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Impact of elbow angles on Flow-Induced Vibration in Crude Oil Pipelines

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Abstract

Pipelines carrying fluids are primarily used in oil and gas industry. These pipelines may experience vibrations caused by high-pressure fluctuations in fluids, leading to a turbulent flow scheme. High vibration level poses a serious risk to the pipeline system, as it could cause pipes to vibrate intensely, severely impairing fatigue cracking. The interaction between the fluid and the structure leads to what is known as flow-induced vibrations (FIV). In this paper, a one-way FIV numerical analysis was conducted using ANSYS® Workbench, by modeling flow in elbows with different angles. Elbows are one of the critical parts along a pipeline, as they are mainly used to redirect fluid flow direction. The data regarding the pipe and the crude oil specifications are based on information received from Mellitah Oil and Gas Company. Stress, modal, and CFD analyses were carried out on elbows with three different angles. Two quite distinct flow velocities are considered, one representing the standard flow, and the other representing an extreme case of high flow velocity. Due to this extreme case, changes in modal parameters, in stress, and in deformations were observed along the pipes. This study emphasizes the importance of geometric features and the effect of sudden changes in fluid flow velocity on pipeline structures.

Keywords: Flow induced vibration, pipelines, crude oil, static analysis, modal analysis.

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تأثير زوايا الأكواع على الاهتزازات المستحثة من التدفق في خطوط أنابيب النفط الخام

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الملخص:

تُستخدم الأنابيب لنقل السوائل بشكل رئيسي في صناعة النفط والغاز. قد تتعرض هذه الأنابيب لاهتزازات ناتجة عن تأرجح في قيم الضغط العالية في السوائل، مما يؤدي إلى نظام تدفق مضطرب. يُشكل مستوى الاهتزاز العالي خطرًا كبيرًا على نظام الأنابيب، حيث يمكن أن يتسبب في اهتزاز الأنابيب بشدة، مما يؤدي إلى تصدعات خطيرة ناتجة عن الاجهاد المتكرر. التفاعل بين السائل والهيكل يؤدي إلى ما يُعرف بالاهتزازات الناتجة عن التدفق (FIV). في هذه الدراسة، تم إجراء تحليل عددي أحادي الاتجاه للاهتزازات الناتجة عن التدفق (FIV) باستخدام برنامج ANSYS® Workbench ، من خلال نمذجة التدفق في الأنابيب المنحنية ذات زوايا مختلفة وهي 45°، 90°، و135°. الأكواع (elbows) تعتبر من الأجزاء المهمة في خطوط الأنابيب، حيث تُستخدم بشكل رئيسي لتحويل اتجاه تدفق السائل من اتجاه لآخر. استخدمت الدراسة بيانات ومواصفات أنبوب النفط الخام الخاص بشركة مليتة للنفط والغاز، حيث تم إجراء تحليلات الإجهاد (stresses)، الطور(modal) ، وتحليلات ديناميكا السوائل الحسابية (CFD) لثلاثة زوايا مختلفة للأكواع وسرعتين مختلفتين للتدفق، الأولى تمثل التدفق القياسي، بينما الأخرى تمثل حالة متطرفة ذات سرعة تدفق عالية. نتيجة لهذه الحالة المتطرفة، تم ملاحظة تغييرات في كل من معلمات الاطوار، الإجهادات، والتشوهات على طول الأنبوب. تُبرز هذه الدراسة أهمية الخصائص الهندسية وتأثير التغيرات المفاجئة في سرعة تدفق السائل على بنية الأنابيب.

الكلمات المفتاحية: الاهتزازات الناتجة عن التدفق، خطوط الأنابيب، النفط الخام، التحليل الاستاتيكي، تحليل الأطوار.

