LARGE EDDY SIMULATION STUDY OF A WALL-INDUCED PERTURBATION OF VORTEX SHEDDING FROM A SQUARE CYLINDER

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ABSTRACT

The turbulent flow field around a square cross-section cylinder mounted near a solid wall has been simulated using Large Eddy Simulation. Critical and sub-critical cylinder-to-wall separations are investigated. The three-dimensional nature of the base region flow is well resolved by the multi-block grid system employed. It is shown that for both regimes, the interaction between shear layer and the vorticity generated along the wall in the wake can give rise to periodic wake fluctuations without the traditional vortex formation and shedding process. The results are shown to be consistent with experimental observations. This paper focuses on the vorticity dynamics in the gap and post-gap region along the wall and their role as a "surrogate" generators of vortex shedding. While there is clear quantitative difference between the two cases, namely much higher periodicity in a critical case, the two cases reveal essentially the same shedding mechanisms.

INTRODUCTION

Modification of vortex shedding from a two-dimensional obstacle mounted parallel to solid wall has been the subject of several studies due to its practical importance, for example, to aerodynamic loading or to mixing phenomena. Fundamentally, this flow is a useful diagnostic tool for understanding complex coherent-turbulent interactions (Bosch & Rodi, 1996). When the cylinder-to-wall separation, *S*, is below a critical value, periodic shedding of vortices is suppressed. Traditionally, it has been postulated that the vorticity generated along the wall reduces the circulation of the near-wall shear layer, thereby inhibiting the coupling of opposing shear layers needed for periodic formation. Recent studies for square cylinders indicate, however, that the suppression of periodic vortex shedding may be more related to the reattachment of the shear layer on the bottom face of the cylinder (Bailey et al., 2002). In the critical range, $0.4 < S/D < 0.6$, where D is the cylinder side length, experimental data indicate that vortex formation is perturbed by the reattachment of the shear layer on the cylinder face adjacent to the wall. It thus becomes paramount to understanding the suppression mechanism that the vorticity budget in the very thin shear layers near the bottom face of the cylinder be adequately resolved. Experimentally, the task of resolving the flow in the obstacle/wall gap is extremely difficult. The flow is highly sensitive to intrusive devices, the very thin nature of the shear layer requires high spatial resolution and considerable access limitations are placed on optical velocimetry techniques by this long and confined geometry. The difficulties prompted the current numerical analysis by Large Eddy Simulation. The experimental data indicate that there exists a sub-critical range, $0.3 < S/D < 0.4$, for which periodic wake fluctuations can be observed downstream of the obstacle even though the shedding does not seem to originate in the cylinder base region. This raises further questions about the role of the wall in the vortex formation (or suppression) process. Does it just suppress the coupling between the upper and the lower cylinder edges (and thus prevents shedding locus alteration), or does it serve as an alternate source of vorticity leading to the generation of "surrogate" shedding downstream, which interfere with the base region formation? If the latter is true, as our current analysis suggests, which mechanicsm(s) govern this process?

DETAILS OF IMPLEMENTATION

The experimental setup (Figure 1) and the numerical domain closely match each other. The definitions of coordinate system and key size parameters are shown in the figure. The flow domain details are given in (Matovic &

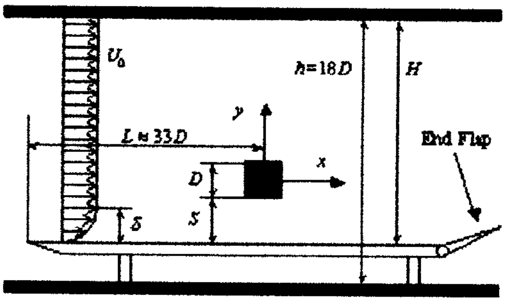


Figure 1: Experimental setup of the flow around the square cylinder test rig.

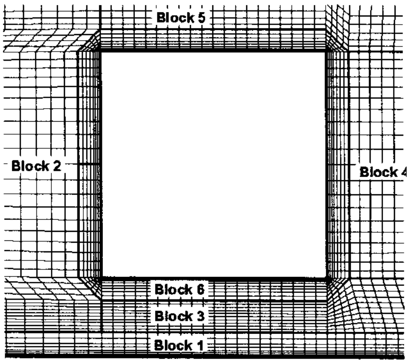


Figure 2: Numerical mesh detail around the square cylinder

Martinuzzi, 2001).

