STATIC ANALYSIS AND HEALTH MONITORING OF PIPELINES IN NPPs WITH NOISE CONSIDERATION

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ABSTRACT

The study proposes a numerical methodology for assessment of physical parameters which are critical to damage detection and structural health monitoring of pipelines propagating fluids under high temperatures. The thermal gradient of the fluid, self-weight of the piping system, and the pressure exerted on the pipe walls are taken into consideration for static analysis. The displacement, stresses and strains are computed for the imposed loads.

The boundary conditions for a pipeline element is assigned through translational and rotational springs whose stiffnesses are unknown. The expression for the boundary stiffnesses are derived by coupling the internal pressure due to fluid flow with thermal loading and weight. The dependent and independent parameters for deciphering the degradation of the pipe element are identified to minimize instrumentation for health monitoring. The primary aspects of damage being investigated are wall thinning due to corrosion resulting in stiffness degradation.

In practical scenarios, it has been observed that excessive instrumentation of a structural component for health monitoring, might result in measurement noise. Hence, artificial noise is introduced to the measurement stresses and strains in a Gaussian distribution form, which is corrected through a numerical algorithm.
INTRODUCTION

Non-destructive evaluation of piping in reactor assemblies is crucial for monitoring leaks, internal pressure variations and thermal stress concentrations which are indicators of possible pipe break. It is very difficult to monitor significant parts of a piping assembly due to inaccessibility and extended operating periods where proactive monitoring becomes difficult. Hence, it becomes imperative to strategize a mechanism that would allow extended periods of safe and continuous operation without requiring frequent maintenance. This has caused a shift from traditional preventive maintenance measures to more active monitoring approaches through non-destructive evaluation and in-situ component inspection techniques. Pipeline component selection for situation-based maintenance involves selection and optimization of certain parameters associated with the factors affecting the health of the individual components such as high thermal gradients or thinning due to corrosion. The diagnosis and detection of these abnormalities are performed by identifying a number of strain parameters which can be supervised through strain gauges and other instrumentation techniques. In addition to instrumentation of the pipeline system, a structural health monitoring strategy includes periodic observation and assessment of periodically sampled strain measurements from a collection of sensors, the prediction of operating life of individual components and the interpretation of damage-sensitive information to determine the current structural conditions through mechanics and statistics based analysis methods.

PARAMETER SELECTION FOR HEALTH MONITORING

The stability of pipelines conveying thermal fluids strongly depends on the type of boundary conditions for a finite pipe length. The article attempts to identify the primary contributing stresses acting on a pipe section of finite length and treat the boundaries as a system of translational and rotational springs. The boundary conditions are then configured by setting up pseudo static equations of motions and solving for the unknown stresses using the maximum principal stress and maximum shear stress failure theories. It should be noted that for cylindrical pipes subjected to internal pressure, the treatment of the pipe as a membrane fails to represent the true stresses in the edges of the shell, as the joints between the cylindrical cross sections at the end of the vessel are accompanied by local bending and thermal stresses.

In the first stage of analysis, the individual forces acting on the pipe are identified and taking each one of them into consideration the equation of motions due to the influence of these factors are noted. The principal stresses are computed by resolving the force components along the centre-line of the pipe in the longitudinal direction, radial direction and along the circumference. The longitudinal stresses are caused as a result of axial force loading, thermal forces and bending stresses. The stresses along a radial line from the center through the pipe surface is caused by tensile stresses due to internal fluid or vacuum pressure. The circumferential principal stress or hoop stress have a tendency of breaking open the pipe wall due to internal pressure and act along the tangent to the cross section. Since the pipeline can have any configuration the required stress and strain elements as well as the fluid pressure tend to vary along the length and diameter of the cross section. The bends in the pipe have pressure limitations which can cause hoop stresses to exceed the yield strength of the material under the operating temperature. By introducing a rotational/translational spring for a cross-section the yield strength requirements can be optimized by either changing the pressure gradient or temperature. Each of these variations are considered and the detailed computation of shear force, bending moment, deflections, stress and strain components are carried out. The trend of these parameters along the radial and longitudinal direction of the pipe is noted (see Fig 2 and 3). The pipeline system is safeguarded against temperature changes and thermal expansions by performing a flexibility analysis to insure against overstraining of individual components and exceedance of calculated displacement stress range for hot and cold conditions by incorporating reduction factors.
HEALTH MONITORING AND OPTIMIZATION OF MEASUREMENTS

Since pipeline systems always form a network, we never know what sort of support conditions they have. The general assumption adopted in this article is to have a combination of translational and rotational spring supports of unknown stiffness. So now we have a pipe supported on springs at both ends with a self-weight including the weight of the pipe, insulations and the medium along with thermal forces and induced pressure acting on it. The objective is to obtain relationships between the spring stiffnesses with some known stress/strain parameters. Translational springs are used in case of high magnitude displacements to prevent the transfer of load to nearby sensitive equipment. The rotational springs are used for transferring differential loads arising from thermal gradient or torsional loads to connected elements. The thermal expansion analysis is performed using a guided cantilever restrained at the free end, where the deflection direction perpendicular to the longitudinal axis is not allowed to rotate. This results in a moment which is a function of the length of the span and the perpendicular deflection in addition to EI.

![Diagram of a thin cylinder with stress distribution](image)

Fig 1: Circumferential and longitudinal stresses in a thin cylinder with closed ends under internal pressure [3]

The spring stiffnesses are determined from the flexure equations, deflection equation and some justified assumptions. An important feature of health monitoring is to ascertain which parameters need to monitored to get an effective diagnosis of the structures system health. We need to be careful when we choose our parameters by virtue of which we wish to define the health of our pipe. For example, we need not measure both axial and hoop stress as they are interdependent.

