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Research paper

Numerical simulation of aspect ratio effect of the rectangular cylinder on the aerodynamic noise

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Abstract

The purpose of this paper is to investigate the effect of aspect ratio on vortex shedding, and transient flow-induced noise over a rectangular cylinder is presented. The freestream velocity is assumed 50 m/s. URANS equations with turbulence model $k-\omega-SST$ are employed to flow analysis. Aerodynamic noise calculations are performed using the FW-H analogy. The rectangular cross-section with various lengths and widths is considered. A comparison of the results extracted in the present study with the experimental results of other references indicates the accuracy of the present research. The aspect ratios from 0.6 to 6 (equivalent to Reynolds numbers from 2.5×10^4 to 5.6×10^4) are studied. The simulations can be divided into two categories. In the first category, the ratio of length to width (R = B/H) is less than one, and in the second one, this ratio is greater than one. In the first case, noise is reduced by a relatively low slope. But in the second condition, the behavior of noise is different in various ratios and the slope of noise variations is high. The flow structure is also discussed in this paper. It is founded that for the first category, by increasing the aspect ratio, both the fluctuations and aerodynamic forces are reduced, and the longitudinal wake zone is increased. But in the second category, fluctuations of flow may be increased or decreased in various aspect ratios.

1. Introduction

The study of unsteady flow over thick objects, especially when they have different geometries, is increasing since they have a lot of applications in various industries. The action and reaction of the fluid flow and the bluff body cause aerodynamic noise. Studying the flow over a rectangular cylinder is very important in aerodynamics, wind engineering, electronic equipment cooling, marine engineering (such as in wharves, piers, and ships), and most notably, bridges and high-rise buildings [1-3]. In the construction of long bridges and high-rise buildings exposed to the unsteady flow of wind, the study of their aerodynamics and fluctuations have drawn much attention. Since their schematic is very similar to cylinders with rectangular cross-sections, much research has been performed on the transient flow over these rectangular cylinders. Sohankar *et al.* [4] investigated the flow over a cylinder with a square cross-section and Reynolds numbers ranging from 10^3 to 5×10^6. They considered the

Reynolds numbers greater than 20,000 as high Reynolds numbers. By using the Unsteady Reynolds-Averaged Navier–Stokes (URANS) model, Iikarino *et al.* [5] numerically investigated the transient flow over a rectangular cylinder and compared the results with the experimental data. They observed that the numerical study accurately predicts the vortex shedding and the separation points. Davis *et al.* [6] presented the numerical solution of the flow over a rectangular cylinder at high Reynolds numbers using the LES model and compared it with the experimental data. The error between these two methods was negligible. Margnat [7] numerically simulated the sound emitted by a rectangular cylinder at low Reynolds numbers. In a numerical study, Abbasi and Souri [8] achieved the reduction of the aerodynamic noise of a square cylinder by installing a splitter plate. The flow structure over the bluff body depends on the Reynolds number, aspect ratio, and angle of attack. Many experimental studies have been performed on the effect of the aspect ratio on the transient flow over a bluff body. For example, Bearman [9] and Lyn *et al.* [10] studied the sound pressure level generated by a flow over a rectangular cylinder. Curle [11] conducted the noise of a steady flow over a cylinder in which the Mach number is low. He found that the fluctuations of the forces due to the flow field result in sound generation. Nakaguchi *et al*. [12] explored the influence of the aspect ratio of the rectangular cylinders in different Reynolds numbers from 2×10^4 to 6×10^4. They observed that the maximum drag occurs when the ratio of cylinder length to width (R) is R = 0.6. Norberg [13] experimentally achieved a similar result to Nakaguchi *et al.* [12] in the wind tunnel for a rectangular cylinder with different aspect ratios (R = 1/3 − 3) and for the Reynolds numbers ranging from 400 to 3×10^4. Ohya [14] studied a rectangular cylinder with the aspect ratios R = 0.4, 0.5, and 0.6 and Reynolds numbers ranging from 6.7×10^3 to 6.7×10^4, and he showed that for R = 0.5 sudden changes occur in the flow pattern over the cylinder. Okajima [15] studied the laminar flow over a two-dimensional rectangular cylinder with different aspect ratios (R = 0.6 − 8) at Reynolds numbers ranging from 100 to 800. Changes in the Strouhal number and the flow pattern were observed at critical ratios of 2.8 and 6. Shimada and Ishihara [16] performed the numerical investigation of a flow over a cylinder with different aspect ratios R = 0.6 − 8 using the k-ε model. Saha *et al.* [17] explored the influence of the inlet on the wake of a square cylinder. In following this research, Saha *et al.* [18] used the DNS model to analyze the kinetic energy in this cylinder's wake zone at a Reynolds number of 100. Tamura [19] studied the Strouhal number of a transient flow over a three-dimensional rectangular cylinder using the LES model with different aspect ratios. He observed that the Strouhal number has a precise adaption with the experimental model in ratios between 2.5 and 3. Murkami and Mochida [20] using LES, simulated the transient flow over a rectangular cylinder. Tian *et al.* [21] considered the influence of the aspect ratio on the flow structure in a square cylinder numerically. They found that the value of vortex shedding frequency is not sensitive to the aspect ratio. Ricci *et al.* [22] conducted the unsteady flow field around a prism characterized by a rectangular 5:1 cross-section using the LES turbulence model in the presence of incoming turbulence. Two configurations, corresponding to mild and strong incoming turbulence levels were explored. Obtained results were compared to experimental data showing good agreement between experiments and numerical.

