Advanced Materials Research Vol. 845 (2014) pp 271-276
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doi:10.4028/www.scientific.net/AMR.845.271

Finite Element Analysis of Fatigue in Pipelines Due To Slug Flow

A.O. Mohmmed[a], H.H. Al-Kayiem[b] , M.S. Nasif[c] and Z.I. Mohammed[d]

Mechanical Engineering Department, Universiti Teknologi PETRONAS, 31750 Tronoh, Malaysia

[a]ganawa1988@gmail.com, [b]hussain_kayiem@petronas.com.my, [c]mohammad.nasif@petronas.com.my, [d] zaher_ab2001@yahoo.com

Keywords: Fatigue Life; Fluid Structure Interaction; O&G pipelines; Pipe conveying fluid; Slug Flow.

Abstract. Transportation of Oil and Gas from the production site to the terminal or refinery requires the use of long pipelines which procure to develop slug flow regime. This slug may cause cyclic stresses leading to fatigue and results in damaging the pipelines. This paper aims to utilize that design guide and calculate the total fatigue life for the pipeline due to internal slug flow by performing evaluation of the stress range and fatigue life span of the pipeBeam 3element with moving loads in ANSYS commercial software have been used to simulate the slug flow across the pipeline and assess the dynamic response. The total fatigue life for different selected slug parametrs was calculated. The model was validated by comparing with analytical solution in a previous published research and reasonable agreement was revealed. The results show that increasing the slug to pipe weight ratio resulting in higher dynamic stresses and reduction in the fatigue life of the pipe. This model can be utilized for the offshore pipeline if the external environmental effects are considered.

Introduction

The growth of liquid slugs in oil and gas pipeline is a vast and costly problem for the oil firms. Pressure drop in oil production is the main source of the problem which leads to terrain-induce slug flow in the pipeline between production platform and wellhead platform. This type of slug flow condition can create huge transient surges. The transient nature of slugs if not appropriately considered might become climacteric and can hasten material's fatigue with the risk of pipe damage, rising inspection and maintenance costs.

During the life of particular gas-oil production field slug flow can procure to alternating internal fluid loads and intermittent flow characteristics in pipelines, jumpers, and spools. This condition generate time-varying fluid force at various locations through the pipe which procure to significant vibration, fatigue damage and in some cases shove the structural utilization above the allowable limit.

The previous researches, [1-5] focused on utilizing of finite element analysis of specific system with advance consideration of non-linear support system to increase the complexity. However, the analytical solution of simple support beam under slug loading with evaluating the dynamic response for the structure was not addressed in their studies. This analytical solution to characterize the slug flow condition in pipeline was addressed by [6] and the authors provided design process methodology for assessing the pipelines fatigue life.

Therefore it is crucial to understand slug flow induced fatigue and subsequent damage in the pipeline in order to ensure the safety and reliability of these pipelines. Slug flow movement along unsupported pipeline induces cyclic dynamic fatigue stresses that lead the pipeline to fail.

This paper aims to simulate the pipe conveying gas & fluid and precisely calculate the total fatigue life for the pipeline due to internal slug flow by performing simple evaluation of the stress range. The model of the pipe span as beam and the moving slug as moving load along the simply supported beam has been created with three degree of freedom element in ANSYS software. The

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slug was modelled as concentrated load moving along the beam then the stresses at the mid-point was assessed in order to calculate the total fatigue life.

Problem Formulation

Pipe Model. The structural model of the pipe is modeled by Bernoulli beam finite element[7], this element has 2 nodes and 3 degrees of freedom. The slug is modeled as moving point loads as shown in Fig. 1. To facilitate the solution, the following assumptions and simplifications were made:

- The pipe is horizontal with constant cross section and constant mass per unit length.
- The material and geometrical behaviour of the pipe is linear and isotropic.
- The mass of the pipe is huge compare to the mass of the slug.
- Shear effect is neglected.
- The slug move with uniform velocity and the damping direction is proportional to the velocity of vibration.
- The beam is simply supported at the both end.

