Abstract: Fluid–structure interaction has been widely studied in the last few decades due to its wide range of applications in engineering fields. This phenomenon plays an important design role, for example, in offshore risers, high slender buildings, chimney stacks and heat exchangers. The vortex shedding generated from a bluff body can induce high-amplitude oscillations, known as vortex-induced vibrations (VIVs). This study presents a numerical analysis to investigate the impact of surface roughness on VIV in the crossflow direction of a circular cylinder. The study also investigates the impact of surface roughness with variation in mass ratio from 2.4 to 11 at a high Reynolds number \((Re) = 10^4\) using Reynolds-averaged Navier–Stokes (RANS) equations. The study concludes that roughness on a cylinder results in a reduction in amplitude response. Furthermore, the lock-in region is narrower compared to that of a smooth cylinder, irrespective of the mass ratio. However, it is observed that the impact of surface roughness is more significant in high-mass-ratio cylinders where the lock-in region is more squeezed and shifted toward lower reduced velocities. Furthermore, the vortex mode beyond reduced velocities \(Ur = 5.84\) and 7.52 was observed to be 2S for high and low mass ratios, respectively.

Keywords: CFD; vortex-induced vibration; mass ratio; circular cylinder; surface roughness; flow
experimentally investigated the VIV phenomenon on a short rigid cylinder and analyzed the dynamic responses at different surface roughness. The experimental study was performed in the range of 1 m/s to 8 m/s of wind speed in which recording and processing of amplitude response were performed using an accelerometer and LMS Test Xpress software, respectively. The study found that the higher surface roughness resulted in higher amplitude response reductions. Ghazali et al. [2] performed an experimental study in the subcritical range with roughness coefficients varying from Ks = 0.00019 D to 0.0051 D. They observed an increase in frequency vibration with an increase in surface roughness. Gao et al. [3] investigated the impact of the plan wall on the VIV phenomenon at Re = 5000. The results showed that the VIV trajectory of the cylinder is not significantly affected by variation in surface roughness. A cylinder with an initial small gap displayed a coalescing effect with the formation of the weak 2S vortex mode, while there was no coalescing effect for a cylinder with a large initial gap.

The analysis of Okajima et al. [4] covered the subcritical Reynolds number region, and the authors found that a coarse cylinder responds with a shorter amplitude than a polished one. Allen and Henning [5] carried out an experimental study at critical and subcritical regimes to investigate the impact of roughness. A low drag with no oscillation was found in the study. Bernitasas et al. [6] experimentally analyzed the VIV in the range of $8 \times 10^3 < Re < 2.0 \times 10^5$ with rough bands. The study showed that a cylinder’s proximity to a fluid’s flow behavior is highly sensitive to the roughness grit size and width and where the coarse ridges are located. The study showed that abrasion dispersion and scope can be utilized to control or maneuver the VIV response and the span of the lock-in region. Kiu et al. [7], in an experimental study in the range of $1.7 \times 10^4$ to $8.3 \times 10^4$, observed a decrease in oscillation and drag coefficient with an increase in roughness on the cylinder surface. It was also observed that a rough cylinder has greater Strouhal value compared to a smooth cylinder. Gao et al. [8] designed a physical experiment method in which the effect of face unevenness on a riser’s VIV response was studied utilizing a physical study approach; the dislocation responses, friction, aerodynamic forces, tension, vortex-induced frequency and vibration frequency of the risers with various face roughnesses were compared. The VIV amplitude response is higher for the streamwise direction compared to the transverse direction at the low decreased velocities because the VIV lock-in phenomena happen earlier in the streamwise orientation than the transverse orientation. In comparison to the smooth riser, the coarse riser had a lesser VIV amplitude reaction, a greater vortex shedding frequency and a narrower “lock-in” zone.