Literature review shows that most studies on the flow structure have been concentrated on circular cross-section cylinders. In addition, few investigations have been carried out on the rectangular cylinders that examine aerodynamic noise, sound pressure level and fluctuations in the flow. On the other hand, unlike relatively extensive studies on the flow structure of rectangular cylinders with different aspect ratios, no studies have examined the role of aspect ratios in aerodynamic noise generation. Accordingly, the present article studies the occurrence of aerodynamic noise in a rectangular cylinder and investigates aspect ratios at high Reynolds numbers using the turbulence model $k - \omega - SST$. This is implemented to archive a deeper understanding of the unsteady flow structure, the occurrence of vortex shedding and the effect of aspect ratio on the generated sound.

2. Model specifications and numerical scheme

2.1. Governing equation

In the present simulation, the governing equations, including the continuity equation and momentum equation should be solved. These equations are presented as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial(u_i)}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_i \partial x_j} - \frac{\partial}{\partial x_i}(u_i u_j - \overline{u'_i u'_j}) \qquad (2)$$

where ρ, u, and p are the density, velocity, and pressure, respectively.

The analogy of Williams-Hawkins (FW-H) (Eq. 3) [23] is also employed to predict aeroacoustic properties.

$$\frac{1}{c_0^2}\frac{\partial^2 P'}{\partial t^2} - \nabla^2 P' = \underbrace{\frac{\partial}{\partial t}\left(\left(\rho_0 u_{j_n} + \rho(u_n - v_n)\right)\delta(f)\right)}_{\text{monopole}} - \underbrace{\frac{\partial}{\partial x_i}\left((P_{ij}n_j + \rho u_i(u_n - v_n)\delta(f)\right)}_{\text{dipole}} + \underbrace{\frac{\partial^2}{\partial x_i \partial x_j}\left(T_{ij}H(f)\right)}_{\text{quadrupole}} \qquad (3)$$

where $H(f)$ and $\delta(f)$ is the Heaviside function and the DIRAC Delta function, respectively. Also, τ_{ij} and P' are respectively the viscous stress and sound pressure in the far field.

2.2. Problem description

In the present study, numerical analysis of the flow-induced noise on a rectangular cylinder and the effect of different ratios of length-to-width at high Reynolds numbers is explored. Firstly, to verify the results, a squared cylinder with a length of 10 mm is considered. freestream velocity over the cylinder is 50 m/s. The dimensions of the cylinder are adopted from Octavianty' and Asai's model [1] which is an experimental study. The Reynolds number founded on the square side length and freestream velocity is 3.3×10^4. Flow domain and boundary conditions have been shown in Fig. 1. To record the noise generated from the cylinder, two microphones as shown in Fig. 1, have been set in different locations.

2.3. Computational mesh

In order to accurately estimation of severe gradients, especially near walls, a sufficient grid to prevent potential mutations must be created. Fig. 2 shows a computational domain with meshing. It can be observed that a finer grid exists near the wall. The grid near the wall is chosen such that y^+ is less than 1.

The independence of the results from the computational grid has been done, which has been fully described in the previous research of the authors [8].

In order to ensure the correctness of the selected time step, the independence of the results from the time step has been examined. For this purpose, flow simulation was performed in four different time steps and the results were extracted.

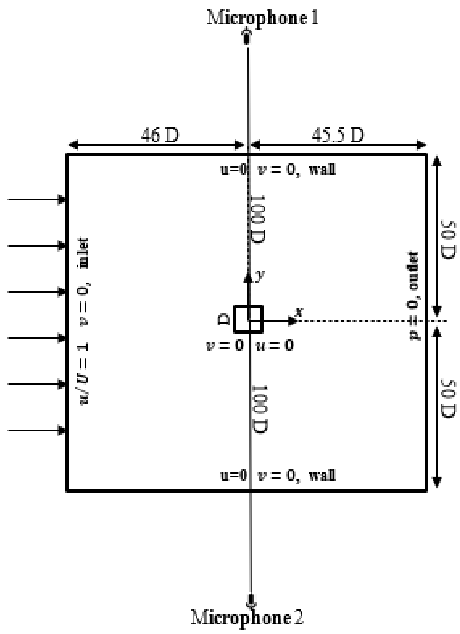


Fig. 1. Flow domain and the boundary conditions.