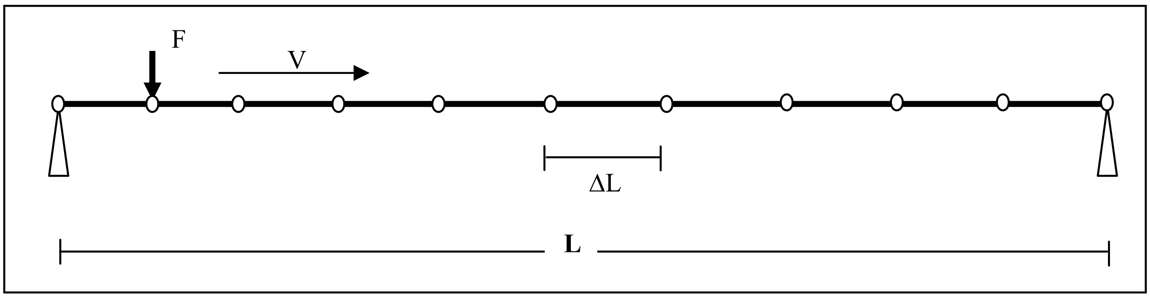


Fig.1.Schematic of simply support finite element pipe model.

Fig. 1 illustrates a 2-D simply support pipe with moving load Fat constant velocity V, where L and ΔL are the pipe span and element length, respectively. The equation of motion for simply supported beam with a moving load formulation for finite element is represented in Eq. 1.as:

$$[M]\{\ddot{d}\} + [C]\{\dot{d}\} + [K]\{d\} = \{f\} \tag{1}$$

Where, M, C and K denote the mass, damping, and stiffness matrix of the structure, respectively. $\ddot{d}$, $\dot{d}$, and d represent acceleration, velocity, and displacement, respectively, and f denotes the load apply by the slug on the pipe, as external body force vector. Ancillary details for the derivation of the finite element solution is illustrated in [8].

Eq. 1 was integrated to obtain the dynamic response of the pipe. This was performed by using Newmark scheme [9], in which nodal loads are calculated by determining the position of the slug unit at each time step. For explicit solution of the finite element set of the resulted equations, the time step, Δt was estimated as function of slug velocity, length of the pipe, and the number of nodes, as in Eq. 2:

$$\Delta t = \frac{L}{v_{su} N_n} \tag{2}$$

The basic assumptions that the pipe was rigid and at rest were used as initial conditions to calculate the dynamic response of the pipe. Then, the dynamic stresses at each node on the pipe model were obtained for each time step by:

$$\boldsymbol{\sigma}^{\mathbf{e}}_{(\mathbf{x},\mathbf{t})} = \mathbf{E}\mathbf{B}_{(\mathbf{x})}\mathbf{u}^{\mathbf{e}}_{(\mathbf{t})} \tag{3}$$

Where, σ, B, E, u, are longitudinal element stress, matrix of element shape derivatives, Young modulus, nodal displacement, respectively, and superscript e, x, and t, are element, position, and time, respectively.

Calculating time varying stresses at each node in the pipe provides maximum stress, σ_{max} and minimum stress, σ_{min} for a selected slug cases which are presented in Table. 2. Thus the mean stress, σ_m and stress range, σ_a can be calculated by the mean of:

$$\sigma_m = \left|\frac{\sigma_{max} - \sigma_{min}}{2}\right|; \tag{4}$$

nd

$$\sigma_a = |\sigma_{max} - \sigma_m|. \tag{5}$$

Stress life Based Fatigue Approach

Fatigue life in fatigue analysis is calculated at one location in the structure. This process should be repeated if the fatigue life is desired at multiple various locations. In this study fatigue life is evaluated at mid-point span (L/2) because it is exposed to highest stresses. Values of alternate and mean stresses are used in standered fatigue formula [10] to evaluate the fatigue life. Fig. 2. illustrates the crucial inputs for fatigue analysis which are: material properties, local stress properties and loading history. RQC-100 steel material properties and pipe dimensions are shown in Table 1. Three different cases identified the effect of slug characteristics in the total fatigue life for the pipeline, these cases are shown in Table 2.

