deceleration phase promotes the reverse flow on the inner-wall side where the adverse gradient exists originally because of the curvature effect. The region of reverse flow spreads most at the end of the deceleration because, at this time, the adverse pressure gradient disappears and turns into the favorable gradient that induces the flow acceleration in the axial direction. During the acceleration phase (not shown here), the favorable pressure gradient occurs in the entire duct, and for this reason the flow is redirected downstream. The flow direction changes repeatedly during the deceleration and acceleration of the flow over the engine cycle. As seen from the vorticity contours with the velocity vectors, the transverse vortices can be seen in the region of reverse flow. The turbulent fluctuation seems to contribute to the appearance of these vortices, which change in location and size according to the engine cycle.

In the second bend at the maximum \( (t = 4 \text{ ms}) \) and deceleration \( (t = 7 \text{ ms}) \) phases, the flow is directed downstream in the duct axis direction. At the end of the deceleration \( (t = 10 \text{ ms}) \), the reverse flow can be seen on the outer-wall side upstream of the second bend. The reverse flow observed in the first bend propagates toward the second bend upstream through the straight duct. A common feature at the first bend is that the strong reverse flow appears on the inner-wall side even though the secondary flow morphologies for both bends differ from each other. This indicates that the pressure gradient associated with the pulsation plays a major role in the appearance of the reverse flow during the deceleration.

3.3 POD analysis

Although the time-resolved PIV data can show the evolution of the flow field with high temporal resolution, the limited camera memory meant that too few cycles were obtained in the measurement to perform statistical analyses such as phase-averaging. Our time-resolved PIV system could obtain data from at most 10 cycles per measurement. The convergence analysis of the stereo PIV data gave a convergence of approximately 20% with 10 cycles; it is difficult to obtain well-converged averaged fields from the time-resolved PIV data. Therefore, we propose using POD analysis in our pulsatile turbulent case to extract the most significant flow structure from the limited number of samples. We sampled 800 successive fields (corresponding to the duration of one engine cycle) for the POD analysis; the number of available vectors in each sample is 2,078 for the first bend and 2,366 for the second bend. Because there are fewer samples than velocity data, it is better to use snapshot POD (Sirovich, 1987), arriving at an eigenvalue problem for a square matrix whose size is the number of samples. The method of snapshot POD analysis used herein is described briefly below. The reader is referred to Meyer et al. (2007) for more detail.

The two-velocity-component fields \( \mathbf{u}(t_1), \mathbf{u}(t_2), \ldots, \mathbf{u}(t_N) \) collected at times \( t_1, t_2, \ldots, t_N \) are arranged in the matrix form

\[
\mathbf{U} = [\mathbf{u}(t_1) \quad \mathbf{u}(t_2) \quad \ldots \quad \mathbf{u}(t_N)].
\]

The snapshot POD leads to the following eigenvalue problem for the velocity correlation matrix \( \mathbf{R} = \mathbf{U}^T \mathbf{U} \):
\begin{equation}
RA_n = \lambda_n A_n ,
\end{equation}

where \( \lambda_n \) is the eigenvalue ordered according to its size and \( A_n \) is the corresponding eigenvector. The size of each eigenvalue is associated with the contribution of the corresponding mode to the original velocity field. The \( n \)th POD mode is given by

\begin{equation}
\phi_n = \frac{UA_n}{||UA_n||}
\end{equation}

Mode convergence is assured according to Semeraro et al. (2012). We consider three different datasets, one consisting of 200 samples (a quarter of one engine cycle), one consisting of 800 samples (one engine cycle), and one consisting of 1,600 samples (two independent engine cycles). Figure 7 shows the energy distributions of the three datasets for the first bend. The eigenvalue cascade for \( N = 200 \) deviates from the others as the mode number increases. With 200 modes, the relative deviation between the datasets of \( N = 200 \) and 800, which is defined by

\[ |\lambda|_{N=800} - |\lambda|_{N=200} / |\lambda|_{N=800} \],

is 42.7%, while \[ |\lambda|_{N=1600} - |\lambda|_{N=800} / |\lambda|_{N=1600} \] is 2.0%. The eigenvalue cascades for \( N = 800 \) and 1,600 agree well, and thus we choose the dataset with 800 samples in this analysis.

The POD modes 1 and 2 for the first bend are shown in Fig. 8 (left). The most energetic structure (mode 1) contains approximately 97% of the total energy, whereas mode 2 contains only approximately 1%. The flow field of mode 1 represents a simple pattern: we assume this to be the change of the flow speed in the duct axial direction. The flow pattern of mode 2 is similar to the flow reversal observed in the instantaneous field at the end of the deceleration (Fig. 6), but the flow direction is adverse because of the bidirectional characteristic of the POD. We assume that the higher-order modes (not shown here) represent the cycle-to-cycle and turbulent fluctuations.