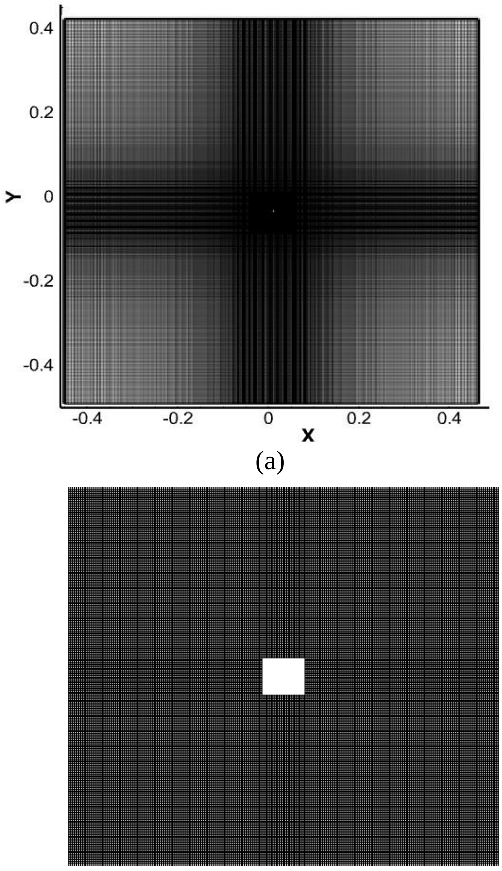


Fig. 2. Mesh of the computational domain; (a) Mesh structure for the full computational domain and (b) computational grid close to cylinder.

Table 1 shows the values of the Strouhal number and Peak of sound pressure level (SPL*p*) in different time steps. It is observed that SPL*p* is not change much in the time step of 0.00001 to 0.000001. Also, the effect of time step on the Strouhal number is very small. Accordingly, in order to reduce the cost and computational time in the performed analyzes, a time step of 0.0001 is considered.

Table. 1. Independence of the results from the time step.

Time step (s)	St	Peak of sound pressure level (SPL*p*)
0.01	0.118	62 dB
0.001	0.125	73 dB
0.0001	0.132	90 dB
0.00001	0.132	90.5 dB

2.4. Solver settings

Ansys-Fluent software is employed for the simulations. The URANS model is used for an exact time-accurate solution. To accurately estimate eddy viscosity, the Two-equation turbulence model k-ω SST is used [24-26]. The SIMPLE algorithm employs a correlation between velocity and pressure field. A second-order upwind scheme is employed for the specific spatial and temporal discretization of the governing equations. In the present analysis, the time step and total time are considered 0.001 s and the total time is 0.6 s. Based on the results obtained from the present simulation, the frequency of vortex oscillations and the occurrence of the vortex shedding phenomenon is about 660 Hz. It is clear that in order to properly predict this phenomenon and its details, the data sampling frequency needs to be several times the vortex shedding frequency. Considering the results independence of the time step, it was found that time step 0.0001 s (equivalent to 10 kHz data sampling frequency) is appropriate. By comparing the frequency of data sampling and the vortex shedding, it is clear that the present analysis is able to identify this phenomenon and the details of its occurrence with good accuracy. The criterion for stopping the calculations is the convergence of the residues equal or less than $10^{-7.}$ In addition, the recording of acoustic pressure is chosen 10 kHz.

2.5. Validation

Table 2 and Fig. 3 compare the aerodynamic parameters and the obtained velocity with the experimental results, respectively, which show good compatibility between them. Good agreement is observed in comparing the velocity and pressure profiles obtained in the present study with experimental ones. Although one can be observed good consistency in the drag coefficient, the lift fluctuations owing to the inappropriate assessment of the separation place, overestimate the experimental model. Also, it is recognized that the mesh density (70000) for the current simulation is reliable.

Table. 2. Aerodynamic coefficient validation.

Author	$\overline{C_D}$	C'_L	St
Present study (Re =3.3× 10^4) (k-ω-sst)	2.034	1.394	0.132
Tian *et al.* [2] (Re = 2,14 × 10^4) (k-ω-sst)	2.06	1.492	0.138
Samion *et al.* [3] (Re = 2,2 × 10^4) (k-ω-sst)	2.1	1.43	0.126
Lyn [4] (Re = 2,14 × 10^4) (Exp)	2.1	-	0.13

