Influence of Load Steps and Boundary Conditions on Torsion of Free Span Pipeline

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Influence of load steps and boundary conditions are investigated with three-dimensional (3-D) free-span pipeline responses with torsional (\(\theta_x\)) coupling of a pipeline through the biaxial (y) bending responses. The static pipe-span equilibrium is achieved with its self-weight and buoyancy and the external torsional moment induced by the cross-flow (y-directional) current on the pipe span sagged in the z-direction. Load steps taken in two different sequences of applying static loads can twist pipe span in entirely different patterns, changing coupled dynamic responses as well. Two boundary conditions of the span supports are fixed-fixed and fixed-pinned, and give two different torsional responses. 3-D coupled axial (x-), bending (y- and z-) and torsional (\(\theta_x\)) responses, both static and dynamic, to the z-directional impact loadings, are modeled and analyzed by a nonlinear FEM method for a 16-in pipeline. Impact load of triangular impulse type is applied in the vertical (z-) direction to excite the pipe span in its static equilibrium. Significant torsional vibrations occur by the cross-flow current, especially for longer spans. The torsional (\(\theta_x\)) coupling is very sensitive to the time-step size in achieving numerical stability and accuracy.

SYNOPSIS

3-D nonlinear pipeline free-span responses coupled with torsion were first analyzed by Chung, Cheng and Huttelmaier (1995). A ship anchor impact on a pipeline was investigated previously for the 2-D cases with a 16-in diameter pipeline by Al-Warthan et al. (1993). For the present analysis of the same size places its emphasis on the 3-D effect with torsional coupling. It includes effects of:

(a) the sequence of the load steps of the net weight of the pipe and the cross-flow drag;
(b) boundary conditions; and
(c) impulse impact load.

Finite element modeling (FEM). A pipe finite element code was developed to model the nonlinear 3-D dynamic behavior of a pipeline. Other special features of the analysis procedure include an updated Lagrangian formulation as used to account for geometric nonlinearity and elastic behavior.

Pipe modeling. The present free-span pipeline is modeled by a beam with 2 boundary conditions at the supports (Fig. 1). The pipe was discretized with equal element lengths (Fig. 2). The pipe geometry and properties for the analysis are given in Table 1. The pipe spans (Fig. 1) are fixed at both ends in the x-, y-, z-, and \(\theta_x\), \(\theta_y\), \(\theta_z\)-directions for Fig. 1b while one end pinned for Fig. 1c.

| Outer Pipeline Diameter, \(d\) | 16 in |
| Span Length, \(L\)       | 230 ft |
| Wall Thickness, \(t\)    | 0.5 in |
| Pipe Mass Density, \(\rho_p\) | 15.21 slug/ft^3 |
| Young's Modulus, \(E\)   | \(4.32 \times 10^9\) lb/ft^2 |
| Drag Coefficient, \(C_D\) | 1.0 |
| Sea Water Density, \(\rho_w\) | 1.99 slug/ft^3 |

Table 1 Pipe geometry and properties

Loads on Pipe Span

Static load. Static loads acting normal to the pipe axis consist of the pipe's net weight \([= \text{self-weight (W)} - \text{buoyancy (F_B)}]\) of the pipe span in the z direction and the steady state drag due to the cross-flow current in the y direction. For the present analysis, the self-weight includes the fluid inside pipe.

Hydrodynamic loads. The computer code models the effect of normal fluid forces on a pipe as vector \(F_N\), which consists of inertia force and drag (Chung et al., 1980). For the present investigation, a simple hydrodynamic force is used with zero wave particle and current velocities for 2-D cases and with nonzero current velocity for 3-D cases. The tangential drag, \(F_{D_t}\), due to the axial vibration and internal flows, is referred to in Chung et al. (1996).

Impact loads. When a heavy object falling in the z-direction hits the pipe span at an initial velocity, \(v_0\), its impact forces, \(F_p\), are represented by triangular impulse impact loading (Fig. 3). The impact excites the pipe span which is initially in static equilibrium.

First, the static equilibrium configuration of the pipe span is computed with the static loads described above. The pipe span in its equilibrium...
state is excited by the impulse load for dynamic analysis, using the 3-D nonlinear FEM code (Chung et al., 1995).

Static Equilibrium State: Load Steps and Boundary Conditions

It was demonstrated previously (Chung and Cheng, 1996: Table 2) that the pipe configuration in static equilibrium can be entirely different in torsion (Fig. 4) when identical loads are applied in different sequences.

Boundary conditions. Numerical examples are tested with two boundary conditions: (1) BC1 = both ends of the pipe are fixed; and (2) BC2 = one end of the pipe is fixed, while the other end is pinned, allowing rotation about the x-axis.

Load steps. The static equilibrium configuration of the free span for a nonlinear pipe system coupled in the x-, y-, z-, and 6x-directions is computed in 80 load steps. For the first sequence \((LS1)\) the weight \((W)\) and buoyancy \((F_B)\) are applied in steps 1–20, in the z-direction of the span, and the cross-flow drag, \(F_{DV}\), in steps 21–80, caused by the current flow velocity, \(V_{CV}\), in the y-direction. For the 2-D \((x-\text{and } z)\)-directions, \(V_{CY} = 0\) and no twist. The loads are applied in a ramp fashion. For the second sequence \((LS2)\) of load steps, the static equilibrium configuration of the sagged pipe span is obtained first with the application of the net weight \((W-\text{F_B})\) in 20 steps, and then \(F_{DV}\) is applied to get the final static equilibrium configuration. The cross-flow drag on the sagged pipe span can induce large pipe torsion, which is coupled through the 3-D responses in the x-, y-, z-, and 6x-directions. The pipe twist, \(\theta_x\), is an incremental value relative to \(\theta_0 = 0\) at the left end of the pipe (Fig. 1).

