INVESTIGATION OF CRACK GROWTH BY LOADING FATIGUE DUE TO FLUID AND STRUCTURAL COUPLING VIBRATIONS IN THE JOINT OF THERMOWELL WELDING IN GAS PIPELINE

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Abstract

One of the types of damage in structures is cracking, which leads to many failures when it initially starts to grow. The aim of this project is to investigate the growth of fatigue cracking at the joint of thermowell welding to the main pipeline. Thermowell is used to measure fluid flow temperature. Methane gas flows in the main pipeline, which creates vibration in the pipe. In this study, the problem is divided into two parts. Initially, the problem of fluid coupling and structure is solved and the range of displacement is obtained in the welding section. In the second stage, by creating the initial crack with a length of 1 mm, this range is periodically attributed to the welding section. And crack growth diagrams are obtained with respect to time and the effect of frequency on the stress contour. The results show that the growth rate increases with increasing frequency. Therefore, by changing the geometry of the thermowell and reducing its frequency, it reduced the rate of growth of damage in the weld. Decreasing the thickness of the shell and reducing the diameter of the thermowell reduces the frequency, but increases deformation and failure.

Keywords: Vibration, Weld, Fluid-Structure Interaction, Crack, Thermowell.

1 Introduction

Various tools such as valves, gauges, etc. are installed on oil, gas, etc. pipelines to control and monitor. Thermowells are one of these devices that are used to measure fluid flow temperature. Part of the thermowell is placed inside the pipeline to measure the temperature, the geometry of which is a cylindrical or incomplete cone. The collision of fluid flow with this part causes vibrations and fatigue in different parts of the thermowell (including thermowell, outlet, weld, flange). It is necessary to study the vibrations of the thermowell and the effect of geometry on the vibrations and fatigue of its various parts in the form of fluid and structural couplings. The FSI is a multifaceted problem in a system in which fluid flow leads to a change in solid structure and, on the other hand, a change in the solid form, leads to a change in the boundary conditions of the fluid problem. For instance, the airflow around the wing of the plane leads to change the shape of the wing (though partially), which will subsequently change the air flow pattern around the wings. In general, a FSI system can be considered as a weakly coupled or strongly coupled. If the internal structure

or fluid contains a change in the solid structure, a slight pressure is transferred to the field of flow and thus an insignificant deformation of the fluid flow can be detected; these systems are known as weakly coupled systems. In our subject, the piping issue is of this kind of FSI. In 2004, Michler [1] compared the discrete and continuous solving methods for numerical simulation of a fluid-structure interaction. The evaluation of the accuracy of these methods has shown that their cost and computational efficiency are also compared. In a discrete method at any time step, only a repetition of the fluid-structure interaction is required, resulting in a lower computational cost than the continuous method at any time step. In contrast to the discrete (component) method, it is a continuous method that appears to be uniquely stable and significantly more precise without any conditions. It can be used a larger time step than the discrete method for the same level with higher precision. But computations that take place in a continuous method at any time step are more expensive than discrete methods. However, for the continuous method, there is still potential for reducing computational costs. Chakrabarti in 2005 [2], in a book on numerical models of fluid-structure

interaction, a wide range of numerical computing techniques have been introduced in the field of fluid mechanics and numerical calculations for the fluid effect on marine structures. In 2012, Hou et al [3] In their study of numerical methods for fluid and structure interaction, the interaction between the incompressible fluid flow and the immersion structure, have been addressed in a nonlinear multi-physical phenomenon. The immersion method is an irregular mesh method. In the article, they examine the basic formulation of the immersion fringe method, immersion domain method and other immersion methods. Fluid-structure interaction in a turbine blade and its history studied by Tashakori et al [4], the fluid-structure interaction phenomenon and its history are studied by X and Y. they use simulation by using structural and fluid flow section of ANSYS software. The results show that by increasing the speed of inlet flow, the amount of blade tip deviation increases and also its impact increases on fluid pressure exerted on the rotor. In the year 2016 Dubyk et al [5] Check out analyze the impact of the transported fluid on the natural frequencies of a pipeline. It is shown that treating fluid as an added mass at the axial vibrations can lead to significant errors. Moore [6] He studied previous studies on the production and transmission of noise and vibration in piping systems. Fong et al [7] They investigated the natural frequency of the fluid coupling and the structure in a pipeline in the viscoelastic bed using the finite element method. They used beam Euler-Burnley's theory to model the pipeline and achieve partial derivative equations and using the Galerkin method, they obtained mass, stiffness, and damping matrices. The results of their studies show that as the hardness increases, the frequency bed increases, and as the damping coefficient increases, the natural frequency base decreases. Wu et al [8] They also used the FSI method to check the vibrations of the compressor tubes using the fluid coupling method and the structure. Zeid et al [9] They investigated the vibrations of the fluid coupling and the control valve structure with COMSOL software to determine its shape to have the least vibrations. They used experimental measurements to measure vibrations and currents to validate their work. In this study, are investigated the vibration caused by the collision of the fluid and the crack growth in the weld of the lower part of the cylindrical thermowell with the ASME PTC 19.3 TW 2016 standard. Research on fluid and structural contact in thermowell has also been joined by Zhao et al [10] investigated