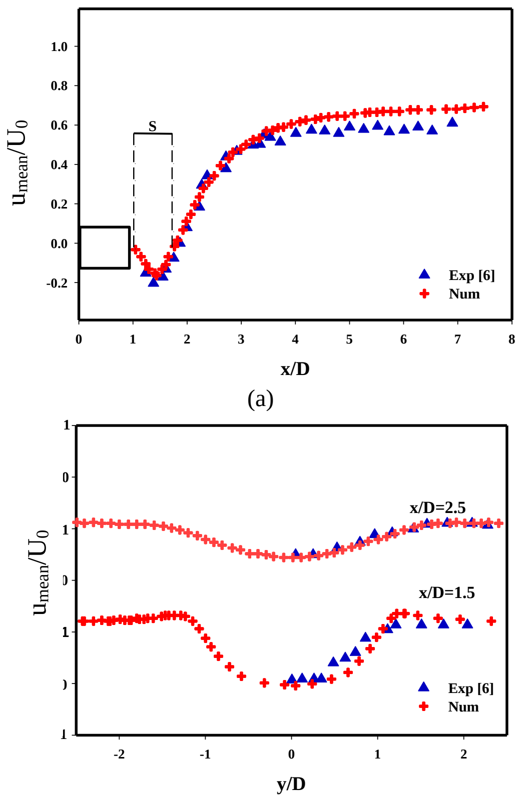


Fig. 3. Distribution of mean velocity in streamwise and spanwise direction comparing to experimental [6]; (a) streamwise mean velocity on centerline and (b) mean velocity at two streamwise locations.

In Fig. 4. the SPL versus the St in the locations of microphones 1 and 2 in the numerical and experimental [27] are compared, revealing good consistency, especially in peak SPL. It is clear that in other limits of the St, the variance in SPL might be further than 15dB, which is due to two-dimensional modeling and does not estimate the separation position well. Meanwhile, the peak of SPL is more significant, and the results precision of the current simulation can be verified.

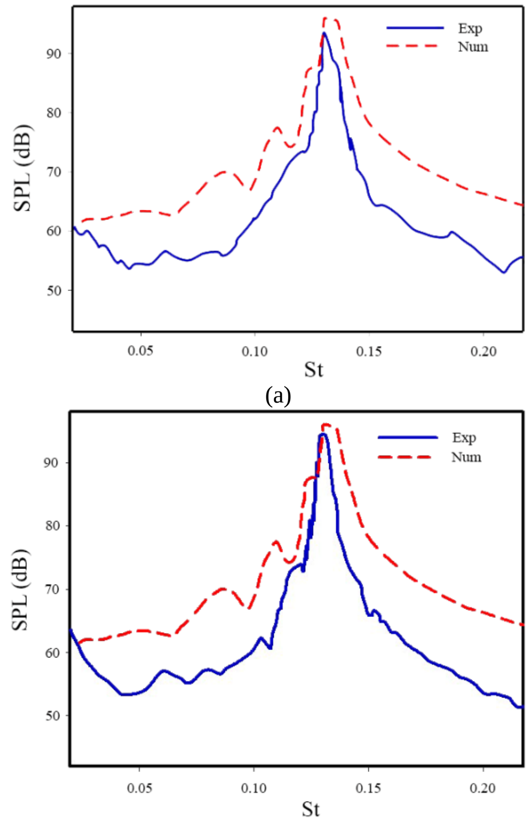
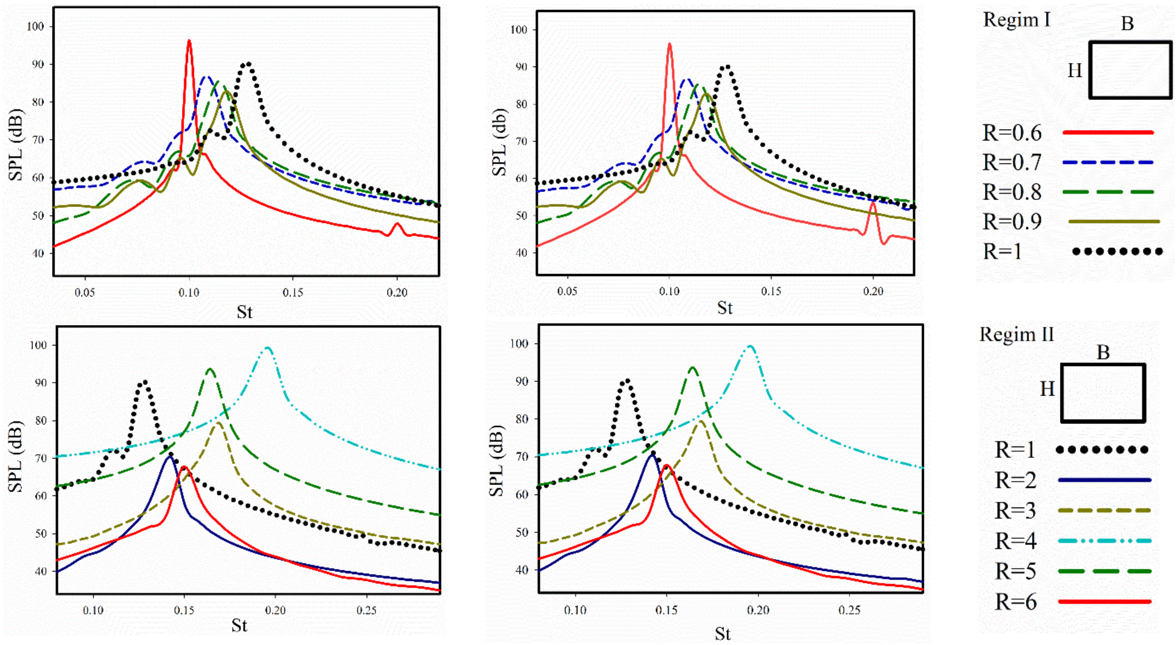


