
Determination of Hydrodynamic Excitations Generated by Two-Phase Water-Vapor Flow in a 90-Degree Elbow Using Computational Fluid Dynamics (CFD) Analysis

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Abstract: - Two-phase flow is a major source of flow-induced vibrations (FIV) in pipeline systems, especially when the hydrodynamic fluctuations generated by the fluid contain frequencies close to the natural frequencies of the structure. Under these conditions, the dynamic response of the pipeline can be amplified, with effects on displacements, stresses, and fatigue behavior. This paper analyzes the already formed two-phase water-vapor flow in a 90-degree elbow, resulting from a pressure drop in a system conveying water at a temperature of 151°C and a pressure of 5.7 bar (a). The flow was numerically simulated in OpenFOAM using the Volume of Fluid (VOF) method to model the water-vapor phases. The hydrodynamic forces exerted on the elbow wall were extracted from the transient simulation and analyzed in the time domain to identify the dominant components of the excitation. The forces obtained from the Computational Fluid Dynamics (CFD) analysis were subsequently used as input data in a unidirectional fluid-structure interaction (FSI) analysis by inputting them in the form of a time history. Thus, the dynamic response of the pipe in the elbow region and its vicinity was evaluated in terms of displacements caused by hydrodynamic excitations. The results show that the CFD-FSI approach allows for the preliminary identification of the effect of two-phase flow on pipeline vibrations and can be used as a basis for further analyses regarding dynamic stresses, accelerations, and fatigue risk.

Keywords: - two-phase flow, void fraction, computational fluid dynamics, flow-induced vibration, natural frequency, fluid-structure interaction.

1. INTRODUCTION

Fluid flow is an important aspect to monitor in pipeline systems, especially when fluid flow can induce vibrations within the pipeline's natural frequency spectrum [1]. In the modal analysis [2] of pipelines performed to determine natural frequencies, only static aspects are considered, such as the self-weight, the weight of the fluid, the weight of the insulation, the stiffness/flexibility of the supports, etc. The dynamic component must be treated separately, but it must nevertheless be included subsequently to determine its influence on the configuration of the pipeline system.

Flow-Induced Vibration (FIV) is a common phenomenon in process systems, nuclear power plants, and fluid transport pipelines, often leading to the occurrence of dangerous vibrations [3]. Flows

can be classified as single-phase flows and multiphase flows. Two-phase flow is a simplified form of multiphase flow [4].

Two-phase flow is divided into liquid-gas [5], liquid-liquid [6], gas-solid, and liquid-solid [4].

The literature indicates that a sufficient experimental database is not yet available for various aspects of gas-liquid two-phase flow, including large-diameter pipes, associated regime transitions, interface-area-dependent friction correlations, etc. [3].

Research conducted to date focuses primarily on small diameters, such as the work by Hossain et al. [7], which addresses a 90-degree elbow with a diameter of 0.0525 m (2 inches), or Yang Liu et al. in their study on two-phase flow [8]. Other studies address larger diameters, such as the work by Chinenye-Kanu et al. [9], which adopted the

numerically validated model for a pipe with an internal diameter of 52.2 mm (2 inches) by Hossain et al. [6] for a 203.2 mm (8-inch) pipe and found that the peak frequencies were higher for the smaller-diameter pipe than for the larger-diameter pipes [4].

Benguigui [10] numerically investigated vibrations induced by two-phase flow using a Computational Fluid Dynamics (CFD) code based on the two-fluid Euler–Euler approach. The study focuses on water/steam cross-flow in steam generator tube bundles and implements a fluid–structure interaction method that allows for solid displacement under the action of forces generated by the two-phase flow. Although the geometry differs from that of a pipe elbow, the study is relevant because it shows that two-phase FIV requires a dedicated multiphase CFD and Fluid-Structure

Interaction (FSI) [15] approach, and that the void fraction, flow regime, and mixture properties strongly influence the vibrational response.

CFD simulation codes [16,17] are used to model these flows, and their application to date has primarily focused on single-phase flows. Increased computational capabilities and the need for detailed understanding of the physical phenomena during transient regimes have enabled the extension of their use to these types of flows as well. [18]

Two-phase flow can be classified according to the flow regime into bubble flow, slug flow, churn flow, and annular flow for vertical pipes, and for horizontal pipes into stratified flow, slug flow, annular flow, or bubble flow. These flow types are shown in Figure 1 below.

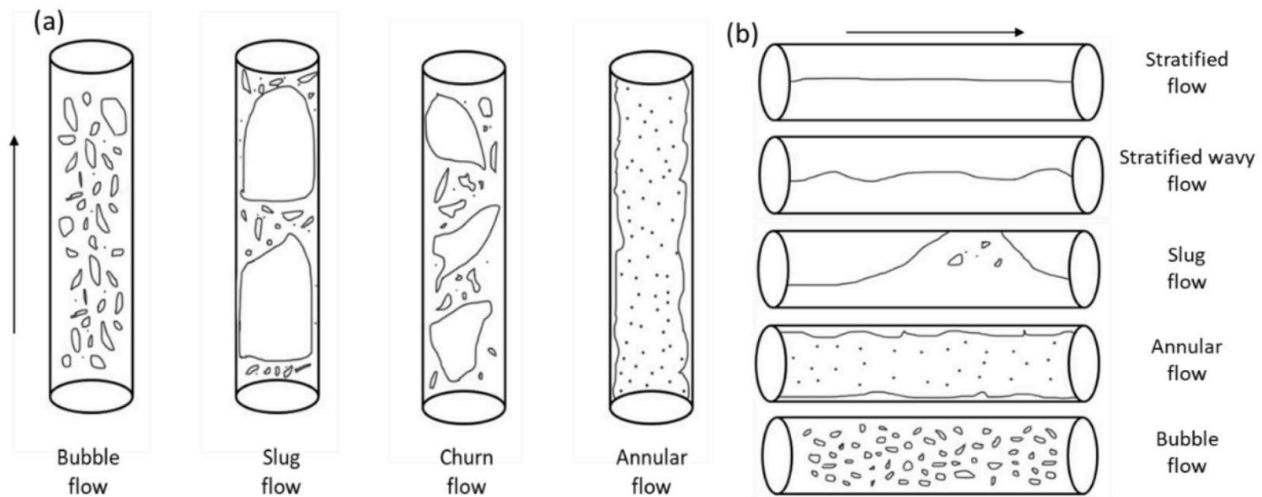


Figure 1. Two-phase flow in horizontal pipes (a) and in vertical pipes (b) [4]

The areas most prone to this phenomenon are bends [11, 12], as they can cause a change in the flow regime due to the combined action of centrifugal forces, inertial forces, gravitational forces, and buoyancy forces [13].

