Flow-Induced Vibration (FIV) Fatigue Assessment Tool Using a Mechanistic Approach

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Abstract

Flow-induced vibration (FIV) fatigue is a common issue in process piping. The kinetic energy of the fluid flowing through the pipework may induce vibration and consequently fatigue failure. There is currently a gap in industry methods for assessing the likelihood of such failure. The Energy Institue (EI) Guideline employs highly qualitative and overly conservative, semi-empirical schemes for assessing the associated risks (likelihood of failure) to pipework. Alternatively, finite element analysis (FEA) / computational fluid dynamics (CFD) modelling can be used to estimate the fatigue life. However, it requires expertise in numerical methods of solid and fluid mechanics. This research project uses analytical methods to formulate an equation of motion for a given piping configuration, geometry and operating conditions from which the shaking stress and subsequently the fatigue life of small-bore connections (SBCs) due to flow-induced vibration can be estimated. An Excel spreadsheet (or computer programme) will then implement these analytical methods, creating a simple, validated assessment tool for the user to estimate the fatigue life of a piping system.

1 Introduction

Turbulent flow in process pipework causes vibration and inducing shaking stresses in the pipes raising the potential for pipe fatigue failure. Kinetic energy of the fluid flowing through the pipework may induce vibration fatigue failure. This issue of vibration fatigue failure of pipework is particularly prominent in small-bore connections (SBCs) to mainline piping where fatigue cracks are most likely to occur at the base of the welded joints (see Figure 1). Loss of containment from fatigue damage is a serious health, safety and environment concern, not to mention potential asset damage and loss of production impact due to plant shutdown.

Methods currently used in industry outlined in Energy Institute Guideline (EI) (Energy Institute, 2008) which are a set of standards for assessing the Flow Induced Vibration (FIV) risk, or likelihood of failure (LOF), use semi-empirical formulae which do not assess the fatigue life of the pipework. They are highly qualitative and overly conservative. The EI Guideline is regarded as a sufficient screening tool for greenfield projects where facility is being designed from scratch. In brownfield project situations, an existing facility may have been safely operating for many years with LOF above the EI method threshold, but a situation may arise where increase in flow rate is required.

Figure 1 Example photos of SBC attached to mainline piping (left) and FIV fatigue crack at SBC weld to mainline (right) (Wood Beta Machinery, 2022).

Alternatively, FEA/CFD modelling methods can be used for estimating fatigue life of process pipework. However, it requires in-house or contracted specialists with expertise in numerical methods of solid and fluid mechanics. Analysis to understand risk of vibration fatigue failure would need to go beyond FEA as it can only compute the stress and oscillating frequency of the pipes. Fatigue S-N curves would be required to then determine the fatigue life. Hence, there is a gap in the industry approach to the issue of FIV fatigue in piping; there is no ability to assess fatigue life without having to perform FEA.

The objective of this research project is to use analytical methods to develop an assessment tool for the fatigue life of mainline pipework and consequently small-bore connections undergoing shaking stress due to flow-induced vibration. The benefit of this assessment tool will be that the Client will be provided with a method to estimate the fatigue life of pipework given the pipe configuration, geometry, and operating conditions. By estimating the fatigue life of the pipework, the Client will be able to address associated risks more effectively.

2 Process

This project involves a combination of fluid mechanics, vibrations and solid mechanics. Hence, formulating an analytical solution for estimating fatigue life due to FIV required that the project be broken up into four key objectives, as outlined in Figure 2 below.

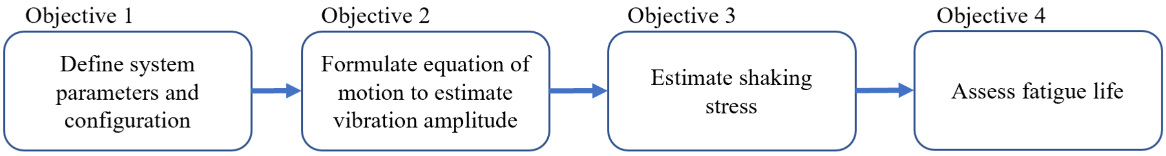

Figure 2 Analytical solution overview (step-by-step process)