Fig. 4. Numerical and experimental [27] acoustic SPL versus St; (a) microphone (1) and (b) microphone (2)

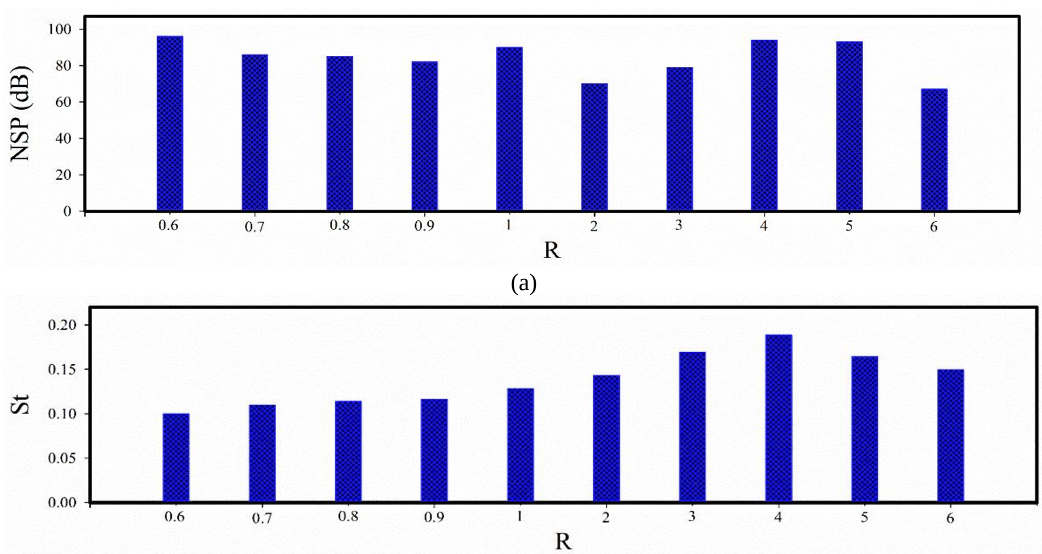
3. Results and discussion

In this study, the effect of the aspect ratio on the unsteady flow, vortex shedding, and aerodynamic noise for the thickness of 10 mm and various lengths is investigated. In order to determine the influence of the aspect ratio, various values of R = B/H are considered to be in the range from 0.6 and 6, in which B is the side length of the cylinder cross-section and H is the cylinder height. In Fig. 5, the sound pressure level is illustrated versus the Strouhal number for various aspect-ratios. In the first regime of the flow (i.e., R < 1), initially, increasing aspect ratios equal to 0.1 causes a decrease in the sound intensity by 15%. But then, by increasing this ratio, the pressure level changes are not significant. It is also clear that by increasing the ratio from 0.9 to 1, the sound intensity is increased. In the second case (i.e., R > 1), the sound intensity behavior is varied at different aspect ratios.



(a) (b)

Fig. 5. Sound pressure level a rectangular cylinder with different aspect ratios; (a) microphone (1) and (b) microphone (2).



(a)

(b)

Fig. 6. Variation of (a) Strouhal number and (b) SPL with aspect ratio.

It is observed that at R = 0.6 and R = 6, the maximum and the minimum value of the sound pressure level are occurred, respectively. Since the distance between each receiver and the source of sound is equal, the sound pressure level is the same for different R ratios.

In order to compare the SPL and Strouhal number in different aspect ratios, the variations of SPL and Strouhal number at different R ratios are shown in Fig. 6. In the first regime (i.e., R < 1), by increasing R, the SPL decreased whereas the Strouhal insignificantly increased. Regarding the relationship $St = fD/U$, the

Strouhal number has a direct correlation with the hydrodynamic diameter. Since at aspect ratios less than one, the Reynolds number is less than the condition where the aspect ratio is equal to one, as is observed at R = 0.6 (with the Reynolds number of 2.5 × 10^4), the effect of the hydrodynamic diameter is greater than the Strouhal number. In R > 1, the Reynolds number is greater than the condition where the aspect ratio is one, such that at R = 6, the Reynolds number is 5 × 10^4; therefore, the effect of the frequency is greater than that of the hydrodynamic diameter. So, when the aspect ratio is greater than one, the Strouhal number depends on the frequency, contrary to the first regime, in which the hydrodynamic diameter is influential.