Armin et al. [9] performed numerical studies to investigate the VIV phenomenon in multiple cylinders by developing a mathematical model. The study was validated with experimental results. The study also addressed the impact of the wake of the upstream cylinder on the downstream cylinder. The mathematical model developed in the study was capable of forecasting the lock-in regime and maximum oscillation in both leading and trailing cylinders. Liqun et al. [10] studied the mechanism by which harbor seals detect fish. The authors utilized the DNS for the VIV phenomenon on harbor seals. The study also compared the results with different shapes of the same characteristic length. The study evidenced low drag and reduced oscillation using the whisker model. Wang et al. [11] experimentally investigated the VIV phenomenon under influence of stretching in vertical risers. Badhurshah et al. [12] used the immersed boundary method to analyze the VIV phenomenon of a circular cylinder. Simulations were carried out with linear and bistable springs. The study evidenced a higher lock-in regime using bistable springs. Lin et al. [13] investigated the flow characteristics of tandem arranged cylinders (apart by 5 cm). The upstream cylinder was kept fixed whereas the downstream cylinder was made flexible. The study evidenced the strong impact of added mass correlation with the mode of vortex shedding in case of a single cylinder.

Tofa et al. [14] performed an experimental study on two identical cylinders in the subcritical range. They discussed the correlation of phase difference with cylinders. Smaller oscillations were observed at lower phase differences. Ming Zhao and Liang Cheng [15]
numerically analyzed the impact of the free end on the vortex-induced vibration (VIV) of a rigid circular cylinder at Re = 300. It was observed that if a fixed cylinder’s length is less than two cylinder diameters, vortex shedding is suppressed in the wake region. In another study, Zhao et al. [16] numerically analyzed the VIV behavior with multiple cylinders at Re = 150. The study showed the maximum and minimum amplitude at space ratios of 1.5 and 2.0, respectively. It is also found that minimum impact on the lock-in regime is observed when the space ratio is equal to or greater than 2.5, in the case of connected cylinders. Soti et al. [17] studied the VIV phenomenon at Re = 100 and 150 with a high mass ratio with variation in channel height. Oscillation amplitude is decreased with a decrease in the channel height. The study also showed that the initial branch almost disappears when channel height increased up to 2 D, where D is the diameter of the cylinder. In addition, with an increase in damping, the extracted energy is decreased, irrespective of the channel height. Han et al. [18] modified the law of wall to study the impact of surface roughness on the VIV phenomenon. Chen et al. [19] numerically analyzed the VIV phenomenon using DNS near a stationary wall with Re = 500. They observed significant variation in cylinder displacement due to vortex interaction with the proximity wall.

The study of Liu et al. [20] is related to the impact of mass ratio on the VIV phenomenon at a smaller Reynold number. The numerical results demonstrate that the mass ratio significantly affects the fluid force and vibration amplitude, particularly in the lock-in region with a mass ratio of less than 1.0. It is observed from the literature that most of the available analyses are carried out at smaller Reynold numbers (less than 5000) to investigate the impact of surface roughness, and limited research is available on high Reynold numbers.

The main objective of this article is to analyze the impact of surface roughness on the VIV phenomenon with mass ratio = 2.4 and 11 at Re = 10$^4$. For each mass ratio, six different reduced velocities in the range of 2 to 14 were used for this numerical study, and the results are compared with a smooth cylinder.

2. Domain Specifications

Since the flow domain size significantly affects the flow behavior, it is important to choose the domain size such that disturbance due to the boundary wall is avoided. As reviewed in the literature [21], various researchers used the domain size of up to 45 D (inflow direction) $\times$ 16 D (crossflow size): however, it has been concluded by Zdravkovich [22] and Zhao ([15,16,23]) that to avoid disturbance due to wall boundary, the blockage ratio of 5% should be ensured in numerical analysis.