improvement of the damaged thermowell of the fast-breeder reactor based on vibration analysis and also studied the effect of using a cone thermowell, which showed that the resonance phenomenon caused the reactor's thermowell to fail. Haslinger et al [11] investigated flow-induced vibration testing of replacement thermowell designs. Megahed et al [12] They investigated the failure of the welded part of the tram. In their study, the effect of heavy impact on crack growth and the effect of primary crack dimensions and other crack growth parameters on weld fatigue life have been investigated. Badur et al [13] They studied the force generated by an unsteady current on a steam turbine thermowell. Variable factors from fluid to thermowell, such as pressure, pressure peak, etc., have been investigated numerically and analytically. The results show that the pressure distribution curve passes around the shape and value of the thermowell, so in addition to the amplitude of the force applied to the thermowell, its direction also changes. Joints are jointed to the main pipe in different ways, which is one of the most widely used welding methods. In this paper, the growth of cracks in the weld of the joint section of the thermowell to the methane gas pipeline by the method of fluid coupling and structure is investigated. Thermowell is jointed to the pipeline by olet. The analysis of this problem is divided into two parts. First, the problem of fluid coupling and structure (FSI) is investigated and the effect of thermal geometry parameters on vibrations is obtained. In this case, it enters the structure in a cyclic manner and the growth rate of the crack is investigated.

2 Flow and structure couplings

The FSI method used in this paper is a combination of CFD¹ and CMS² methods. Generally solving problems with multiple physics is very difficult in analytical form. Therefore, such issues are often solved using numerical and experimental methods. Advanced numerical methods and popular commercial software applications in the CFD and CMS domains that make use of these methods, there are two different solutions for solving FSI problems using software, a Monolithic approach solution and Partitioned approach solving, which are described in each of these strategies. In Figure 1, you can see the breakdown of all types of FSI solutions [14].

¹ Computational Fluid Dynamics

² Computational Structural Mechanics

Fig. 1. Solving procedures in FSI [14].

In this study, partitioned approach and One-way coupling is used, in this way, each of the problems is solved individually in the separate solvent, meaning that the fluid does not change during a structural solution, and vice versa. The fluid and structure equations are solved periodically in two solvents, and the information of each solution is exchanged at the point of contact of the fluid with the structure. The process of this type of problem solving in Figure 2 The process of exchanging information at the level between the two ranges of solvers is called the solder coupler. It has two types of one-way couplings and two-way couplings [15].

Fig. 2. Partitioned approach [15].

One-way coupling is a mode that influences the movement of the fluid on the structure, But the structure's response to the fluid is ignored. As an example, in solving the issue of the propeller of the ship, the problem is considered as a one-way coupling. Figure 3 shows a diagram of the one-way coupling method.

Fig. 3. One-way coupling- flow chart [15].

3 The Phenomenon of Growth and Fatigue Crack Propagation

The study of the phenomenon of creation and expansion of fatigue cracks is shown in Figure 4. After applying the load, persistent slip bands are formed. Sliding in the direction of these sliding strips causes extrusion and intrusions on the surfaces. These defects act as the focus of stress, creating the ability for fatigue cracks to begin to grow from these points. Therefore, the main type of crack growth is in the direction of fatigue slip strips, which are formed by micro crack propagation in these directions. Figure 4 shows fatigue crack propagation.