1. Introduction

Pipelines carrying fluid may experience undesired vibrations and suffer from serious stresses due to because of vibrations and stresses

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causes by Flow Induced Vibration (FIV). These would affect the performance, safety and service lifetime of these pipelines. Thicker fluid, with high mass density, would have higher effects than gas, for instance, due to its mass. The main cause of FIV is the instability of fluid flow, where flow velocity fluctuations may occur due to high pressure or velocity differences, thus resulting into turbulent fluid flow [1]. The natural frequencies of the pipeline structure, and its dynamics in general, should fall between specific limits to prevent unwanted operational conditions. FIV may result in resonances and fatigue failure problems [2], thus the goal is to prevent these from happening during the design and operation stages. This is mainly a concern in pipelines used oil & gas industry, where crude oil is the transported fluid. The pipeline system usually contains straight-line line, elbows of different types, valves, strainers, and few apparatuses along the line. All these are potential causers of FIV problem [3]. When a fluid encounters unbalanced forces owing to pressure gradients, substantial pressure differences are the cause of vortices, which in turn cause turbulence and undesired structural vibrations [4]. The FIV studies dates back to the early 20th century, where the first notable event that spurred significant research was the collapse of Tacoma Narrows bridge in 1944 due to aeroelastic flutter. Later on, and due to advancement in computational fluid dynamics, more detailed studies surged, where few are mentioned in what follows.

Y L Zhang, D G Gorman and J M Reese [5] derived the dynamic equilibrium matrix equation for a separate pipe element holding a flowing fluid using the Lagrange principle and the Ritz approach. The Eulerian approach and the concept of fictitious loads were used for kinematic correction to evaluate nonlinear geometric vibrations and produce a linear mathematical model. The vibratory behavior of a fluid was then investigated. The findings of the linear vibration model for fluid pipes and the experimental data were compared about pipe transit. Additionally, vibration issues with first-stretched fluid-conveying pipes were investigated at different pipe starting axial tensions and flow rates. Peter Vasilyev and Leonid Fromzel [6] gave a thorough study that examined the state of pipe vibration analysis. The most likely source of vibration caused by flow was thought to be the acoustic resonance of the medium (water or steam). The mathematical model and related computer code, NETPULS, were designed for the assessment of an acoustic oscillation in a liquid or gaseous medium. Acoustic excitation, that

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might occur in pipelines, was investigated. The outcome of NETPULS software was used to assess mechanical vibrations in the pipeline. R. Veerapandi et al. [7] addressed the computational and analytical analyses a FIV in a pipeline. The fluid dynamic behavior mainly in angular type valve regions was explored and the modal analysis of the pipe system was examined. The analysis of FIV was carried out by examining the turbulence in the gas flow within the piping system during subcooling. CFD analysis was conducted using Ansys® CFX solver. Yu Jiang and Lei Zhu [8], under the interplay between the fluid and the structure, examined the same issue of a pipeline filled with fluid. A v-shaped pipeline was investigated using Ansys® software. An experimental study was also conducted using liquid-filled pipeline, where frequency measurements were taken and the simulation model was adjusted accordingly to validate it. It was demonstrated that pressure has very little influence on natural frequencies and that the natural frequency of a loaded pipeline reduces dramatically when compared to an empty one, due to extra mass of the fluid. According to the simulated modal analysis, the mode shapes of the pipeline full with liquid and the pipeline empty have the same mode shapes for the first six natural frequencies, but then differ. The simulation model worked as a replica for the experimental model with certain level of accuracy. Etim S Udoetok [9] created a model studying the vibrations brought on by internal fluid movement through pipes. The model was created for situations in which a free pipe section ends are clamped and when they are merely supported. The methodology combined engineering analysis and complicated mechanics to produce new, straightforward equations that compare positively. These equations were verified experimentally with acceptable agreement.

Manoj Dangal and Subodh Kumar Ghimire [10] looked at the vibrations in pipes carrying fluids with various end condition configurations and materials. The mathematical formula for the vibration caused by flow in fluid-conveying pipes was created by adopting Hamilton's energy concept. The vibratory characteristics of the fluid utilized in the pipe were studied using FEA. It was found that increasing fluid velocity had the dual effects of increasing damping and reducing hardness. As a result, when fluid flow speed increased, the fundamental vibration frequency dropped. The crucial flow speed is the flow rate, which corresponds to the fundamental vibration frequency. The obtained results could be

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used to reduce vibration-related failures in systems such as HVAC pipe installations, petroleum transportation, and other related sectors. Kamal Haziq and Izzuddin Zaman [11] conducted a study to utilize both one-way and two-way fluid-structure interaction (FSI) techniques to examine the effects of internal pipeline faults on the fluid flow pressure drop and velocity profile. The FSI multiple analysis system, which includes transient structural analysis, fluent analysis, and system coupling, is implemented using the ANSYS® workbench. The mutual interaction between the fluid domain and the pipe structure was studied using the two-way coupling approach. Laminar flow and turbulent flow were used to calculate the structural deformation, structural velocity, von Mises stress, and pressure of the fluid. This study demonstrated that as the fluid input velocity rises, the pipe overall deformation, velocity distribution, and von Mises stresses increases accordingly. The results in both situations showed that, in comparison to the problematic flow, the two-way savory flow had distortions, speeds, strains, and pressures far greater than the pipe structure.

