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Original Article

Dynamic and Fatigue Analysis of Dense Phase Transfer Lines Subjected to Slug Flow

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Abstract *- Pipe failures in dense phase transfer lines were detected in a Polyethylene (PE) granule process plan due to excessive vibration. A dynamic time–history analysis and a fatigue evaluation were performed to identify the root cause and mitigate vibration, in addition to the existing static stress analysis study. The piping system is designed for slug flow, in which moving solid/liquid material which is driven by gas pockets generates various transient forces at elbows. Time–History Inputs (TIH) and Time–History Location (THL) files were, as a result, constructed from the vendor slug forces, elbow geometry, and inter–elbow distances. Unlike the static profiles, time–history analysis here applies to force–time data directly and then evaluates the response incrementally through each event. Further analysis showed that these static methods tend to overpredict the stresses combined with dynamic time–history analysis, while the fatigue evaluation confirms a safe mode of operation over the overall expected life cycle. Time–history dynamics is essential for any realistic stress and fatigue predictions in slug-loaded transfer lines and avoiding unnecessary overdesign. This study provides opportunities to investigate more details for condition monitoring maintainability gaps, as well as to resolve the problem.*

Keywords *- Dense phase transfer line, Dynamic analysis, Fatigue life, Piping systems, Slug flow.*

1. Introduction

Granule handling facilities containing transfer lines frequently operate in conveying, where vibration and fatigue concern due to intermittent multi-phase slug flows. Slug flow comprises a moving liquid or solid mass that is then accelerated by a gas, producing a short-duration impact force at elbows, and also supports it repeatedly with each arriving slug. This dynamical nature of these varying loads also alters the stress distribution, frequency modal responses, and the fatigue life of any piping system in general. Previous studies have shown that flow patterns and transition regimes significantly influence hydrodynamic forces and pressure fluctuations in multi-phase transport systems [1]. However, it is also observed that most conventional design practices heavily rely on static stress envelopes, which do not capture transient pulse shapes, phase relationships, or modal interactions. Thus, the predicted stresses may be either overly conservative or unrealistic for a fatigue evaluation. It is observed that a typical slug flow profile in piping is shown in Figure 1.

Recent investigations into modal and dynamic responses have shown that transient load forces in dual-phase gas–liquid slug flow can significantly amplify the system's response, which depends on slug frequency, mixture velocity, and line geometries [2]. Similarly, other time-history simulation methods show [3] that the direct application of measurement or estimated force–time data can predict the structural response at fine time increments. These varying dynamic approaches are yielding a more realistic representation of system behaviour compared with different static methods. Fatigue remains a primary failure mode in every piping system subjected to cyclic loading. As described by Stephens et al. [4], the fatigue life of metals is determined by the causal relationship between stress range, material limit, forces, and cumulative damage.

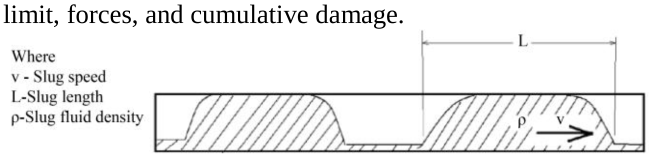

Fig. 1 Typical Slug flow profile

To ensure long-term structural integrity, fatigue assessments must be performed in accordance with code-based procedures such as those outlined in ASME Section VIII, Division 2 [5]. Incorporating those fatigue principles with dynamic load analysis provided a fixed framework for assessing the reliability of slug-loaded transfer lines. Despite these recent advances, very limited research has been reported for dense-phase transfer lines conveying polymer granules, where slugs and different frequent flow reversals occur. The primary novelty of this extensive study involves performing the detailed time-history dynamic analysis combined with fatigue assessment per ASME Section VIII Division 2, which evaluates the long-term integrity of slug-laden dual-phase transfer lines. These results, in the end, demonstrated the importance of dynamical modelling to capture various realistic stress cycles and further guide improvements for piping support design.

1.1. Contribution

We present a plant case study where repeated failures were observed in supports and piping. These prompted a detailed evaluation using coupled time–history and fatigue analysis. Using slug pulses derived from vendor data and plant geometry, we (i) construct TIH/THL inputs; (ii) compare dynamic vs. static stresses; (iii) evaluate fatigue per ASME Div. 2. The study highlights that time–history is necessary for slug–loaded lines to obtain reliable margins and guide effective mitigation strategies.

2. System, Slug Loads, and Time–History Inputs

2.1. Piping Configuration and Elbows

The line contains eight directional changes (elbows) where slug forces act. Figure 2 depicts the flow path, elbow nodes (A07–B24), and key supports used in the analysis. Inter–elbow distances that govern slug arrival times are summarized in Table 1.

