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Research Note

Experiments on Pulsation Effects in Turbulent Flows, Part II: Investigation on Grid-Generated Turbulence

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In this paper, pulsating grid-generated turbulence is studied. A two-component hot wire anemometry technique is used. The pulsation effects on characterizing length scales and the statistical description of fluctuations are studied in comparison with their stationary counterparts. No significant change in the character of the turbulent flow with pulsation is observed.

INTRODUCTION

Homogeneity and isotropicity of Grid-Generated Turbulence (GGT) has been a field of interest for the last 70 years [1-3]. However, no serious attention has ever been paid to the effects of pulsation on GGT. In periodic pulsating flows, the velocity or the pressure field undergoes a well-defined oscillation at a fixed frequency and amplitude.

Turbulent periodic flows occur in a variety of engineering applications. Low frequency large amplitude pulsation is particularly encountered in the turbocharging of internal combustion engines, for which the developing of reliable models to predict the instantaneous performance is of practical importance [4,5].

In the previous study on pulsating GGT, the emphasis was placed on the effects of pulsation on the mechanism of cascading energy, the turbulent kinetic energy, isotropicity and homogeneity of the turbulent flow field [3].

While the results were consistent and indicated the negligibility of the pulsation effects on GGT [5], this study focuses on other important features of turbulence. The characterizing scales (integral length scale and Taylor's micro scale) and the probability density of velocity fluctuations for the variations of frequency in pulsating GGT, are investigated here.

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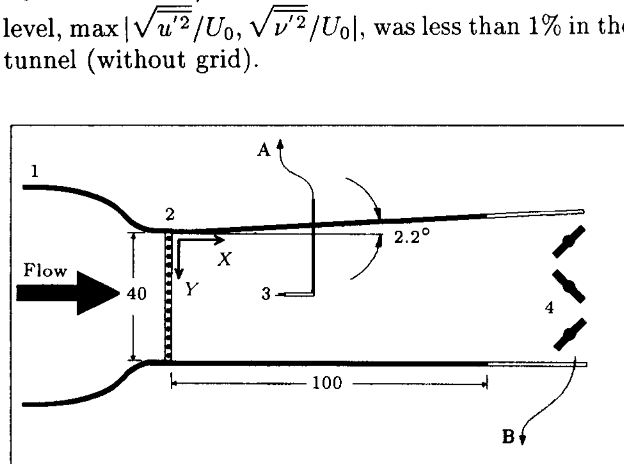
EXPERIMENTAL SET-UP AND UNCERTAINTIES

General Specifications

Experiments were performed in the same open circuit subsonic wind tunnel as in [3], Figure 1a. The turbulent flow was studied in the 40 × 40 × 100 cm, slightly divergent (2.2°) test section. A uniform grid made of perpendicular round bars (D = 4 mm, M = 17 mm, σ = 0.45) was used. In all cases the measurements were carried out along the tunnel centerline axis with $U_0 = \overline{u} = 10$ m/s and $R_M = 1.0 \times 10^4$. Turbulence level, $\max|\sqrt{u'^2}/U_0, \sqrt{v'^2}/U_0|$, was less than 1% in the tunnel (without grid).



1. Wind tunnel (test section); 2. Grid; 3. Dual-sensor-probe; 4. Pulsation generator (rotating vanes); A: Instantaneous velocity signal in volts (Figure 1b); B: Reference signal in volts (Figure 1c).

Figure 1a. Experimental facility (dimensions in cm).

Pulsation Mechanism

A rotating vane set in the tunnel (Figure 1a) generated the sinusoidal pulsating flow, Figure 1b (for more detail see [6]). The free stream was pulsated at 8.5, 13 and 18 Hz. An inductor sensor delivered the reference pulse voltage (e) to detect the beginning of each cycle (Figure 1c) and to measure the phase difference between the pulsating flow at different data points. No phase difference between the data points was found [3]. Due to the divergence of the test section, $\overline{u}$ and $|\tilde{u}|$ decreased in a streamwise direction $d\overline{u}/dx \approx -0.8$ (sec^{-1}), $d|\tilde{u}|/dx \approx -1.2$ (sec^{-1}). The pulsation amplitude decreased with increasing the pulsation frequency. Typical values of the normalized energy of pulsation ($\overline{\tilde{u}\tilde{u}}/\overline{u}^2$) at 8.5, 13 and 18 Hz were 0.13, 0.09 and 0.05, respectively. The turbulent stress term ($-\overline{u'\nu'}$) was zero, as expected in all GGT experiments [3].

