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Statistical analysis of the hydrodynamic forces acting on pipe bends in gas–liquid slug flow and their relation to fatigue

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ABSTRACT

In this paper, the *resultant* hydrodynamic force (F_R, where $F_R = \sqrt{F_x^2 + F_y^2}$) acting on pipe bends will be discussed. A hypothesis that the peak (resultant) forces, $F_{R,peak}$ acting on pipe bends can be described by the normal distribution function will be tested, with the purpose of predicting the mean of the $F_{R,peak}$ ($F_{R,mean}$) and the standard deviations of the $F_{R,peak}$ ($F_{R,\text{ standard deviation}}$) generated. This in turn allows prediction of the probability of the largest forces that occasionally occur at various flow rates. This information is vital in designing an appropriate support for the piping system, to cater the maximum force over a long period of operation. Besides, this information is also important in selecting a pipe material or material for connections suitable to withstand fatigue failure, by reference to the S–N curves of materials. In many cases, large numbers of response cycles may accumulate over the life of the structure. By knowing the force distribution, 'cumulative damage' can also be determined; 'cumulative damage' is another phenomenon that can cause fatigue, apart from the reversal maximum force.

1. Introduction

Slug flow is difficult to model in that slugs have varying lengths, densities, and configurations; the forces acting on pipe bends or other pipe fittings vary with the slugs. Distribution analysis of the resultant forces acting on pipe bends, due to the hydrodynamic behaviour of slug flow, may be applied to serviceability checks and fatigue cycle counting. This provides guidance to the designer whether or not the dynamics are of importance i.e. not safely covered by fatigue load factors in conventional checks. A brief summary of metal fatigue is attached in Appendix A.

Santana et al. (1993) reported that two-phase slug flow has been evident in the piping systems at ARCO's Kuparuk River Unit, North Slope, Alaska since shortly after startup in 1981. They further reported that the forces associated with slug flow had caused excessive movement of partially restrained piping. Unrestrained elbows, tees and vessel nozzles and internals were subject to deformation and cyclic stress. Eventually, the magnitude and number of stress reversals caused fatigue cracking in piping branch connections and a pressure vessel nozzle. They mentioned that research had been carried out on the impacts of slug flow on their operating facilities. ARCO installed a data acquisition system that records historic information such as the frequency of slugs and accompanying stress reversals for a time period of a year or more, to provide an accurate indication of the number and magnitude of stress reversal cycles experienced by piping, vessel, and support structures. This will have allowed fatigue usage of the components of ARCO's modified design to be estimated, and it will also have been useful in predicting the remaining fatigue life of the components. However, Santana et al. give no detail of the data acquired.

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Nomenclature

A	area [m^2]
C	constant []
D	pipe diameter [m]
F	force [N]
g	gravitational acceleration [$m\,s^{-2}$]
h	liquid height (above pipe base) [m]
H	hold-up, $H_k = (A_k/A)$ where k is the corresponding fluid phase []
H_L	liquid hold-up in the liquid slug body, $H_L = (A_L/A)$ []
ID	internal diameter [mm]
j	superficial velocity (i.e. Q/A) [$m\,s^{-1}$]
j_s	superficial slug velocity, $j_s = j_L + j_G$ [$m\,s^{-1}$]
l	length [m]
l_e	elongation [m]
M	slope of a linear correlation []
N	number of slugs or force cycles []
N_i	expected number of cycles to failure at $stress_i$ or F_i []
n	number of samples []
n_i	cycles at $stress_i$ or F_i []
P	absolute pressure [Pa]
p	probability []
R	bend radius (centre line) [m]
t	time [s]
u	actual velocity [$m\,s^{-1}$]
u_s	slug velocity, $u_s = 1.2 j_s + 0.41$ [$m\,s^{-1}$]
X	independent variable in a linear correlation ($Y = MX + C$) []
x-	x-direction []
Y	dependent variable in a linear correlation ($Y = MX + C$) []
y-	y-direction []

Greek symbols

α	angle as shown in Fig. 5 [rad]
ϕ	angle of bend [rad]
μ	dynamic viscosity [Pa s]
ϖ	angular velocity [$rad\,s^{-1}$]
π	≈3.142 []
ρ	density [$kg\,m^{-3}$]
σ	surface tension [$N\,m^{-1}$]
σ_C	standard error of constant C in ($Y = MX + C$) []
σ_M	standard error of slope M in ($Y = MX + C$) []
σ_Y	standard error of variable Y in ($Y = MX + C$) []
θ	angular coordinate in polar coordinates (see Fig. 4) [rad]

Subscripts

A	see Fig. 4: when liquid enters the section, A = liquid and B = gas: when gas enters the section, A = gas and B = liquid
a'	point a' in Fig. 4
B	see Fig. 4: when liquid enters the section, A = liquid and B = gas: when gas enters the section, A = gas and B = liquid
b'	point b' in Fig. 4
c'	point c' in Fig. 4
d	downstream pipe after the bend
d'	point d' in Fig. 4
e'	point e' in Fig. 4
G	gas phase
i	inside pipe (in Eqs. (2) and (3))
i	integer number ith (other than in Eqs. (2) and (3))
j	integer number jth
j_s	superficial velocity
L	liquid phase
l	length
M	slope of a linear correlation, $Y = MX + C$
max	maximum
mean	mean of the peak forces identified from statistical analysis
o	outside pipe
peak	the largest force during transit of a slug unit
PFM	piston flow model
R	resultant
s	slug unit
u_s	slug velocity
x	x-direction
y	y-direction

The linear cumulative damage rule as defined by Miner (1945) is used in the majority of fatigue life calculations. This rule assumes that if a bend has received n_1 cycles at $stress_1$ for which the expected number of cycles to failure is N_1 then a fraction n_1/N_1 of the useful life is used up (Alexander and Brewer, 1963). The ‘cumulative damage’ is calculated as

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots = \sum_{i=1}^{i} \frac{n_i}{N_i} \tag{1}$$

Failure will occur when $\sum_{i=1}^{i} n_i/N_i = 1$. A design value less than unity is generally used. Cook and Claydon (1992) reported that tests have shown significant scatter and a marked load order dependency and values of cumulative damage between 0.3 and 3 have been obtained. Despite this load order dependency, there has been no physical basis supporting the assumptions behind Miner (1945)’s rule; although this has widespread usage in service life prediction in early stages of design. Cook and Claydon (1992) further mentioned that in order to account for such a large scatter in fatigue test data and variability in critical damage constant defined above, a factor of 1/5th or less is typically used in design life calculations.

In addition, investigation showed the fatigue strength of un-welded pipe is twice of the welded pipes, as a result of high stress concentration on the notch at the weld root (Gurney, 1968). At a pipe bend there are higher stresses than exist in adjoining straight runs of pipe (Gurney, 1968). Under an applied bending moment the cross-section of the pipe tends to become oval, as shown in Fig. 1. The fatigue strength of a bend will be a function, by a factor less than unity, of the fatigue strength of the material.

The usefulness of the research is not confined to conventional bends. In oil and gas production systems, typical seabed connections are divided into four generic groups: elastomeric flex, mechanical hose, flexible hose and metal flex joints. Nevertheless, all these joints are exposed to the risk of fatigue