Scientia Iranica, Vol. 10, No. 2, pp 238–247

SCIENTIA
IRANICA

Experiments on Pulsation Effects in Turbulent Flows, Part I: Investigation on Simple Shear Flows

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This article describes the results of experimental observations in pulsating Simple Shear Flows (SSF). A uniform-mean-gradient shear flow was generated within the test section of an open circuit wind tunnel. Transverse arrays of honeycomb channels with differing resistances were used to generate shear flow at low shear rates (less than 20 s^{-1}). A set of rotating vanes pulsated the flow field at 8.5 Hz and 18 Hz. Instantaneous velocity was measured by employing a two-component hot wire anemometry technique. The experimental credibility of the facility was established in stationary SSF. In pulsating flows the pulsation effects on mean shear rate, the kinetic energy of turbulence, Reynolds stresses and the probability density of stream-wise velocity fluctuations were studied. It was found that deviation from stationary turbulence with pulsation at 8.5 Hz was more significant than that at 18 Hz. The modified form of the governing equations for pulsating flows was derived. The emphasis of the analysis was placed on the production and dissipation mechanisms in pulsating SSF. The results are discussed in connection with the modified equations and physically plausible explanations are offered to interpret the laboratory observations. It is concluded that the anisotropic dissipation mechanism may be responsible for the observed experimental results.

INTRODUCTION

This study is concerned with pulsating Simple Shear Flows (SSF). No previous effort to document the effect of pulsation on SSF has been reported in the open literature. The purpose of the present experimental study was to provide an understanding of the way pulsation might interact with turbulent mechanisms such as production and dissipation in SSF. These interactions could be identified through various terms in the averaged equations for momentum, turbulence kinetic energy and turbulent dissipation rate. This identification is made possible by the introduction of 'triple decomposition' in the governing equations. The triple decomposition approach is based on the fact that random hydrodynamic motion subjected to pulsation can be decomposed into mean, fluctuating and pulsating parts. An attempt has been made in this study to derive the modified form of the governing equations and to provide an interpretation for experimental observations. One prominent feature of shear flows is the coupling of turbulence to the mean shear of the flow through the mechanism of turbulent energy production. Homogeneous turbulence sustained by a constant mean shear is the simplest flow, in which the interactions between turbulence and mean flow can be studied. The practical significance of uniformly sheared turbulence lies in its value as a test case for the verification of general turbulence theories and models and, also, in its structural resemblance to common flows, such as the outer part of turbulent boundary layers.

Corrsin was the first to realize the laboratory set up of stationary homogeneous shear flows [1]. The majority of the investigations undertaken afterwards have been dedicated to comprehensive laboratory study of stationary homogenous shear flows. Most of the complexities concerning the studies of the interaction of

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turbulence with the mean velocity gradient come from the complicating effects of rigid walls, non-turbulent streams and large-scale inhomogeneities associated with non-uniform shear. There is a consensus that, in flows where turbulent shear stress is carried by eddies comparable in size to the shear field zone, the integral scales grow monotonically downstream [2-4]. Giving sufficient flow development time, $\tau^* = (X/\overline{u})(d\overline{u}/dY)$, an asymptotic state establishes in which the Taylor micro scale remains longitudinally constant (despite increasing transversally), with increasing mean velocity [3]. Tavoularis [5] suggested a weak exponential stream-wise growth of turbulent kinetic energy in agreement with his semi-analytical prediction [6], which was experimentally verified afterwards [7].

Although much has been learned from previous experiments on stationary homogeneous shear flows, an improved understanding of the pulsation effects on SSF is yet to be established. The distinct feature of the present experiments is that the simple shear flow is subjected to well-defined and controlled oscillations of the free stream. Many engineering applications are concerned with modeling the effects of pulsation on turbulent shear flows, notably in the fields of aerodynamics and turbomachinery. An unbounded flow with uniform mean shear and statistically homogeneous velocity fluctuations is a suitable test case on which pulsation can be imposed. Such a flow is subject to basic physical mechanisms of turbulence but free from the complicating boundaries effects.

In part I of this study, the emphasis was placed on investigating the effects of pulsation on turbulent shear flows. Shear flows occur in a variety of engineering applications and acquiring an improved understanding of their behavior is of prime importance in turbulence modeling.

In part II, however, fundamental investigation on grid-generated turbulence subject to pulsation will be presented. The pulsation effects on characterizing length scales and the statistical description of fluctuations were studied. No signification change in the character of the turbulent flow with pulsation was observed.

In this study, the credibility of the experiments was established by duplicating some reported measurements in stationary SSF. Experiments on SSF were extended to the pulsating case. The observations were discussed in connection with the modified governing equations and suggestions for further work were provided.

EXPERIMENTAL ARRANGEMENT

The experimental facility employed in the previous studies on pulsating grid-generated turbulence was used for this study [8]. Figure 1 shows the sketch of

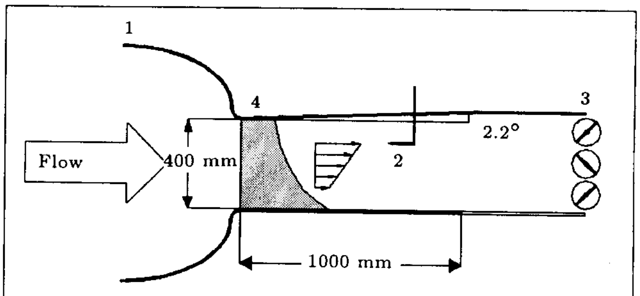


Figure 1. Experimental facility.