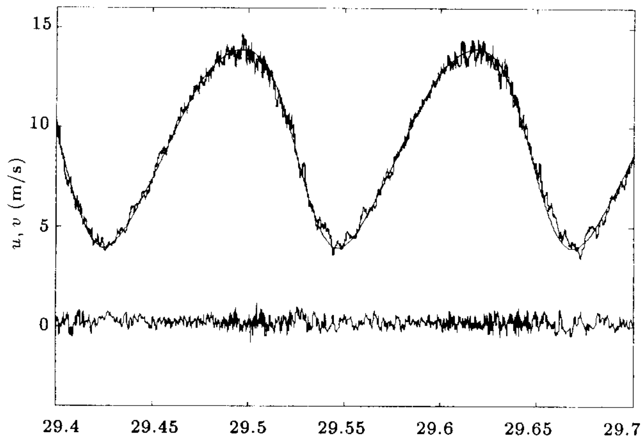


Figure 1b. Typical record of the instantaneous velocity (u, v) signals ($f_p = 8.5$ Hz) along with the corresponding periodic part ($\tilde{u}$) separated.

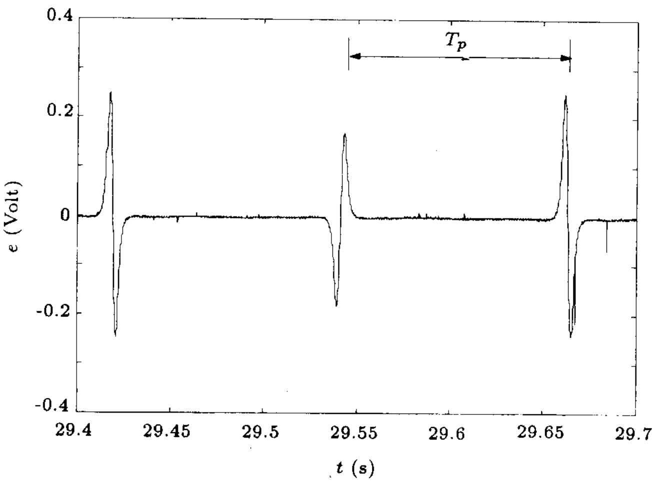


Figure 1c. Typical record of the reference voltage signal (e) used in determination of phase differences between data points.

Data Acquisition

A dual sensor hot wire probe (DANTEC 55R51), operated at a constant temperature of 80% overheat, using a DISA 55M01 anemometer, was used to measure the instantaneous velocity components. The calibration of the X-probe was performed in the tunnel using an accurate Pitot tube (5-15 m/s, ± 0.8% at mid range) [7]. A calibration accuracy of 5% was obtained. For analog to digital conversions, a KEITHLEY DAS-1700 HR board (accuracy 16 bit; 8 channel) was used. For each channel, 480000 samples were recorded. The average sampling duration was an 800-pulsation period. The credibility of the data acquisition and processing 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 frequency response of the system used was 3 kHz.

Data Processing

The pulsating and fluctuating components of the velocity were separated from the mean velocity. The absolute value of the Fast Fourier Transform (FFT) of the original velocity signal was plotted, in which large peaks correspond to the mean velocity, the principal frequency and its harmonics. The small peaks correspond to the fluctuations. By selecting the first two or three of the large peaks (depending on the case) and setting zero in place of small peaks a new vector was obtained. The inverse FFT of the new vector gave a periodic signal that fitted well to the original signal but was not fluctuating. The credibility of this method in separating low frequency pulsation from high frequency fluctuation was established in [3].

