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Research Article

Flow-Induced Vibration on the Control Valve with a Different Concave Plug Shape Using FSI Simulation

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Control valves have always been recognised as being among the most crucial control equipment, commonly utilised in versatile engineering applications. Hence, the need has arisen to identify the flow characteristics inside the valve, together with the incurred vibration induced as a result of the flow passing through the valve. Thanks to the tangible and fast progress made in the field of the flow simulation and numerical techniques, it has become possible to better observe the behavior of the flow passing inside a valve with view to examining its performance. Hence, the paper at hand is mainly concerned with introducing the modeling and simulation of a control valve. On the contrary, the flow system in a control valve is marked by a complex structure and nonlinear characteristics. The reasons for those qualities could be attributed to its construction as well as the fluid flow phenomena associated with it. It is especially for the sake of investigating and observing the flow characteristics, pertaining to a control valve equipped with different concave plug shapes and different openings, that the three-dimensional FSI simulation is conducted. In addition, it would be possible to make use of the obtained results relating to the three-dimensional analysis to achieve low noise and high efficiency improvement. Furthermore, all results will be validated on experimental grounds.

1. Introduction

Control valves are intrinsic components that are integrated in several manufacturing operations and industrial processes. The function of such valves is to open and close so that they could connect or suspend a fluid supply in addition to manipulating the feeding of liquids and gases in a certain process. One of the fields that benefit from such valves is the steam feeding assigned the task of heating a vulcanizing press or for plastic injection. Moreover, the design and structure of the control valves are known to have versatile shapes and various materials, corresponding to the liquid, steam, or gas utilised in several factories.

Analysis of flow passing through the control valve is of great importance in engineering practice because transient flow could have very negative consequences that could in certain cases ultimately lead to the failure of the system. The vibration causing this failure is generated from the force acting on the plug. The fluid characteristic behavior changes according to the plug geometry. Thus, reducing the vibration acting on the system could be attained via limiting the force working on the plug. So the problem now is choosing the best geometry which generates the minimum force when the fluid is passing through the control valve.

The regulation characteristic of the control valve and the valve authority are the two basic parameters determining the shape of the final regulation curve and the quality of the control process in the pipework. The regulated device may be, for example, a heating system radiator, a steam turbine, a combustion engine, or any other element whose working effect, such as thermal power and rotational speed, can be adjusted quantitatively by changing the fluid flow rate. The relationship between the response of the controlled element and the input function, in the steady state, is usually referred to as the static (regulation) characteristic. Such relationships are generally nonlinear. For example, a twofold growth in the medium mass flow does not double the device power output. For convection radiators, which are commonly used in heating systems, this relationship is approximately logarithmic. This is described in detail in [1–3].

The so-called valve authority has been acknowledged as one of the chief parameters determining the value adjustment. Thus, the work at hand is mainly concerned with introducing the relations that would help calculate the value relating to the value authority, as well as determine its impact as far as the valve regulation characteristic curves are concerned [4].

Furthermore, the control valve inner authority is known to be one of the two main parameters determining the regulation characteristics pertaining to the control valve. It also helps, together with the external authority, identify the shape regarding the final regulation characteristics, when working in the pipework. Besides, the shape of the initial characteristics of the regulation element of the valve is considered as the other parameter helping to understand the regulation characteristics regarding the control valve. Hence, the final shape of the control characteristic of the valve could be formed by selecting an appropriate characteristic of the valve regulation element, by means of shaping the element (the plug) geometry [5].

In order that the optimum force incurring the minimum vibration could be obtained, a use has been made of fluid structure interaction simulation, so as to analyse the vibration induced on the fluid passing through the control valve with different concave plug shape. Fluid-structure interaction (FSI) is regarded as a multiphysics phenomenon, featured in a system where the flow of a fluid would lead a solid structure to deform. That deformation would, in turn, incur changes regarding the boundary condition of a fluid system. This can also occur the other way round, where the fluid flow properties would be liable to changes incurred as a consequence of variations and deformations showing signs in the structure.

Many researchers have studied the characteristics of the fluid passing through the control valve [6–8]. Furthermore, many of the research studies, used as reference sources, support and background for this work. Many papers and books have been consulted, but most of them are briefly mentioned and some of them are discussed along the work. Amirante et al. [9] worked on investigating the fluid forces working on an open center directional control valve. The study has basically aimed at evaluating the driving forces acting on three-fourths of hydraulic center directional control valve via computational fluid dynamic analysis (CFD model). The study has also extended to embrace a complete numerical analysis regarding the flow forces working on the spool of an open center ON-OFF hydraulic directional control valve. The analysis was realized at different flow rate values. The results put in evidence that the maximum flow force occurred when the recirculation flow rate vanished, while in the first opening phase, the flow forces acted in the opening direction. The peak value of the flow force increased the pumping flow rate, but its position remained fixed. The study has culminated in providing some of the very crucial indications, in as far as the values of the efflux angle and the distribution of the flow rate inside the valve are concerned. Davis and Stewart [10] studied globe control valve performance using computational fluid dynamic analysis modeling (CFD model). The researchers could qualitatively predict the inherent valve characteristics relating to globe-style control valve by means of devising a simplified axissymmetric numerical model. The model could as well help quantitatively assume the value of Cv over a large range of percentage openings. After the plug retracted beyond the plane of the seat, the accuracy in predicting the Cv decreased significantly, but this occurred only at the highest values of percentage openings. Pountney et al. [11] studied the of turbulent flow characteristics of servo-valve orifices using a numerical scheme based on the k-εturbulences model. The study has made it clear that a successful application of the numerical analysis of flow through a servo-valve could be attained for a simplified orifice model. Also, the research has offered numerical results relating to a range of spool gap areas for the sake of portraying the flow characteristics besides comparing them to laminar and turbulent flows. The valve geometry was seen to affect the jet angle and in turn increased jet angle minimized spool forces. He stated that an important valve design consideration is the cavitation prevention. Bernad et al. [12] studied vorticity dynamic in hydraulic power equipment. They used computational fluid dynamic (CFD) analysis. The researchers have also considered a poppet valve geometry that was typical and assumed an axisymmetric computational domain, with pressure inlet/outlet boundary conditions. Furthermore, the steady flow solution has been computed. Yet, the study has not involved some important issues such as the 3D effects and the potential flow unsteadiness. That additional small swirling component might be the onset of axial symmetry breaking, leading to poppet oscillations.

2. Model Description

A three-dimensional geometry of a single-seated control valve, with a different concave plug shape, was created using Rhino 2012 software package. Moreover, the geometry was extended to include parts of both upstream and downstream pipes until reaching the position of installation of both upstream and downstream pressure transducers. An internal view for the configuration of the valve to be investigated is shown in Figure 1.

(1) Flat face plug: in this case, a plug is used with flat face as shown in Figure 2; the plug opening changed from 5% to 40%

(2) Plug with concave shape no. 1: in this case study, the plug with concave shape, as shown in Figure 3, is described in the following equation:

$$y = 0.0067x^2 - 0.0066x + 0.026. \quad (1)$$

(3) Plug with parabolic shape no. 2: in this proposed system, the plug with concave shape as shown in Figure 4 is described in the following equation:

$$y = 0.0053x^2 - 0.0065x + 0.033. \quad (2)$$

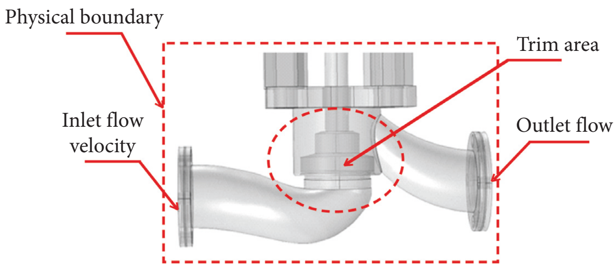


Figure 1: An internal view for the valve configuration.

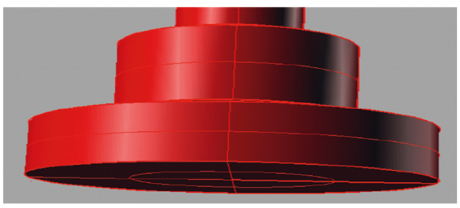


Figure 2: Flat face plug.