In this study, the domain size of 45 D $\times$ 20 D is used, fulfilling the criteria mentioned in the literature (Figure 1). As depicted in Figure 1, the inlet is kept at a distance of 15 D and the top and bottom walls are kept at a distance of 10 D from the center of the cylinder. To achieve the Reynolds number $= 10^4$, the uniform velocity of 0.3149 m/s at inlet, a cylinder with a diameter equal to unity and a fluid with $\rho = 10^3$ kg/m$^3$ and $\nu = 0.03149$ kg/m$^{-8}$ are used. The results obtained in the current study are compared with the available results of a smooth cylinder having the same parameters except for the roughness. The smooth cylinder results are taken from the experimental study by Hover [21] and numerical studies by Nguyen [24] and Usman et al. [25].

For numerical stability, the working domain is split into two parts. The region immediately surrounding the cylinder is meshed using structured quadrilateral elements, while the remainder is meshed using triangular elements. The mesh is constructed such that the area next to the cylinder’s wall has a very fine mesh, while the area farther out from the cylinder has a coarse mesh. Figure 2a,b represent the mesh and mesh close-up view near the cylinder. The dimensionless distance first layer cell height, known as the y+ value, should be less than or equal to unity in accurately solving the flow.
To make sure the $y+$ is at unity (for the smooth case), the first cell layer height is placed at $1.4 \times 10^{-3} \text{D}$ from the cylinder surface, where $D$ is the diameter of the cylinder. A homogeneous pressure of 0 Pa is provided at the discharge boundary. The top and bottom walls of the flow field are both subject to a symmetrical boundary requirement. A no-slip condition is imposed on the cylinder surface which will ensure the capturing of the characteristic of boundary layer separation and vortex generating behavior. In order to capture the motion of the cylinder, a dynamic mesh is used with boundary motion. A UDF is utilized to extract the forces associated with the cylinder due to vortex shedding in each iteration. A diffusion-based dynamic smoothing method is used. Better mesh is produced through diffusion, which also enables high-amplitude cylinder oscillations without any restrictions on motion direction.

The VIV phenomenon for a rough cylinder is studied at two different mass ratios ($m^* = 2.4$ and 11). For this study, the roughness height ($K_s$) 0.02 D is used. Figure 3 [26] shows the schematic diagram of the equivalent sand model. To incorporate this roughness height, the size of the roughness element should be less than the centroid of the first mesh node as shown in Figure 4. To incorporate this roughness height, the first layer for mesh is changed from 0.0014 to 0.006.
3. Results and Discussion

The case studies are performed for rough cylinders with a roughness height (Ks) of 0.02 D, where D is the diameter of the cylinder, having mass ratios of 2.4 and 11. In all the cases, Re = 10,000 has been maintained with an inlet velocity of 0.3149 m/s. The simulations are performed within the span of reduced velocity of \(2 \leq U_r \leq 14\). Figure 5 shows amplitude response in the crossflow direction at various reduced velocities for mass ratios 2.4 and 2.11 with and without surface roughness.

![Figure 5. Comparison of amplitude responses for a smooth cylinder and a rough cylinder (i.e., Ks/D = 2 \times 10^{-2}) with m* = 2.4 and 11.](image)

With a surface roughness height of 0.02 D and a reduced velocity of 2.5, the amplitude response \((A_y/D)\) of the cylinder was found to be \(A_y/D = 0.08\) and 0.0065 for mass ratios of 2.4 and 2.11, respectively (Figure 5) which is relatively small in comparison to that of the smooth cylinder (where amplitude captured was 0.23 and 0.045 for mass ratios 2.4 and 2.11, respectively [25]). Figure 6 represents vortex mode at higher and lower mass ratio at different reduced velocities. Drag forces and lift forces acting on the cylinder were also observed to be small at the higher mass ratio (Figure 7).
Vortex mode at Ur = 3.78

Vortex mode at Ur = 5.84

Vortex mode at Ur = 7.52

Vortex mode at Ur = 8.77

(a) mass ratio m* = 2.4
(b) mass ratio m* = 11

Figure 6. Vortex mode at different reduced velocities with roughness Ks = 0.02 D: (a) m* = 2.4 and (b) m* = 11.