the set-up generating a linear velocity profile in the test section. A two-component hot wire anemometry technique, with a maximum frequency response of 3 KHz, was used in the test section of the wind tunnel in which a variable blockage method for pulsating the free stream at 8.5 Hz and 18 Hz was used. The amplitude to mean velocity ratios at 8.5 Hz and 18 Hz were 0.4 and 0.17, respectively. A KEITHLEY DAS-1700 HR data acquisition board (16 bit precision; 8 channel), along with Test Point® and Matlab® software packages, were used. The specifications of the wind tunnel and the pulsation mechanism, along with the accuracies of the measuring devices and data acquisition-processing systems were described in more detail in our previous study [8]. The pulsating and fluctuating components of the velocity were separated from the mean velocity by using the FFT-based method developed in our experiments on grid-generated turbulence [8]. A 'shear generator' was designed and constructed to generate a reasonably uniform-mean-gradient shear flow. It consisted of an array of channels with a hexagonal cross section (honeycomb), transversally cut by a water-jet technique. The linear velocity profile was obtained in the test section, due to a linear variation of the hydrodynamic resistance of the channels ($30 < L/D < 100$). The dimension of the shear generator, in a transverse direction (H), was 0.4 m. The aluminum partitions used in making the honeycomb channels were 0.1 mm thick and the hydraulic diameter of the channels (D) was 5 mm. Unless otherwise explicitly stated, the centerline speed, $\overline{u}_c$, sampling frequency and sampling duration in all experiments were constant and equal to 3 m/s, 6 KHz, and 60 seconds, respectively. The credibility of the data acquisition and data processing methods in providing repeatable results was inspected in all cases. By doubling the sampling frequency and duration and repeating the calculations five times, the uncertainty of the results were found. The Reynolds number, based on the hydraulic diameter of the honeycomb cross-section and centerline velocity, Re_D, was 1.0×10^3. Measurements were carried out downstream of the shear generator in longitudinal and transverse directions within the plane of symmetry of the test section.

GOVERNING EQUATIONS IN PULSATING FLOWS

Triple decomposition is customarily used [9] to describe the time-dependent, turbulent behavior of a general dependent variable, $f(x,t)$, which could be expressed as the summed contribution of the three parts as, given by Equation 1:

$$f(x,t) = \overline{f}(x,t) + \tilde{f}(x,t) + f'(x,t). \quad (1)$$

These components are the mean, periodic and fluctuating, respectively. Equations 2 and 3 give the definitions of time and phase averaged terms, respectively:

$$\overline{f} = \frac{1}{N}\sum_{n=0}^{N} f(x, n\Delta t), \quad (2)$$

$$\tilde{f} = \frac{1}{N}\sum_{n=0}^{N}[f(x, t+nT_p) - \overline{f}]. \quad (3)$$

Here $N\Delta t$ should be much greater than the period of pulsation (T_p). Triple decomposition was used to obtain modified conservation equations for mass and momentum, Equations 4 and 5, respectively.

$$\overline{u}_{i,j} = 0, \quad (4)$$

$$\overline{u_j}.\overline{u_{i,j}} = -\overline{p_{,i}}/\rho + \upsilon\overline{u_{i,jj}} - (\overline{u_i'u_j'} + \overline{\tilde{u}_i\tilde{u}_j})_{,j}. \quad (5)$$

The modified transport equation for the kinetic energy of turbulence, $k = 0.5(\overline{u_i'u_i'})$, was obtained, as given by the following equation.

$$k_{,t} + \overline{u}_j k_{,j} = -\overline{u_i'u_j'}\overline{u}_{i,j} - \overline{u_i'u_j'\tilde{u}_{i,j}} - \frac{1}{2}(\overline{u_i'u_j'\tilde{u}_j} + \overline{u_i'u_i'u_j'})_{,j}$$
$$-\frac{1}{\rho}(\overline{p'u_j'})_{,j} + \upsilon k_{,jj} - \upsilon\overline{u_{i,j}'u_{i,j}'}. \quad (6)$$

The second and third terms on the right hand side (two new terms), represent production and diffusion due to pulsation, respectively. By following the same approach as that of the stationary case, the modified equation for the dissipation rate, $\varepsilon = \upsilon\overline{u_{i,j}'u_{i,j}'}$, in pulsating SSF, was obtained as follows:

$$\varepsilon_{,t} + \overline{u_j}\varepsilon_{,j} = -2\upsilon\overline{u_{i,l}'u_{i,j}'}\overline{u}_{j,l} - 2\upsilon\overline{u_{i,l}'u_{j,l}'}\overline{u}_{i,j}$$
$$-2\upsilon\overline{u_j'u_{i,l}'}\overline{u}_{i,lj} - (\overline{u_j'\varepsilon'} + 2\upsilon\overline{u_j'(p'/\rho)_{,ll}} - \upsilon\varepsilon_{,j})_{,j}$$
$$-2\upsilon(\overline{u_i'(p'/\rho)_{,l}})_{,il} - 2\upsilon\overline{u_{i,l}'u_{i,j}'u_{j,l}'}$$
$$-2\upsilon^2\overline{u_{i,lj}'u_{i,lj}'} - 2\upsilon\overline{u_{i,l}'u_{j,l}'\tilde{u}_{i,j}}$$
$$-2\upsilon\overline{u_{i,l}'u_{i,j}'\tilde{u}_{j,l}} - 2\upsilon\overline{u_j'u_{i,l}'\tilde{u}_{i,lj}}$$
$$-2\upsilon\overline{\tilde{u}_j u_{i,l}'u_{i,lj}'}. \quad (7)$$

Here, $\varepsilon' = \upsilon u_{i,l}'u_{i,l}'$ is the instantaneous dissipation rate. In addition to the standard terms for production, turbulent and molecular diffusion and the destruction of ε, the last four terms represent destruction due to pulsation.

RESULTS AND DISCUSSIONS

Stationary Flow

The major reason for carrying out experiments on stationary flows was to establish the credibility of the set-up for further experiments on pulsating SSF. A series of experiments on stationary SSF, for which reliable data existed, was carried out to validate the performance of the shear generator used in this study. The landmark study of Champagne et al. [3] (hereinafter referred to as CHC) was partly duplicated. The centerline velocity was set to 13 m/s and the mean transverse velocity gradient, $d\overline{u}/dY$, was 18.8 s^{-1}, nearly the same conditions as those in CHC experiments (H = 0.3 m, $\overline{u}_c$ = 13 m/s, $Re_H = 2.6 \times 10^5$, $d\overline{u}/dY = 12.9$ s^{-1}). The Reynolds number in this study was $Re_H = 3.47 \times 10^5$. However, our test section was smaller in length ($X/H < 2.5$) than that used in CHC experiments ($X/H < 11.0$). The sampling frequency and duration in this study were 4 KHz (per channel) and 30 seconds, respectively.