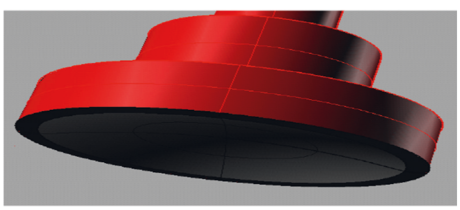


Figure 3: Plug with concave shape no 1.

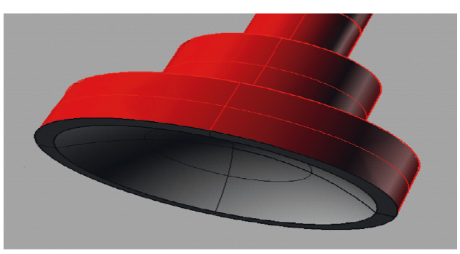


Figure 4: Plug with concave shape no 2.

3. Model Assumptions and Numerical Solution

The flow model provides a baseline for the simulation of the turbulent flow, passing through the control valve. The following assumptions are to be applied:

(1) The flow is isothermal

(2) The flow is incompressible

(3) The flow is Newtonian (i.e., the viscous stresses are proportional to the rates of deformation)

(4) Body forces are neglected

(5) No slip condition at the wall boundaries

The inlet boundary conditions implemented in this study were changed according to the state of the fluid flow study. The outlet boundary conditions are constant in all state of study. Velocity inlet boundary condition has been used for the valve inlet, while pressure outlet boundary condition is used in the valve outlet. Inlet velocity varies from 1 to 5 m/s. The pressure outlet has been equal to zero gauge pressure. COMSOL is a state-of-the-art computer program for modeling fluid flow and heat transfer in complex geometries. It provides complete mesh flexibility, solving flow problems with unstructured meshes that can be generated about complex geometries with relative ease. It supports various mesh types such as 2D-triangular/quadrilateral, 3D-tetrahedral/hexahedral/pyramid/wedge, and mixed (hybrid) meshes.

3.1. Mesh Generation. The prepared geometry has entailed creating a grid by utilising COMSOL software package. The mesh is of structure type, and it was made of tetrahedral cells. In addition, the cells were noted to have clustered in the trim area of the valve, in which large gradients of flow parameters were expected. Figure 5 gives an overview for the created mesh. The mesh was created for different valve openings of 10, 20, 30, and 40%. On the contrary, Figure 5 shows the created mesh for the valve's plug in the free stream.

3.2. Experimental Setup. The experimental test rig was designed to circulate a water flow within a closed loop system. The aim of the design is to achieve the following goals:

(i) The system hydraulic losses to be as minimum as possible

(ii) The provision of different flow rates and pressures, at the test section

(iii) It is essential for the water flow, introduced to the test section, to be fully developed turbulent flow

(iv) The circulated water flow is continuously filtered

(v) The arrangement of the pressure pick-up points minimizes the error in the pressure readings

(vi) The easiness of scavenging of any air bubbles that may be present in the circulating water

The test rig has a total length of 8.0 m and a width of 2.0 m. A line diagram and a general view for the designed test rig are displayed in Figure 6. The experimental test rig allows water circulation at flow rates up to 41 m^3/h. The test rig mainly consists of five main areas as follows:

(i) Water tank

(ii) Main chassis

(iii) Piping system

(iv) Delivery piping system

(v) Test section

4. Theoretical Results and Discussion

4.1. Analysis of FFT at Different Valve Opening and Different Velocity Inlet for Flat Face Plug

4.1.1. Case of Flat Face Plug Theoretical with Flow Speed 1 m/s and Different Valve Openings. Figure 7 shows the time history and frequency domain for the lift force acting on the flat face plug at inlet velocity of 1 m/s and different valve

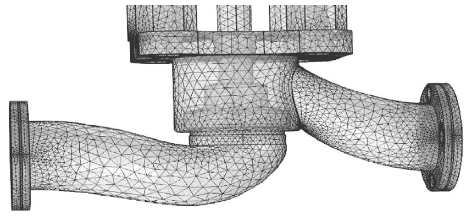


Figure 5: Control valve mesh.

Figure 6: Experimental test rig.

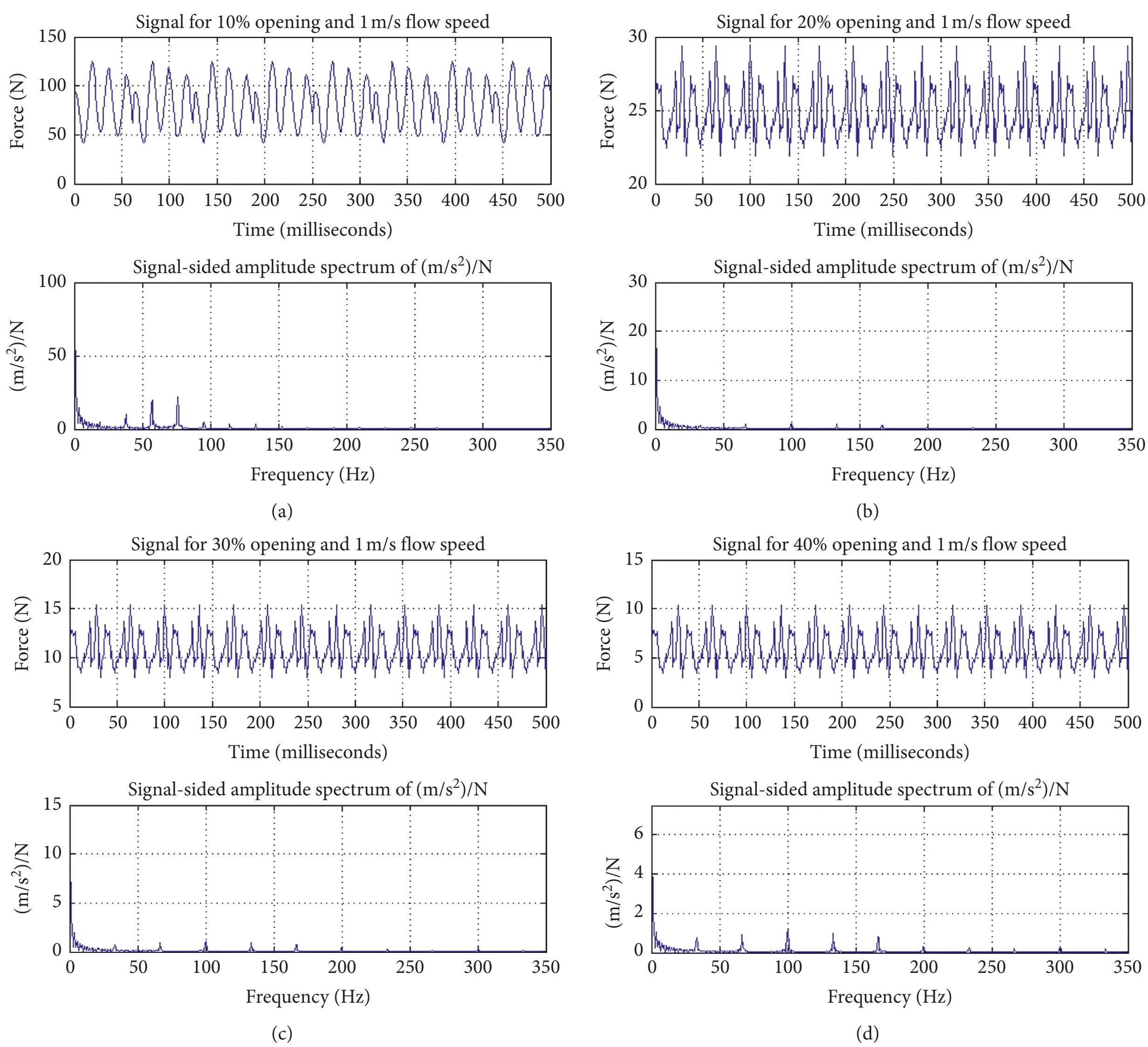


Figure 7: Flat plug as represented theoretically at a flow velocity of 1 m/s under different valve openings. (a) 10% valve opening; (b) 20% valve opening; (c) 30% valve opening; (d) 40% valve opening.