2. Model Description

To assess the impact of change in crude oil flow velocity in a pipeline, three elbows with angles of 45^o, 90^o, and 135^o are used. This analysis focuses on demonstrating the effect of fluid flow on the static and dynamic responses of the elbows. The structures are composed of two pipes, each of 3 m length, connected at one of the three angles mentioned before. An extra 0.1m span is used as a fixing area to model displacement constraint at the two ends, as illustrated in Fig. 1 and Fig. 2. All elbows have a radius of 350 mm. The pipes have an internal diameter of 0.1m, wall thickness of 3mm, and made of Nickel alloy Inconel 600. This alloy is typically employed in the Libyan Mellitah oil & gas company, and is used for transporting crude oil due to its known excellent corrosion resistance, high-temperature strength, oxidation resistance, and high tensile strength. The mechanical properties of Nickel alloy Inconel 600 are as given in Table and Table 2.

Table 1. Properties of the Nickel alloy.

Young's modulus	Mass density	Ultimate tensile strength	Yield tensile strength	Poisson ratio
210 MPa	8474 kg/m^3	800 MPa	500 MPa	0.3

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Table 2. Properties of the crude oil used. (source: Mellitah oil&gas Co.)

Mass density	Viscosity
850 kg/m^3	1.275 kg/m.s

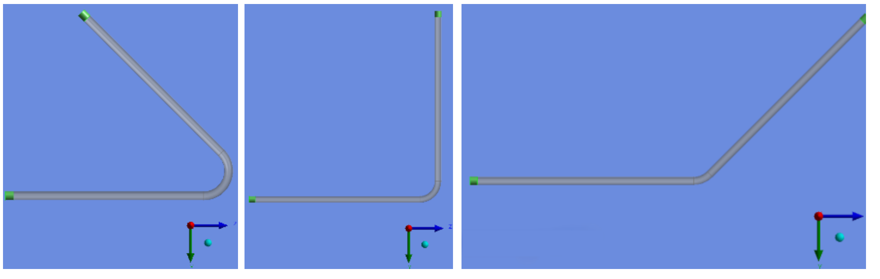

Fig. 1. The elbows structural models with angles 45^o, 90^o and 135^o.

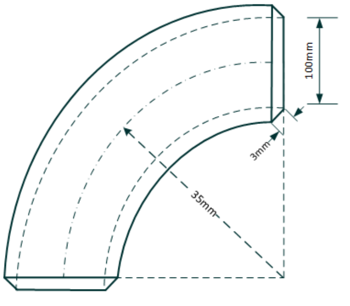

Fig. 2. Descriptive diagram of the elbows.

The ANSYS® analysis model was developed as follows: the geometry was first built, then transferred to the CFD module where pressures on internal surfaces are calculated, then transferred to the static module where stresses and deformations are calculated, then to the modal analysis module with prescribed load imported from the CFD analysis (prestressed model), and finally to the modal analysis module without the effect of fluid loads. In what follows, the obtained results are analyzed for two scenarios: one representing the standard velocity of crude oil flow of 4m/s, and the other representing the extreme case of high flow velocity of 20m/s.

3. Simulation results and discussion

The first section of results deals with structural modal analysis of the unstressed structures, i.e., zero effect of fluid velocity is

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considered, thus allowing to observe the effects of fluid pressure presence and investigate its consequences. A structural modal analysis is conducted on the unstressed model and the only the first three mode shapes are demonstrated in Fig. 3. Most of these mode shapes are characterized by a deflection of pipe spans. The first 20 natural frequencies are calculated for the sake of comparison in the following sections.