In this paper, multiphase flow, specifically water–vapor two-phase flow in a 90-degree elbow with a nominal diameter of 12 inches and an internal flow diameter of 308 mm, is simulated. The initial fluid state corresponds to subcooled liquid water at 151 °C. Due to the pressure drop in the system, the local pressure decreases below the saturation pressure corresponding to this temperature, leading to partial vaporization by flashing [14]. The present paper does not investigate the flashing phenomenon mentioned above, but rather the behavior of an already formed water–vapor mixture.

The purpose of this paper is to evaluate the hydrodynamic excitation induced by two-phase water–vapor flow in a pipe elbow, for a volume fraction of 10% vapor and 90% liquid. The

excitation is quantified by the fluctuating forces exerted by the fluid on the pipe wall and by their spectral analysis, as a preliminary step for evaluating the potential for inducing structural vibrations.

2. THEORETICAL BACKGROUND

Two-phase water–vapor flow is a flow regime in which the liquid phase and the vapor phase coexist in the same domain. In high-temperature pressurized water systems, two-phase flow can occur when the local pressure decreases toward the saturation pressure corresponding to the fluid temperature, favoring the formation of vapor. Similarly, under a condition of constant pressure, a change in temperature toward the saturation temperature can also result in phase change.

Under these conditions, the flow can no longer be described as single-phase, since the local properties of the mixture depend on the distribution of the two phases [4].

3. DESCRIPTION OF THE ANALYZED GEOMETRY

This paper analyzes the two-phase water–steam flow through a 90° elbow with an inner diameter of 308 mm (12 inches) and a radius of curvature of 1.5D. The flow geometry, modeled in Autodesk Fusion 2702.1.47 software, is oriented such that the inlet section is arranged vertically along the z-axis, and after the change of direction in the elbow, the flow develops horizontally along the y-axis. To provide a more realistic representation of the flow development and to reduce the influence of boundary conditions on the region of interest, the elbow was extended with straight sections both upstream and downstream. The geometry of the analyzed flow domain is presented in Figure 2 and is consistent with that studied in the work by Cotoban et al. [19] in terms of diameter and flow parameters for the 12-inch flow section.

The pipe material used in the structural analysis was carbon steel ASTM A106 Grade B. The mechanical properties introduced in the AutoPIPE model were Young's modulus at reference temperature $E=202.71$ GPa, Young's modulus at operating temperature $E_{hot}=194.89$ GPa, Poisson's ratio $\nu=0.30$, and density $\rho=7833$ kg/m³ kg/m³.

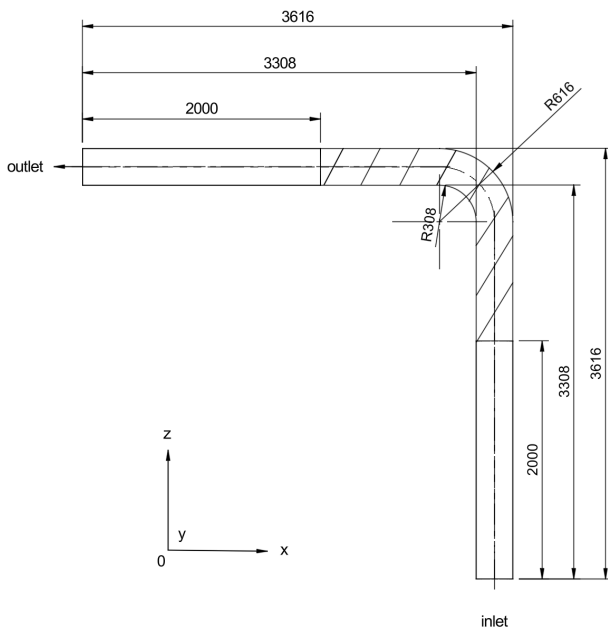


Figure 2. Flow geometry

4. MODELING ASSUMPTIONS

The following assumptions were used for the modeling:

- The CFD domain is considered downstream of a pressure drop generated by the partial closure of a control valve, and the water-

vapor mixture is already formed in the analyzed domain.

- The pressure under normal operating conditions (before the pressure drop) of the upstream system is $p_0=0.57$ MPa(a), and the temperature is $T_0=151$ °C.
- The initial vapor volume fraction was set as follows: vapor fraction = 0.1, water fraction = 0.9.
- The VOF (Volume of Fluid) method does not explicitly calculate the thermodynamic generation of vapor through flashing, but rather transports and redistributes the phases already present.
- The mass flow rate remains constant at 80 t/h, and the inlet velocity of the mixture is recalculated to account for the different densities of water and steam.
- A single velocity field for the water-vapor mixture was assumed.
- Gravitational acceleration was assumed to be 9.81 m/s².

5. PROPERTIES OF THE FLUIDS USED

The initial fluid values are specified in Table 1. The fluid properties are those specified by NIST – National Institute of Standards and Technology [20].

Table 1. Fluid parameters before two-phase flow

Parameter	Liquid
Temperature T_0 [°C]	151
Pressure p_0 [bar(a)]	5.7
Density [kg/m ³]	916.12
Specific volume v_0 [m ³ /kg]	0.0010916
Internal energy u_0 [kJ/kg]	635.92
Enthalpy h_0 [kJ/kg]	636.55
Entropy s_0 [kJ/(kg·K)]	1.8519
C_v [kJ/(kg·K)]	3.5186
C_p [kJ/(kg·K)]	4.3095

The hypothesis of a pressure drop and the formation of a two-phase mixture with a vapor volume fraction of 0.1 and a water volume fraction of 0.9 following an isenthalpic process was considered. The parameters of the two-phase fluid are listed in Table 2. The fluid properties are those specified in NIST [20].