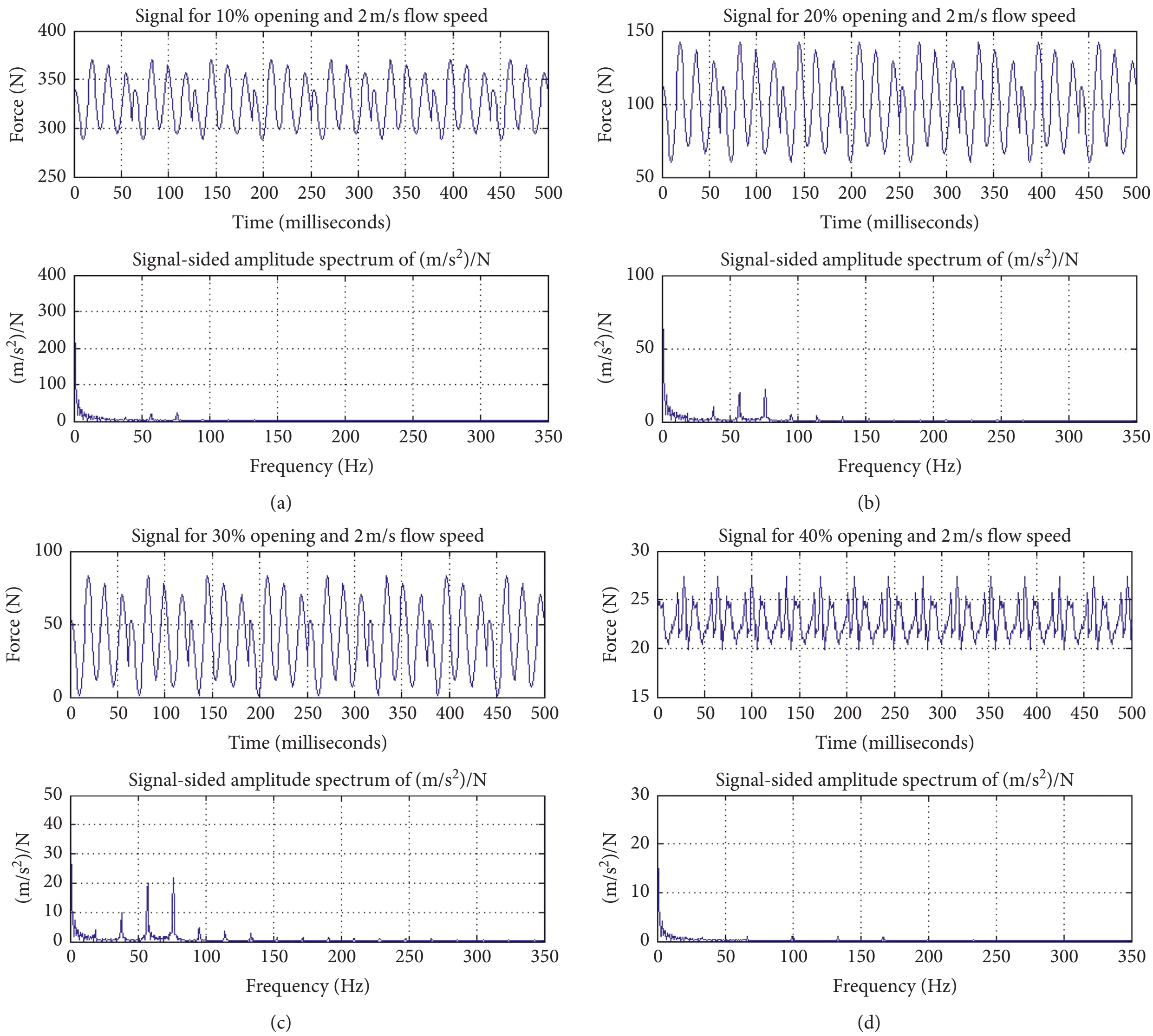


Figure 8: A theoretical representation of flat face plug at a flow velocity of 2 m/s under different valve openings. (a) 10% valve opening; (b) 20% valve opening; (c) 30% valve opening; (d) 40% valve opening.

openings regarding the one-way coupling simulation. The lift force curve behavior is the same compared to the different valve openings at the same inlet velocity. The magnitude of the lift force tends to increase due to the valve opening decrease. The amplitude of natural frequency at the flow speed of 1 m/s with valve opening of 10% was greater than that at other openings. On the contrary, the natural frequency will be shifted with small amplitude.

4.1.2. A Theoretical Outline regarding the Flat Face Plug in Case of a Flow Speed of 2 m/s under Different Valve Openings. Figure 8 shows that the amplitude of natural frequency at the flow speed 2 m/s with valve opening 10% was greater than at other opening. On the contrary, the natural frequency will be shifted with small amplitude. The magnitude of the lift force is noted to increase when the valve opening decreases and its increase is compared with the previous case at inlet velocity of 1 m/s at the same valve opening. The behavior of lift force under the inlet velocities of 1 m/s and 2 m/s is noted to be the same as that featured at the inlet velocities of 3 m/s, 4 m/s, and 5 m/s. For concave plug shape P1 and P2, the trend of natural frequency for flat face plug is the same but the amplitude of natural frequency for plug P2 is smaller than flat face plug p1 and flat face plug.

Pressure values are observed to drop at different valve openings under different inlet velocities.

4.1.3. A Theoretical Illustration of Flat Face Plug in Case of a Flow Speed of 1 m/s under Different Valve Openings. Figure 9 shows the pressure drop for control valve for inlet velocity of 1 m/s and different valve openings. It could be observed that the pressure drop pattern in the case of 10% opening is similar to the other openings. Tangible