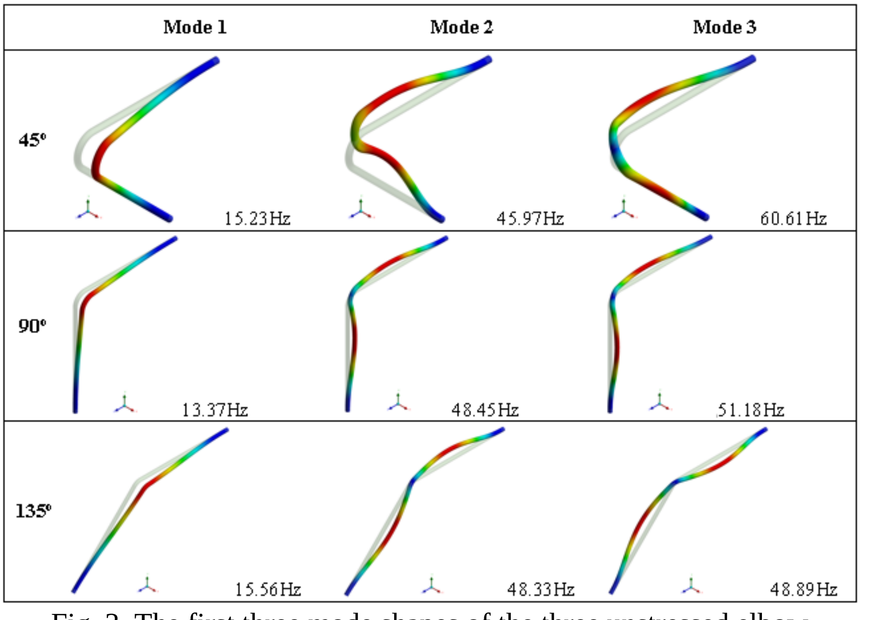

Fig. 3. The first three mode shapes of the three unstressed elbow structures.

The second section of results illustrates the three analyzed modules: fluid flow dynamic analysis, stress and deformation analysis, and prestressed modal analysis. The first part demonstrates the results of a fluid flow velocity of 4 m/s. This is selected as an average of crude oil f in pipelines. The second part illustrates the extreme flow velocity of 20 m/s. The case of this extreme velocity could be originated due to wrongful operation of valves thus creating high pressure gradients, or due to faulty pipeline design. In certain scenarios like short pipelines or during pigging operations, the velocity might temporary be elevated to these values [12].

3.1 Due to flow velocity of 4 m/s

3.1.1 Fluid flow model (CFD model)

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These models (with the three different elbow angles) comprise the structure and the fluid domain filled with crude oil. The meshing was performed with an average element size of 0.05m, resulting in ~17364 nodes and ~2472 elements. The mesh sizes were sufficient to obtain converging and stable solutions. A fluid input velocity of 4 m/s was used as a boundary condition, with the fluid entering the pipe at one end. A zero-gauge pressure condition was imposed at the other end.
The velocity profiles inside each of the three pipes, resulting from laminar crude oil flow, are illustrated in fig 4.
. The velocity distribution near the relaxed elbows exhibits higher values due to lower flow resistance.

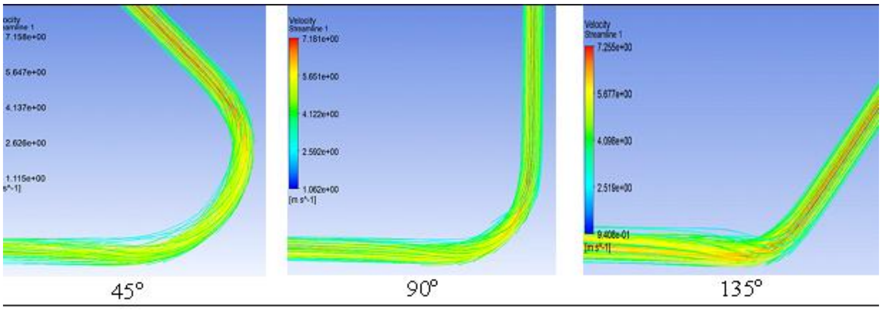

Fig. 4. Flow velocity distribution inside the three elbows: v=4 m/s.