Figure 2 shows the linear velocity profile obtained downstream of the shear generator at three downstream stations ($X/H = 1.25, 1.75$ and 2.25). A plausible degree of linearity for the velocity profile was obtained far from the rigid walls ($0.35 < Y/H < 0.75$) for all stations. A deviation from the expected linear profile near the rigid walls was noticeable, due to the presence of the boundary layer. This effect was more pronounced near the upper wall (slightly divergent 2.2°), because the boundary layer becomes thicker while the positive pressure gradient decelerates the flow field. Thus, all results are presented within

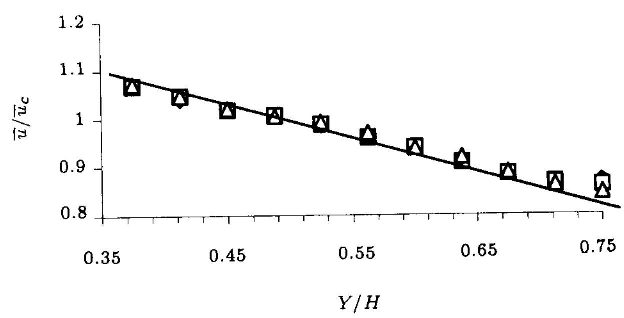


Figure 2. Velocity profiles at three downstream stations in stationary flow; (□) $X/H = 1.25$, (♦) $X/H = 1.75$ and (△) $X/H = 2.25$, Mean shear rate: $d\overline{u}/dY$=18.8 (s^{-1}) and $\overline{u}_c$ = 13 m/s.

the linear range ($0.35 < Y/H < 0.75$) in this paper. It is noteworthy to focus on the differences between the present set-up and that of CHC. The shear generator in CHC experiments consisted of parallel channels of equal width with adjustable internal resistances, in which a square splitter rod along the centerline of each channel exit plane, was used to reduce the length and time scales of the initial turbulence. The turbulence level of the empty tunnel in CHC experiments was 0.15%. In our experiments, the turbulence level in an empty tunnel was 1% but the honeycomb channels reduced the turbulence to an acceptable level and nearly the same results were found. CHC results indicate that the turbulent intensities decrease while the normalized turbulent stresses increase, monotonically, downstream before the establishment of an asymptotic state fairly downstream ($X/H > 10$) [3]. The measurements of the turbulent intensities in a transverse direction at three downstream stations are presented in Figure 3. The normalized turbulent stress, $-\overline{u'\nu'}/\sqrt{\overline{u'^2}}\sqrt{\overline{\nu'^2}}$, is presented at the same stations in Figure 4. The results show the same trend, in good agreement with those reported by CHC, in the same range of X/H values. Average values are presented in Table 1 for better comparison.

The reported results of the stationary shear flows in the literature indicate that the stream-wise integral length scale, Λ_u, grows monotonically downstream and attains an approximate length of 1.5D to 1.8D in an asymptotic state fairly downstream [3-6]. The transverse integral length scales are known to be a fraction of the stream-wise scale ($\Lambda_\nu \approx 0.23\Lambda_u, \Lambda_w \approx 0.34\ \Lambda_u$) [6]. Thus, relatively fine structures of order $O(10^{-3}$ m) were expected in our set-up. Owing to insufficient resolution of the measuring system, direct measurement of the various length scales was not possible in this study. Figure 5 presents a comparative summary of the development time for the present study, along with the results from previous stationary SSF experiments (adapted from [10]). Depending on the development time in shear flows, the 'low' shear zone, $\tau^* < 0.25$ and the 'high' shear zone, $\tau^* > 2.5$, are defined after Harris et al. [4]. In the 'high' shear zone they achieved an asymptotic state in

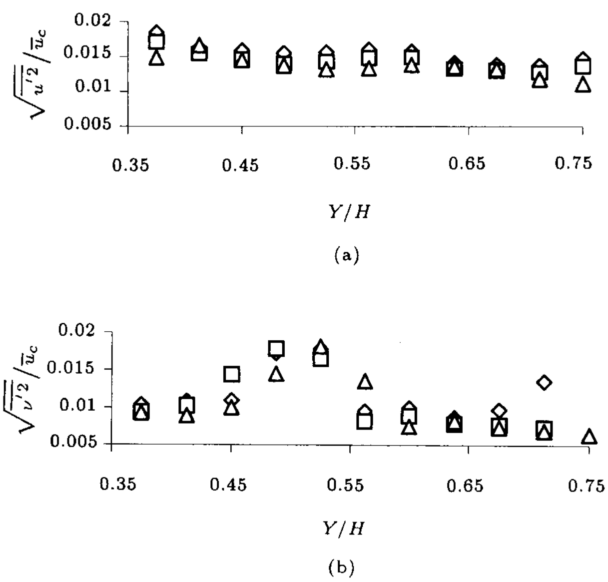


Figure 3. Variation of the turbulent intensities in transverse direction at three downstream stations; (□) $X/H = 1.25$, (◇) $X/H = 1.75$ and (△) $X/H = 2.25$.

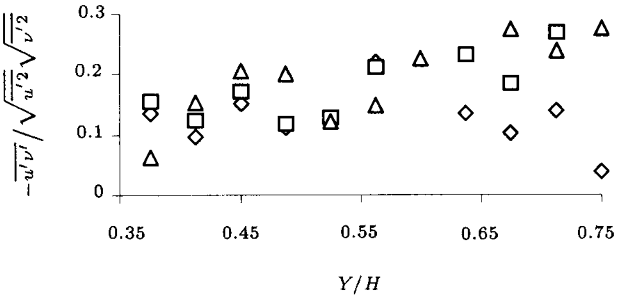


Figure 4. Variation of the velocity fluctuation correlation coefficient in transverse direction; (◇) $X/H = 1.25$, (◇) $X/H = 1.75$ and (△)$X/H = 2.25$.