Table 2. Two-phase fluid parameters

Parameter	Saturated liquid	Saturated vapor
Reference temperature T_2 [°C]	150.86	150.86
Pressure [bar(a)]	4.8724	4.8724
Density ρ [kg/m ³]	916.20	2.6039
Specific volume v [m ³ /kg]	0.0010915	0.38404
Dynamic viscosity η [Pa·s]	1.8150e-4	1.3989e-5
Kinematic viscosity ν [m ² /s]	1.9810e-7	5.3731e-6
Thermal conductivity [W/(m·K)]	0.68084	0.030434
Surface tension σ [N/m]	0.048558	-

6. DETERMINATION OF PRESSURE AS A FUNCTION OF IMPOSED VOLUME FRACTIONS

The conversion of the volume fractions into mass fractions of the two fluids was determined using the vapor mass fraction equation (1) [21].

$$x = \frac{\alpha_v \cdot \rho_v}{\alpha_v \cdot \rho_v + \alpha_l \cdot \rho_l} \quad (1)$$

where x is the mass fraction of vapor, α_v is the volume fraction of vapor, α_l is the volume fraction of liquid, ρ_v is the density of vapor, and ρ_l is the density of liquid.

The final saturation pressure was determined based on the assumption of an isenthalpic process, taking into account the vapor volume fraction $\alpha_v = 0.1$ and the water volume fraction $\alpha_l = 0.9$. The volume fractions were converted to the mass fraction of vapor x using equation (1), and the specific enthalpy of the two-phase mixture was calculated using equations (2), (3), and (4), according to the formulation for liquid–vapor mixtures presented by Moran and Shapiro [22].

$$h_0 = h_2 = (1 - x) \cdot h_l(p_f) + x \cdot h_v(p_f) \quad (2)$$

$$h_0 = h_l(p_f) + x \cdot h_{lv}(p_f) \quad (3)$$

$$h_{lv} = h_v - h_l \quad (4)$$

where h_l is the enthalpy of the saturated liquid at the final pressure (p_f), and h_v is the enthalpy of the saturated vapor at the final pressure (p_f).

Using the NIST tables [20] in equation (3) resulted in a post-vaporization pressure of 4.8724 bar (a) and a temperature of 150.86 °C, given the imposed conditions regarding the volume fraction of water and vapor.

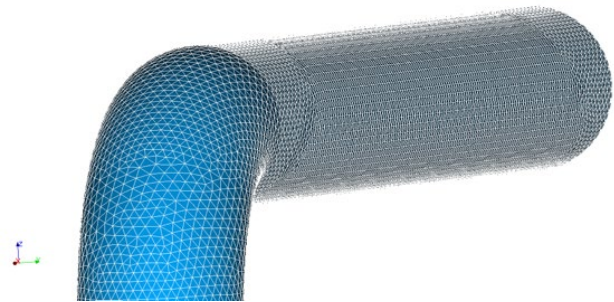
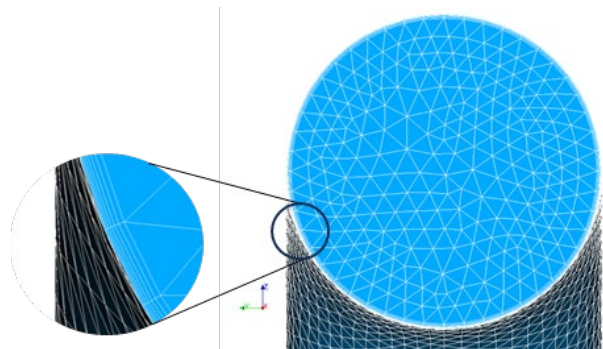
7. MODEL DISCRETIZATION

The fluid domain was discretized using SALOME 9.15.0 software, employing the NETGEN 2D and NETGEN 3D algorithms. This includes the straight fluid inlet and outlet sections and the 90-degree elbow. The resulting numerical grid is shown in Figure 3.

To accurately represent the flow near the wall, the Viscous Layer assumption was used, whereby prismatic layers were introduced near the surface of the pipe wall as per Figure 4.

The maximum element size was set to 20 mm, and the minimum size to 9 mm, for both the NETGEN 2D and NETGEN 3D algorithms. The viscous layer was defined with a total thickness of 5 mm, 7 layers, and a scaling factor of 1.3.

The resulting final mesh contains 576,903 cells, of which 268,450 are prismatic elements and 308,453 are tetrahedral elements. The total number of vertices is 197,418, and the total number of faces is 1,308,010. The domain has three boundary patches, corresponding to the Inlet, Outlet, and Wall surfaces. The quality of the flow domain discretization was verified in OpenFOAM 13, resulting in a maximum non-orthogonality value of 51.8997 and an average value of 12.0592, values that fall within the acceptable limits for running in OpenFOAM [23].

**Figure 3.** Model discretization**Figure 4.** Viscous layers of the model

8. CFD SIMULATION

The numerical simulation of the water–vapor two-phase flow was performed in OpenFOAM 13, using an Eulerian Volume of Fluid (VOF) approach to track the phase distribution in the fluid domain. The continuity (5) and momentum (6) equations are solved continuously in the computational analysis [24, 25]. The CFD simulation was run for a transient time interval of 30 seconds.

The continuity equation for the two-phase mixture is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (5)$$

The momentum equation for the two-phase mixture is:

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u u) = -\nabla P + \nabla \cdot [(\mu + \mu_t)(\nabla u + \nabla u^T)] + F + \rho g \quad (6)$$

The vapor volume fraction equation is:

$$\frac{\partial \alpha_v}{\partial t} + \nabla \cdot (\alpha_v u) = 0 \quad (7)$$

where ρ is the density of the mixture, u is the velocity vector of the mixture, p is the pressure, μ is the dynamic viscosity, μ_t is the turbulent viscosity, F represents the volume/surface forces included in the model, g is the acceleration due to gravity, and α_v is the volume fraction of vapors.