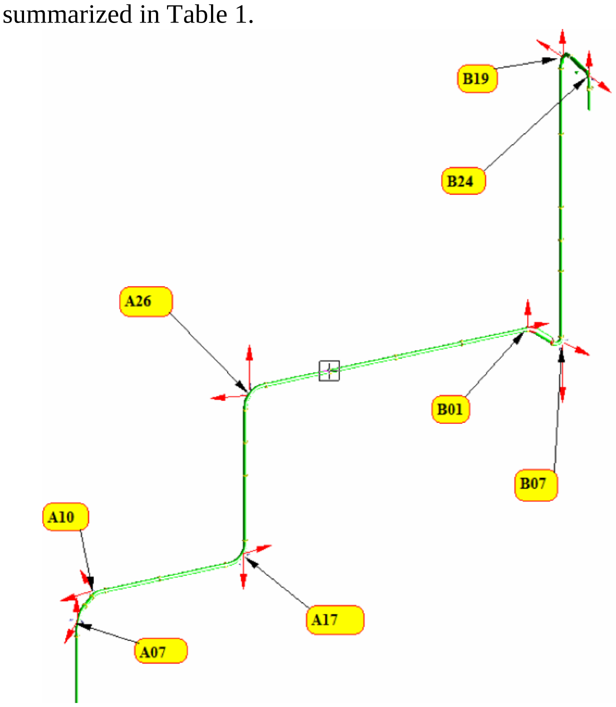

Fig. 2 Dense phase transfer line schematic with elbow/node labels

Typical upstream slug frequency was 8 slugs/min (before the plug splitter) and 6 slugs/min downstream, consistent with plant operation.

Table 1. Distances between elbows along flow (used to determine slug arrival times)

Start (Node)	End (Node)	Distance (m)	Δt (s)
A07	A10	4.523	0.50
A10	A17	13.750	1.51
A17	A26	15.850	1.74
A26	B01	2.590	0.28
B01	B07	3.565	0.39
B07	B19	27.160	2.98
B19	B24	5.400	0.59

2.2. Slug Pulse Shape and Characteristic Times

Each elbow has an elbow angle θ (radians), radius R, the slug length L, and the mixture velocity V, then the pulse shape is defined by Equation 1.

$$T_r = \frac{R\theta}{V}, T_d = \frac{L - R\theta}{V}(L > R\theta), T_{tot} = 2T_r \vdash 2T_d \quad (1)$$

Physically, the force rise over T_r since the slug enters first and accelerates around the bends, then remains near a peak for T_d as the slug traverses around the bend, and decays over T_r duration as it exists.

Figure 3 illustrates the characteristic history; characteristic times at each elbow are listed in Table 2.

Table 2. Characteristic times at elbows (inputs to TIH/THL). Radius *R* (mm), Diameter (in), = 9.101m/s, angle θ (deg)

Elbow	R (m)	θ (deg)	T_r (s)	T_d (s)	T_{tot} (s)
A07	1600	90	0.276	0.105	0.657
A10	1600	45	0.138	0.243	0.519
A17	1600	90	0.276	0.105	0.657
A26	1600	90	0.276	0.105	0.657
B01	457.2	30	0.026	0.355	0.407
B07	457.2	90	0.079	0.429	0.587
B19	1600	90	0.276	0.232	0.784
B24	533.4	90	0.092	0.416	0.6

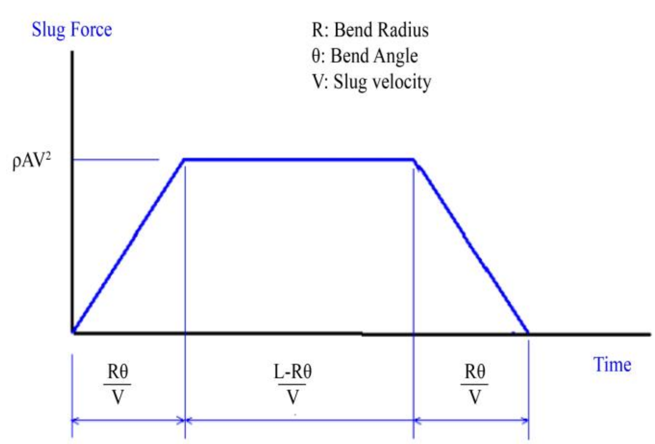

Fig. 3 Elbow slug force versus time

2.3. Slug Loads in Elbows

Vendor data showed significant differences in force magnitudes between 90° and 45° elbows, primarily due to geometry. The forcing functions acting on an elbow consist of axial (F_{axial}) and orthogonal (F_{ortho}) components, as illustrated in Figure 4.