Previous results have shown that only force fluctuations affect the noise generated [28]. It was also found that the lifting force has a more important role than the drag force. So, the fluctuations of the lift force in different cases are explored. Also, the mean drag has been investigated due to its importance in the destruction of the structure. Therefore, the investigation of C_D and C_L at different aspect ratios is important. C_D and C_L in a rectangular cylinder have fluctuating nature. So, to facilitate the comparison of the results, the values of the drag coefficient are averaged. in different cases of the rectangular cylinder (different R). The average values of the drag and fluctuations lift coefficients at different aspect ratios are shown In Fig. 7. As proved in other studies, these values are generally reduced by increasing the aspect ratio, which is also consistent with the experimental results. According to the results of Nakaguchi *et al.* [12], the drag force has the maximum value (2.88) at R = 0.6. Since the noise variation is proportional to the lift force, it is clearly observed in Fig. 7(b) when the noise is increased, the lift value is also increased. Next, the flow characteristics, including the average and instantaneous values (at the end of the analysis, i.e. 0.65 s) are described. Mean pressure contour diagrams are also discussed.

Fig. 8 illustrates the mean pressure contours for various case studies.

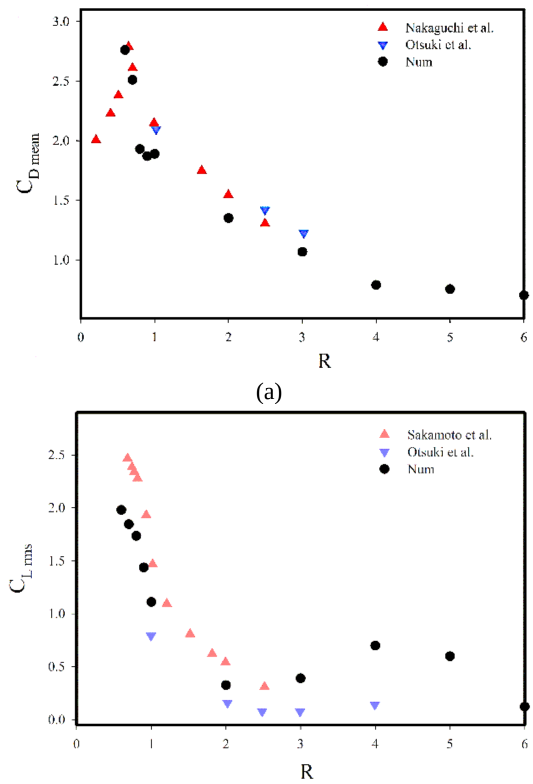


Fig. 7. Variations of aerodynamic characteristics for different aspect ratios (Nakaguchi *et al.* [12], Otsuki *et al.* [28], Sakamoto *et al.* [29]); (a) average values of the drag and (b) root mean square of the lift coefficient.

It is clear that by increasing R, the difference in the upstream and downstream pressure of the cylinder reduced, which decreases the drag force. In fact, increasing the aspect ratio causes large vortices on the surface of the cylinder to occur on both sides of the cylinder, causing the greatest reduction in pressure in these areas. While there is no severe pressure drop in downstream. The result is a reduction in the aerodynamic force entering the cylinder in the direction of flow. There is a good agreement between the results of Fig. 7(a) and the contours of Fig. 8. On the other hand, the symmetrical shape of the cylinder causes the sides of the cylinder not to have a significant pressure difference, so the force on the cylinder in the direction perpendicular to the flow will not be significant.

In Fig. 9, vorticity contours are shown in different cases.