The RANS (Reynolds-Averaged Navier-Stokes) approach, using the k- ε turbulence model, was employed to model turbulent effects. This model introduces two additional transport equations: one for the turbulent kinetic energy k , determined by equation (8), and one for the turbulent dissipation rate ε , determined by equation (9), as presented in the OpenFOAM documentation [26]. These are based on the Reynolds number [27], determined by equation (11). Based on these quantities, the turbulent viscosity is determined, which contributes to modeling the effect of turbulent fluctuations on the mean flow field.

The turbulence intensity was estimated using equation (10) [28].

The resulting values are summarized in Table 3.

$$k = \frac{3}{2} (UI)^2 \quad (8)$$

$$\varepsilon = C_\mu^{3/4} \frac{k^{3/2}}{l} \quad (9)$$

$$I = 0.16 \cdot Re^{-1/8} \quad (10)$$

where $l = 0.07D$, and represents the characteristic length, and D is the inner diameter of the pipe

$$Re = \frac{\rho \cdot u \cdot l}{\mu} \quad (11)$$

where ρ is the fluid density, u is the fluid velocity, l is the inner diameter of the pipe, and μ is the dynamic viscosity.

Table 3. Values of Re, I, k, ε

Parameter	Value
Reynolds number (Re)	5.64×10^5
Turbulence intensity (I)	0.03055 (3.055%)
Turbulent kinetic energy (k)	$1.8466 \times 10^{(-4)} \text{m}^2/\text{s}^2$
Turbulent dissipation rate (ε)	$1.0585 \times 10^{-5} \text{m}^2/\text{s}^2$

The transport equations for turbulent kinetic energy k and the turbulent dissipation rate ε are presented by Su et al. [24] as equations (12) and (13).

$$\begin{aligned} \frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho v k) = \\ = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k - \rho \varepsilon \end{aligned} \quad (12)$$

$$\begin{aligned} \frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho v \varepsilon) = \\ = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_1 \frac{\varepsilon}{k} G_k - C_2 \rho \frac{\varepsilon^2}{k} \end{aligned} \quad (13)$$

Initial and boundary conditions

The volume fractions imposed at the inlet and in the initial field were $\alpha_l = 0.9$ and $\alpha_v = 0.1$.

A uniform velocity corresponding to a mass flow rate of $\dot{m}=80$ t/h was imposed at the inlet. The mixture density was determined using equation (14) from the volume fractions and densities of the two phases listed in Table 2, resulting in a value of 824.84 kg/m^3 .

$$\rho_{mix} = \alpha_l \cdot \rho_l + \alpha_v \cdot \rho_v \quad (14)$$

The average velocity was calculated from the mass flow rate using equation (15), resulting in a value of 0.36263 m/s .

$$U = \frac{\dot{m}}{\rho_{mix}} \quad (15)$$

At the outlet, the modified hydrostatic pressure p_{rgh} was applied, corresponding to the final saturated state, as determined in Section 6, namely $p_{rgh} = 487,240 \text{ Pa(a)}$, which is associated with the final saturation temperature $T_2 = 150.86^\circ \text{C}$. At the inlet, the pressure is not imposed directly, but is

calculated by the OpenFOAM software within the pressure-velocity coupling. The local static pressure is obtained using equation (16) [29]:

$$p = p_{rgh} + \rho gh \quad (16)$$

The local density of the mixture is not constant, but depends on the local volume fractions of water and vapor, according to equation (13).

Control Zone and Monitoring of Flow Parameters

In addition to monitoring the inlet and outlet surfaces of the domain, a control zone was defined to analyze the variation of characteristic flow parameters in the vicinity of the elbow. This is shown in Figure 2, in the hatched area. Within this zone, the average values of the modified hydrostatic pressure p_{rgh} , velocity, and volume fractions of the liquid and vapor phases were monitored.

These parameters allow for the evaluation of the evolution of two-phase flow over time and provide information regarding the momentum variations of the mixture in the control zone. Based on these parameters, the redistribution of the phases in the vicinity of the elbow and its influence on the hydrodynamic forces transmitted to the pipe wall can be analyzed.

Determination of flow-generated forces

The forces exerted by the fluid on the wall were determined using the *forces* function in OpenFOAM, applied to the Wall patch. This function integrates the pressure and viscous shear stress values over the selected surface.

The forces exerted by the two-phase flow on the elbow wall were determined using the *forces* function in OpenFOAM, applied to the Wall patch. According to the OpenFOAM documentation [30], the total force consists of the pressure contribution determined according to equation (17) and the viscous contribution determined according to equation (18), calculated discretely on the faces of the patch. The *forces* function integrates these contributions at each sampling time, resulting in a time series of the total force on the elbow wall.

$$F_p = \sum_i \rho_i s_{f,i} (p_i - p_{ref}) \quad (17)$$

$$F_v = \sum_i s_{f,i} (\mu R_{dev}) \quad (18)$$

where i represents the faces of the patch, $s_{f,i}$ is the surface vector of the face, p_i is the pressure on the

face, p_{ref} is the reference pressure, ρ_i is the density factor used by OpenFOAM depending on the shape of the pressure field, μ is the dynamic viscosity, and R_{dev} is the deviatoric stress tensor.

9. DETERMINATION OF PIPE VIBRATIONS INDUCED BY TWO-PHASE FLOW

To evaluate the structural response of the pipe under the action of two-phase water–vapor flow, the results obtained from the CFD numerical simulation were used as input data in a one-way Fluid–Structure Interaction (FSI) structural analysis. In this approach, the flow field is determined by CFD analysis, and the resulting hydrodynamic forces are subsequently transferred to the structural model, without the structural response being fed back into the flow domain.

The 90-degree elbow used in this analysis, shown in Figure 5, is part of the piping system analyzed in the paper by Cotoban et al. [19]. In the structural model, the vertical axis was defined as the Y-direction, corresponding to the Z-direction in the CFD simulation; the horizontal X-direction of the structural model corresponds to the -X-direction, and the transverse Z-direction of the model corresponds to the Y-axis in the CFD simulation. Therefore, the force components obtained from the CFD simulation were transformed and applied to the structural model in accordance with the local coordinate system used in AutoPIPE.