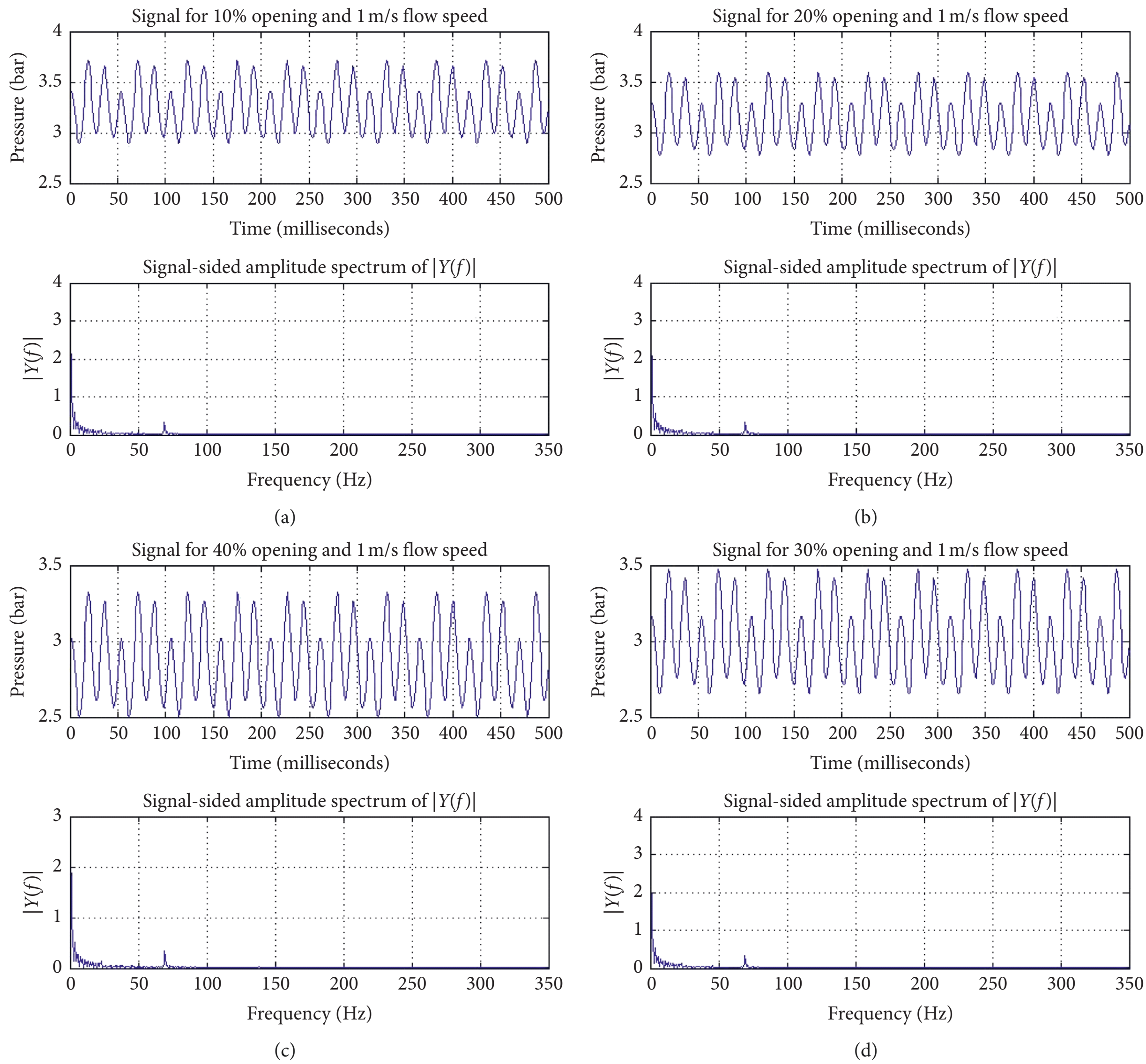


FIGURE 9: Pressure drop for flat face plug with flow velocity 1 m/s and different valve opening. (a) 10% valve opening; (b) 20% valve opening; (c) 30% valve opening; (d) 40% valve opening.

variations could be discerned regarding the amplitude of the pressure drop in different valve openings. The major magnitude is observed in case of 10% opening and minor magnitude in case of 40% opening. This can be observed in other cases of inlet velocities 2, 3, 4, and 5 m/s.

4.3. Displacement Analysis at Different Valve Opening and Different Velocity Inlet for Flat Face Plug

4.3.1. Case of Flat Face Plug Theoretical with Flow Speed 1 m/s and Different Valve Opening. The displacement of the valve plug at 1 m/s with different valve openings is first described (see Figures 10(a)–10(d)). The amplitude displacement of the valve at flow speed of 1 m/s and with valve opening 10% is greater than the amplitude of the displacement at the same speed but with valve opening 20% by 70%. Also, the percentage between openings of the valve 20% is not exceeding 50% greater than the case of opening valve 30%. At the end of this case, the amplitude displacement of opening valve 30% is greater than the valve opening 40% by 60%. Accordingly, the control valve displacement is noted to be directly proportional with the inlet velocity at constant valve opening. The maximum amplitude displacements were found to be at 10% opening and 5 m/s inlet velocity. The amplitude displacements start to decrease gradually, when increasing the valve's opening. The minimum amplitude displacement was found at 40% opening and 1 m/s inlet velocity. At constant inlet velocity and valve opening, the maximum displacement can be found in the valve with flat face plug and the minimum displacement can be found in the control valve with plug p2.

4.4. Examination of Valve Pressure Contours for Valve with Flat Face Plug. Figure 11 displays the pressure contours for

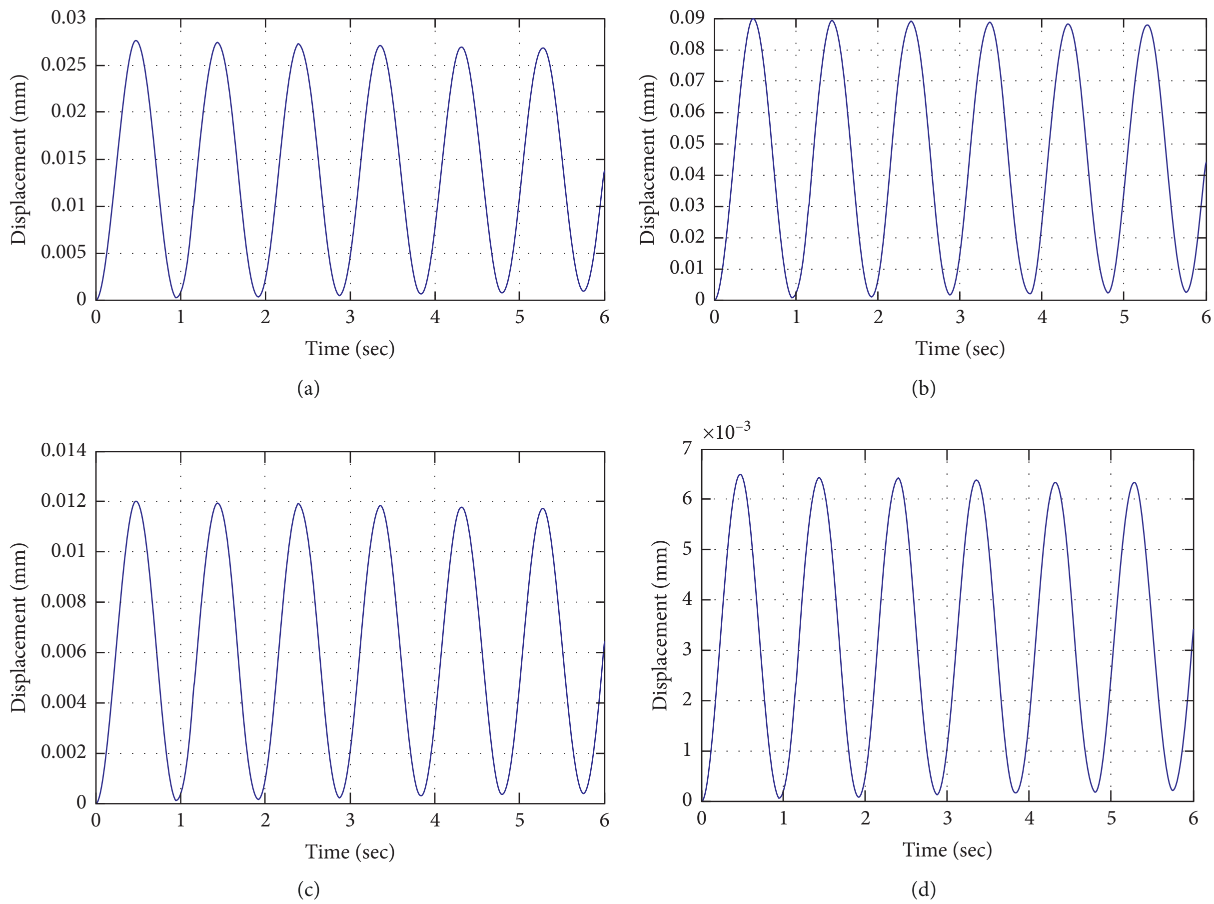


Figure 10: Displacement for flat face plug with flow velocity 1 m/s and different valve opening. (a) 10% valve opening; (b) 20% valve opening; (c) 30% valve opening; (d) 40% valve opening.