Fig. 4. Fatigue crack propagation [12].

micro cracks are located along the sliding plates, which have maximum shear stress, and begin to grow and propagation. As micro cracks grow, they tend to propagation perpendicular to the maximum tensile stress. Life of the fatigue depends on the condition of the surface of workpiece and because the fatigue cracks are always from the free surface of the metals that are under the load of the cycle and cause initial the crack. Initial cracking as well as the entire fatigue process is controlled by the plastic deformation of the cycle. Therefore, cracks in the initial locals where the plastic deformation of the cycle is higher than the average value. The focus of microscopic stress will be due to the unevenness of the surface. The cracks are generally investigated under 3 opening modes. The shape of these modes is shown. Mode I is the openness of the tensile type, Mode II is the opening of the shear type of the plate, and Mode III is the opening of the rupture type. Any other type of cracked opening can be expressed as a combination of these modes.

Fig. 5. Definition of crack growth stress in polar coordinates [16].

If a homogeneous body with a sharp crack with a radius of curvature of the tip of the crack is considered zero and the desired load, the amount of stress and displacement in the polar coordinates in each of the modes studied in the stress and strain states of the plate around the tip crack will be in the form of equations expressed by Williams (1957). According to the coordinates of Figure (5) for mode I, the stress field is as follows [16]:

Mode I

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2}\right),$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2}$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left(1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2}\right), \tau_{yz} = 0$$

$$\sigma_z = \nu(\sigma_x + \sigma_y) \text{ plane strain}, \tau_{zx} = 0$$

0 plane stress

In mode II loading, the stress fields obtained as:

Mode II

$$\sigma_x = -\frac{K_{II}}{\sqrt{2\pi r}} \sin \frac{\theta}{2} \left(2 + \cos \frac{\theta}{2} \cos \frac{3\theta}{2}\right),$$

$$\tau_{xy} = \frac{K_{II}}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2}\right)$$

$$\sigma_y = \frac{K_{II}}{\sqrt{2\pi r}} \sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2}, \tau_{yz} = 0$$

$$\sigma_z = \nu(\sigma_x + \sigma_y), \tau_{zx} = 0$$

in mode III

$$\sigma_x = \sigma_y = \sigma_z = \tau_{xy} = 0, \tau_{yz} = \frac{K_{III}}{\sqrt{2\pi r}} \cos \frac{\theta}{2},$$

$$\tau_{zx} = -\frac{K_{III}}{\sqrt{2\pi r}} \sin \frac{\theta}{2}$$

In these relations ν , the Poisson coefficient and the coefficients of KI, KII and KIII are defined as follows [16]:

$$K_I = \lim_{r \rightarrow 0} \sigma_y \sqrt{2\pi r}, K_{II} = \lim_{r \rightarrow 0} \tau_{xy} \sqrt{2\pi r},$$

$$K_{III} = \lim_{r \rightarrow 0} \tau_{yz} \sqrt{2\pi r} \quad (6)$$

In many workpiece, the load is less than the strength of the material, and the workpiece ends its durability after several alternation and eventually fails. This number of loads ranges from a few tens of load cycles to several million load cycles. In such cases, the failure of the workpiece initial from the areas where there is a very small initial crack in the part and due to the concentration of stress in that area,

- (1) the crack gradually grows and enlarges. Such a failure is called fatigue alternate loads. Modeling such a phenomenon in limited component software requires more information than failure modeling in static loading. There are several models for modeling the crack propagation rate, including the
- (2) Paris model, the Newman-Forman, Dikong, Sin model, of which the Paris model is more common. The Paris model is a simple model. In this model, it is assumed that there is an exponent relation between the stress intensity coefficient and the growth rate of the crack. This model reflects the behavior in the second area of crack growth and abandons the first area. The following equation expresses this model.

$$\frac{da}{dN} = C(\Delta K)^{n'} \quad (7)$$

In this model, C and n' are the material constants that are obtained by fitting a diagram on the experimental data. The Paris model is simple to use and widely used and is important in areas where the second area of crack propagation. When a lot of experimental data is not available, the Paris model is used less because of the need for coefficients. This model can be used for almost all materials. The experimental value of n' is usually obtained between 2 and 4, this value decreases

with increasing strength. There are several ways to model cracks in limited component software such as Abaqus. In general, these methods are divided into two categories: classical methods and modern methods. The classical method itself consists of two methods, which are [17]:

- ❖ Surface-Based Cohesive Behavior
- ❖ Virtual Crack Closure Technique

And a new method:

- ❖ Extended Finite Element Method(xFEM)

Modeling the initial and crack propagation in older methods requires the design of a network of elements, taking into account the possibility of crack growth. If modeling also involves propagation and opening cracks, the task will be much more complicated and difficult. In this way, the path of crack propagation must be predicted in advance and the design of the elements must be placed on this path. In this method, the location of the singularity crack tip is defined, which in itself requires the use of a specific type of element. The new method is known as XFEM (Extended Finite Element Method). Many of the complexities and limitations of the static method have been addressed by enriched elements. In this study, is used the XFEM method, which is currently very common in studies [18].

4 Statement of the Problem

The geometry and dimensions of the problem are shown in Figure 6. Methane gas flows at a pressure of 44 bar and velocity 3 m/s into the tube with an inner diameter of 97 cm. Due to the collision of the gas flow with the thermowell, part of which is inside the pipe stress occurs in the upper parts of the thermowell. In this study, the greatest stress is created in the olet joint section to the main pipeline, which is also experimentally proven and cracks usually propagated in the welded part. The mesh used is of the structural type, and in the welding section, which aims to investigate the crack propagation, it is considered smaller. Figure 7 shows a view of the mesh problem.

Fig. 6. Geometry and dimensions of the problem.

Fig. 7. Geometry with mesh networking.

Compare the frequency results and the properties of the various materials in the problem, including methane gas, main pipe, thermowell, flange, thermowell pipe, olet and welding, are shown in Tables 1 to 7.

5 Results and Discussion

One of the main parts of the research work is to investigate the accuracy of problem solving. For this purpose, in this section, comparing the results of the solution of the problem of fluid and structure couplings in the Abaqus software is compared with the results of other researchers for direct tube. The tube is selected according to the ASME B36.10M-2000 standard and the eighteen Schedule. Steel with an outer diameter of 26.6 mm and a thickness of 3.9 mm and a length of 20 cm have been used in simulation and relations, and the boundary conditions for this pipe are double-clamp. The fluid used in this section is water, which has a density of 1000 kg/m^3 and is at 20°C . Young's modulus for the tube 210Gpa and the Poisson ratio 0.3 and a density of 7850 kg/m^3 . The flow rate of the fluid inlet is also 15 m/s. If we consider the first frequency of vibrations and consider the higher modes, the fundamental frequency can be obtained as follows [19]:

$$\omega = (\beta_1)^2 \sqrt{\frac{E_1}{m + m_0}} \cdot \sqrt{1 - \frac{0.55m_0 v^2}{E_1 \beta_1^2}} \quad (6)$$

According to Table 7, the frequency values obtained from Abaqus software are well matched with the analytical results of Equation (6). The pressure contour is seen in Figure 3 in the fluid passing through the pipe and the stress contour in the thermowell set (including the thermowell, flange, thermowell tube, olet and welds). In Figure 2, the thermowell set has 3 welds. The greatest amount of stress is created in the lower weld, which connects the thermowell to the main pipe by the olet. Figure 4 shows the concentration of the stress in the welding section that first connects to the main pipeline. Therefore, it is better to investigate the growth of cracks at this weld surface. One of the most important factors in thermowell vibrations and as a result of crack propagation is the geometric properties of the thermowell. It is shown that the thickness of the thermowell wall in these cases is 3 mm, which the outer diameter is 6 mm more than the values mentioned.

Fig. 8. Pressure contour in fluid and stress contour.

Fig. 9. Stress contour at weld olet joint to the main pipe.

A- Frequency changes with internal radius change.

B- Maximum displacement change with internal radius change.

Fig. 10. Frequency and maximum displacement changes with internal radius changes.

A- Frequency changes with thickness of the tube change.

B- Maximum displacement change with thickness of the tube change.

Fig. 11. Frequency changes and maximum displacement by changing the thickness of the tube.