The time-history analysis was defined as a dynamic loading case, using the time-dependent hydrodynamic forces obtained from the CFD numerical simulation. The total duration of the signal input into the structural analysis was 30 seconds, corresponding to the total duration of the CFD simulation.

Since the total force contains both an average component, associated with the static load, which is accounted for in the software's static analysis, and a fluctuating component, responsible for hydrodynamic excitation, the force signal was decomposed into the following form [31]:

$$F_i(t) = \bar{F}_i + F_i'(t) \quad (19)$$

where $F_i(t)$ is the total force in the i -direction, $\bar{F}_i$ is the mean component, and $F_i'(t)$ is the fluctuating component of the force.

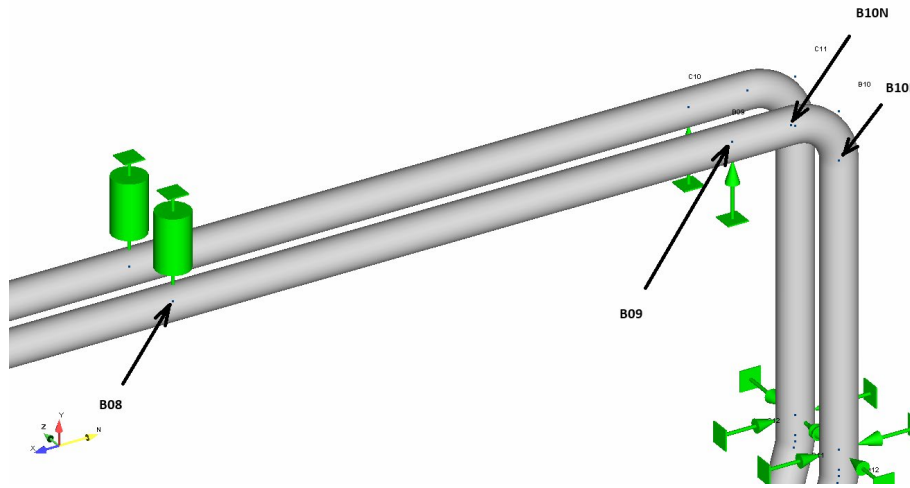


Figure 5. 90-degree elbow within the piping system

The mean component was calculated over the entire analyzed time interval, namely 0–30 seconds, according to the following equation:

$$\bar{F}_i = \frac{1}{N} \sum_{j=1}^N F_i(t_j) \quad (20)$$

The excitation force $F_i'(t)$ used in AutoPIPE software was determined from equation (19) for each force component, namely F_x , F_y , and F_z .

From a structural point of view, the response of the pipeline is governed by the general equation of motion for the discretized system:

$$[M]\{\ddot{d}(t)\} + [C]\{\dot{d}(t)\} + [K]\{d(t)\} = \{F(t)\} \quad (21)$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{d(t)\}$ is the displacement vector, $\{\dot{d}(t)\}$ is the velocity vector, $\{\ddot{d}(t)\}$ is the acceleration vector, and $\{F(t)\}$ represents the vector of forces applied over time.

The excitation forces in the form of a time history were applied at node B09, a node located downstream of the 90-degree elbow, as shown in Figure 5. To evaluate the local effect of hydrodynamic excitation, the displacements obtained in the elbow area and its vicinity were analyzed, specifically at nodes B08, B09, B10N, B10F, and B11.

10. RESULTS AND DISCUSSIONS

10.1 Interpretation of the two-phase flow results

Analysis of the resulting two-phase flow plots

The results obtained from the two-phase flow were processed using ParaView 6.1.0 software and are shown in Figure 6. These results are

representative of the 0.2, 1, 5, 10, 20, and 30-second time steps, respectively.

The graphical analysis shows that vapors tend to accumulate in the upper part of the pipe after the elbow. This is normal, given their lower density compared to the liquid phase. The kinetic energy of the flow is insufficient for the inertial forces to counteract the buoyancy force, favoring gravitational stratification.

Analysis of the resulting data

The dataset resulting from the transient simulation of two-phase flow, specifically, the history of the hydrodynamic forces exerted on the elbow wall, was processed using spectral analysis via the Fast Fourier Transform (FFT) [32]. This analysis was applied to identify the dominant components of the hydrodynamic response within the simulated time interval, according to equation (22).

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-i \frac{2\pi kn}{N}} \quad (22)$$

The resulting values are presented in Figure 7, where the time-dependent evolutions of the hydrodynamic forces and the corresponding FFT spectra for the three directions X, Y, and Z are summarized, with a spectral resolution of 0.033 Hz. The x-axis of the time-domain plots represents the effective duration of the transient simulation, namely 30 seconds.

It can be observed that the highest values of the hydrodynamic forces occur in the x and z directions, which correspond to the main flow directions in the elbow region. The F_y component has considerably lower values, indicating that the lateral stress is smaller compared to the stresses in the main flow plane.