3.1.2 Static analysis of the prestressed model

Due to fluid flow velocity, the pressure is formed and stresses are exerted by the fluid on the inner walls of the elbow structures. To find the resulting stresses on the inner walls, a static analysis is performed using loads imported from the fluid domain model (CFD model). These loads originate from the pressure profile acting on the inner walls of the pipeline. The same mesh used for the unstressed modal analysis is used here. The equivalent stresses and total deformations are calculated.
This stage is crucial for investigating the effects of fluid flow on the structure, which is essential in the design stages of pipelines manufactured for transporting crude oil. It is important to note that the only loads present in this model are due to fluid flow pressure. Fluid dynamics indicate that sharp angles are expected to have higher pressure exerted on their internal walls compared to flat or more relaxed angles. This could clearly be observed in Fig. 5 (a, b and c). The stress distribution is higher at the sharp 45° elbow,

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compared to the other two, and is minimum at the outlet, as per the boundary condition.

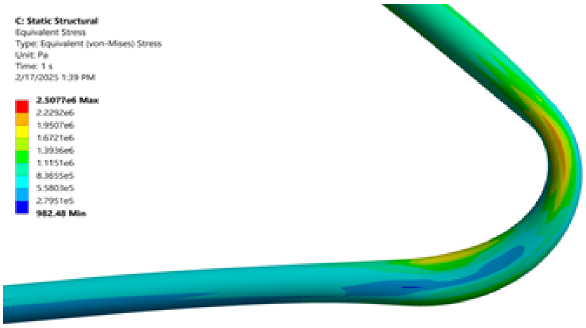

Fig. 5(a). Stress distribution inside the 45^o elbow: v=4 m/s.

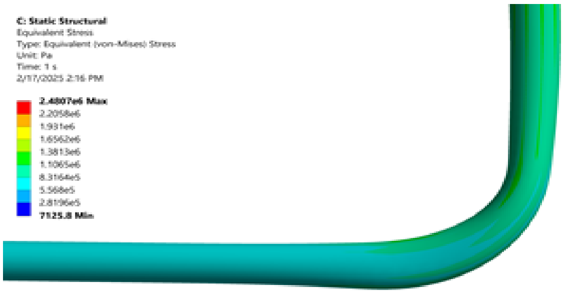

Fig. 5 (b). Stress distribution inside the 90^o elbow: v=4 m/s.

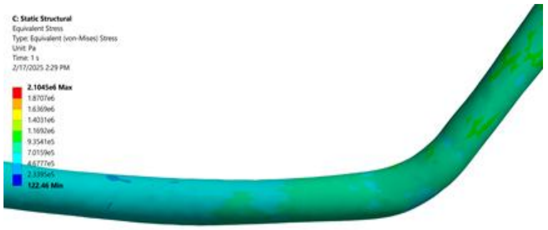

Fig. 5(c). Stress distribution inside the 135^o elbow: v=4 m/s.

3.1.3 Modal analysis of the prestressed model

This step is crucial to study the impact of the stresses generated by crude oil flow in the pipeline on the dynamic behavior of the entire structure. The loads from the CFD model are imported into this modal analysis. The first 20 natural frequencies are calculated for the sake of comparison in what follows. In general, the maximum change in natural frequencies is found at the elbow angle of 45^o, as

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expected, although the change is very low (less than 1%), due to low flow velocity.

3.2 Due to extreme flow velocity of 20 m/s

3.2.1 Fluid flow model (CFD model)

The same models are run again with the same finite element size and mesh, but with crude oil fluid entering the elbow at 20 m/s. The velocity profiles inside each of the three elbows are illustrated in Fig.6 خطأ! لم يتم العثور على مصدر المرجع.(a, b and c). The velocity distribution near the more relaxed elbows exhibits higher changes, as pipe wall resistance is lower.