As the reduced velocity was increased to 3.78, a significant increase in amplitude response (Ay/D = 0.65 and 0.53 for mass ratios 2.4 and 11, respectively) was measured, which is almost the same as that in the case of the smooth cylinder at m* = 2.4; however, roughness at the higher mass ratio result in a significant reduction in amplitude. The 2P vortex mode was observed at both low and high mass ratios (cylinder with roughness) in the wake region (Figure 6) which is completely different from the vortex mode observed in smooth cylinder case, i.e., P + S and 2S modes at lower and higher mass ratios [25]). A lower cd and a higher cl response were observed in comparison to a smooth cylinder at the lower mass ratio. At Ur = 5.84, amplitude responses Ay/D = 0.51 and 0.015 are recorded for lower and higher mass ratios, respectively; the amplitude response is relatively lower in the case of the lower mass ratio when compared with the smooth cylinder, whereas at the higher mass ratio, the roughness almost suppressed the oscillation. The 2T and 2S vortex modes were recorded in the wake region for lower and higher mass ratios, respectively, whereas the 2P vortex mode was observed in the case of the smooth cylinder [25]. The 2P mode is observed for the smooth case at lower and higher mass ratios.
Figure 7. Cont.
The study was performed to investigate the impact of surface roughness (i.e., $K_s/D = 2 \times 10^{-2}$) on vortex shape, crossflow amplitude and lock-in region with lower ($m^* = 2.4$) and higher ($m^* = 11$) mass ratios. The results obtained from this study were compared with those for a smooth cylinder available in the literature. All the parameters in both cases were kept the same. It is concluded that roughness on a cylinder surface has a significant impact on the high mass ratio problem compared to the low mass ratio. The crossflow oscillation is significantly reduced due to surface roughness at both lower and higher mass ratios. However, higher mass ratio and lower mass ratio oscillations are almost completely suppressed (more than 90% with roughness) beyond reduced velocities of 5.84 and 8, respectively. At the higher mass ratio, drag forces were found to be high in the lock-in region and low outside of the lock-in region. It was found that surface roughness narrowed the lock-in region more in case of the higher mass ratio compared to the lower mass ratio. In addition, an overall decreasing trend in the cylinder amplitude response is recorded. Furthermore, the lock-in region is shifted toward the lower reduced velocities due to roughness in the higher mass ratio problem. Regarding force coefficients, it is observed that roughness reduced the drag coefficient significantly in case of the low mass ratio. In addition, the vortex mode is changed to 2S at all reduced velocities beyond $Ur = 3.78$ in higher mass ratio problems, whereas the same behavior is found in lower mass ratio problems beyond the reduced velocity of 7.5. Overall, it is concluded that higher mass ratio cases are significantly affected due to surface roughness.

4. Conclusions

At $Ur = 7.52$, the amplitude response computed is $Ay/D = 0.021$ and 0.0092 for $m^* = 2.4$ and 11, respectively, which is very small in comparison to the smooth case [25]. At reduced velocity $Ur = 8.77$, the amplitude response reduced significantly to $Ay/D = 0.015$ and 0.0074 for lower and higher mass ratios, respectively. The 2S vortex mode was observed at $Ur = 7.52$ and $Ur = 8.77$ for both lower and higher mass ratios with roughness, whereas in the smooth cylinder case, 2P and 2S modes at $Ur = 7.5$ and 2T and 2S modes at $Ur = 8.77$ are observed at lower and higher mass ratios, respectively. At $Ur = 11$, the amplitude response of $Ay/D = 0.013$ and 0.0064 for $m^* = 2.4$ and 11, respectively, is computed, which is very small compared to the smooth cylinder case.

**Figure 7.** Force coefficients $C_d$ (Red) and $C_l$ (Blue) at different reduced velocities with surface roughness $K_s = 0.02 D$: (a) mass ratio $m^* = 2.4$ and (b) mass ratio $m^* = 11$. 

(a) Mass ratio $m^* = 2.4$  
(b) Mass ratio $m^* = 11$

Funding: The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through a large group project under grant number RGP.2/83/43.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that supports the findings of this study are available within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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