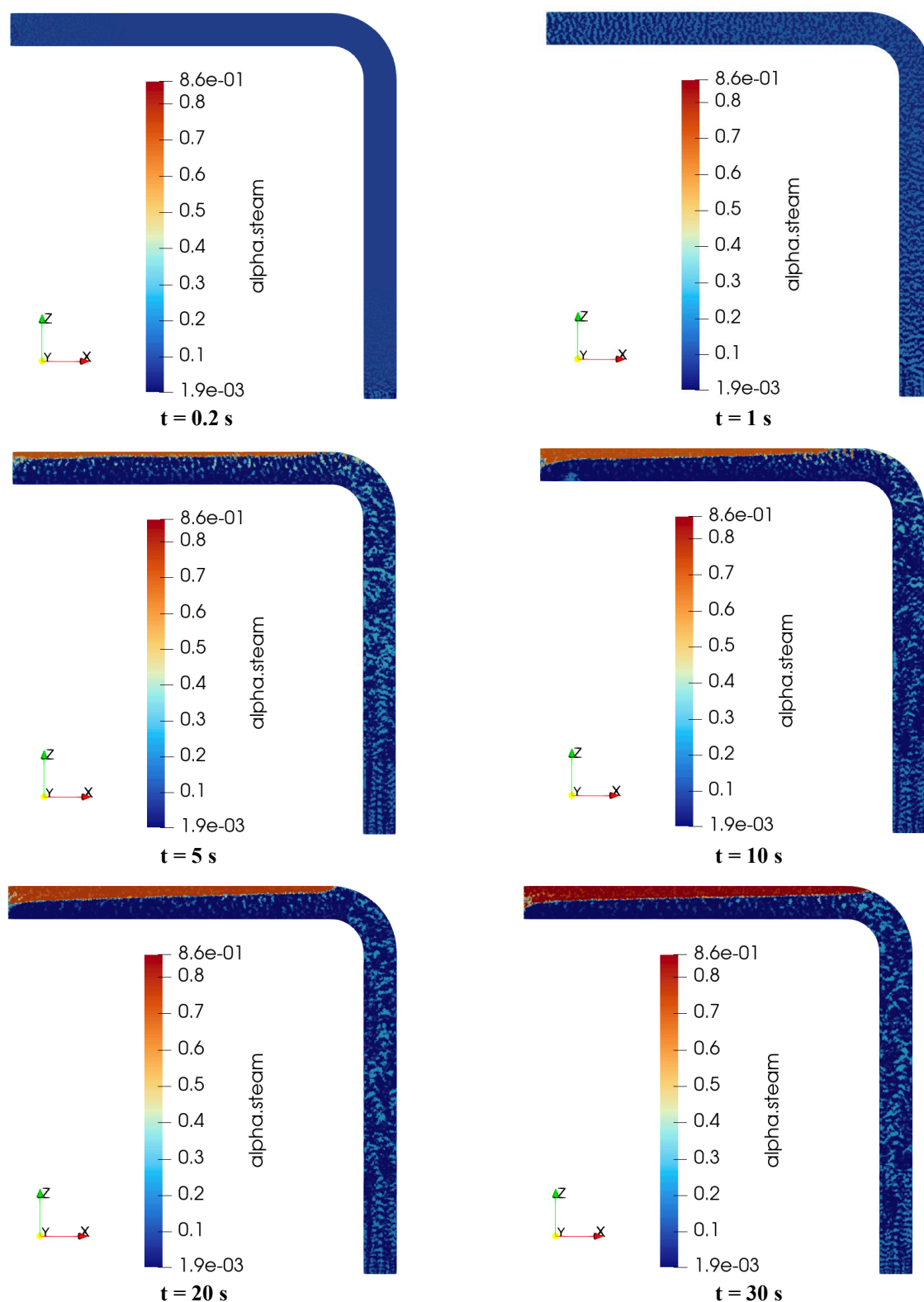


Figure 6. Simulation model $t = 0.2\text{s}$, $t = 1\text{s}$, $t = 5\text{s}$, $t = 10\text{s}$, $t = 20\text{s}$, $t = 30\text{s}$

The F_z component shows a marked decreasing trend starting approximately at $t = 3\text{ s}$. This evolution can be associated with the redistribution of the vapor phase and its accumulation in the upper part of the pipe after the elbow. Since the density of the vapor is much lower than that of the liquid, the local increase in the vapor volume fraction leads to a

reduction in the local density of the mixture and, consequently, to a change in the hydrodynamic forces transmitted to the pipe wall.

The FFT analysis indicates that the dominant amplitudes of the forces are concentrated in the low-frequency range, particularly in the interval approximately $0\text{--}0.25\text{ Hz}$, for all three components.

Outside this range, the spectral amplitudes decrease significantly, with values generally in the order of tens of Newtons or lower.

By comparing these results with the natural frequency range reported by Cotoban et al. [19], namely 0.4892–1.7564 Hz, it can be observed that the dominant excitation frequencies remain below the first reported natural frequency of the piping system, 0.4892 Hz. The present results do not indicate a direct resonance condition. However, low-

amplitude spectral components outside the dominant range may still contribute to the structural response if their frequencies approach or overlap with one of the natural vibration modes [33,34] of the pipeline system.

The possibility of structural response amplification should be further investigated for other operating conditions that may generate spectral components closer to the natural frequencies of the pipeline.

