# Steady flow past two square cylinders in tandem

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## 1. ABSTRACT

In the present work, two-dimensional, incompressible steady flow around a pair of identical square cylinders in tandem arrangement is studied numerically using stabilized finite-element formulation. Reynolds number (*Re*) is based on free stream speed and cross flow width of the cylinder and is fixed at 40. The spacing ratio denoted in the present work as *S/D* and defined as the ratio of distance between the centers of cylinder to the cross flow dimension of the cylinder is varied from 2-10 in steps of 2. With increase in *S/D*, the wake interaction between both the cylinders weakens and both cylinders forms separate wakes for *S/D* ≥ 6. Three distinct flow patterns are identified in the given range of *S/D*. Interestingly, for *S/D* = 6, a weak recirculation zone other than the closed wake of the upstream cylinder appears near the downstream cylinder in the gap region. This recirculation zone disappears with further increase in *S/D* and both cylinders act as an isolated cylinder.

## 2. INTRODUCTION

Flow past a bluff cylinders had been an area of deep interest for many researchers in the past due to its vast industrial applications. A detailed review for the same can be found in Zadravkovich (1977), Sumner (2010) and many more. The presence of one or more such obstacles in the vicinity of the other makes the analysis even more complex. Two or more than two cylinders can be arranged in three possible arrangements, namely tandem, side-by-side and staggered (Zadravkovich, 1977). Some insights about flow past two square cylinders at low *Re* can be found in Lankadasu and Vengadesan (2008), Patil et al. (2008) and Sohankar (2011). The present study focuses on the flow past a pair of identical square cylinders arranged in tandem at five distinct *S/D* ranging between 2 ≤*S/D*≤ 10. The work aims at understanding the fluctuations in flow variables as a function of *S/D*. The schematic of the problem definition along with the boundary conditions is shown in Figure 1. The inlet and exit of the domain is provided with free stream and stress free boundary conditions, respectively. Cylinder surfaces are no-slip surfaces. Both the lateral walls free-slip walls.

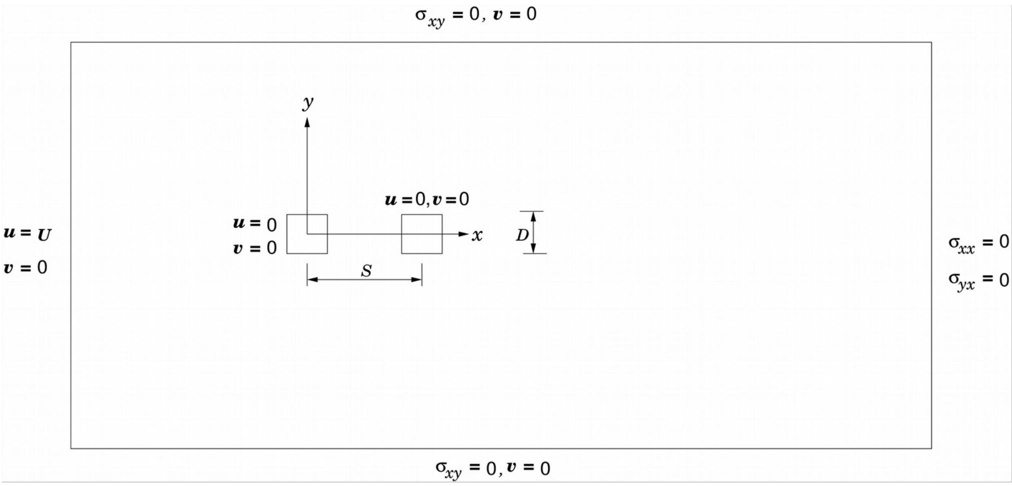


**Figure 1: Problem definition for steady flow past a pair of identical square cylinder in tandem arrangement.**

## 2. METHODOLOGY

A non-uniform, multi-block, structured, collocated finite-element mesh with approximately 94000 nodes and 93000 bilinear quadrilateral elements is used to discretize the domain of interest. Steady incompressible Navier-Stokes equations along with Continuity equation is discretized using stabilized finite-element formation. The discretized algebraic equations are solved using a matrix-free **G**eneralized **M**inimal **Res**idual (**GMRES**) solver. The mesh convergence and validation has been performed and was found to be in aggrement.

## 3. RESULTS

Results in terms of streamlines, vorticity and eddy length are presented for spacing ratio varying between 2 and 10. To understand the sole effect of spacing ratio, *Re* is kept fixed at 40.

***The Flow***

Flow patterns in terms of streamline contours for spacing ratio range considered is shown in Figure 2. As apparent from Figures 2a and 2b, For low spacing ratios (*S/D* = 2 and 4), wake of the upstream cylinder reattaches on the downstream cylinder. For these cases, classical close wake structure is observed only behind downstream cylinder. *S/D* = 6 (Figure 2c) is found to be a critical spacing ratio where the reattachment of separated shear layers on the rear cylinder ceases and the classical close wake appears for the first time behind both the cylinders. Here it is interesting to note that a pair of weak antisymmetric rotating eddies are also generated near the forward stagnation point of the downstream cylinder. With further increase in the magnitude of the spacing ratio, both cylinders behave like two distinct isolated (negligible effect of the presence of other bluff object) cylinder. Thus, three distinct flow regimes are identified namely precritical (S/D < 6), critical (*S/D* = 6) and postcritical (S/D > 6).

