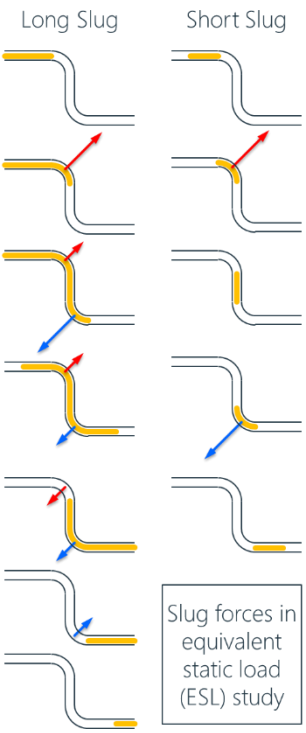
Technical primer:
Slug flow dynamic analysis

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Slug flow

Slug flow is a type of two-phase (liquid/gas) flow in a pipe where large bubbles of gas are separated by slugs of liquid. Slug formation depends on the liquid and gas velocities but can also be terrain-induced (created in low spots in the piping).



Slugs create a force at a direction or diameter change in piping, due to changing momentum. Both the slug front and slug tail create a net force.

It is useful to distinguish between short slugs, that act on one elbow (or fitting) at a time, and long slugs, that act on two or more elbows simultaneously (and therefore create a net force on the piping segment). The image at right shows an example of the two lengths of slugs.

Note that severe slugging may not be as much as a risk as normal slugging, due to the higher velocity of normal slugs [3] [4]. Severe terrain induced slugging usually occurs at lower flowrates, where liquid can fall out of the stream and collect in low areas.

Equivalent static load (ESL)

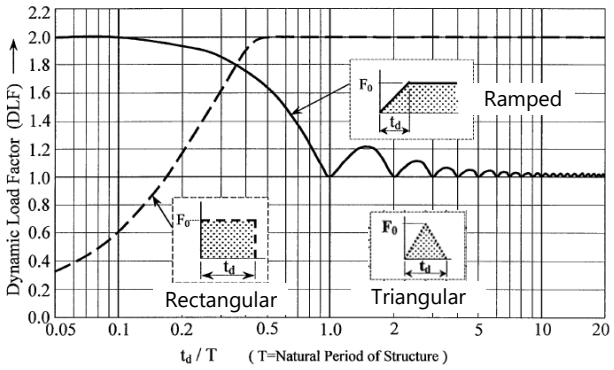
Slugs are impulse-type dynamic loadings (unlike periodic or random dynamic loads) which can be analyzed using an equivalent static load (ESL) methodology. This methodology simulates a dynamic load using a static load and a dynamic load factor.

Dynamic load factor

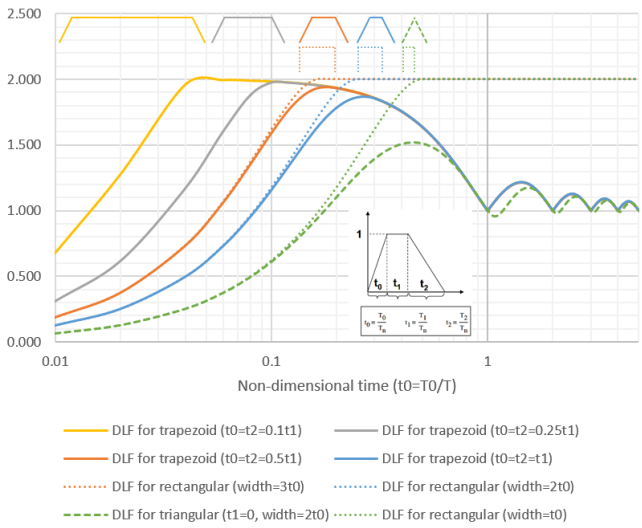
The dynamic load factor (DLF) is the ratio of maximum displacement or stress of the dynamic response of a structure divided by the static response of a structure, for a given load. The DLF is multiplied by the dynamic load to give a static equivalent load for use in an ESL study.

An important factor in the calculation of the DLF is the natural period of the structure (*T*) which is the inverse of the natural frequency (*f=1/T*) of the structure. In general, the lowest natural frequency of the structure (considering the force direction and location) should be used in the calculation. For example, a force at an anti-node or in a direction different than the mode shape should be ignored.

Commonly used DLFs are shown in the figure below [5], where t_d is actual time and t_d/T is non-dimensional time. In most cases, it is conservative to use DLF=2 for long slugs.



In the case of short slugs, the impulse force shape is trapezoidal. The DLF is more sensitive to the slug length and velocity, relative to the elbow length, however using DLF=2 is also conservative. This can be seen from the figure below [6], where structure natural period $T_n=T$, actual time is T_0, T_1, and T_2, and non-dimensional time is t_0, t_1, and t_2.