Table 1. Stationary flow: Normalized turbulence intensities and Reynolds stress in comparison with the results of Champagne et al. [3].

X/H	$\sqrt{\overline{u'^2}}/\overline{u}_c$	$\sqrt{\overline{\nu'^2}}/\overline{u}_c$	$-\overline{u'\nu'}/\sqrt{\overline{u'^2}}\sqrt{\overline{\nu'^2}}$
1.25	0.02	0.01	0.14
1.57	0.01	0.01	0.18
2.25	0.01	0.01	0.21
3.37 (CHC)	0.02	0.02	0.27
5.00 (CHC)	0.02	0.02	0.33

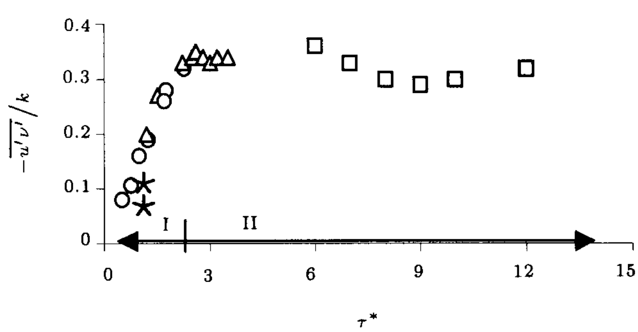


Figure 5. Variation of the normalized Reynolds stress with flow development time τ^* in stationary shear flow experiments (adapted from [10]). (o) Rose [11], (△) CHC [3], (□) Harris et al. [4] and (*) This study, I: Low shear zone and II: High shear zone.

the flow field, for which the following relations hold: $-\overline{u'v'}/k \approx 0.3, \overline{u'^2}/k \approx 1, \overline{v'^2}/k \approx 0.4, \overline{w'^2}/k \approx 0.6$. The development time for the present study lay close to the lower limit of the experiments of Rose [11] in the 'low shear zone' due to the low rate of shear generated and the spatial limitation of the test section used. In this region, turbulence needs more development time to achieve an asymptotic state where the rate of turbulence dissipation is balanced by the rate of production, due to the mean shear [4].

The results on the stationary SSF show that credible measurements in SSF can be carried out in the set up used. Thus, it was expected that the same methodology could be employed for studying pulsating SSF. Due to lack of previously reported data on pulsating SSF, the results were compared with those of stationary SSF, performed with the same centerline velocity in each case.

Pulsating Flows

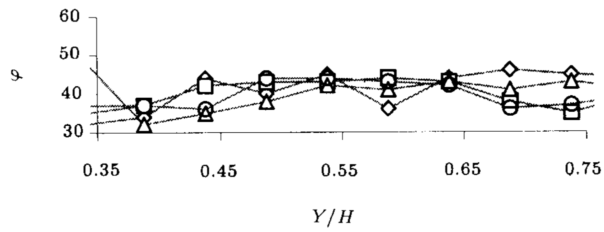
Here, selected findings of the experimental observations used in pulsating simple shear flows are reported. The shear flow was pulsated at 8.5 Hz and 18 Hz. Measurements were carried out at four stations in the test section ($X/H = 1.25, 1.58, 1.9$ and 2.25). Due to the unwanted vibration effects of the tunnel in the pulsating SSF experiments, the mean velocity was set to 3 m/s. The Reynolds number was $\text{Re}_H = 8 \times 10^4$. The development time, τ^*, calculated based on the time averaged centerline velocity in pulsating SSF, was less than 2.5. Therefore, similar to the stationary SSF, all pulsating results correspond to the 'low shear' zone in Figure 5. Figures 6a and 6b show a variation of phase angles, measured with respect to the reference signal, in the transverse direction in pulsating SSF, at 8.5 and 18 Hz, respectively. The respective average phase lags at 8.5 Hz and 18 Hz were 40° and 52° in the test section. The measured values were more scattered at 8.5 Hz.

The exact values of the time averaged centerline velocities at the four stations are given in Table 2. The pulsation amplitudes normalized by the corresponding centerline velocities are presented in Figures 7a and 7b at 8.5 Hz and 18 Hz, respectively. The pulsation amplitude decreases with increasing the pulsation frequency, because the effective blockage of the vane set mechanism increases with increasing the angular velocity of the vanes. The typical value of $\partial|\tilde{u}|/\partial Y$ was approximately 0.06 s^{-1}. The pulsation amplitude was more scattered at 8.5 Hz than that at 18 Hz.

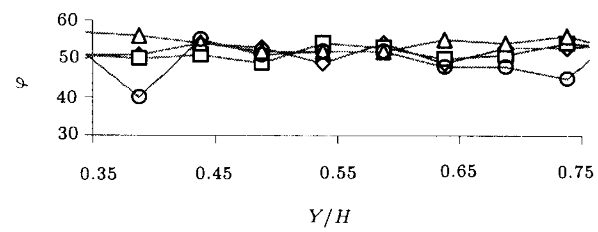
Table 2. Centerline velocities at various stations in stationary and pulsating experiments.