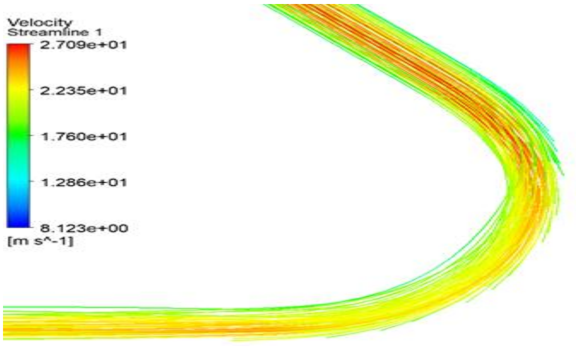

Fig. 6(a). Flow velocity distribution inside the 45° elbow: v=20 m/s

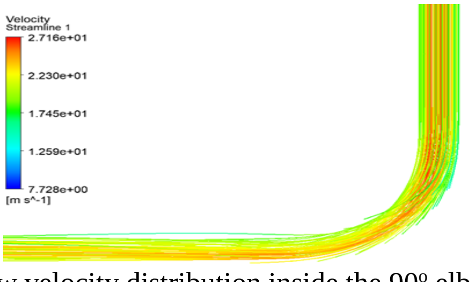

Fig. 6(b). Flow velocity distribution inside the 90° elbow: v=20 m/s

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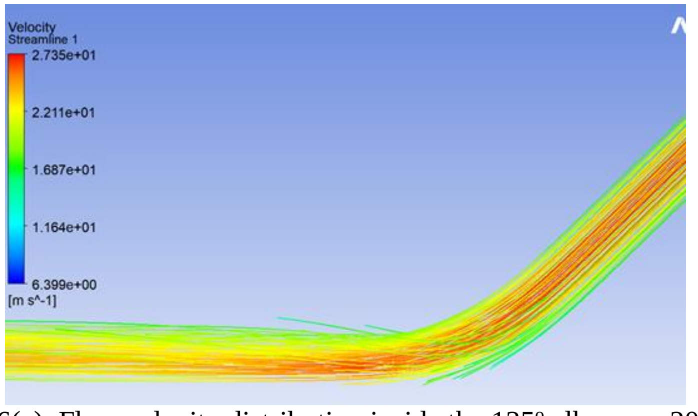

Fig. 6(c). Flow velocity distribution inside the 135° elbow: v=20 m/s

3.2.2 Static analysis (prestressed model)

The velocity profile is transferred to the structures, and the static analysis model is solved using loads imported from the CFD solution. The same mesh is again used, and the equivalent stresses and total deformations are calculated. This is conducted to investigate the effects of fluid flow on the structure. The only loads present in this model are due to fluid flow pressure. The stress distribution inside the three elbows are demonstrated in Fig. 7 خطأ! لم يتم العثور على مصدر المرجع.(a, b and c). The stress distribution is higher at the sharp 45° elbow, compared to the other two.

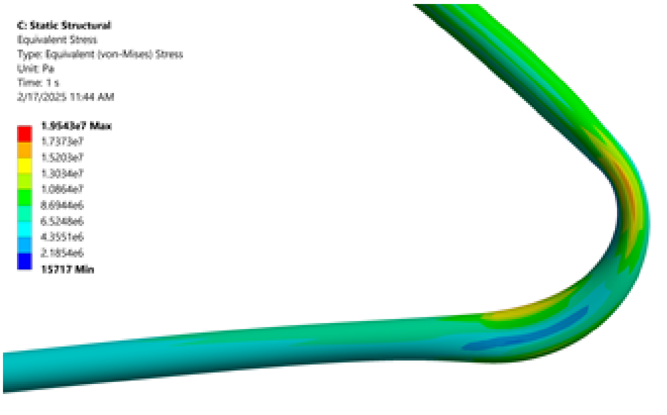

Fig. 7(a). Stress distribution inside the 45° elbow: v=20 m/s.

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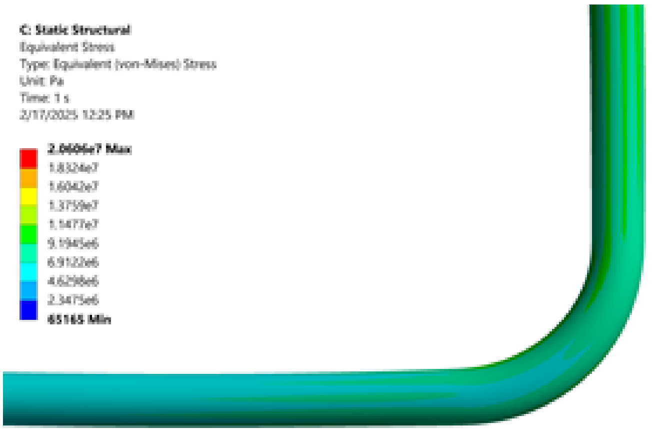

Fig. 7(b). Stress distribution inside the 90° elbow: v=20 m/s.