For very short impulses, the following formulas [7] can be used to calculate the DLFs, where non-dimensional time, $\beta=t_d/T$.

$$DLF_{ramped} = 1 + \frac{|\sin(\pi\beta)|}{\pi\beta} \approx 2 \; as \; \beta \to 0, \beta \geq 0$$

$$DLF_{rectangular} = 2|\sin(\pi\beta)| \approx 2\pi\beta \; as \; \beta \to 0, \beta < 0.5$$

$$DLF_{triangular} = \left(\frac{4}{\pi\beta}\right)\sin^2\left(\frac{\pi\beta}{2}\right) \approx \pi\beta \; as \; \beta \to 0, \beta < 0.3$$

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Forces

The dynamic force on a 90° piping elbow is related to the fluid kinetic energy and the pipe inner area. The equivalent static force or load, F_{ESL}, is shown below, where *DLF* is the dynamic load factor, ρ_L is the liquid slug density, ρ_G is the gas density, v_s is the slug velocity, and *A* is the pipe inner area. The force direction is radial outward from the bend radius center-point to the middle of the bend.

$$F_{ESL} = DLF \cdot \sqrt{2} \cdot (\rho_L - \rho_G) \cdot {v_s}^2 \cdot A$$

Fluid dynamic software may calculate the dynamic loads on a set of components or sections of pipe. These are called force sets. To apply force sets to an FEA model, it is common to apply half the force to both ends of a component or pipe span.

Methodology

An ESL study should follow the following steps:

1. Calculate the dynamic impulse-type (transient) load vs time on the piping component either using empirical calculations or fluid dynamic software. This force can either be at a single location (eg, elbow) or on a set of components ("force set").
2. Calculate the appropriate DLF based on the dynamic load shape and the lowest piping natural frequency that is likely to be excited by the load.
3. The equivalent static load (ESL) is calculated by multiplying the dynamic load by the DLF.
4. Apply the ESL to the piping model as a static load. If there are multiple loads (eg, at different elbows, reducers), apply them separately as different load cases. Do not apply the loads simultaneously.
5. The equivalent static displacements, stresses, and reaction loads can be calculated from the FEA model. These will be equivalent to the actual maximum displacement, stress, or reaction that would have been found if a full transient dynamic analysis was done. Think of the ESL method as a snapshot of the worst-case results at a particular time in the dynamic response of the system. Note that these results should be assumed to be zero-to-peak.
6. Compare the equivalent static stresses to the relevant fatigue limit, remembering that fatigue limits tend to be stress ranges (peak-to-peak) and ESL results are zero-to-peak.

Fatigue

Intermittent slugs may exceed the fatigue limit but not build fatigue damage quickly due to the low cycles. Slug forces will tend to excite the piping natural frequency and slowly die out. A rule of thumb is one (1) impulse-type transient event that creates decaying vibrations will tend to create the equivalent of about six (6) cycles of constant amplitude vibration, assuming a system damping ratio of 1%.

If the fatigue limit is exceeded during the ESL analysis, then a full fatigue analysis is recommended to calculate fatigue damage or fatigue life. Note that BS 7608 [2] states that "occasional high stress ranges that contribute <1% of the total damage may be ignored", which may allow rare slugging events to be excluded from the fatigue damage assessment.

Water hammer

The methodology described in this primer is also applicable to water hammer forces, with two major changes due to the high speed of sound of water hammer pulses:

- Water hammer forces occur quickly, therefore the forces should be applied simultaneously to a model [5], not individually like in a slug flow ESL analysis. This can create challenges in understanding the phasing between forces and force sets, but the worst-case phasing can be assumed.
- Water hammer forces occur for a short duration, therefore, they tend to have a low DLF. Using a DLF=2.0 can be overly conservative in a water hammer ESL analysis. Also, the timestep in the hydraulic transient analysis (HTA) needs to be small enough to accurately capture the pulse shape.

References

[1] "Guidelines for the Avoidance of Vibration Induced Fatigue Failure in Process Pipework", Second Edition January 2008, Energy Institute, London.

[2] British Standard BS 7608:2014+A1:2015, "Guide to Fatigue Design and Assessment of Steel Products", British Standards Institution, 2015.

[3] "Transient vibration guidelines for fast acting valves screening assessment", OTO 2002/028, HSE, 2002.

[4] "The Characteristics and Forces Due to Slugs in an S-Shaped Riser", I.A.F. Das, Cranfield University, PhD Thesis, 2003.

[5] "Pipe Stress Engineering", L. C. Liang-Chuan, A. Tsen-Loong, Peng Engineering, ASME Press, 2009.

[6] "The Dynamic Load Factor of Pressure Vessels in Deflagration Events", ASME PVP2011-57210, Y Xu & K Young.

[7] "Harris' Shock and Vibration Handbook", Fifth Edition, C. M. Harris & A. G. Piersol, 2002.

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