X/H	Stationary	8 Hz	18 Hz
1.25	3.27	3.09	3.12
1.57	3.20	3.09	3.07
1.90	3.26	3.13	3.09
2.25	3.19	3.14	3.14

Figure 8 presents mean velocity profiles in pulsating flow at 8.5 Hz and 18 Hz, in comparison with the stationary counterparts with the same mean centerline velocity at two stations. All velocity profiles demonstrated a plausible degree of linearity around the centerline region at all stations. No change was

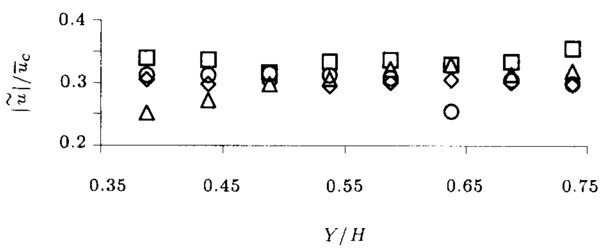


(a) $f_p = 8.5$ Hz

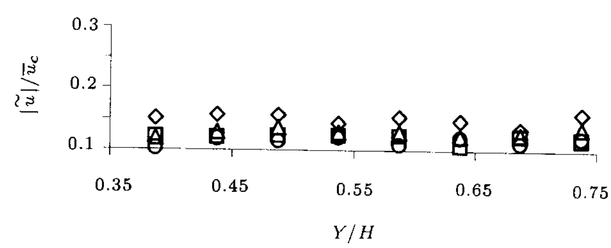


(b) $f_p = 18$ Hz

Figure 6. Variation of phase angle in transverse direction (in degree). (◊) $X/H = 1.25$, (□) $X/H = 1.57$, (△) $X/H = 1.9$ and (○) $X/H = 2.25$.



(a) $f_p = 8.5$ Hz



(b) $f_p = 18$ Hz

Figure 7. Variation of the normalized pulsation amplitude in transverse direction. (◊) $X/H = 1.25$, (□) $X/H = 1.57$, (△) $X/H = 1.9$ and (○) $X/H = 2.25$.

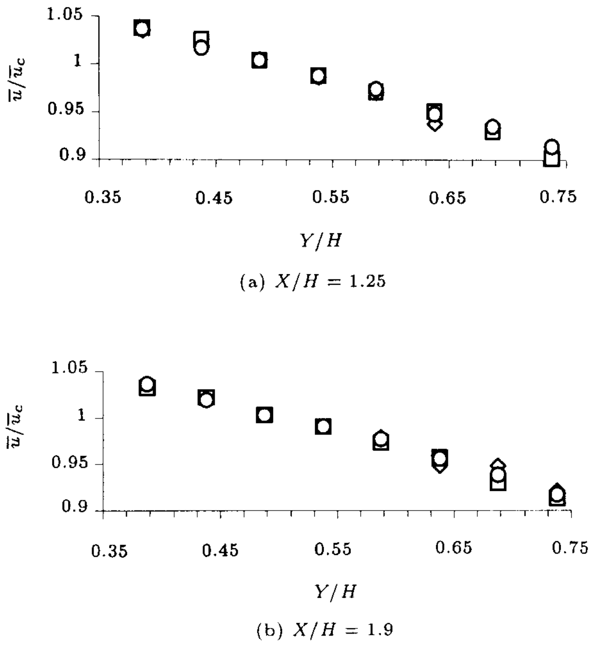


Figure 8. Profiles of the normalized mean velocity gradient at two stations. (◊) Stationary flow, (□) 8.5 Hz, (o) 18 Hz.

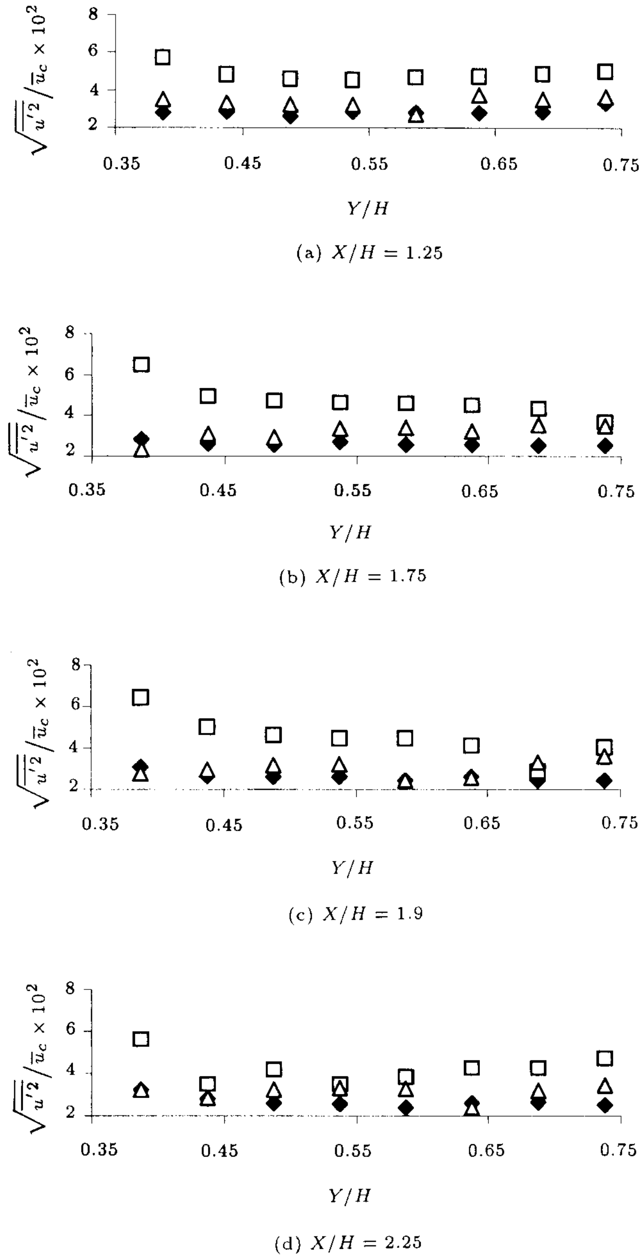
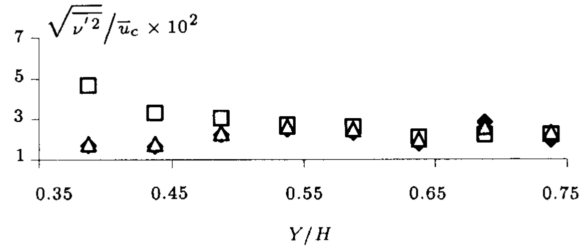


Figure 9. Transverse variation of normalized turbulent intensity in X-direction. (♦) Stationary flow, (□) 8.5 Hz and (△) 18 Hz.