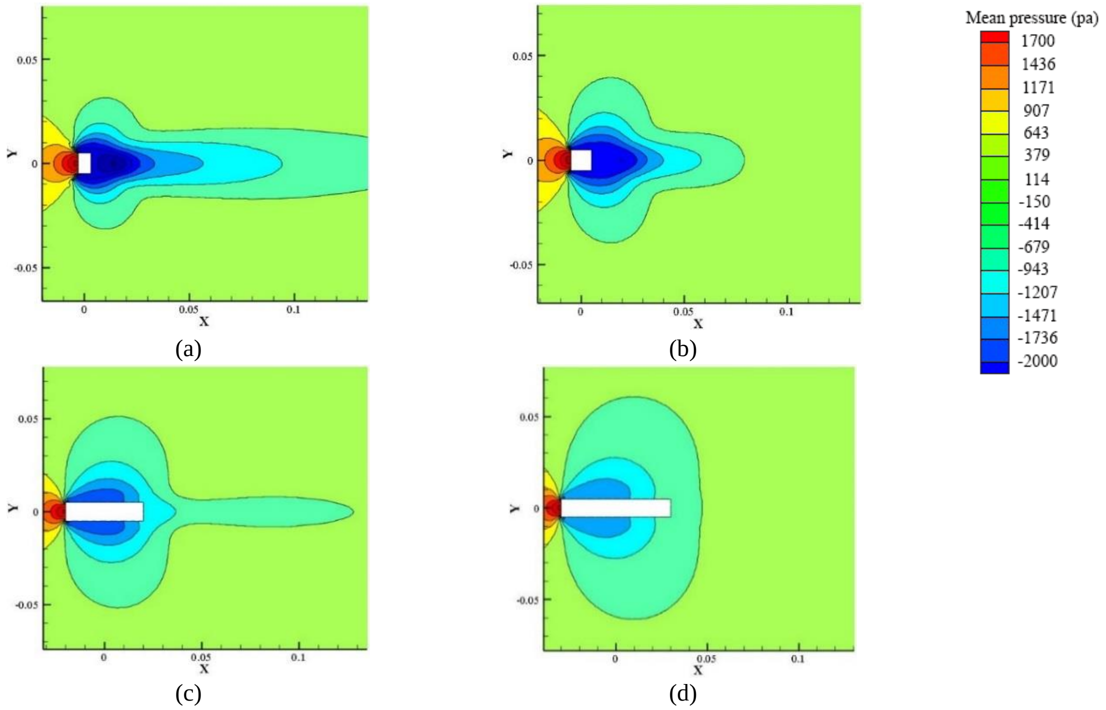


Fig. 8. Mean static pressure contours in different cases of rectangular cylinder; (a) $R = 0.6$, (b) $R = 1$, (c) $R = 4$, and (d) $R = 6$.

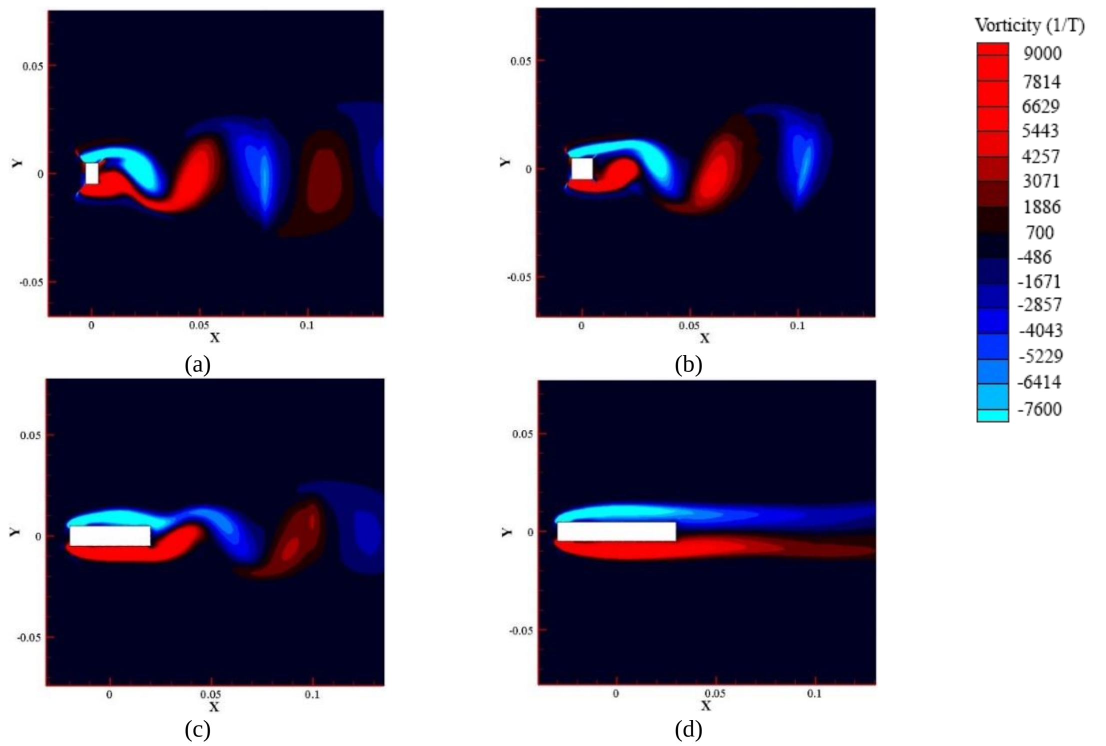
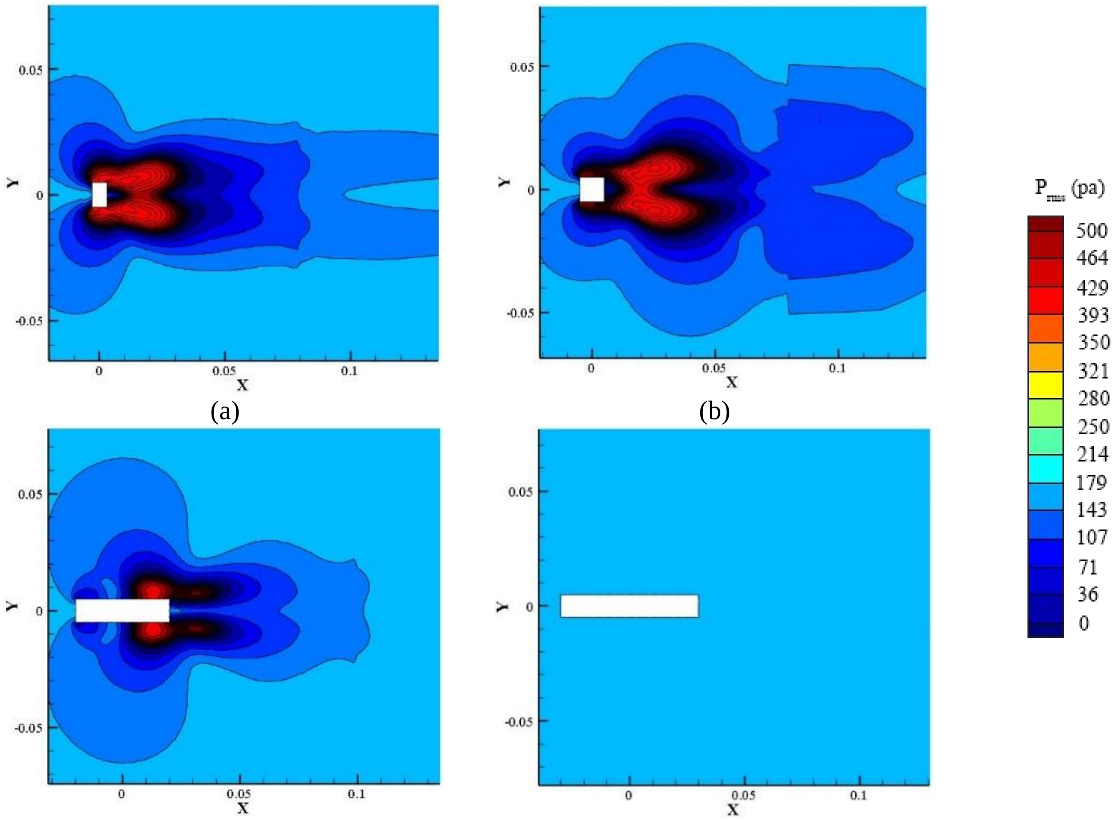