The new study is done with modified grid of much higher resolution in the cylinder and wall boundary layers, and a longer cylinder length (in spanwise direction). The boundary layer around the cylinder is meshed with a "C" grid (Figure 2) with wedge-shaped cells emanating from each cylinder corner, an arrangement naturally providing fine resolution at all four re-entrant corners. Grid dependence tests demonstrated superiority of this arrangement compared with the one used in (Matovic & Martinuzzi, 2001) where the grid was kept orthogonal and the refinement was achieved solely by stretching the cell size.

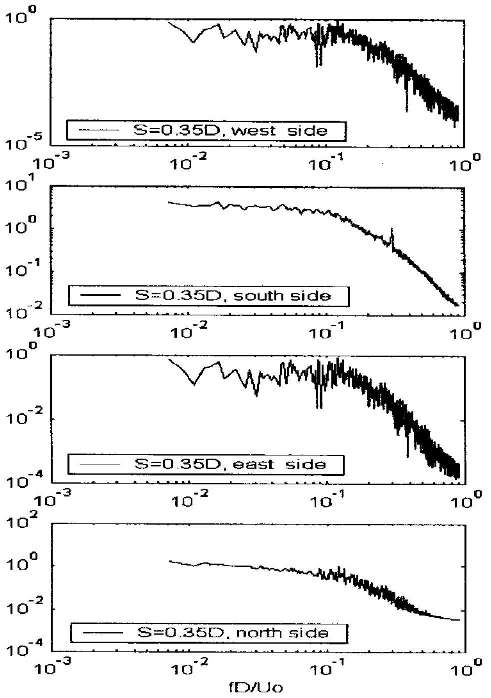


Figure 3: Averaged pressure spectra at four sides of the square cylinder. Gap size is *S/D*=0.35. Each spectrum is an average of spectra at 81 spanwise directions.

The inflow conditions were set to match experimental data (*Re*=19,000, based on *D*, the on-coming turbulent boundary layer thickness of 0.5*D*, measured at the location of the cylinder, but with the obstacle removed). The calculations were performed by a parallel, MPI-based in-house multiblock structured grid code FLEX, running on a 288 processor SunFire engine, using 21 processors. The code is adapted to parallel runs by assigning each block to a separate processor. In current configuration, a seven-by-three block pattern was used, distributing load to 21 processors. Results are presented for three different gap sizes: *S/D* = 0.35, 0.4 and 0.5. In each case, sequences spanning 10 to 20 basic shedding cycles were saved and analyzed, with the typical resolution of 400 saved frames per one shedding cycle. It should be noted that these parameters are approximate, given the variability in the shedding cycles themselves. Numerical results are compared with experimental data of Bailey *et al.* (2002a,b). The available experimental data used for comparison differ slightly in the gap size: the *S/D*=0.33; 0.40 and 0.53.

RESULTS

Three cases, *S/D*=0.35, *S/D*=0.40 and *S/D*=0.50 are examined in detail. The data analysis presented here is focused around two questions: (a) what is the role of the gap size and the presence of the wall in the vortex formation process and (b) how does the gap size affect the spanwise vorticity patterns?