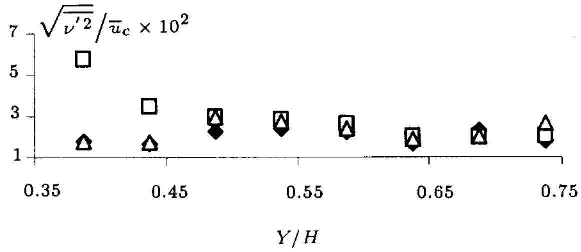
found in the mean strain rate ($d\overline{u}/dY \cong 3$ s^{-1} for all stations) with pulsation. The gradient of the mean velocity in the stream-wise direction was also measured ($d\overline{u}_c/dX = -0.3$ s^{-1}) at the centerline. Of particular interest, from the viewpoint of the objective of these experiments, was the observation of the probable pulsation effects on turbulent intensities.

Transverse variation of the normalized turbulent intensities, ($\sqrt{\overline{u'^2}}/\overline{u}_c^2, \sqrt{\overline{\nu'^2}}/\overline{u}_c^2$), is presented in Figures 9 and 10, respectively. Variation of the normalized Reynolds stress, ($-\overline{u'\nu'}/\sqrt{\overline{u'^2}}\sqrt{\overline{\nu'^2}}$), in a transverse direction, is shown in Figure 11. It was found that at 8.5 Hz, turbulent intensities and, consequently, turbulent kinetic energy, are considerably higher than those corresponding to 18 Hz and to the stationary flow. The same distinct behavior at 8.5 Hz was observed in a transverse variation of the Reynolds stresses, as shown in Figure 11. The uncertainty in the determination of the kinetic energy and Reynolds stresses was 10%.

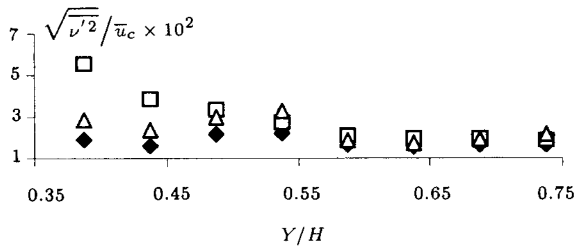
It is well known that turbulence is a random process in time and space. A statistical description of this randomness in isotropic turbulence is a Gaussian distribution. In turbulent shear flows near the rigid walls, the distribution has been found more or less skewed [12]. Assuming Gaussian distribution might be very helpful for simulating real turbulent fields, because they can be made more accessible to theoretical treatment. Significant deviation from Guassian distribution may invalidate some basic assumptions of turbulence models. This point was inspected in this study. Figures 12 and 13 show a transverse variation of the flatness (Kurtosis) and skewness factors at a typical station, $X/H = 1.9$, respectively. Table 3 gives a summary of the average values at all stations. Uncertainties in the determination of F_u and S_u were 20% and 30%, respectively. The results concerning the stream-wise velocity fluctuations, clearly indicate a distinct feature at 8.5 Hz, where deviations from Gaussian distribution were significant. Pulsating the flow field at 18 Hz did not lead to the same result. The transverse velocity fluctuations could be described with Gaussian distribution in all cases.



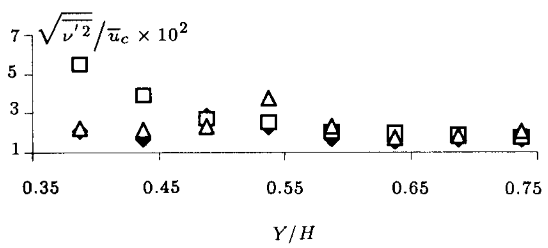
(a) $X/H = 1.25$



(b) $X/H = 1.75$

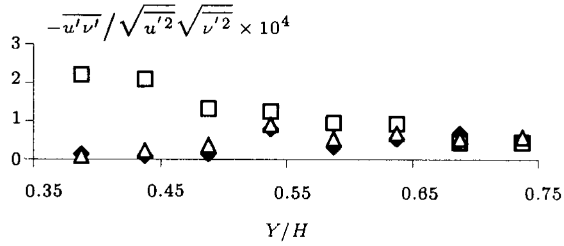


(c) $X/H = 1.9$

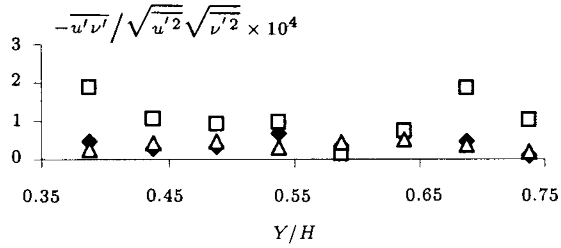


(d) $X/H = 2.25$

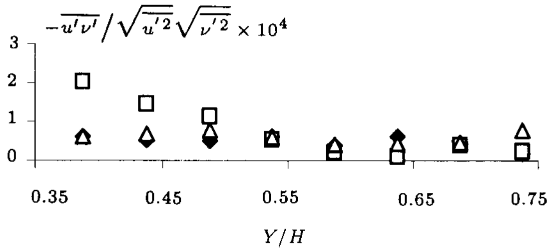
Figure 10. Transverse variation of normalized turbulent intensity in Y-direction. (♦) Stationary flow, (□) 8.5 Hz and (△) 18 Hz.



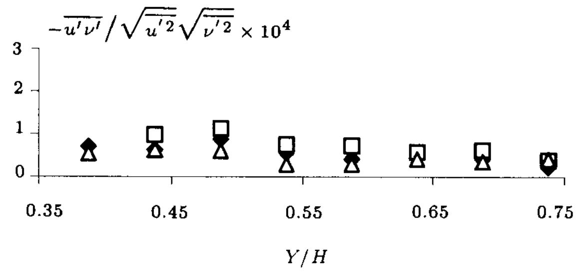
(a) $X/H = 1.25$



(b) $X/H = 1.75$



(c) $X/H = 1.9$



(d) $X/H = 2.25$

Figure 11. Variation of normalized Reynolds stress in transverse direction. (♦) Stationary flow, (□) 8.5 Hz and (△) 18 Hz.