Fig. 9. Instantaneous vorticity (ω_z) contours in the near wake. The red contour indicate that the positive vorticity contours (counter-clockwise) and the blue contour indicate the negative vorticity contours (clockwise); (a) $R = 0.6$, (b) $R = 1$, (c) $R = 4$, and (d) $R = 6$.



(a) (b) (c) (d)

Fig. 10. Contour of root mean square pressure in different aspect ratio; (a) $R = 0.6$, (b) $R = 1$, (c) $R = 4$, and (d) $R = 6$.

Vortex formation affects the pressure around the cylinder. The flow is separated at the front corners of the rectangular cylinder, and the shear layers are directed downstream. For cylinders with larger aspect ratios, shear layers interact with the cylinder. Bearman and Trueman [30] showed that for cylinders with larger aspect ratios, due to the effect of the leading attack of the cylinder, the vorticity is formed more stretched.

The maximum pressure fluctuations occur at the cylinder's top and bottom. Fig. 10 shows the contour of static pressure fluctuations. It is clear that in Fig. 10(a) and Fig. 10(b), the fluctuations are very high under the effect of vortices and fluctuations occurrence. By increasing R, the pressure fluctuations are generally reduced. According to the figure, there are no pressure fluctuations in Fig. 10(d).

4. Conclusions

In this paper, the effect of aspect ratio (R) on the unsteady flow structure and sound due to flow around a rectangular cylinder is investigated numerically. The flow is simulated by the URANS equations and applying the turbulence model k-ω-SST. The aspect ratios from 0.6 to 6 (equivalent to Reynolds numbers from 2.5×10^4 to 5.6×10^4) was studied. B is the cylinder side length and H is the rectangular cylinder height. Two categories of simulations are performed. A comparison of the SPL results extracted in the present study with the experimental results indicates the accuracy of the present research. The study of the unsteady flow structure and aerodynamic noise in cylinders with different aspect ratios indicated the following results:

- In the R < 1 category, by increasing R, the SPL, and the vortex shedding frequency are reduced simultaneously. In the R > 1 category, by increasing the aspect ratio, the noise and the frequency may increase or decrease at various aspect ratios (R). For example, at R = 4, the noise and frequency are maximum in the category, and at R = 4, these characteristics are minimum.

- In the first category (i.e., R < 1), in which Reynolds numbers are less than the reference Reynolds number (i.e., Re < 3.3×10^4), the effect of frequency on the Strouhal number is low and the hydrodynamic diameter has a greater effect on the Strouhal. But in the second category (i.e., R > 1), in which the Reynolds number is greater than the reference Reynolds number (i.e., Re > 3.3×10^4), the frequency effect is greater than the effect of the hydrodynamic diameter on the Strouhal number.
- The results show that in 0.6 < R < 6, with increasing the aspect ratio, the coefficients of aerodynamic forces decrease.
- At a aspect ratio of more than one, the vortices form at the top and bottom of the cylinder and reduce the intensity of separation and vortex shedding.

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