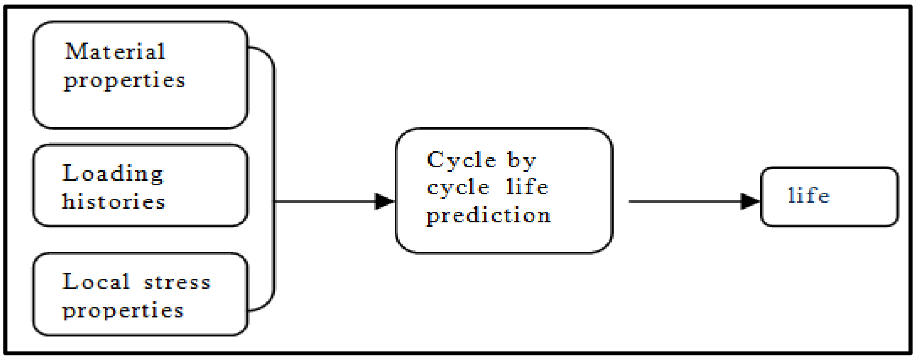


Fig.2. Fatigue Analysis Prediction Strategy [11].

Table 1. Mechanical properties and geometric parameters of the pipe.

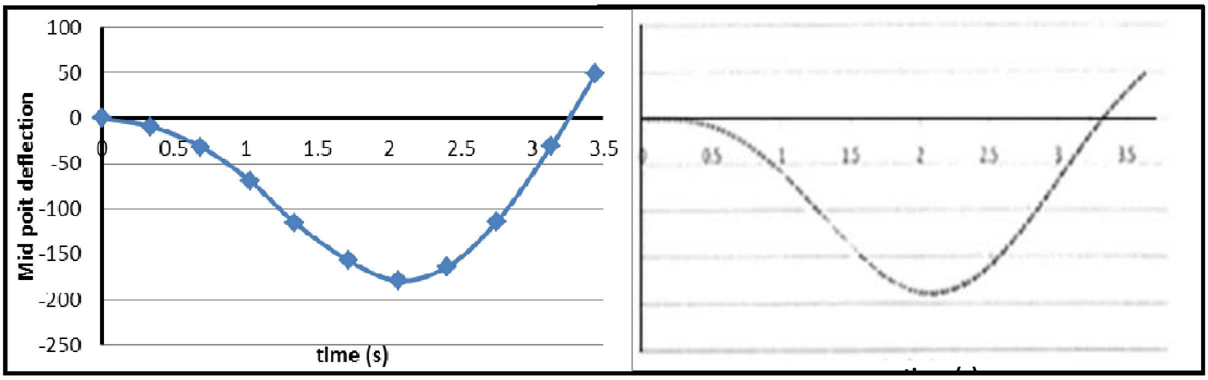
Parameter	Units	Values
Pipe Outside Diameter (D)	mm	323.9
Wall Thickness (t)	mm	12.7
Density (ρ)	kg/m^3	7850
Yong's Modulus (E)	GPa	205
Tensile strength (U_s)	MPa	931
Fatigue Strength coefficient (σ_f')	MPa	1240
Pipe Unit Weight	kg/m	97.47
Damping Ratio (β)	--	0.015
Speed Parameter (α)	--	0.4

Table 2. Parameters of the selected slug cases

Case	Slug Length (m)	Slug Density (kg/m^3)	Slug Weight (kg)	Slug / Span Weight (%)
Slug1	2	1025	143.5	3
Slug2	13.6	1025	974.7	20
Slug3	17.4	1025	1247.8	25.6

Results and Discussion

Validation. To validate the proposed model of slug motion along the pipe, the analytical solution case represented by [6] is adopted. Fig. 3-a shows the analytical results of [6], while fig 3-b shows the numerical simulation results obtained in the present study using ANSYS 14.5 software. These figures are displaying the mid-point deflection in a simple pipe at all time. The simulation results of the present analysis are in good agreement with the analytical predicted results. The maximum deflection determined by the simulation is 179.7 mm occurred at time 2.067 s, while it is 184.6 mm occurred at 2.1 s as predicted analytically by [6].Summary of comparison is shown in Table 3.



(a) (b)

Fig. 3, Mid-point deflection for case 1. (a) By ANSYS simulation, (b) analytical solution from [6]

Table 3. Comparison between the analytical and numerical simulation Results

Parameter	Simulation (ANSYS)	Analytical [6]	% of Error
Time of Max deflection (s)	2.067	2.1	1.57 %
Value of deflection (mm)	179.7	184.6	2.65 %

Stress Analysis. Fig. 4 displays the simulation results of stress range values for the three aforementioned slug cases. The maximum induced stresses in the pipe are occurred when slug/span weight ratio is 25.5% and take place after 2.422 s with a value of 465.3 MPa. By reducing the slug /span weight to 20%, the maximum stress is 363.5 MPa occurred at the same time. Furthermore, when the slug/span weight was reduced to 3%, the maximum induced stress is 53.51 MPa.