Table 3. Flatness and skewness factors in experiments on stationary and pulsating flows (8.5 Hz and 18 Hz) at all stations.

Station	$X/H = 1.25$			$X/H = 1.57$			$X/H = 1.9$			$X/H = 2.25$		
Condition	**Stat.**	**8.5 Hz**	**18 Hz**	**Stat.**	**8.5 Hz**	**18 Hz**	**Stat.**	**8.5 Hz**	**18 Hz**	**Stat.**	**8.5 Hz**	**18 Hz**
F_u	3.1	11.1	4.1	3.4	9.7	3.7	3.5	8.1	3.9	3.7	9.4	3.8
F_ν	2.0	4.0	2.7	3.4	3.6	2.7	4.5	4.4	2.8	4.9	4.8	2.8
S_u	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	-0.2	0.0
S_ν	-1.1	-1.3	-1.1	-1.2	-1.1	-1.2	-1.1	-1.2	-1.2	-1.3	-1.3	-1.2

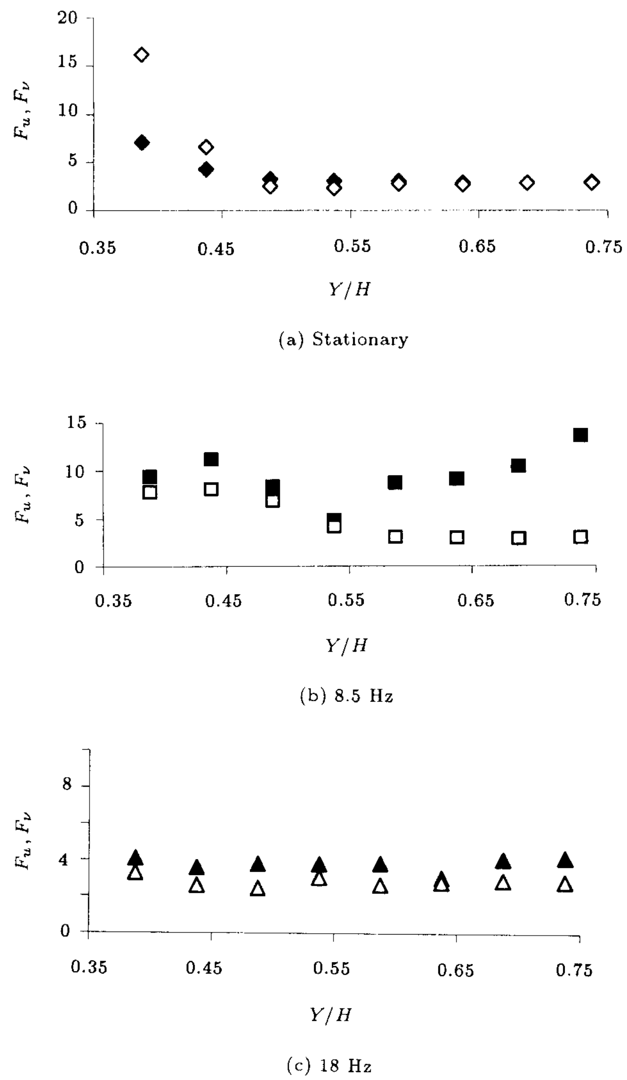


Figure 12. Variation of the flatness factor in transverse direction for u-fluctuations (black) and v-fluctuations (white).

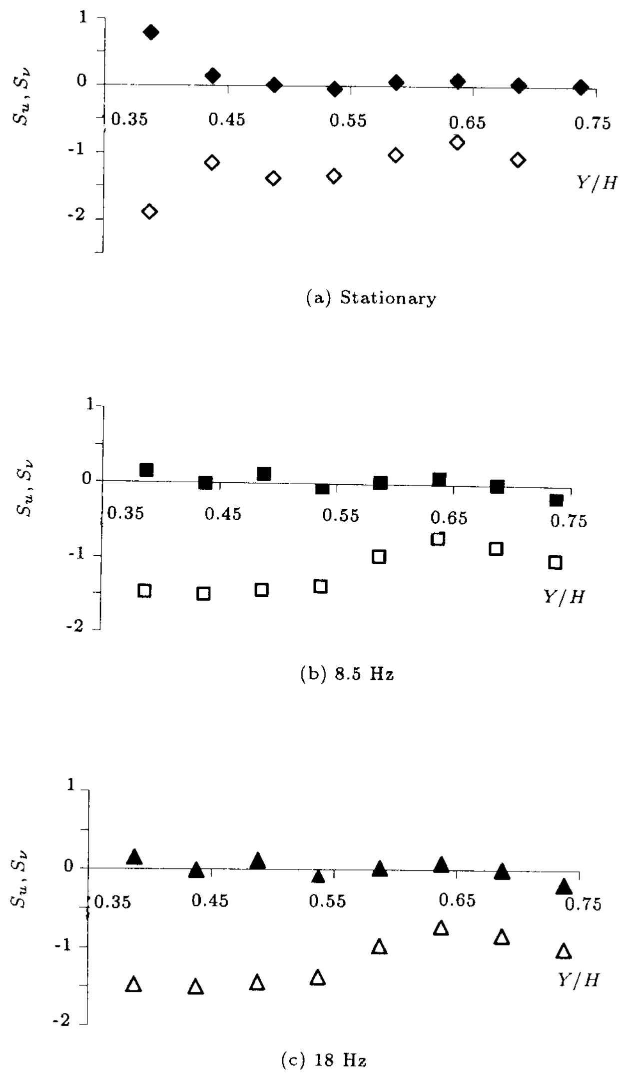


Figure 13. Variation of the skewness factor in transverse direction for u-fluctuations (black) and v-fluctuations (white).

The results, presented here clearly indicate that pulsation of a simple shear flow can cause an elevated level of turbulent stresses. However, the increase in turbulence levels appears to be frequency dependent. Turbulent intensities and the Reynolds stress at 8.5 Hz were considerably larger (roughly 250%) than corresponding stationary values (Figures 9 and 10). However, at 18 Hz, the change in the turbulent intensities and the Reynolds stress, in comparison with stationary values was relatively small (roughly 25%). Explanation of the observed behavior requires consideration of turbulent mechanisms in pulsating flows. The role of pulsation frequency and amplitude in the modified governing equations cannot be separately discussed, however, different terms in the equations can be evaluated according to the experimental results.