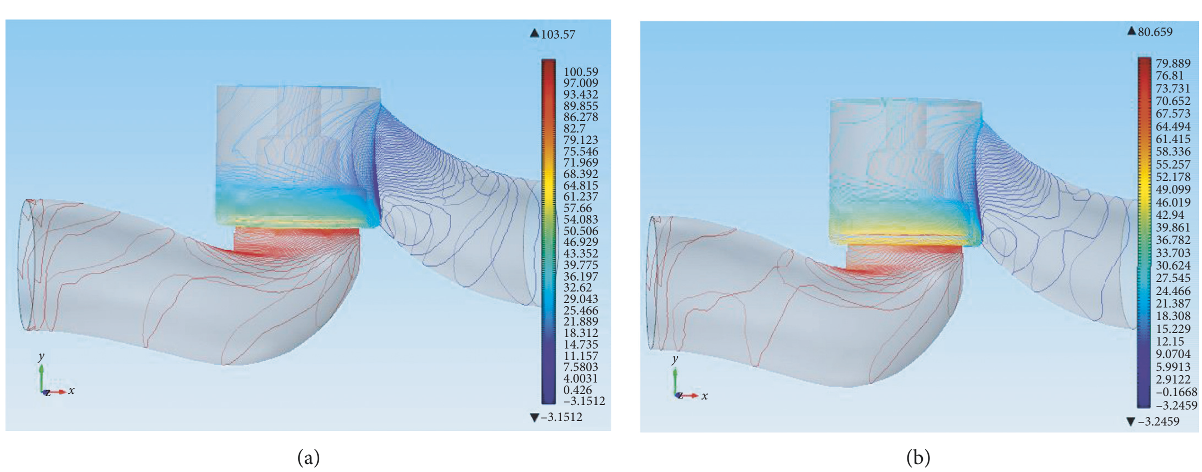
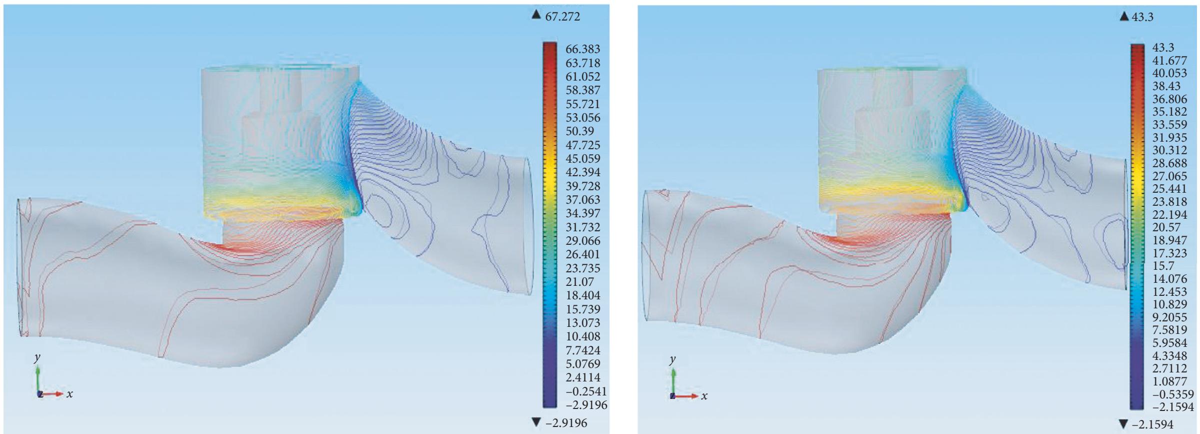
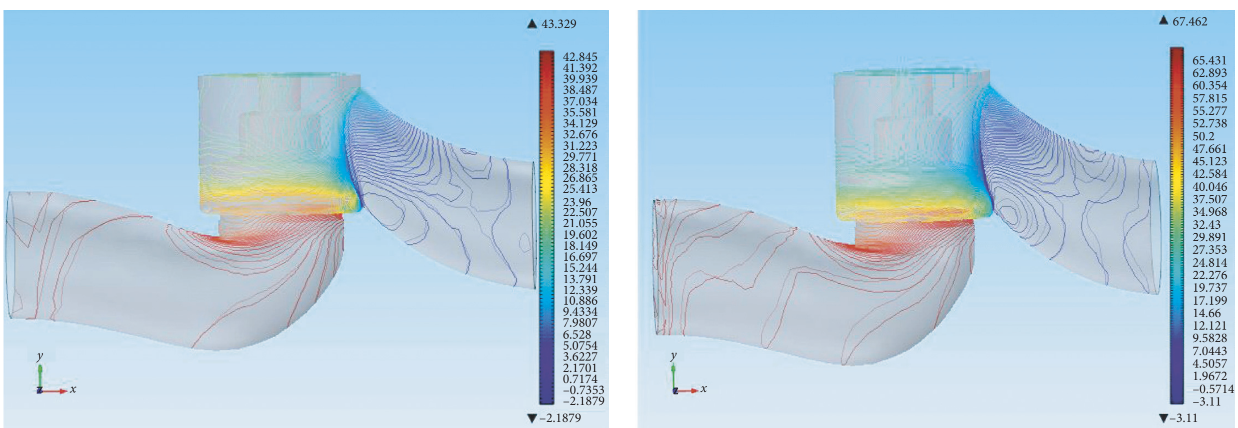


Figure 11: Continued.



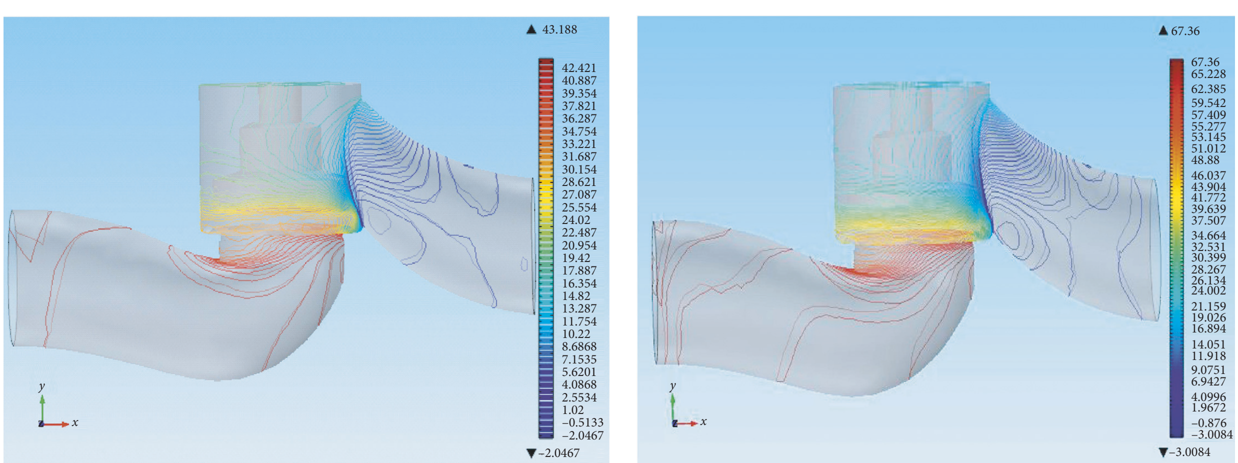
(c) (d)

Figure 11: Pressure contours for flat-faced plug at different openings and $v = 2$ m/s. (a) 10% valve opening; (b) 20% valve opening; (c) 30% valve opening; (d) 40% valve opening.



(a) (b)

Figure 12: Pressure contours for p1 plug at different openings and $v = 1$ m/s. (a) 10% valve opening; (b) 20% valve opening.



(a) (b)

Figure 13: Pressure contours for p2 plug at different openings and $v = 1$ m/s. (a) 10% valve opening; (b) 20% valve opening.

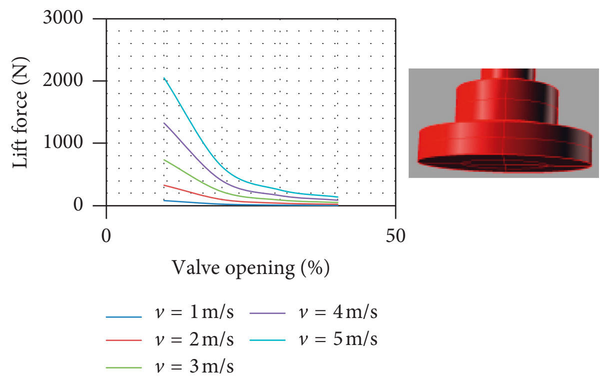


FIGURE 14: Relation between lift force and valve opening at different inlet velocity for flat face plug.