EXPERIMENTAL RESULTS AND DISCUSSION

Pulsation effects on the turbulent characteristic scales were studied. Figures 2 and 3 show the streamwise variation of the Taylor's micro and the integral scales at 8.5, 13 and 18 Hz in comparison with stationary cases. In the calculation of the integral length scale, an integration of the Eulerian autocorrelation [5] was carried out from 2 Hz to 2 KHz. The results of the calculations for the integral scales were repeatable with an uncertainty of 10%. The results are consistent and show the order of magnitude of scales [3]. The results of stationary turbulence show that $\Lambda_u \approx 2\Lambda_\nu$ and $\lambda_u \approx \sqrt{2}\lambda_\nu$ which are in good agreement with Comte-Bellot, G. et al. [6]. The turbulent Reynolds number

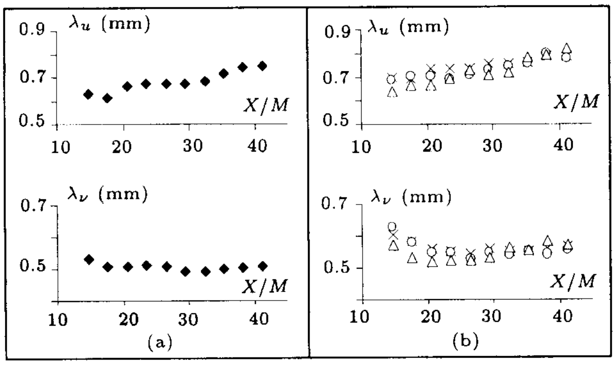


Figure 2. Stream-wise variation of Taylor's micro (dissipation) length scales along the test section centerline. (a) Stationary flow: (♦); (b) Pulsating flow: (×) 8.5 Hz, (o) 13 Hz and (△) 18 Hz.

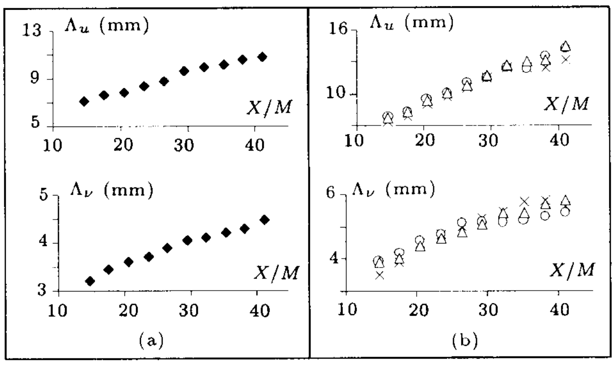


Figure 3. Stream-wise variation of turbulent macro (integral) length scales along the test section centerline. (a) Stationary flow: (♦); (b) Pulsating flow: (×) 8.5 Hz, (o) 13 Hz and (△) 18 Hz.

(Re_λ) was roughly 10 in all experiments. Although Taylor's micro-scale (λ) does not characterize any specific group of eddies, λ^{-2} may be thought of as the mean square wave number of sinusoidal velocity fluctuations, weighted according to their contribution to the total energy [8]. The results of this study show the monotonic growth of Taylor's micro-scale in good agreement with reported results in the literature [9]. Figure 3 also shows that the typical size of integral scales, fairly downstream (nearly homogeneous state), is 13 mm, equal to the mesh size of the grid and in good agreement with Comte-Bellot, G. et al. [9]. No significant change in turbulent length scales was found with pulsation.

It is shown that pulsating GGT does not change the expected decay rate for the RMS of the velocity fluctuations [3]. Another interesting statistical analysis of the fluctuations may be a deviation from the Gaussian distribution. Skewness and flatness (Kurtosis) factors describe the shape of the probability density distribution [5].

In stationary GGT (Gaussian distribution), the corresponding values are $S = 0.0$ and $F = 3.0$. Figures 4 and 5 show the streamwise variation of these two factors. In pulsating GGT, v-fluctuations are more deviated than v-fluctuations from the Gaussian distribution. This effect was more pronounced farther downstream ($X/M > 30$) and can be attributed to the disturbances caused by rotating vanes. While in pulsating boundary layers, deviation from the Gaussian distribution is attributed to the intermittency phenomenon [10]. However, this study shows that it may be attributed, in part, to the nature of the large amplitude pulsation. Figure 1b shows that the pattern of fluctuations at peaks (at 14 m/s) is different from that of the valleys (at 4 m/s). The uncertainties in calculation of the skewness and flatness factors were 20% and 30%, respectively.