3-D FEM analysis. The 3-D coupling with torsion due to the cross-flow current changes the results further from the 2-D results. The torsional moment with \(V_{CV} = 8 \text{ ft/s}\) gives a maximum twist angle at the midspan, \(\theta_0 = 0.00172 \text{ rad} (0.985\text{°})\), with \(BC1\) and \(LS2\) for \(L = 230 \text{ ft}\) (Fig. 5 and Table 2). The characteristics of the pipe twist by these two load steps, \(LS1\) and \(LS2\) under \(BC1\), differ entirely in both location and magnitude. The longer the total spans with the cross-flow current are, or the faster the \(V_{CV}\) becomes for 3-D coupled responses, the larger the torsional moments and pipe twist \((\theta_x)\) become.

In the BC2 case, the maximum static pipe twist occurs at the pinned end instead of the midspan (Fig. 4c). The maximum values of the static twist \((\theta_x)\) response (Table 2) show that different boundary conditions can result in greatly different twist angles with \(LS2\) (Fig. 4).

<table>
<thead>
<tr>
<th>(V_{CV}) (ft/s)</th>
<th>(BC)</th>
<th>(Z_{max}) (ft)</th>
<th>(\theta_{max}(\text{rad}))</th>
</tr>
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<tr>
<td>2</td>
<td>BC1</td>
<td>-1.807</td>
<td>2.099x10^{-4}</td>
</tr>
<tr>
<td>2</td>
<td>BC2</td>
<td>-1.806</td>
<td>1.157x10^{-4}</td>
</tr>
<tr>
<td>8</td>
<td>BC1</td>
<td>-1.020</td>
<td>1.722x10^{-4}</td>
</tr>
<tr>
<td>8</td>
<td>BC2</td>
<td>-1.019</td>
<td>1.100x10^{-4}</td>
</tr>
</tbody>
</table>

Table 2 Comparison of maximum bending and torsion in static equilibrium between BC1 and BC2 with LS2: L = 230 ft

Eigenvalues

The static pipe deflection occurs by its net weight \((W-F_B)\), and the sagging changes the eigenvalues, and the axial force has no effect (Table 3). Eigenvalues are computed for the linear systems of the straight as well as sagged (or deflected) pipe configurations of L = 230 ft, respectively.

Excitation by Impulse Impact Loading

The pipe span in its static equilibrium configuration as initial condition is excited by impulse impact loads of \(F_Z = 10^5 \text{ lb}\) (Al-Warthan et al., 1993) applied in the z-direction to the mid-span load (Fig. 3). The cross-flow drag, \(F_{DV}\), applied in the y-direction \((V_{CV} = 0, 2, 4, 8 \text{ ft/s})\) induces the pipe torsion, which is coupled in the x-, y-, z-, and 6x-directions. Torsional moment is found to be very sensitive to time-step size, noticeably more than other modes of the responses. As the amplitudes of the pipe tension become large for a given \(F_{DV}\), vibrations reduce the mean deflection in the z-direction, as compared to the static deflection.

For a longer span \((L = 230 \text{ ft})\) and \(BC2\), \(BC2\) makes the static responses different from those with \(BC1\). Dynamic responses with \(BC2\) are also different from the corresponding responses with \(BC1\). As the axial and torsional responses are coupled, the torsional eigenvalues with \(BC2\) are quite different from the corresponding cases with \(BC1\) and also from those of the axial vibrations. For a shorter pipe span \((L = 90 \text{ ft})\), the vibrational characteristics are somewhat different from the longer pipe span, \(L = 230 \text{ ft}\).

Contrary to the results that the static twist angles (Table 2 and Fig. 4) with \(BC2\) are an order-of-magnitude larger than the twist with \(BC1\), the amplitudes of the corresponding torsional vibrations with \(BC2\) are smaller, and the amplitudes of the shear stresses at the fixed end are also much smaller.

Mathematical basis of the 3-D nonlinear FEM code and further analysis are referred to in Chung and Cheng (1995, 1996).

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References


Влияние Последовательности Нагрузок и Границных Условий на Кручение Подвесного Трубопровода

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Краткое содержание

Исследуется влияние нагрузок и граничных условий на трехмерную (3-D) реакцию подвесного трубопровода путем совместного рассмотрения деформации кручения (Fx-) и двуконого (y) изгиба. Статическое равновесие приваживающего участка трубы является результатом равновесия силы собственного веса, силы плаунчери и внешнего момента деформации кручения, вызванного силой перпендикулярной (вдоль оси y) течением на вертикально расположенном участке трубы. Последовательность приложения нагрузок может приводить к различным типам закручки трубопровода и изменять суммарную динамическую реакцию.

Два типа граничных условий, реализующие два способа закрепления приваживающего трубопровода - жесткий-жесткий и жесткий-шарнирный, приводят к различным крутящимся откликам. Различные виды статических и динамических реакций 16-ти дюймовой трубы на вертикальные нагрузки моделируются и анализируются на основе нелинейной модели конечных элементов (МНК). Исследуется процесс выведения трубы из статического равновесия за счет импульсной нагрузки треугольной формы действующей в вертикальном направлении. При наличии поперечного течения процесс сопровождается появлением вращательных вибраций, особенно значительных для длинных пролетов. Процессы связанные с кручением (Fx-) существенно влияют на величину шага по времени в числовой схеме, необходимого для достижения точности и устойчивости решения.