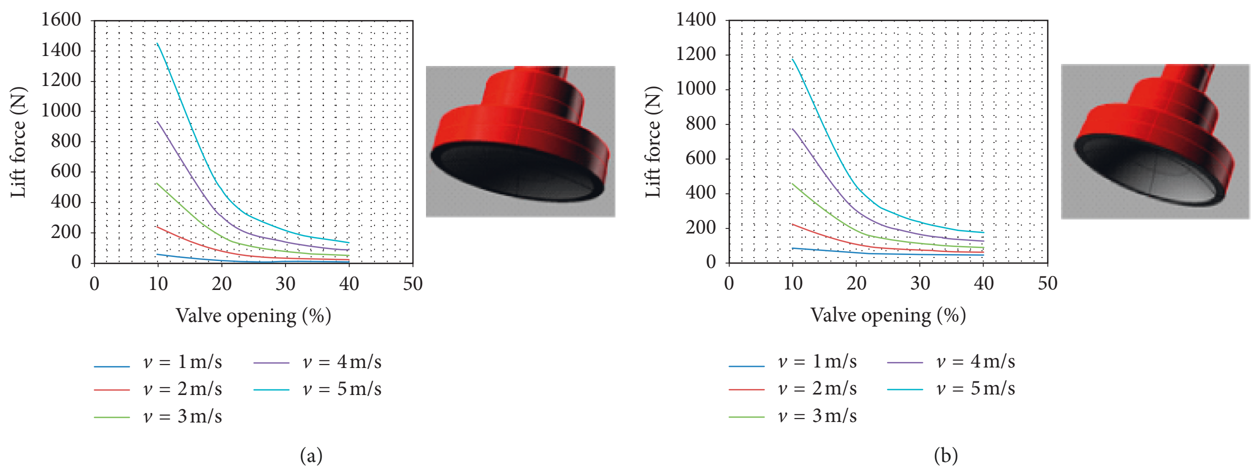


FIGURE 15: Relation between lift force and valve opening at different inlet velocities for plug p1 (a) and p2 (b).

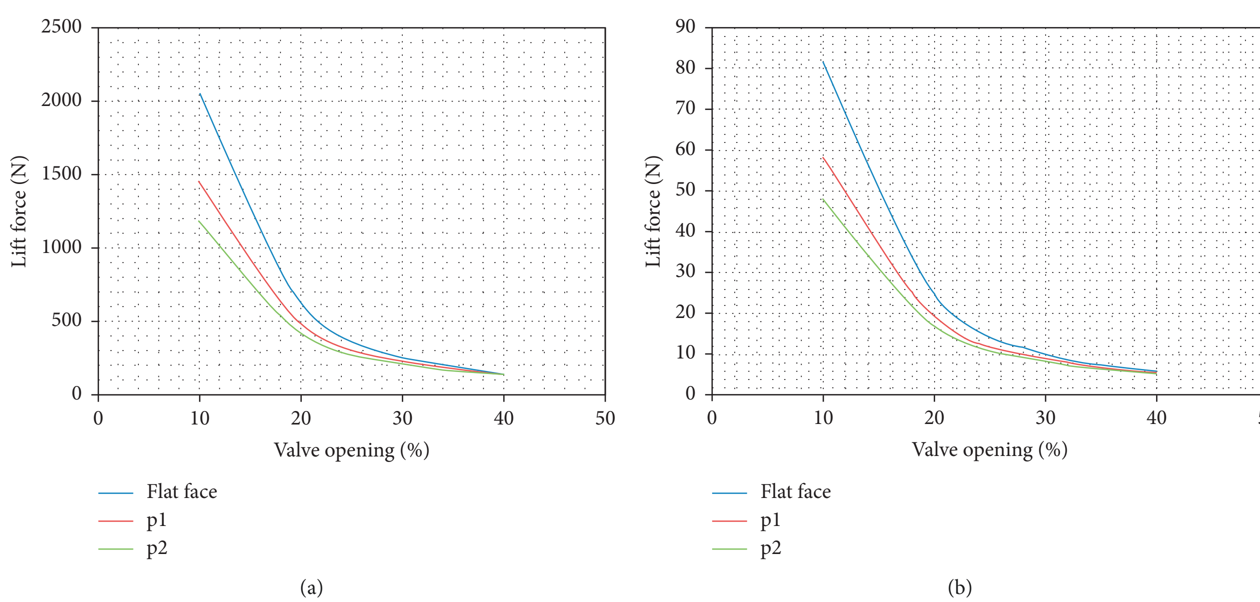


FIGURE 16: Relation between lift force acting on different plug geometries and percentage valve opening at v = 1 m/s (a) and 5 m/s (b).

valves with flat face plugs. Each valve is shown at opening 10, 20, 30, and 40 percent. In each case, the pressure value tends to decrease in the downstream direction with the largest pressure gradient occurring in the plug and seat region. No significant pressure changes are observed upstream of the valve. Just minor and marginal changes are

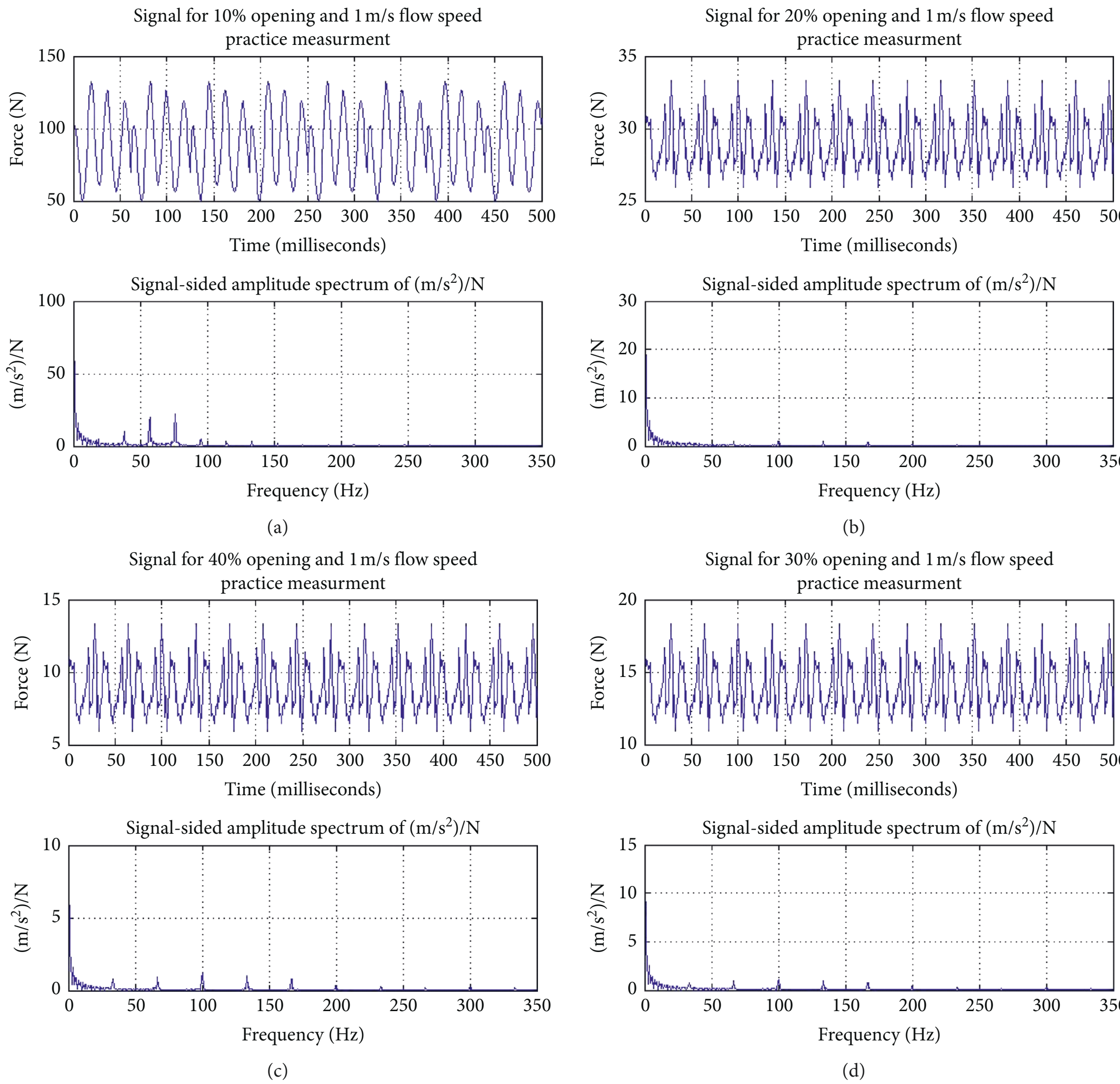


Figure 17: Lift force acting on flat face plug with flow velocity 1 m/s and different valve opening. (a) 10% valve opening; (b) 20% valve opening; (c) 30% valve opening; (d) 40% valve opening.

noted downstream of the plug. The pressure changes are observed when the valve opening percent and flow inlet velocity change. At small valve opening, the pressure increases around the plug region and it decreases at low inlet velocity. At constant valve opening and inlet velocity and different plug shape, the vortices in the region of plug sets increase when the plug shape concave increases. Because of increasing the vortices, the back flow would increase and would as well generate the force in opposite direction. The lift force generates due to the fluid passing through the control valve and then the net lift force decreases, as shown in Figures 12 and 13.