2.1 Equation of motion

An equation of motion is used to describe the mechanical behaviour of the mainline pipe with the kinetic energy of the turbulent fluid flowing through the pipe acting as the excitation. . The equation of motion for the free transverse vibration of a straight, tension-free fluid-conveying pipe (see Figure 3) is given by equation 2.1 (Blevins, 1990).

$$EI\frac{\delta^4 y(x,t)}{\delta x^4} + (\rho A v^2)\frac{\delta^2 y(x,t)}{\delta x^2} + 2\rho A v\frac{\delta^2 y(x,t)}{\delta x \delta t} + (\rho A + m)\frac{\delta^2 y(x,t)}{\delta t^2} = 0, \qquad (2.1)$$

where E is Young's modulus, I is the second moment of area, m is the mass of the pipe per unit length, ρ is the density of the fluid, v is the velocity of the fluid, A is the internal cross sectional area, x is the axial position along the pipe and y(x,t) is the transverse displacement of the pipe at given position and time.

From the equation of motion (Equation 2.1), a general solution for the vibration amplitude can be solved by applying the boundary conditions for a pipe with fixed supports such that the deflection at each of the supports is zero. Consequently, the equation of motion of a small-bore branch (generally cantilever pipe with lumped mass) can be solved by taking the vibration amplitude of the mainline pipe as abutment excitation (see Figure 4).

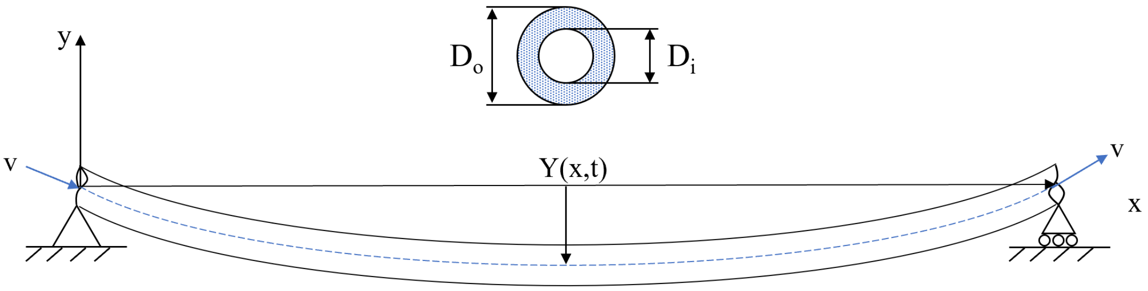

Figure 3 Fluid conveying pipe with pinned ends (Blevins, 1990).

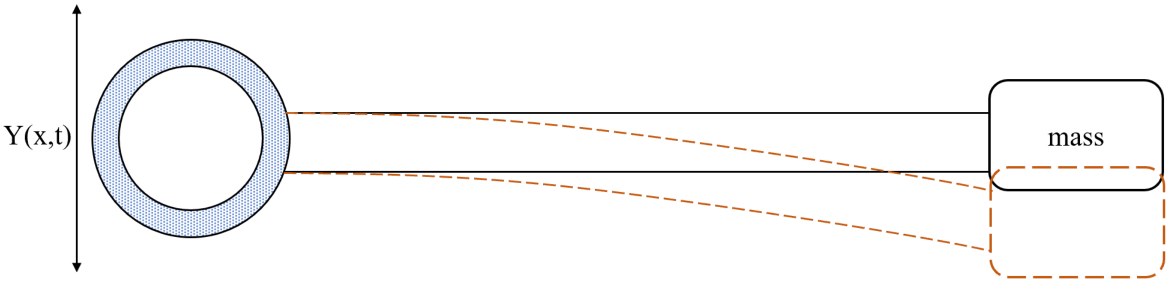

Figure 4 Fluid conveying pipe with pinned ends (Blevins, 1990).

2.2 Shaking stress

The shear force Q and bending moment M can be calculated by multiplying the second and third spatial derivatives of the deflection by the second moment of area and Young's modulus of the pipe, see equations 2.3 and 2.4 (Bishop, 1960).

$$M(x) = EI\frac{\delta^2 Y(x)}{\delta x^2}\ [Nm] \qquad 2.3$$

$$Q(x) = EI\frac{\delta^3 Y(x)}{\delta x^3}\ [N]. \qquad 2.4$$

The total shaking force at the small-bore connection (SBC) will be a combination of axial forces, bending moments and shear forces determined from the equation of motion. Methods provided in Budynas and Nisbett (2020) will be used to determine the total shaking stress in welded connection. Conservative values of stress concentration factors will be usedwhen calculating the shaking stress on the pipework.