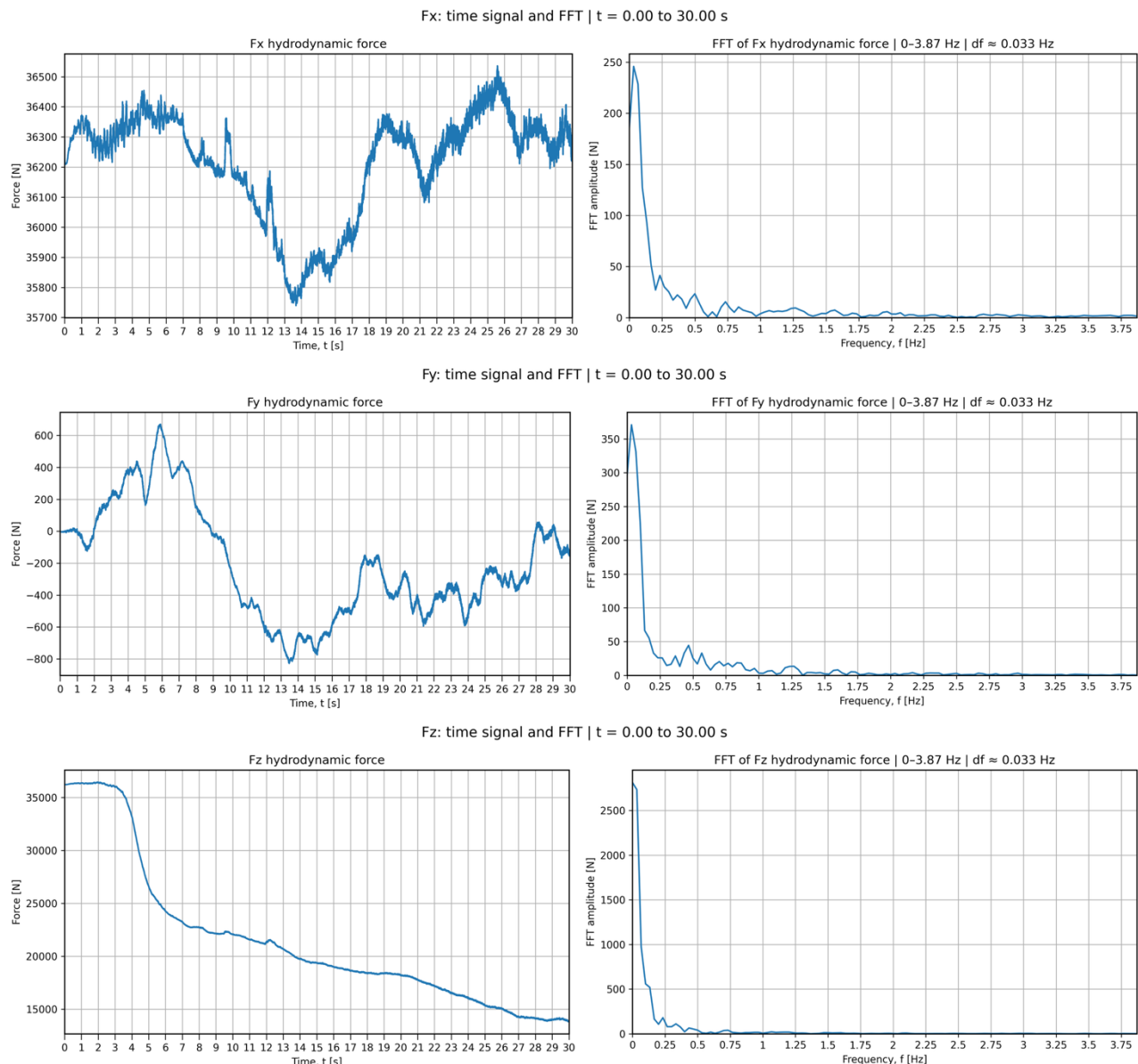


Figure 7. Time-history plots of the hydrodynamic forces and FFT spectra along the x, y, and z axes

The initial vapor volume fraction was set to $\alpha_v = 0.1$. As shown in Figure 8, the vapor fraction fluctuates both at the inlet and at the outlet of the control zone. At the inlet, a general downward trend in the vapor fraction is observed toward the end of the analyzed interval, while at the outlet, a progressive increase relative to the initial value is observed. This difference indicates the

redistribution of the vapor phase within the computational domain and the local accumulation of vapor in the elbow region and especially downstream of it, as also highlighted in Figure 6 at $t = 30$ s.

Analysis of the power spectral density (PSD) of the vapor volume fraction indicates a concentration of fluctuation energy in the low-frequency range,

particularly in the 0–0.25 Hz interval, both at the inlet and at the outlet of the control zone. Results showing the same trends were also obtained for the

average values of the modified hydrostatic pressure p_{rgh} , velocity, and volume fractions of the liquid phase at the inlet and outlet sections.

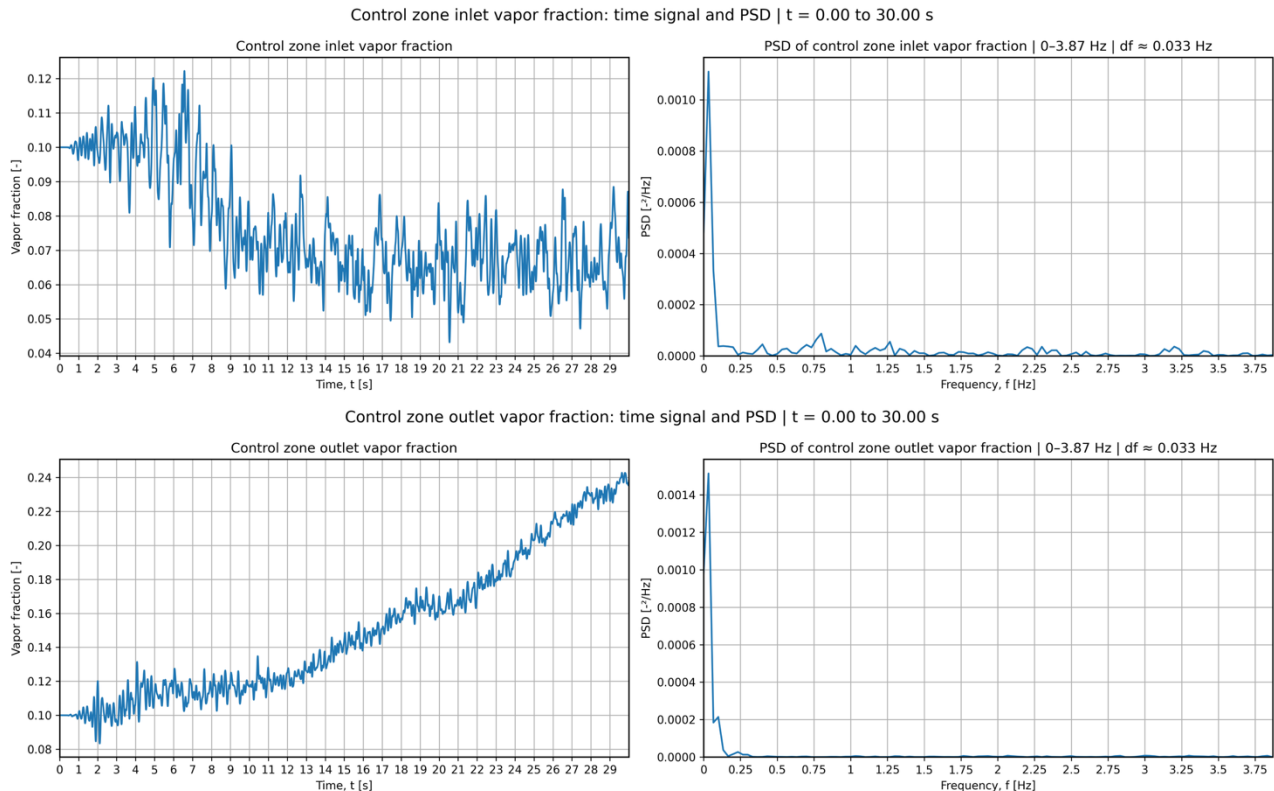


Figure 8. Vapor fraction control zone and spectral power density analysis

10.2 Interpretation of fluid-structure interaction results

The resulting maximum displacements are on the order of millimeters, as can be seen in Table 4. Figure 9 shows the time evolution of the translations in node B09 in the three directions, for the total duration of the analysis of 30 seconds.