An advantage of using POD is that no temporal information is lost through the computation. The temporal information, the so-called POD coefficients, can be recovered by projecting the instantaneous field onto the POD modes and is given by

\begin{equation}
a_n(t) = \phi_n^T u(t).
\end{equation}

The graphs presented in Fig. 8 show the first two POD coefficients, indicating when the corresponding POD modes are active. The waveform of the coefficient of mode 1 matches the bulk velocity data, showing that the most energetic structure is naturally the axial flow. The coefficient of mode 2 takes the largest absolute value but is negative at the end of the deceleration \( (t = 10 \text{ ms}) \). This implies that the significance of the flow reversal, which is the reversed vector pattern of POD mode 2, increases most when the bulk velocity is minimum. It is clear from comparing the phases of coefficient \( a_2 \) and the bulk velocity that the flow reversal coincides with the change in the bulk velocity.
The instantaneous field can be reconstructed by projecting the energetic POD modes onto the coefficients. For example, the field reconstructed using the first \( n \)th POD modes is expressed as

\[ \mathbf{u}_n(t_j) = \sum_{i=1}^{n} a_i(t_j) \phi_i. \]  

Figure 9 shows the fields reconstructed using modes 1 and 2 (capturing more than 98% of the total energy) for both bends (corresponding to the results presented in Fig. 6 at \( t = 4 \) ms and 10 ms as the original instantaneous data). In the reconstructed field of the first bend at the end of the deceleration, there is reverse flow along the inner wall. However, the small-scale transverse vortices that appear in the original instantaneous field cannot be found because the small-scale structure associated with the turbulence and the cycle-to-cycle variation is contained in the neglected
higher-order POD modes. For pulsatile flow data from a limited number of cycles, the POD analysis works as a superior filtering tool to detect energetic flow structures (including fluctuations) in the instantaneous field. Downstream of the bends at the end of the deceleration, the flow on the outer-wall side of the first bend is in the duct axial direction, while, for the second bend, the reconstructed result captures the flow away from the outer wall, which is consistent with the Lyne-type secondary flow observed in the phase-averaged field of the stereo PIV data (Fig. 5).

4. Conclusions

Two types of PIV measurements were performed to investigate pulsatile exhaust flow within an S-shaped test section comprising a double bend and a straight duct. The experimental results presented in this paper provide important information about the temporal evolution of flow structures, as well as being useful for CFD validation in future work.

The phase-locked stereo PIV revealed the secondary and axial flow structures in the duct cross section at four different phases. A Dean-type secondary flow forms as the flow passes through the first bend, while Lyne-type vortices appear downstream of the second bend and localize the Dean-type vortices to the wall sides. The results also show that there are no significant changes in the overall secondary flow patterns over time. In a square duct, weak secondary motions would appear at the duct corners due to Reynolds stress imbalance. This flow, known as secondary flow of the second kind, has not been considered in this work. Sugiyama et al. (1995) investigated numerically turbulent flow in a square-sectioned 90° bend at Re = 40,000. They suggested that the secondary flow of the second kind was overwhelmed by that of the first kind, which is due to the radial pressure gradient and the centrifugal force, up to the cross section 1D downstream of the bend exit, and that the 10D straight duct was needed to develop the secondary flow of the second kind downstream of the bend. Our stereo PIV results are associated with the secondary flow of the first kind because the measurement planes are close to the bends. Therefore, the flow physics presented herein would serve as a design guideline for a real engine exhaust in which a circular-sectioned pipe is used.

The time-resolved PIV was conducted at a constant sampling rate of 10 kHz, revealing the transitions of the flow fields in the bend planes. An adverse pressure gradient occurs along the entire duct when the flow decelerates, and this combines with the curvature effect to cause reverse flow to develop from the inner wall. This local flow reversal can also be viewed as flow separation, and it is considered to be peculiar to the pulsatile case. Flow separation and reattachment repeatedly coincide with flow deceleration and acceleration, respectively.

Snapshot POD analysis was used for the time-resolved PIV data instead of phase-averaging because of the limited number of samples. Modes 1 and 2, as ranked by energy content, represent the axial flow and the reverse flow, respectively. The time history of the POD coefficients reveals when the corresponding modes increase in significance. The instantaneous fields can be reconstructed using the first two modes and capture the most energetic flow structures. Because POD can also be performed as a filtering technique, this method would be useful for comparing quantitatively between PIV and LES, providing instantaneous data containing fluctuations.

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