Pressure records

Pressures on the cylinder. To assess the presence

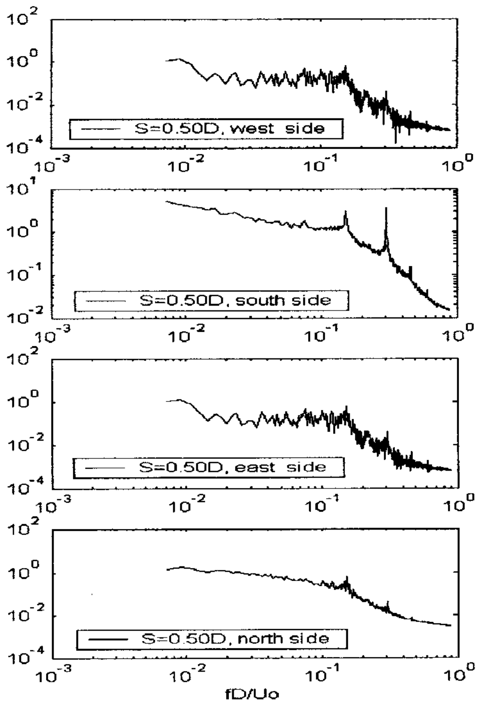
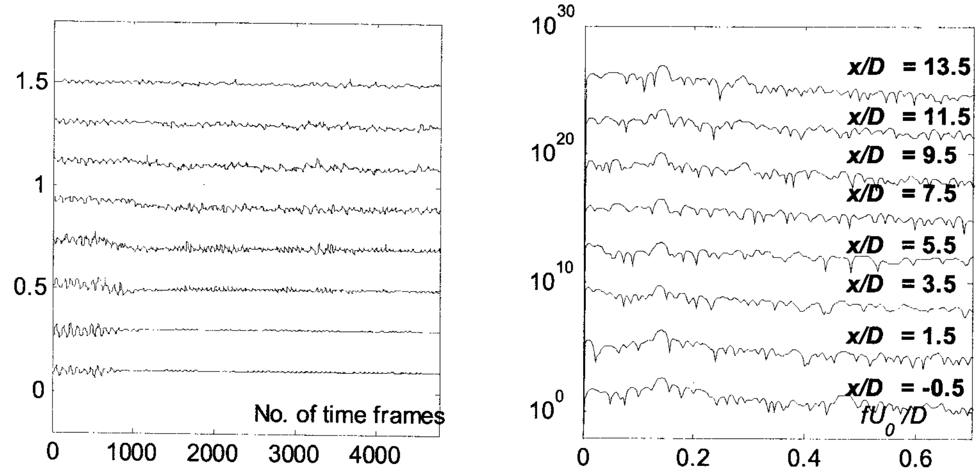
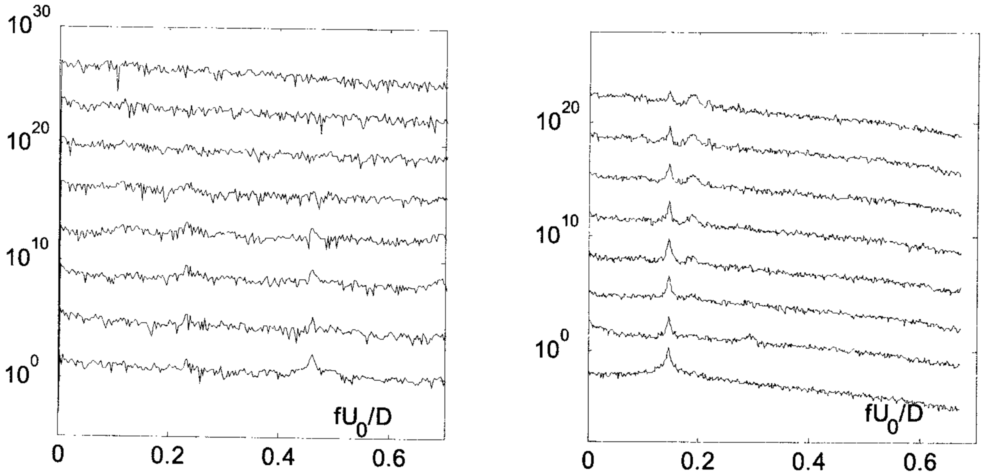


Figure 4: Averaged pressure spectra at four sides of the square cylinder. Gap size is *S/D*=0.50.Each spectrum is an average of spectra at 81 spanwise directions.



(a) LES time series **(b) LES spectra, startup phase**



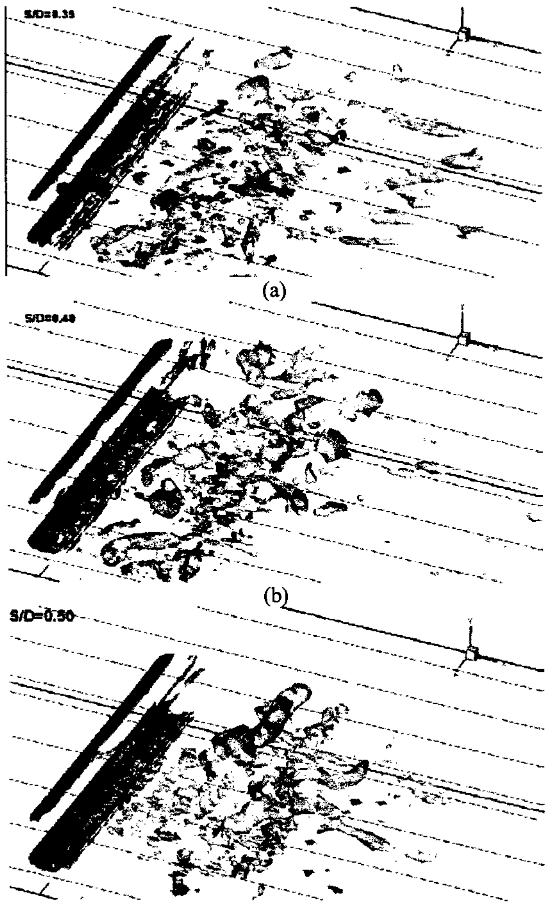
(c) LES spectra, developed phase **(d) Exp. spectra**