2.3 Fatigue life estimation

The British Standards 7608 (or equivalent standards) will be used to estimate the fatigue life of the welded joints of the small-bore connections which is where failure is anticipated to occur. The first step is selecting the weld class of the connection. After determining the weld class of the connection, the number of cycles which the joint can withstand will be estimated using the S-N curve shown in Figure 5 below. The fatigue life can then be estimated by dividing the number of cycles by the frequency of the shaking stress.

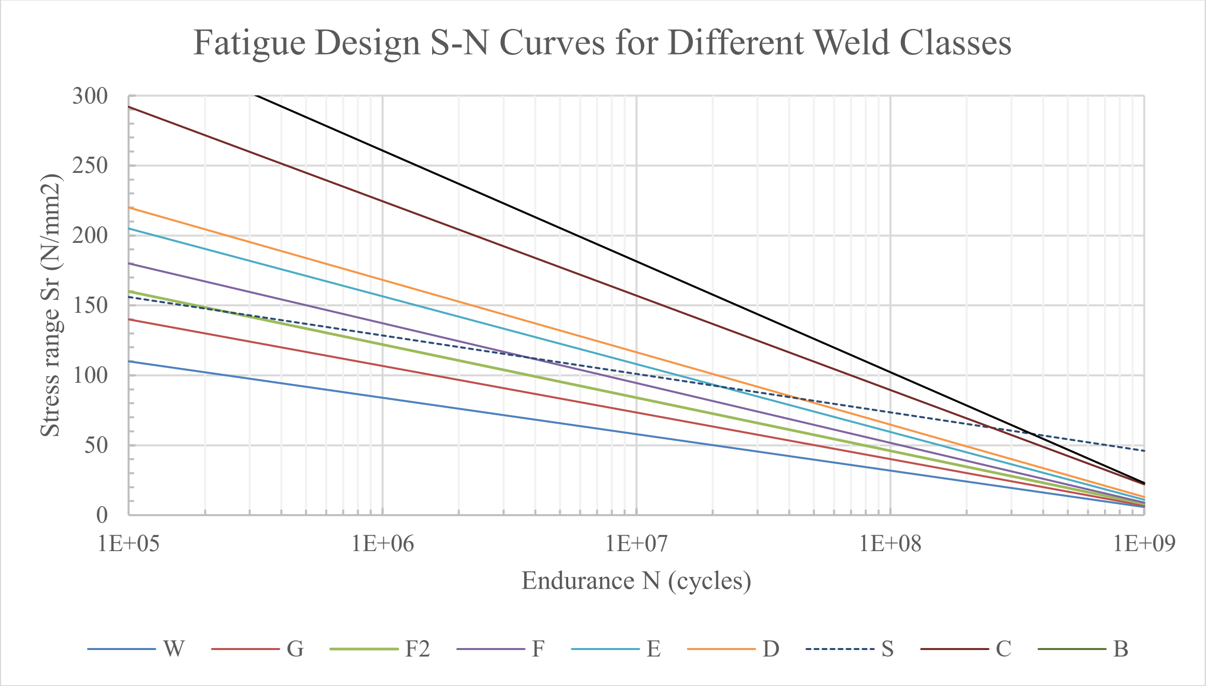

Figure 5 Fatigue Design S-N Curves for Different Weld Classes (BS 7608, 1993).

2.4 Excel spreadsheet / computer programme

An Excel spreadsheet (or computer programme) will be developed to implement the analytical solution to the equations of motion. This will allow the user to select a support configuration (sets boundary conditions), select the pipe material properties and geometry, input the pipe dimensions, input the fluid properties (density, viscosity etc.) and the flow parameters (velocity, pressure etc.), and output the amplitude and frequency of the shaking stresses experienced at the critical points. The user will then be referred to BS 7608 and follow the steps described in section 2.3 above to find the fatigue life.