Fig. 7(c). Stress distribution inside the 135° elbow: v=20 m/s.

3.2.3 Modal analysis (prestressed model)

A modal analysis was again run for the flow velocity of 20 m/s. The impact of the stresses generated by crude oil flow in the pipeline on the dynamic behavior of the three elbows was investigated. The first 20 natural frequencies are calculated for the sake of comparison, as shown in the following section. In general, the maximum change in natural frequencies was found at the 45° elbow, with a maximum change of about 5%.

3.3 Comparison of obtained results

The main cause of FIV is the load resulting from fluid flow. This load, in the form of prestresses, greatly varies with flow velocity. The flow velocity of only 4 m/s resulted in an equivalent maximum stress of 2.5077e6 Pa inside the pipe with the 45° elbow, also with a

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maximum deformation of 3.7728e-5 m, compared to the other elbows of 90° and 135°. As for the analysis with an increased flow velocity of 20 m/s, an equivalent maximum stress of 1.9543e7 Pa inside the pipe with the 45° elbow, also with a maximum deformation of 2.9492e-4 m, when compared to the other elbows of 90° and 135°.

The changes in natural frequencies due to the flow velocity are observed to be very low for the case of the 45° elbow with a flow velocity of 4 m/s. The maximum change was ~0.63% in the 20th mode shape frequency, which could be considered negligible. For the other two elbows, the changes in natural frequencies were almost zero.

The case with a higher flow velocity of 20 m/s seems to be the critical case. The changes in natural frequencies for each type of elbow are illustrated in Table 3 for the first 12 mode shapes. The change in natural frequency is observed in the 45° elbow case, hitting a maximum of ~5%, see Fig. 8. These changes are due to prestresses originating from the flow velocity, which modify the dynamic behavior of the structure. All these analyzes are conducted considering a laminar flow pattern. Higher changes could probably be expected for a turbulent flow pattern.

Table 3. Natural frequencies for the three elbows under flow velocity of 20 m/s.

No	45° elbow			90° elbow			135° elbow		
	Unstr. (Hz)	Str. (Hz)	Diff.%	Unstr. (Hz)	Str. (Hz)	Diff.%	Unstr. (Hz)	Str. (Hz)	Diff.%
1	15.23	15.20	0.024	13.374	13.377	-0.003	15.566	15.609	-0.043
2	45.97	46.15	-0.180	48.453	48.572	-0.119	48.338	48.441	-0.103
3	60.61	60.71	-0.10	51.188	51.295	-0.107	48.899	49.002	-0.103
4	81.22	81.44	-0.22	64.135	64.359	-0.224	64.3	64.405	-0.105
5	93.82	93.92	-0.10	76.926	77.04	-0.114	81.331	81.437	-0.106
6	142.64	143.13	-0.49	151.07	151.29	-0.220	152.84	152.96	-0.120
7	157.23	157.66	-0.43	154.59	154.8	-0.210	153.56	153.68	-0.120
8	239.06	239.34	-0.28	185.06	185.32	-0.260	161.06	161.18	-0.120
9	256.0	256.17	-0.16	205.34	205.46	-0.120	197.78	197.89	-0.110
10	307.9	308.53	-0.58	296.9	297.39	-0.490	267.47	267.54	-0.070
11	319.4	320.01	-0.60	302.66	303.16	-0.500	310.74	310.86	-0.120
12	447.7	449.94	-2.24	344.75	344.86	-0.110	312.52	312.65	-0.130

No = number of mode Unstr. = Unstressed Str. = Stressed Diff. = Difference %

The data in Table 3 is illustrated in Fig. 8 (a,b,and c) for clarity for all the first 20th node shapes. Lower changes in natural frequencies are observed for lower mode shapes, but in general the higher mode shapes are more susceptible to changes.