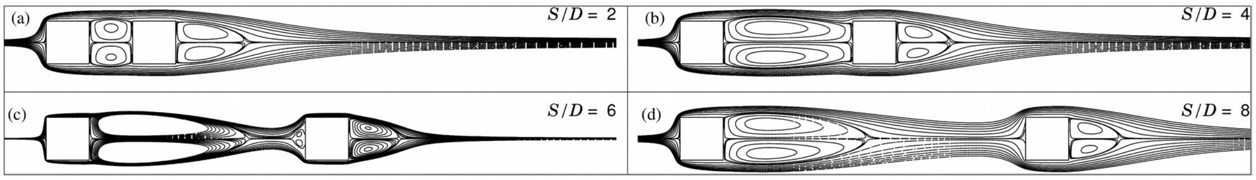


**Figure 2. Flow past a pair of square cylinders in tandem at *Re* = 40 : streamline plots for *S/D* = (a) 2, (b) 4, (c) 6 and (d) 8.**

The effect of spacing ratio on the flow structure is presented via variation of wake length in Figure 3a. While the the upstream cylinder shows a monotonic decrease in the wake length after its evolution at *S/D* = 6, the wake length of the downstream cylinder initially decreases up to *S/D* = 6 and then increases gradually. Figure 3b presents the distribution of surface vorticity on the downstream cylinder. The intersection of vorticity curve with zero line represents either the separation or reattachment points. It is worth noting that for *S/D* = 2 through 6, when the wake of the upstream cylinder has interaction with its downstream counterpart, the reattachment point is not fixed and it gradually move towards forward stagnation point (on the leading edge).

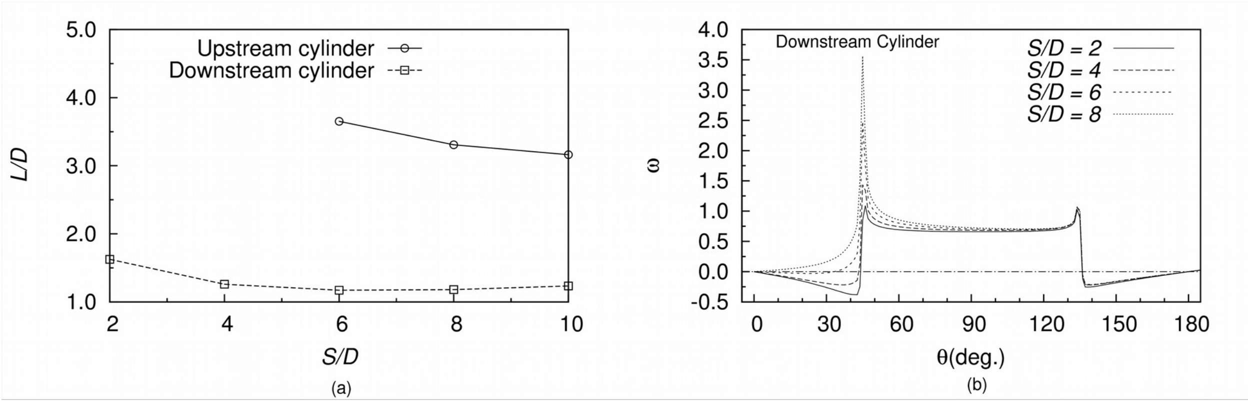


**Figure 3. Flow past a pair of square cylinders in tandem at *Re* = 40 : (a) variation of wake length of upstream and downstream cylinders and (b) surface vorticity distribution around the downstream cylinder as a function of *S/D*.**

## 4. SUMMARY

Flow past a pair of square cylinder in tandem arrangement is investigated numerically for a fixed *Re* of 40 and *S/D* ranging between 2 and 10. Based on the flow patterns observed, three distinct flow regimes are identified namely, precritical, critical and postcritical regimes. In precritical regime (*S/D* = 2-4), the separated shear layers from first cylinder reattaches on the rear cylinder. A closed steady wake behind the downstream cylinder is observed for all condition considered. At a critical spacing ratio (*S/D* = 6) reattachment ceases and a classical closed wake appear for the first time behind the upstream cylinder. In the critical regime, a recirculation zone near the forward stagnation point is also created. As *S/D* increases from 2 to 6 the reattachment point on the downstream cylinder shifts from the corners on the leading edge towards the forward stagnation point. In the postcritical regime, the interaction between the cylinders weakens and they tend to behave as isolated cylinders. While the wake length (measured from the base to the wake stagnation point) of the upstream cylinder decrease monotonically, the wake length of the rear cylinder decreases first up to critical *S/D* and then again starts increasing slowly.

## REFERENCES


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