Table 4. Maximum displacements in the elbow region

Node	X Displacement [mm]	Y Displacement [mm]	Z Displacement [mm]	Resultant [mm]
B08	0.68	0.35	0.58	0.960
B09	0.68	0.00	1.31	1.476
B10N	0.68	0.06	1.34	1.504
B10F	0.59	0.13	1.15	1.299
B11	0.00	0.13	0.00	0.130

It should be noted that the hydrodynamic excitations obtained from the CFD simulation were applied to a single elbow of the piping system, specifically in the area where the local effect of two-phase flow on the structural response was investigated. However, the structural model used

[19] in AutoPIPE represents a much more extensive and complex piping system than the analyzed CFD domain. Performing a two-phase CFD simulation for the entire piping system would require very high computational power.

Based on the graphs in Figure 9, in node B09, the displacement in the X direction had a positive maximum of approximately 0.676 mm at $t=13.95$ s and a minimum of approximately -0.406 mm at $t=25.53$ s. In the Z direction, the maximum positive displacement was approximately 1.305 mm at $t=5.965$ s, and the minimum displacement was approximately -0.894 mm at $t=13.55$ s. As shown in Figure 9, the displacement in the Y direction at point B09 is practically negligible, with values of the order of 10^{-8} mm. Therefore, the structural response at this point occurs predominantly in the X–Z plane.

Therefore, the structural response obtained from the Time History analysis is dominated by displacements in the Z and X directions. This behavior is determined by the geometric orientation of the elbow, the main flow direction, and the way in which the redistribution of the fluid momentum in the elbow region generates variable components of the hydrodynamic force.

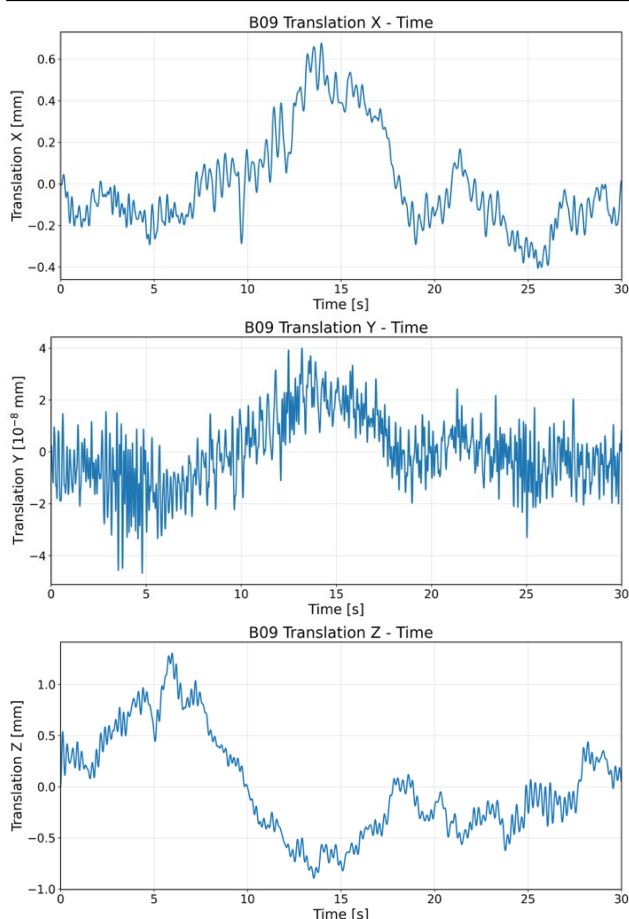


Figure 9. Translations of node B09 along the 3 axes

The results indicate that the fluctuating forces generated by the two-phase flow through the elbow produce a transient structural response on the order of millimeters. The largest displacements occur in the elbow region and its immediate vicinity, particularly in the Z direction. This observation shows that the change in flow direction at the elbow, together with the redistribution of momentum of the water–vapor two-phase mixture, contributes to the structural excitation of the pipe.

The relatively small displacement values can be explained by the relatively low flow velocity and the stiffness of the analyzed pipeline system. However, even displacements on the order of millimeters can become significant during prolonged operation, as the cyclic stress produced by hydrodynamic excitations can contribute to the accumulation of fatigue damage. This effect can be particularly significant in sensitive areas of the system, such as welds, supports, bends, connections, and areas with stress concentrations.

11. CONCLUSIONS

The results obtained highlight the fact that, in the case of two-phase water–vapor flow through the analyzed elbow, the hydrodynamic forces

developed on the pipe wall exhibit a transient nature, determined by the redistribution of the phases and the local variation of the vapor volume fraction.

The one-way FSI analysis performed by transferring the hydrodynamic forces obtained from the CFD numerical simulation to the structural model allowed the determination of the pipe's transient response under the action of the excitations produced by the two-phase flow. The forces introduced into the structural analysis were the fluctuating components of the hydrodynamic forces, obtained by removing the average component calculated over the 0–30 s interval. Through this approach, the time history analysis highlighted how the variations of the forces in the elbow region can produce structural displacements.

As future work, the analysis can be extended by performing additional simulations in order to assess the suitability of different turbulence models for the analyzed two-phase flow, together with improvements in model discretization and mesh independence/ grid sensitivity analysis for different vapor volume fractions.

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