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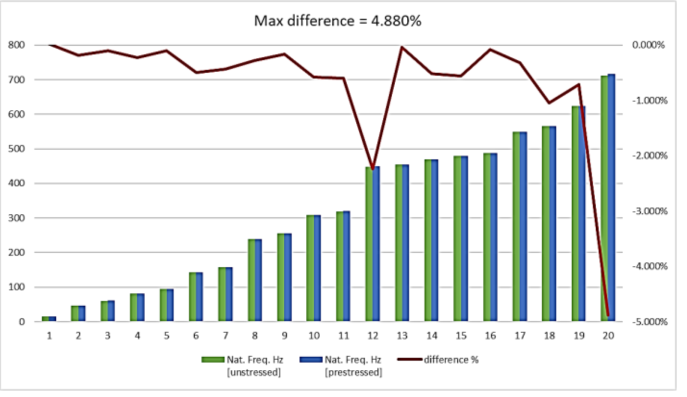

Fig. 8. (a) The changes in the first 20 natural frequencies (unstressed vs stressed models) due to flow velocity of v=20 m/s, for the 45^{o} elbow.

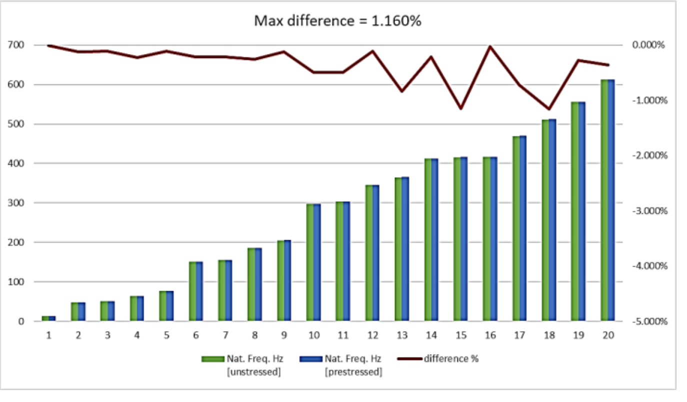

Fig. 8. (b) The changes in the first 20 natural frequencies (unstressed vs stressed models) due to flow velocity of v=20 m/s, for the 90^{o} elbow.

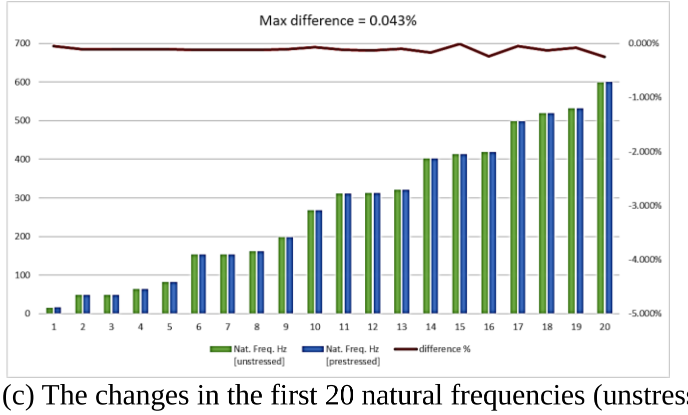

Fig. 8. (c) The changes in the first 20 natural frequencies (unstressed vs stressed models) due to flow velocity of v=20 m/s, for the 135^{o} elbow.

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4. Conclusions

Flow-induced vibration (FIV) was analyzed in three types of pipe elbow structures commonly used in the oil and gas industry for crude oil transportation. At lower flow velocities, the impact on creating prestressed structures was minimal, with only slight effects on their dynamic behavior. In contrast, higher flow velocities resulted in significant changes in the structure's dynamic response. These behaviors were studied within a laminar fluid flow pattern, where sharper elbow angles were found to have a greater influence on natural frequencies. Furthermore, higher flow velocities caused notable changes in modal parameters, stress distribution, and structural deformations along the pipeline. At elevated flow velocities or under large vibration amplitudes caused by prestressed structures, nonlinear effects could become prominent, leading to complex dynamic behavior. This highlights the importance of studying pipelines with longer extensions and various elbow configurations, as these are likely to show substantial changes in natural frequencies and mode shapes due to FIV. Future analyses should focus on examining these phenomena under turbulent flow conditions for a more comprehensive understanding.

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The Authors declare that there is no conflict of interest.

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