Figure 5: Pressure time series and spectra along the plate, for the gap size of *S/D*=0.50 (numerical) vs. *S/D* =0.53 (experimental). Locations of pressure taps are indicated in frame (b) and apply to all four graphs.

of distinct shedding frequencies, power density spectra were produced at the four centres of the cylinder sides. Pressure power spectra for *S/D*=0.35 gap (Figure 3) and *S/*D=0.50 (Figure 4) were constructed for 2200 time steps at each point spanwise (81 points), then averaged along the corresponding line. The four sides of the cylinder, labelled as west, south, east and north represent the frontal side, gap side, wake side and the side opposite to the gap, respectively.

The highest coherence in both cases is evident at the gap (south) side, with a single peak in the S=0.35D case and several harmonics in the S=0.5D case. The strongest peak in both cases corresponds to Strouhal number of 0.288, indicating that there are two shedding events at the gap size for each major shedding cycle. This result confirms the notion that the reattachment at the gap size perturbs the shedding sequence, rather than simply suppressing it (Bailey et al 2002a).

Pressures on the plate (wall). What is the role of the wall in the shedding process? Is it only a geometry constraint which disrupts the skew symmetry of the shedding process itself, or it plays more active role, where some shedding events *originate* at the wall surface, perhaps replacing or supplementing vortex generation at the gap size? The analysis of pressure records from the wall (both experimental and numerical) which we present next is just a first attempt at answering these questions. A series of 8 pressure taps, uniformly distributed between *x/D* = -0.5 and *x/D* = 13.5 in streamwise direction was used to capture pressure records at 400 Hz sampling frequency. The experimental sampling frequency was equivalent to approximately 13 samples per shedding cycle. Pressure records of 1024 points were recorded and used in experimental spectra generation. The numerical data were extracted for the same locations, but the time step used was much finer: about 300 time frames per shedding cycle, with every fifth time step being saved as a time frame. Typically



(a)

(b)

(c)

Figure 6: Snapshots of middle eigenvalue indicating vortex regions of the flow: Gap sizes are (a) 0.35, (b) 0.40 and (c) 0.50. The square cylinder spans between the lower left corner of each frame, aligned with *z* axis.

about 2000 time frames were collected and used for processing.

Pressure records and associated spectra for the *S/D*=0.50 gap size are shown in Figure 5. The pressure time series are recorded from the initial simulation phase (first 900 frames, upwind differencing), followed by the stationary calculations (about 2000 frames, a blend of 90% central differencing and 10% upwind). The pressure fluctuations in the startup phase are of much higher amplitude and exhibit distinct periodicity, especially in the vicinity of the cylinder (*x/D*=-0.5, 1.5 and 3.5). 3D pressure field animations derived from these calculations show a distinct 2D shedding process, which disintegrates into a fully 3D process after the calculation is switched to central differencing. Given the difference between the two phases, the power spectra were obtained for each of them separately (Figure 5b and 5c). Figure 5d shows the experimental spectra at the same locations. There is good matching of Strouhal numbers for the experimental and numerical peaks during the start-up phase spectra, but no such peaks in the developed phase. Instead, there are peaks at the second and fourth harmonic (St=0.23 and 0.45, approximately). The experimental spectra show clear peak at St=0.14, and a developing peak at St=0.18 in the far field. Although it is not clear at this point why does the base shedding frequency disappear from numerical pressure records, it is suspected that the Smagorinsky model, used here, may be overly dissipative. Other models, which allow backscatter in turbulent energy transfer will be employed in future work. The cusp-like shapes of peaks in the numerical spectra are an artefact of zero padding in the spectra and the fact that too few shedding cycles have been captured. Pressure records for the gap sizes of 0.35 and 0.40 exhibit similar trends.