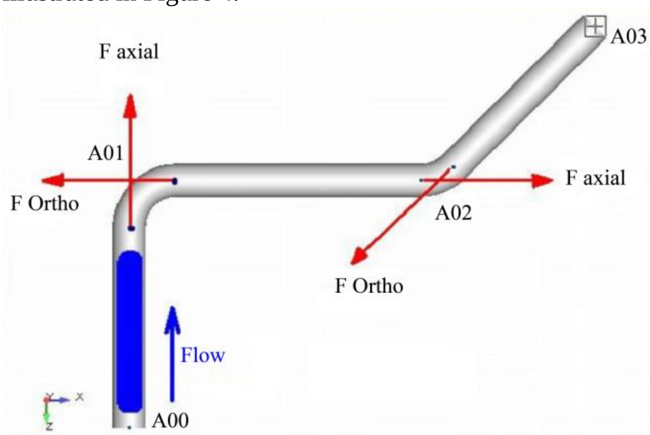

Fig. 4 Typical slug loads in 90° and 45° elbows

The time required for the slug head to exit the bend and attain the maximum slug force is shown in Equation 2.

$$T_r = \frac{R\theta}{V} \quad (2)$$

$R\theta$ is the arc length of the bend, and V is the mixture velocity. First, the peak slug force is shown in Equation 3 as:

$$F_{slug} = \rho A V^2 \quad (3)$$

Where ρ represents mixture density, A cross-sectional area, and V is velocity. The duration of the peak force is sustained for T_d as shown in Equation 4.

$$T_d = \frac{L - R\theta}{V} (L > R\theta) \quad (4)$$

L is the slug length; the decay occurs over a further T_r .

Measured slug frequency is shown in Equation 5 and 6.

$$F_{before} = 8 slugs/min, T_{before} = 60/8 = 7.5 s/slugs \quad (5)$$

$$F_{after} = 6\, slugs/min, T_{before} = 60/6 = 10\, s/slugs \quad (6)$$

Here, F_{before} corresponds to conditions upstream of the plug splitter, while F_{after} applies downstream.

3. Materials and Methods

A validated static stress model of the transfer line served as the baseline for comparison. Dynamic time-history simulations were performed using CAESAR II, applying transient force-time inputs derived from vendor-supplied slug data. Each elbow was first defined with the respective forces, the rise and decay times, and phase delays obtained from Tables 1 and 2.

The step time for simulating the integration solver was set to 0.001 s to accurately capture multiple short-duration pulses. A Rayleigh damping ratio of 2 % was applied to represent structural energy dissipation, while boundary conditions and support stiffness were maintained identical to the static model. Fatigue life was assessed using the stress range method from ASME Section VIII Division 2, Part 5, Paragraph 5.5.3. The computed alternating stresses were compared against design fatigue curves for carbon-steel piping. The Cumulative Usage Factor (CUF) was evaluated by combining slug-induced and thermal cycles to verify that U<1.0.

Validation of input data was performed by comparing predicted slug arrival times and pulse durations with plant operating logs and vendor data sheets. The agreement within ±10 % confirmed that the time-history load functions realistically represented operating conditions.

4. Results and Discussion

The static stress analysis yielded a maximum stress ratio of 0.79 (79 % of the allowable). In contrast, the dynamic time-history analysis reduced the peak stress ratio to 0.56 (56 % of the allowable) due to phase separation of transient loads and damping effects. Table 3 summarize the comparison between static and dynamic results.

Table 3. Comparison between static and dynamic results

Analysis Type	Max Stress/Allowable	Peak Displacement (mm)
Static	0.79	6.8
Dynamic (Time-History)	0.56	5.1

The comparison clearly shows that static methods overpredict stress levels by approximately 29 %, potentially leading to over-designed supports and unnecessary material usage. The fatigue evaluation confirmed that the cumulative usage factor remained below unity for an equivalent of 8.484×10^7 slug cycles, ensuring safe operation. The study also highlighted the influence of elbow geometry and slug frequency on dynamic response. Larger-radius elbows distribute impact loads over longer durations, reducing local stress amplitudes. Conversely, closely spaced elbows caused partial pulse overlap, amplifying vibration at certain supports. Although no field strain measurements were available for direct validation, the predicted stress magnitudes aligned well with observed vibration amplitudes at the plant, suggesting adequate model accuracy.

5. Conclusion

A detailed dynamic and fatigue analysis of dense-phase transfer lines subjected to slug flow was performed. The time-history approach, incorporating realistic slug force–time data, provided more accurate and less conservative stress predictions compared with static analysis. Key Findings include:

- Fixed Static stress profiles can exceed in estimating maximum stresses by approximately 30 % under varying slug-flow conditions.
- Performing dynamic analysis has reduced the stress ratio from an initial value of 0.79 to 0.56, and the fatigue usage factor is reduced to 0.54, guaranteeing safe long-term operation.
- The geometry of Elbows, spacing between pipes, and frequency of slugs strongly influence different transients and should be carefully used in design.

5.1. Design Implications

The results demonstrate that time-history simulation is a practical tool for optimizing support stiffness and spacing, reducing vibration, and avoiding over-design.

5.2. Limitations

The present study relied on numerical modelling and vendor data without experimental strain validation.

5.3. Future Work

Planned research includes laboratory-scale testing and field monitoring to verify predicted stress cycles and improve the characterization of slug-pulse dynamics in dense-phase transport systems.

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