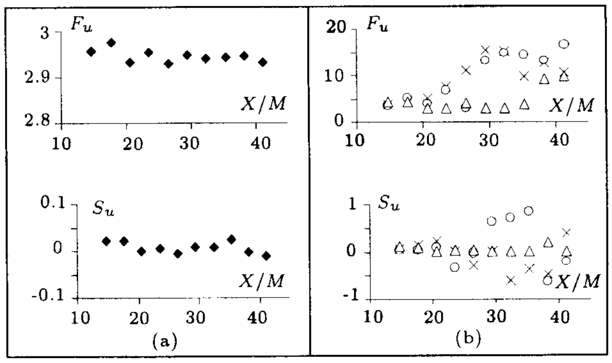


Figure 4. Flatness and skewness factors for u-fluctuations along the test section centerline. (a) Stationary flow: (♦); (b) Pulsating flow: (×) 8.5 Hz, (o) 13 Hz and (△) 18 Hz.

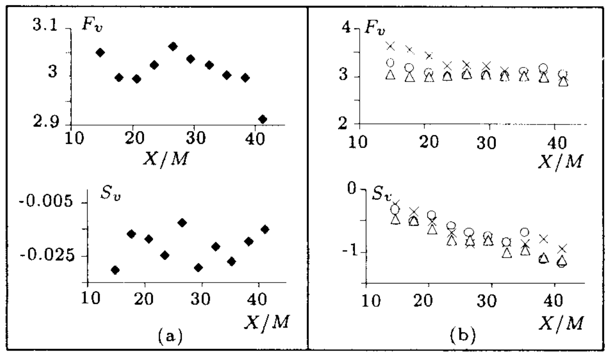


Figure 5. Flatness and skewness factors for v-fluctuations along the test section centerline. (a) Stationary flow: (♦); (b) Pulsating flow: (×) 8.5 Hz, (o) 13 Hz and (△) 18 Hz.

CONCLUDING REMARKS

Experiments on pulsating GGT were carried out. A large amplitude, low frequency sinusoidal variation of the mean flow was studied. The previous study provided new information and consistent results on turbulent intensities, kinetic energy (k), isotropicity, homogeneity, production and diffusion mechanisms in pulsating GGT [3]. This work is a continuation of this previous study. Emphasis is placed on the effects of pulsation on integral scales and Taylor's micro scales and the probability density distribution of fluctuations in GGT.

No significant change in turbulence scales with pulsation was observed. This can be interpreted by the fact that pulsating the free-stream turbulence at frequencies much smaller than those of the turbulence-like Taylor scales cannot affect turbulence. The fluctuations in a streamwise direction were more deviated from the Gaussian distribution than those in a transverse direction.

It is well known that turbulence is a broadband phenomenon, in which any averaged measuring comprises the summed contribution of a continuous range of scales of motion. This point of view is, therefore, in harmony with the observed insensitivity of the mean turbulence to applied pulsation at a single frequency and also in good agreement with reported observations in the pulsating boundary layers [11].

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NOMENCLATURE

F	flatness (Kurtosis) factor, $F_u = \overline{u'^4}/(\overline{u'^2})^2$
k	kinetic energy of turbulence, $k = 0.5(\overline{u'_i u'_i})$ (m^2/s^2)
M	distance between rod center lines in the grid (m)
Re_M	Reynolds number based on mesh size, $\mathrm{Re}_M = U_0 M/v$
Re_λ	Reynolds number based on v-micro scale, $\mathrm{Re}_\lambda = \sqrt{\overline{u'^2}}\lambda_v/v$
S	skewness factor, $S_u = \overline{u'^3}/(\overline{u'^2})^{3/2}$
T_p, t	period of pulsation, time (sec)
U_0	velocity in non-pulsating (stationary) flow (m/s)
$\overline{u}, \lvert\tilde{u}\rvert$	mean velocity, pulsation amplitude in pulsating flow (m/s)
u', v', w'	velocity fluctuations (m/s)
X, Y, Z	longitudinal, transversal and span-wise coordinates, respectively (m)
λ_u, λ_ν	Taylor's micro length scales of u and v, respectively (mm)
Λ_u, Λ_ν	integral (macro) length scales of u and v, respectively (mm)
σ	solidity (projected solid area to total area) of the grid

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