Vortex locations

Various conditional sampling techniques have been suggested in the literature for vortex core identification. More common ones include identification of pressure minima (Hunt *et al*, 1988), closed pathlines (Lugt, 1979), complex eigenvalues of velocity gradient (Chong *et al*, 1990) and as a zone of two negative eigenvalues of $\mathbf{S}^2+\mathbf{\Omega}^2$ (Jeong and Hussain, 1995). We used the last definition, whereby the eigenvalues of the sum of strain and vorticity tensors:

$$\mathbf{S}^2+\mathbf{\Omega}^2 = S_{ik}S_{kj}+\Omega_{ik}\Omega_{kj} \qquad (1.1)$$

are calculated first, then ranked ($\lambda_1 > \lambda_2 > \lambda_3$) and the field of negative middle eigenvalue taken to represent the vortex locations in the flow. Representative snapshots of three-dimensional surface contours of $\lambda_2 = -2$ are shown in Figure 6. While still snapshots are much more difficult to interpret than animated sequences, several features can be distinguished. The two cases with smaller gap (*S/D*=0.35 and 0.40) are similar in showing a large standing vortex on top of the cylinder, and a more slender one at the cylinder bottom, near the leading edge. The "tail" of the bottom vortex is followed by few cascading, spanwise oriented vortices, which provide the seed for a lower shedding vortex stream. Examination of the animation clearly shows that there are unsteady vortices attached to the plate, at about 3-4 diameters downstream. These exist in the first two cases, but are insignificant in the *S/D*=0.5 case, where all the vortices at this downstream location travel at considerable speed. This further corroborates the notion that for small gaps, the wall plays an active role in vortex generation, although the link between this event, 4 diameters downstream, and the core vortex generation within the gap remains unclear.

Streamtraces

Another view of the vortex formation, at least in a single cross section (*z* = const), is provided by the streamline plot of one flow field slice. Snapshots of this kind, also taken from animations, are shown in Figure 7. The dividing streamline originating from the plate, 3-4 diameters downstream the cylinder exists most of the time is cases with smaller gap (*S/D* = 0.35 and 0.40), but is practically always absent in case of *S/D*=0.5. This pattern can be taken as a good indication that the vortices are being generated at the plate, when the gap size is below some critical value (between 0.5 and 0.4).

Additional frames for S/D=0.35 are shown in Figure 8. These show that there exists a complex interaction between the vortices convected from the base region and those forming on the wall at x/D = 3-4. Consider a base vortex along the top shear layer (vorticity of the same sign as that generated at the wall). When this vortex sheds, it can be seen to entrain the vorticity from the wall, resulting in a larger system. From the present results it is not clear

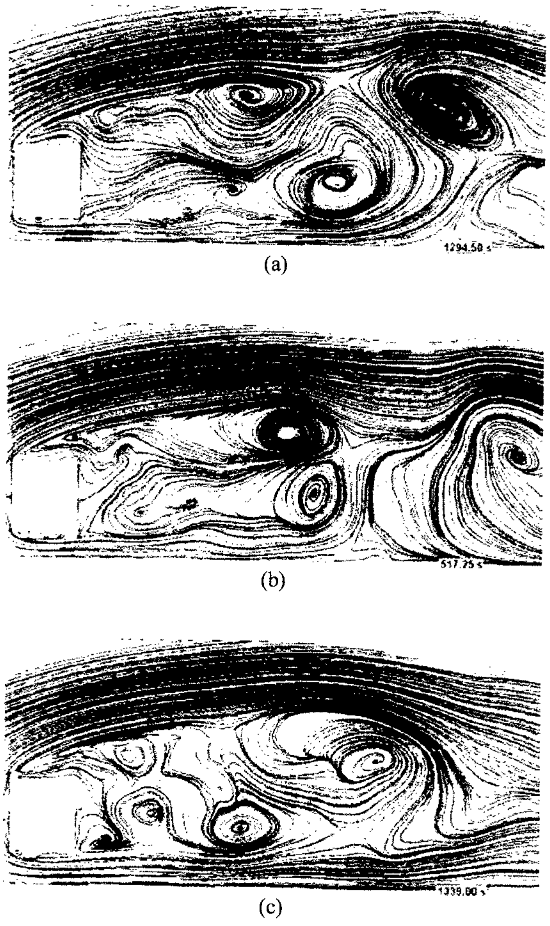


Figure 7: Snapshots of streamline patterns for the constant z plane. Fairly typical snapshots are taken for each case: (a) $S/D = 0.35$; (b) $S/D = 0.40$; (c) $S/D = 0.50$.

whether these vortices merge, in a true physical sense, or undergo a complex pairing, but it is clear that a large circulation can be observed, which is convected downstream. During this process, the opposite sign vortices in the base region are delayed (i.e. do not progress downstream). When this wall structure detaches, the lower vortices shed.