Finally, the FSI results in Figure 14 illustrate the relation between the valve percentage opening and lift force for flat face plug. When the flow passes through the valve with flat face plug with the different inlet velocities, it is observed that the smaller the valve opening is, the larger the lift force under the same flow inlet velocity could get. When the valve opening is large, the lift force is small at the same flow inlet velocity. As the flow inlet velocity increases, the lift force increases for the same valve opening. This means that the lift force reaches its maximum value at smallest opening for the same inlet velocity and it reaches its maximum value at highest flow inlet velocity at the same valve opening. The lift force reaches its minimum value at the large valve opening for the same flow inlet velocity.

4.5. Analysis of the FSI Model for Plug with Concave Shape p1 and p2. Analysis of FSI result for p1 and p2. It is very clear that the curve patterns for FFT and pressure drop and displacement are similar to the result for the flat face plug

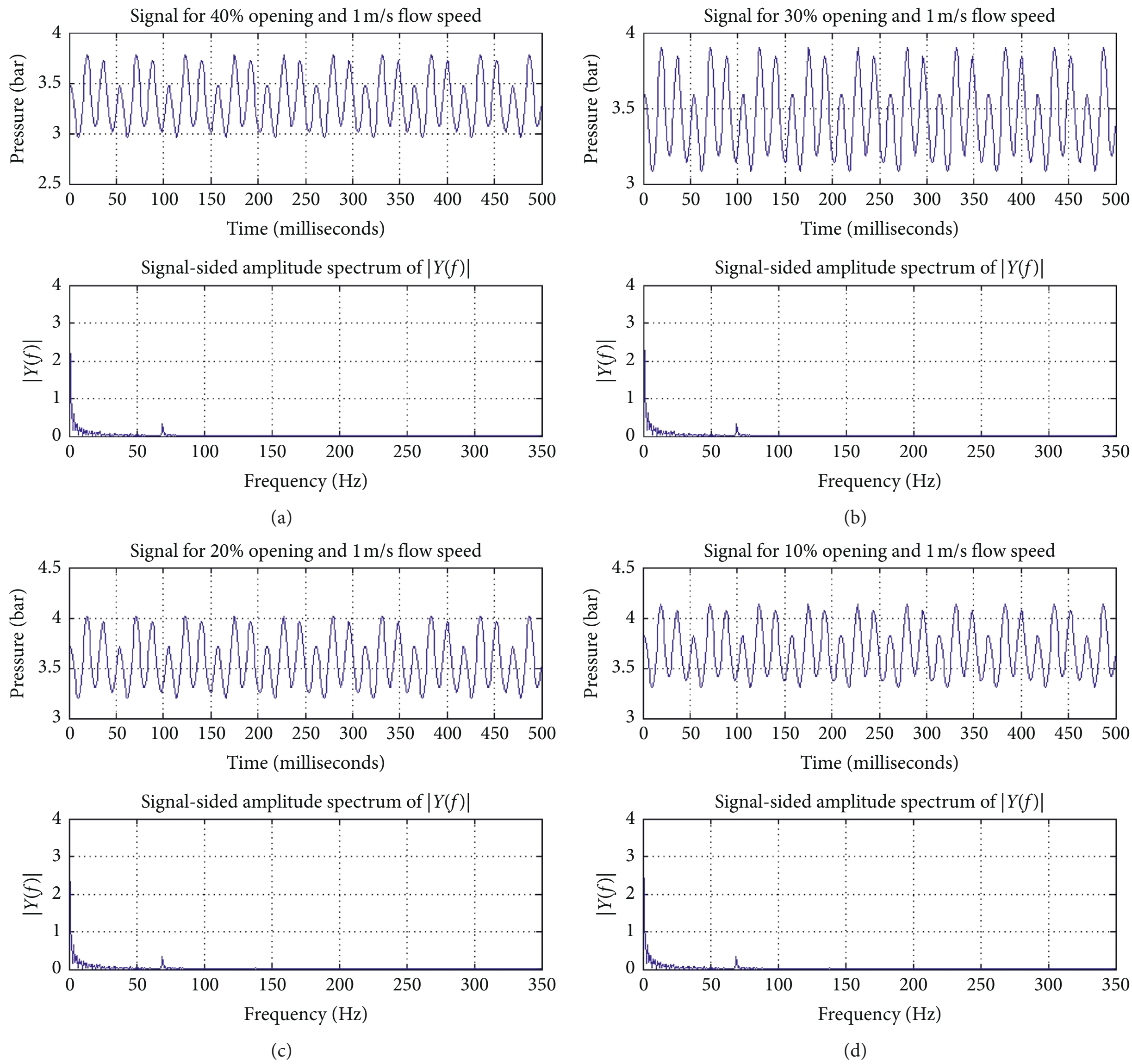


Figure 18: Pressure drop for flat face plug with flow velocity inlet 1 m/s and different valve opening. (a) 10% valve opening; (b) 20% valve opening; (c) 30% valve opening; (d) 40% valve opening.

discussed in the previous section. The difference can be observed in the magnitude of the lift force at all inlet velocity and different valve opening. In the case of P1 and P2, the lift increases when the inlet velocity increases at constant valve opening. Besides, it is observed to decrease when the valve opening increases at constant inlet velocity as shown in Figures 15(a) and 15(b).

4.6. Comparison between Control Valve Plug Shape Flat Face, P1 and P2. Finally, Figures 16(a) and 16(b) show the relation between the lift force acting in the control valve with different plug shape and the different valve opening at different inlet velocities. The lift force acting on the flat face plug at different inlet velocities is always higher than the other lift forces acting on other plugs geometry at different valve openings. The lift force acting on the plug P2 is always smaller than the lift force acting on the other plug shapes. From the previous analysis, it can be observed that when the control valve concave shape increases, the lift force generated on it tends to decrease.

5. Experimental Results

5.1. Analysis of FFT at Different Valve Openings and Different Velocity Inlet for Flat Face Plug

5.1.1. Case of Flat Face Plug Theoretical with Flow Speed 1 m/S and Different Valve Opening. The time history of lift force acting on the flat face plug and its natural frequency are illustrated in Figure 17. The difference between the magnitudes of lift force and its natural frequency amplitude can