If we scrutinize on the results of selected slug cases, the cycle of the stresses is not symmetric in the sense of starting, maximum bale to minimum. The stress start to build up from time 0 s when the slug pass the mid-point and increase gradually up to its maximum value at the period of 2.422 s for all slug cases. Reduction of the stress range value from the maximum to the minimum happened within a period didn't exceeded 0.65 s. It can be concluded that the period of stress build-up takes longer time than stress damping period in the pipe's material for all simulated slug cases.

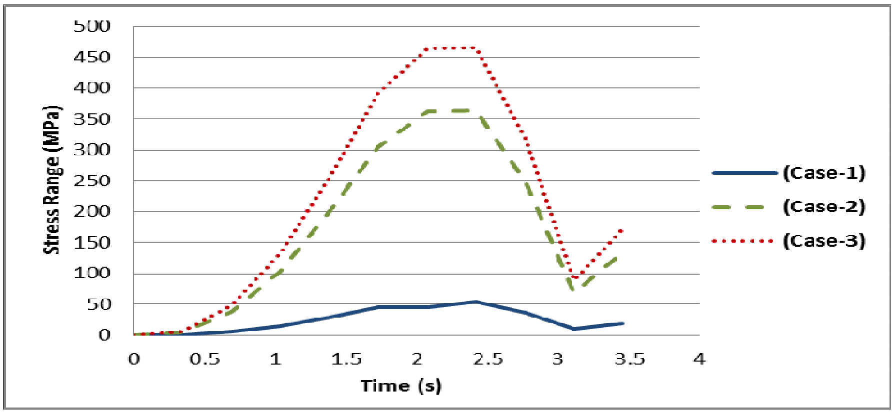


Fig.4. Stress range time history for selected cases.

Fatigue Analysis. From [10], S-N curve for RQC-100 steel with fully reversed loading (R = -1) is given by:

$$S_{Nf} = \sigma_f'(2N_f)^b = 1240(2N_f)^{-0.07} \quad (6)$$

Where, S_{Nf} is fully reserved fatigue strength at $2N_f$reversal.Predicted results of the fatigue life for the three selected slug cases are shown in Table 3.

Table 4. Predicted fatigue life for selected slug cases.

Case	Pipe Span (m)	Fatigue Life (cycles)	Fatigue Life (years)
Slug1	50	1.336×10^{20}	1.466×10^{12}
Slug2	50	10.01×10^{7}	10.98
Slug3	50	2.937×10^{6}	0.32

The prediction results shown in Table 4 revealed that for the case of slug1, an infinite fatigue life with a value of 1.466×10^{12}, while the predicted fatigue life for case of slug2 is 10.98 years. For case of Slug3, the pipe is expected to fail after almost 10 months due to exposure to heavy slug load. However, the model used in this paper is based on applying force with neglecting its inertial effect. It is essential to involve the inertial effect for the highest slug/span weight value to ensure strong coupling between the fluid and solid domain.

Conclusion

In this paper structural simulation model for assessing fatigue life of simply supported pipeline span exposed to slug loads using finite element approach is developed. Three cases of slugs are considered. The dynamic response of the pipe conveying fluid is obtained from the governing equation of motion as the result of slug moving along the pipe model. Then, fatigue analysis is performed and the fatigue life at mid-span node of the pipe is calculated. The estimated life is decreased with increasing of slug/span weight ratio. However, the accuracy of the predicted results is lessen when the slug to pipe weight ratio not negligible. Therefore future amendment of this model is recommended to precisely assess the fatigue life when the slug inertia is not negligible. More analysis will be beneficial if the effect of the support location, i.e. different pipe span is considered.

Acknowledgements

The authors would like to acknowledge the financial support from Universiti Teknologi PETRONAS (UTP). The main and the forth authors are specifically expressing their grateful to UTP for sponsoring their PhD study under the Graduate Assistance (GA) schemes.

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