An elevated level of turbulence at 8.5 Hz may be interpreted through consideration of the corresponding levels of turbulence production diffusion and dissipation.

The pulsation velocity, $\tilde{u}$, introduced by the triple decomposition, enables energy transfer to take place between three participating fields, i.e., mean, turbulent and pulsating velocity fields. However, at frequencies considered here, the pulsating production term $\overline{u'v'}\partial\tilde{u}/\partial y$ was at least one order of magnitude smaller than the conventional turbulent production term. The measured pulsation amplitudes at 8.5 Hz and 18 Hz were different but their derivatives in the transverse direction were approximately the same and about 50 times smaller than the mean shear rate. Thus, nearly all energy transferred to the turbulent field was supplied directly from the mean flow with little dependence on the pulsating velocity amplitude. This finding is consistent with previous studies on wall bounded shear flows [9].

Turbulent diffusion can be physically interpreted as a mechanism responsible for shifting (displacing) physical quantities in space. Figures 9 and 10, however, indicate no shift of turbulence intensities in space. Moreover, careful examination of these figures reveals that the distinct behavior observed at 8.5 Hz cannot be attributed to a change in the turbulence energy redistribution mechanism. This is because the increase in the kinetic energy of turbulence in an X-direction was not at the expense of a decrease in the Y-direction.

Another interesting feature that can be gleaned from careful study of the presented results is a kind of directional preference in the flow field. It was observed that the second, third and fourth moments of the turbulent velocity fluctuation (turbulent shear and normal stresses, skewness and a flatness factors) in the stream-wise direction were considerably larger than those in a transverse direction. This effect was also more pronounced at 8.5 Hz.

It is generally accepted that in shear flows with low shear (zone I in Figure 5), the rate of dissipation has not reached a level to be balanced by the rate of production and, therefore, to achieve the asymptotic state (zone II in Figure 5) [3,4]. In other words, in shear flows where the asymptotic state has not been achieved, dissipation requires more development time, τ^*, to balance the production rate. Thus, the experimental results lead one to believe that, in such shear flows, pulsation may affect the imbalance between dissipation and production mechanisms. It can be also assumed that pulsation in one direction introduces a directional preference in the dissipation mechanism. Larger amplitude and a longer period of influence makes a pulsation at 8.5 Hz more effective than that at 18 Hz in the set-up used. Our observations support this idea.

It should be noted that many turbulence models have been developed, based on the assumption that the small-scale dissipative structures in very large Reynolds number flows are isotropic. This is not the case in those engineering applications where the time scale of some additional effects introducing anisotropy in the flow may be of the same order as the time scale of dominant turbulent mechanisms. The results of this study show that pulsation may be one of these effects and any modeling should mirror this anisotropy.

CONCLUDING REMARKS

The present experimental investigation was intended to study shear flows subject to pulsation effects. In this study, a stationary turbulent shear flow was compared with one developing under the same average conditions, only with an additional pulsating velocity field superimposed. The results were discussed in connection with the modified equations. Although attaining the asymptotic state at large development times, τ^*, was not possible in our set-up, it provided a comparative basis to study the differences between stationary and pulsating shear flows. An important feature of this study was the emphasis on turbulence mechanisms (production, dissipation and diffusion) in pulsating simple shear flows.

No significant change in the measured features of the turbulent flow, with pulsating at 18 Hz, was observed. However, at 8.5 Hz, turbulent intensities and Reynolds stress were significantly larger than those in stationary flow.

The distinct behavior observed at 8.5 Hz was discussed. This behavior could not be attributed to the production mechanism in pulsating flows. The results, therefore, led one to believe that the dominant mechanisms for production of turbulence in pulsating shear flows cannot differ from those in stationary shear flows. This finding was in perfect agreement with several previous studies, which featured development of shear flows near solid walls in boundary layers [9,12,13]. It was also shown that diffusion in pulsating flow could not be responsible for the observed behavior. However, it was suggested that anisotropic dissipation could be introduced in the flow. The experimental evidence showing direction preferences in all moments, confirmed this view. Based on the results of this study, the development of more comprehensive turbulence models for special flow fields, where anisotropic dissipation may be a determinant factor, was recommended.

ACKNOWLEDGMENT

This work was done in accordance with the program for scientific cooperation in Mechanical Engineering between France (Institut National Polytechnique de Lorrain) and Iran (Sharif University of Technology). Strong support from both sides is acknowledged.

NOMENCLATURE

D	hydraulic diameter of the honeycomb channels (m)
f, f_p	frequency, pulsation frequency (Hz)
H	transversal dimension of the shear generator (0.4 m in this study) (m)
k	kinetic energy of turbulence, $k = 0.5(\widetilde{u_i'u_i'})$ (m^2/s^2)
p	static pressure (pa)
Re_H	reynolds number based on the characteristic length $H, Re_H = H\overline{u}_c/\upsilon$
t, T_p	time, period of pulsation (sec)
$\overline{u}_c, \lvert\widetilde{u}\rvert$	mean velocity at centerline, pulsation amplitude in pulsating flow (m/s)

u', v', w'	velocity fluctuations (m/s)
X, Y	longitudinal distance downstream of the grid or the shear generator, transversal coordinate (m)

Greek Symbols

ε	dissipation rate of turbulence (m^2/s^3)
φ	phase difference between pulsating flow at data points and the reference signal (degree)
ρ	density (kg/m^3)
τ^*	flow development time, $\tau^* = (X/\overline{u})(d\overline{u}/dY)$
v	kinematic viscosity (m^2/s)
ω	circular frequency, $\omega = 2\pi f$ (rad/s)

Superscripts

—	time-averaged
~	pulsating component
′	fluctuating component

Subscripts

c	centerline
p	pulsating

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