In the extreme case of zero gap (i.e. flow over square bump), the dividing line emanating from the plate would indicate the end of recirculation bubble. However, once the gap exists, the jet stream passing through it is being bent upwards, and can contribute to the rollup process assisted by the vorticity generated around the stagnation point at the wall. Only when the gap becomes large enough, the jet stream carries enough momentum to stay attached to the wall, preventing vortex formation off the wall surface.

The interplay of these opposing forces, further confounded by the formation of span-wise structures calls for further detailed analysis which would include Re number variation, systematic grid dependence studies and the implementation of different LES subgrid models.

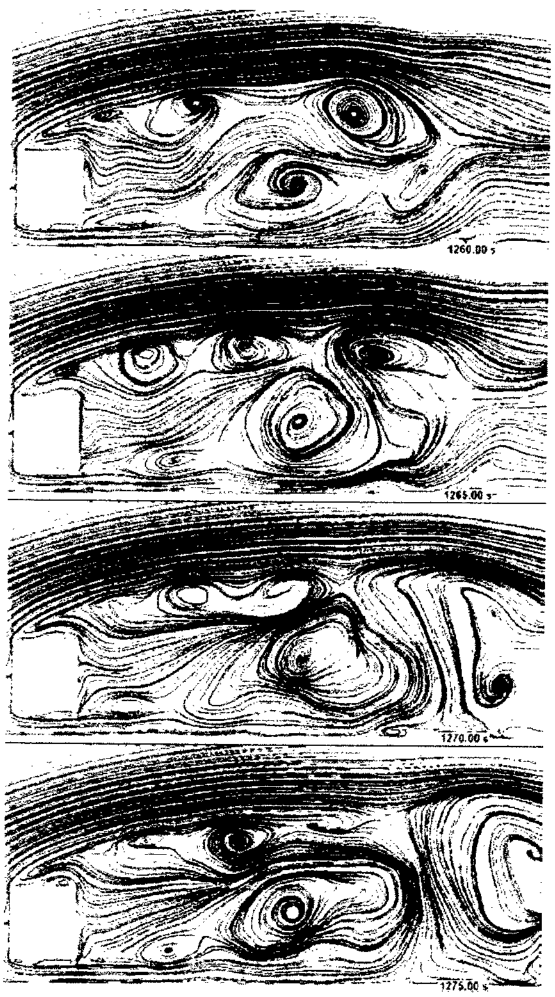


Figure 8: Four streamtrace frames of the S=0.35D case. The frames are 20 time steps appart, covering approximately 20% of a full shedding cycle.

CONCLUSIONS

LES simulation of the flow around the square cylinder were compared with the experimental data for similar Re number. Three cases, with gap sizes of 0.35D, 0.40D and 0.50D were analyzed. High grid resolution and fine time step provide detailed flow picture and are used to examine the role of the wall in the vortex shedding process. Early analysis presented here indicates that the presence of wall actively contributes to the shedding process, particularly for smaller gap sizes. By "actively" we mean that the wall does not represent just a spatial constraint on the flow, but that vorticity generation on the wall interacts with the fluid jet stream passing through the gap and contributes to the shedding process, possibly through the rollup process.

Three-dimensional structure of the vortex core regions, as indicated by the middle eigenvalue of $\mathbf{S}^2+\mathbf{\Omega}^2$, is remarkably changed in a wide gap case (S/D = 0.50) whereby vortex shedding exhibits strong periodicity spanwise, with the characteristic length approximately equal to the gap size, thus creating a string of bead-like vortices. On the other hand, the same analysis reveals the presence of stationary ("sessile") vortex structures emanating from the wall, approximately 4 diameters downstream the cylinder. These structures disappear in the largest gap case, where practically all the vortex structures are being washed off the cylinder trailing edges.

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