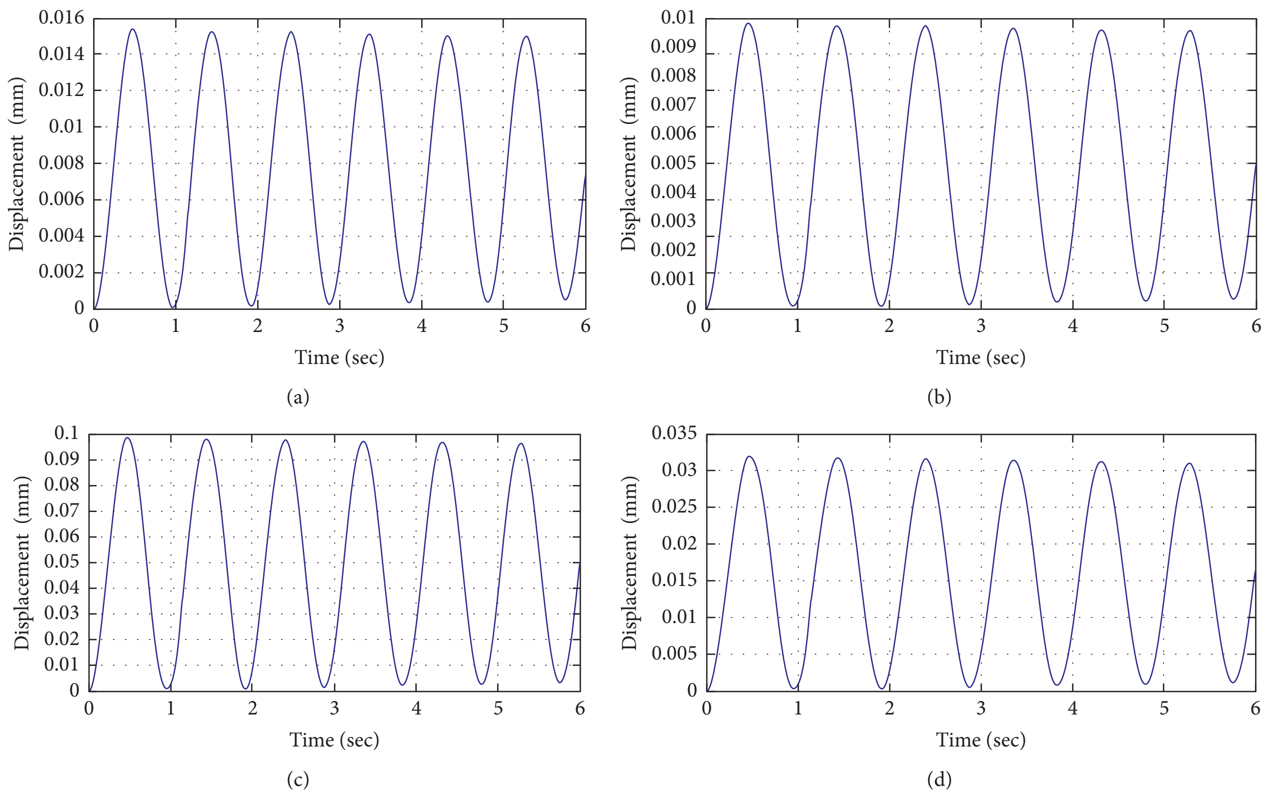


Figure 19: Displacement for flat face plug with flow velocity 1 m/s and different valve opening. (a) 10% valve opening; (b) 20% valve opening; (c) 30% valve opening; (d) 40% valve opening.

be observed. The maximum natural frequency amplitude is noted at valve opening 10%, and the minimum of it is featured at 40% opening. The lift force is inclined to increase when the valve openings decrease. These changes of lift force value due to the vortices occur at the region of plug set due to fluid passing through the valve.

5.2. Analysis for Pressure Drop for Flat Face Plug at Inlet Velocity 1 m/s and Different Valve Opening. Figure 18 shows the time history FFT for the pressure drop for flat face plug at inlet velocity of 1 m/s and different valve openings. The maximum pressure drops were found to be at 10% opening, while the pressure drops start to decrease gradually, when increasing the valve's opening to 20 and 30%. However, the pressure drops, for openings larger than 40%, were noticed to be of smaller values, when compared to corresponding small openings values.

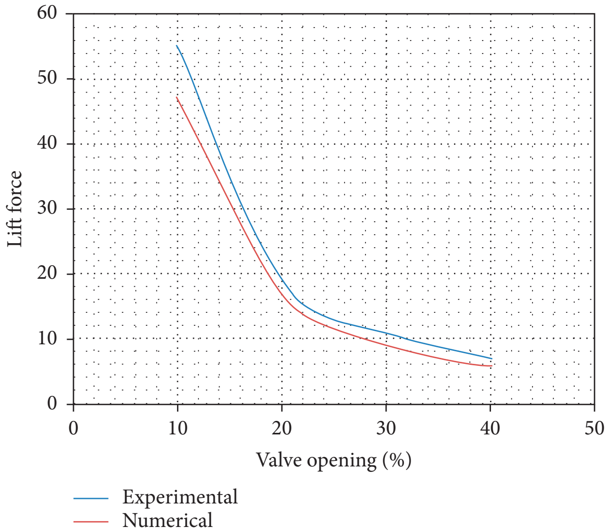
5.3. Displacement for Flat Face Plug at Inlet Velocity 1 m/s and Different Valve Opening. Figure 19 shows the displacement occurring due to the flow passing through the control valve at an inlet velocity of 1 m/s and at different valve openings. Furthermore, differences between the values regarding the different valve openings could clearly be seen. The peak values concerning displacement could be observed at valve opening of 10%, and the minimum value of it would be at opening of 40%.

5.4. Analysis of the Experimental Model for Plug with Concave Shape p1 and p2. Analysis of experimental results for p1 and p2. It is very clear that the curve patterns for FFT and pressure drop and displacement are similar to the results for the flat face plug discussed in the previous section. The difference can be observed in the magnitude of the lift force at all inlet velocities and different valve openings. In the case of P1 and P2, the lift force tends to increase when the inlet velocity increases at constant valve openings. Moreover, it is inclined to decrease when the valve opening increases at constant inlet velocity, whereas it features a decrease when the concave shape increases.

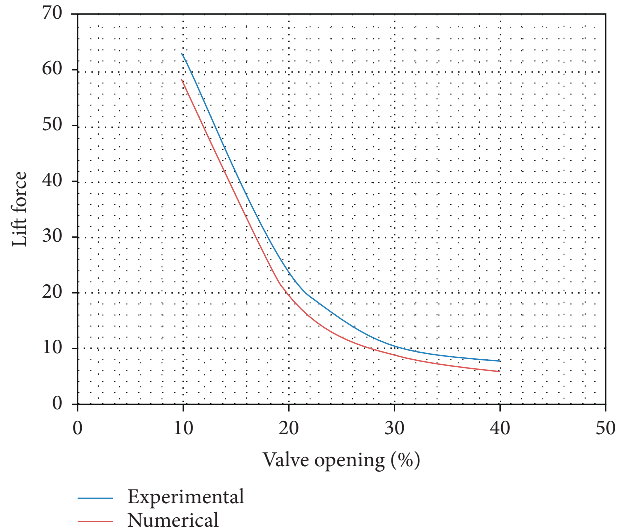
6. Validation

Figure 20 shows the comparison of lift force acting on flat face plug at an inlet velocity of 1 m/s and different valve openings attained by the numerical and experimental methods. It can be seen from the figures that the comparison held manifests good qualitative agreement between the present FSI model and the experimental results. In the case of inlet velocity $v = 2$, 3, 4, and 5 m/s, the numerical and experimental results appear to have approximately the same trend of the previous case of inlet velocity $v = 1$ m/s.

Figures 20(a) and 20(b) show the comparison of lift force acting on P1 and P2 at an inlet velocity of 1 m/s and different valve openings attained by the numerical and experimental methods. Significant differences can be seen in the value of the lift force between the experimental results and their



(a)



(b)

Figure 20: Relation between lift force acting on flat-faced plug and the percentage regarding valve opening at inlet velocity of 1 m/s for present FSI and experimental results.

numerical counterparts but the trend of the curve between the two results appears to be approximately the same. The analyses of the results of the two plugs P1 and P2 at different inlet velocities and different valve openings also seem to be the same.

7. Conclusions

The present work was dedicated towards the study of the hydrodynamic performance of a control valve. The main objective of the study was to obtain a better plug shape that has the minimum vibration when the fluid passes through the control valve using fluid structure interaction simulation by COMSOL 4.3b commercial code. An experimental program was developed, including both flow and vibration measurements, to be executed to carry out necessary tests for the plug control valve, under different plug concave shapes and different valve openings. The following conclusions may be highlighted.

(i) The lift force generated due to the fluid flow passing through the control valve increases when the inlet velocity increases at constant valve opening and it decreases when the valve opening increases at constant inlet velocity for all control valve plug shapes.

(ii) The flow passing through the control valve induces the vortices in the region of plug set. Also, it can be seen that the minimum vortices in the plug set region are featured in case of flat face plug. In addition, the maximum vortices can be observed in the plug set region in case of plug P2.

(iii) The lift force acting on the plug decreases when the concave shape increases. The maximum lift force is obtained in case of flat face plug. The minimum lift force could be generated in case of plug p1.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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