One of the most important geometric properties of a thermowell is its longitudinal vibration (L^* in Figure 1). The frequency of the thermowell is reduced. Figure 12 Frequency change and maximum displacement by changing the height of the thermowell (the part that is inside the pipeline) and Fluid conditions also affect the amount of vibration, in Figure 13. Changing in the ratio of the main frequency to the original natural frequency at different inlet speeds of the fluid in shown Figure

13. which decreases with increasing gas velocity. Figure 9. Frequency and maximum displacement changes with internal radius changes and Figure 11 shows the variation of natural frequencies for various thicknesses of the pipe wall to an internal radius of 3.5 mm. As the thickness of the tube increases, the hardness increases, so the natural frequency increases, which is shown in the diagram. The normal residue diagram and frequency change and maximum displacement by changing the height of the thermowell (the part that is inside the pipeline) shown in Figure 14.

Fig.12. Frequency change and maximum displacement.

Fig. 13. Changing in the ratio of the main frequency.

A- Normal residuals of Maximum displacement

B- Normal residuals of frequency

Fig. 14. Normal plot of residual.

The study of crack growth due to fatigue in this study is performed by creating an initial crack 1 mm long (probability of some weld defects). One of the following parameters is the effect of the frequency of the thermowell on the crack growth. The amplitude of the vibrations enters the welding section as input and the growth of the crack is investigated. The crack growth chart shows the two frequencies entered into the weld section in Figure 15.

Fig. 15. Crack growth diagram and crack propagation contour.

For good design of the thermowell, it is necessary for the sensor inside it to reach thermal equilibrium with the flow of fluid passing through the pipe.

And on the other hand, the geometric dimensions must be such that they do not cause the resonance phenomenon. Increasing the speed of the colliding fluid to the thermowell requires that the frequency of the thermowell be increased to reduce the amplitude of the resulting vibrations, the higher frequency is created when the length of the L^* decreases and its diameter and thickness increase. These factors make it difficult to achieve thermal equilibrium, and the frequency of the thermowell should not be within the frequency range of the fluid flowing through the pipe, so it is necessary to optimize all of these values to the optimal value of all these conditions to some extent satisfactory.

6 Conclusions

In this study, was investigated the crack propagation at the welding local of the joint of the thermowell pipe to the methane gas pipeline. Due to the solution FSI of the stress distribution in the welding section, it was determined that this loading has entered the welding section as a cycle in the second part of the solution. The results of static loading show that the highest amount of stress is created at the weld surface and the side of the weld at the point of the olet joint to the thermowell pipe and the possibility of initial cracks in these points is higher. In real welding, this factor is intensified by surface uneven, which causes stress concentration. In the following, the growth of cracks is investigated by cyclic loading and the crack length in different number of cycles is presented as a diagram. This study demonstrates that crack growth was greater at higher frequencies. The effect of geometric parameters on frequency was also investigated. Therefore, it should be tried to reduce the frequency by changing the geometry of the thermowell to reduce the crack growth, but the frequency of the thermowell should not be in the range of the passing fluid frequency, which will cause an intensification.

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Table 1. Weld material preproperties.

E(GPa)	ν	Fatigue(MPa)	(Kg/m ³) ρ
200	0.3	275	7700

Table 2. Mechanical properties of main pipe.

E(GPa)	ν	C	(Kg/m ³) ρ	K(w/mk)	Wall(mm)	OD(mm)
206	0.3	0.45	7800	700	20.6	1016

Table 3. Olet and Flange material properties.

E(GPa)	ν	(Kg/m ³) ρ	C	K	(MPa) α
250	0.29	7861	447	623	44

Table 4. CH₄ properties.

ρ	Cv	Cp	Vin(m/s)	P(bar)	Dynamic viscosity	Cinematic viscosity
24.5136	1.898	2.56	3	44	13.628	0.556

Table 5. Thermowell properties.

E(GPa)	ν	(Kg/m ³) ρ	α	K
193	0.3	8000	15.9-17.5	16.3-21.5

Table 6. System operation conditions.

T(°C)	Vin(m/s)	P(bar)
35	3	44

Table 7. Compare the frequency results obtained in Abaqus and Matlab (equation 6) for direct pipe.

Mode	1	2	3	4	5	6
Abaqus Empty Pipe	37.51	103.15	201.53	331.73	493.06	684.64
MATLAB Water-Filled Pipe	28.58	85.34	159.86	290.02	412.36	567.28
Abaqus Water-Filled Pipe	29.36	85.57	157.11	288.04	415.47	560.47
Error (%)	2.6	0.266	1.72	0.68	0.75	1.4