3 Preliminary Results and Discussion

The solution of the equation of motion (Equation 2.1) of the mainline pipe can be assumed to be in the form of a polynomial to the 5th order (Equation 3.1),

$$Y(x) = B_1 + B_2x + B_3x^2 + B_4x^3 + B_5x^4, \tag{3.1}$$

where B_n are constant coefficients. Using the boundary conditions of a fixed pipe and applying geometric anlysis of the peak deflection, the coefficient B_5 (Equation 3.2) and the average inverse radius of curvature of the pipe (Equation 3.3) can be taken as (Udoetok, 2018):

$$B_5 = \frac{4.6024}{L^3}, \tag{3.2}$$

$$\overline{\frac{d^2y}{dx^2}} = \frac{1}{\overline{R}} = -0.037123B_5L^2. \tag{3.3}$$

Wolfram Mathematica differential solver (Wolfram Research, 2022) has been used to solve the equation of motion (Equation 2.1) of the pipe for the average inverse radius of curvature and plot the first mode shapes of both a straight four meter long pipe with fixed ends (see Figure 6).

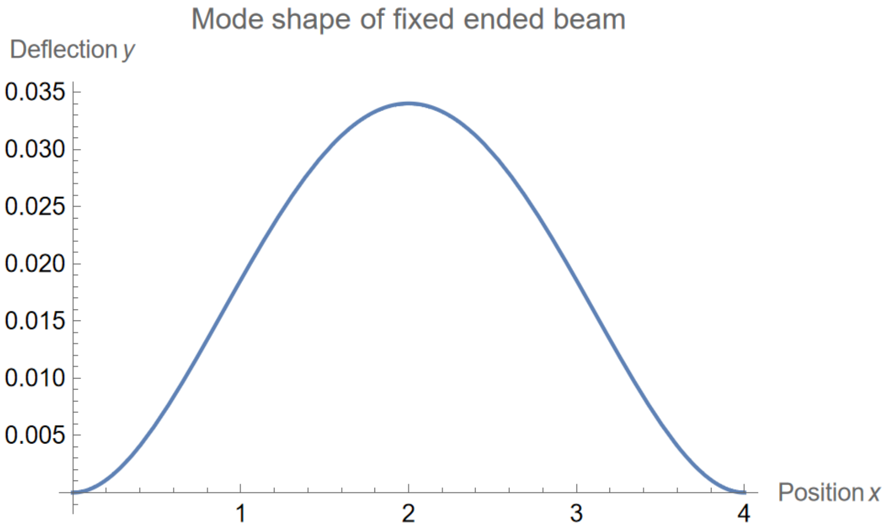

Figure 6 Mode shape of a straight pipe with fixed ends (mainline) plotted using Wolfram Mathematica (Wolfram Research, 2022)

These deflections represent the first mode shapes of mainline piping, and subsequent small-bore branches. As a piping system oscillates close to its natural frequencies, there is the highest risk of failure, and consequently shaking stresses are at their highest. Therefore, it is more likely that failure will occur before higher mode shapes can occur.

4 Conclusions and Future Work

The key to estimating fatigue life via analytical methods is to formulate an equation of motion describing the mechanical behaviour of a piping systems in response to flowing medium forcing excitation. This reduces the excited motion description to a simple equation from which the forces induced by the vibrations can be determined, hence enabling the shaking stress and subsequently the fatigue life to be estimated.

The fluid-structure forces are a function of the radius of curvature of the pipe. Hence, finding the equation for the radius of curvature for given piping configuration will provide the means to determine a non-trivial solution for the equation of motion (Equation 2.1).

Future work to complete this assessment tool firstly includes solving for the the vibration amplitudes of various piping configurations (i.e. with/without lumped masses and cross bracings) will need to be analysed and against with field data provided by the Client. Stress analysis can then be performed, and subsequently the fatigue life estimated. Verifcation of the fatigue life estimates will be carried out through comparison with the available operational data and EI Guideline LOF. Consequently, the analytical solution will be implemented in an Excel spreadsheet / computer programme which will be verified with hand calculations and peer checks.

Future research to improve the FIV fatigue assessment tool should involve extensive verification of the analytical methods by comparison to FEA / CFD modelling. Application of the assessment tool could be broadened by accounting for more vibration inducing mechanisms (i.e. two phase flow, surging, relief force, etc.).

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