Some of the most important factors affecting the health of a pipeline are wall thinning due to corrosion, leakage of joints due to overstraining and excessive deformations due to thermal expansion. The failure modes can be analyzed by correlating the fundamental strain parameters to the spring stiffness coefficients. It has been observed from analysis of a pipe section that the axial or meridional strains \(\varepsilon_{xx}\) and the hoop strain \(\varepsilon_{\theta\theta}\) along with the temperature gradient are the primary measurements needed to decipher the change in wall thickness and spring stiffness. The meridional and radial strains can be expressed as a function of the self-weight, internal pressure, temperature gradient, thickness of the pipe, etc.

\[
\varepsilon_{xx} = \varepsilon_{xx,f} + \varepsilon_{xx,\text{thermal}}
\]

\[
\varepsilon_{\theta\theta} = \frac{1}{2\varepsilon_{xx}} = \alpha E \delta T + \frac{p r}{h}
\]

where, \(\alpha\): coefficient of thermal expansion, \(E\): elasticity modulus, \(\delta T\): temperature gradient, \(p\): internal pressure, \(r\): radius of the pipe and \(h\): thickness of the pipe.
The meridional stresses can be distributed into two components as a result of the thermal expansion and stiffness degradation due to thinning.

\[
\varepsilon_{xx,\text{thermal}} = \alpha \Delta T
\]  

(3)

\[
\varepsilon_{xx,f} = \frac{32 \left( \frac{\alpha x^2}{2} + k_2 x \right) \left( \frac{\alpha x^4}{24} + k_1 \frac{x^3}{6} + k_2 x \right)}{(EI)^3 \pi d^3)
\]  

(4)

The terms \(k_1\) and \(k_2\) represent the coupled rotational and translational stiffness components obtained from the equations of motion

\[
k_1 = \frac{k_t x \left( \frac{\omega Elx^2}{2} - \frac{k_t \omega x^2}{6EI} \right) - k_r \left( k_t \omega x^4 - \frac{k_t \omega x^4}{24EI} \right)}{\left( \frac{k_r x^2}{2EI} - Elx \right)xk_t - k_r \left( \frac{k_t x^4}{6EI} - 1 \right) - k_t \omega x^4 - \frac{k_t \omega x^4}{24EI} \right)} \]

(5)

\[
k_2 = \frac{\left( \frac{k_r x^3}{6EI} - Elx \right)xk_t + k_r \left( \frac{k_t x^3}{6EI} - 1 \right)}{\left( \frac{k_r x^2}{2EI} - Elx \right)xk_t - k_r \left( \frac{k_t x^4}{6EI} - 1 \right)} \]

(6)

where, \(\omega\): uniformly distributed load = self-weight + weight of fluid, \(k_t\) = translational stiffness and \(k_r\) = rotational stiffness.

The longitudinal strain for a pipe section of fixed length is observed to increase at a higher rate for pipes of lower thicknesses as compared to pipes of greater thicknesses. At higher thicknesses the longitudinal strains are very low and don’t increase beyond a certain threshold. It is also observed that for a linearly varying thickness gradient there is an exponential variation in the longitudinal strain. In other words, the ratio of longitudinal strain for a pipe of 250 mm diameter to 500 mm diameter will be much higher than a 500 mm and 750 mm diameter at a fixed length of the pipeline cross section. The hoop strain varies linearly with the temperature gradient. However, the hoop strain is exponentially higher for lower thickness and continues to reduce as the thickness increases.
INTRODUCTION OF EXPERIMENTAL NOISE TO MEASUREMENTS

Structural health monitoring is largely focused on creating a network of sensors for monitoring structure elements and process parameters. In practical cases, it has been found that while taking these measurements, noise seems to persist which results in wrong readings. Our objective is to take a large sample of readings and find the error distribution (predominantly Gaussian) and check how the original reading is affected. Firstly, we introduce some artificial noise in $\varepsilon_{\theta\theta}$ in the form which is a normal distribution of experimental data with mean=0 and a standard deviation=0.05* $\varepsilon_{xx,\text{actual}}$

$$\varepsilon_{\theta\theta} = \varepsilon_{\theta\theta,\text{actual}} + \text{noise}(\eta)$$

where

$$\eta = N(0, \sigma)$$

$$\sigma = 0.05* \varepsilon_{xx,\text{actual}}$$

Accordingly, we obtain plots for the input $\varepsilon_{\theta\theta}$ and output $h$ which we treat as a function of $\varepsilon_{\theta\theta}$ i.e. $h=f(\varepsilon_{\theta\theta})$. Similarly, in the next stage we introduce noise in multiple readings that is $\varepsilon_{xx1}$ and $\varepsilon_{xx2}$.
The error corrections are performed by using the Newton-Raphson method. The observed shifts in the obtained input sample causes a shift in the output data. The errors appear as peaks in the collected data sets. The identification of the inflection allow us to introduce necessary correction parameters to minimize the data collection errors thereby reducing the chances of false positives in a large SHM framework.

CONCLUSION
The article introduces a mechanistic approach for structural health monitoring of a pipeline network subjected to pseudo-static boundary conditions and thermal stresses. The parameters affecting the degradation of a pipeline module are identified and a set of boundary conditions in the form of rotational and translational springs are used to depict stiffness degradation as a result of pipe corrosion/thinning and thermal expansion. The correction of sensor data errors has been discussed briefly to highlight the importance of proactive continuous monitoring techniques that can be optimized for efficient management of pipeline system’s health.

Remote SHM based techniques are expected to greatly reduce exposure levels to radioactivity while preventing catastrophic failures and other secondary defects. It would also allow proactive monitoring while the plant is in operation, thereby reducing maintenance costs. The inspection intervals can be significantly increased as opposed to condition-based maintenance which often involves replacement of intact parts.

REFERENCES