National Aeronautics and Space Administration

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Treatment of Transient Pressure Events in Space Flight Pressurized Systems

Analytical and experimental evidence shows that fast-moving dynamic pressure fluctuations caused by valve actuation, fluid-system priming, fluid discharge, vibration, and flow disturbances can elicit adverse structural response and must be considered in the space flight pressure system design and verification process.

Background

Transient pressure events are fast-moving dynamic fluctuations due to disruptions within the pressurized systems, Figure 1. Since numerous factors influence pressure transients, a comprehensive approach to treating these is absent. Vague or contradictory requirements have led hardware developers to bypass this assessment. Structural failures have occurred in aerospace applications from overloads or fatigue from transients.

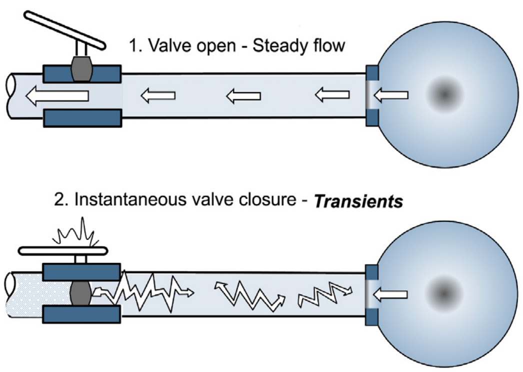

Figure 1: Illustrations of Pressure Transients

Guidelines

Accounting for pressure transients is a multi-disciplinary activity involving Fluids, Dynamics, and Structures. The NESC paper [1] brings clarity to the understanding of transients caused by flow disturbances and documents best practices with case studies and roadmap. A 6-step process (Figure 2) highlights, 1) Pressure System design establishing nominal operating pressure and initial steps to minimize transients, 2) Assessment of pressure transients via fluids analysis or test, 3) Classification of pressure system components, 4) Dynamic response of structure, 5) Establishing Maximum Expected Operating Pressure (MEOP), which includes transient response, 6) Structural verification.

Pressure transients are characterized via simple fluids analyses using the Joukowsky equation or 1D fluid models using coupled first-order partial differential equations involving continuity and momentum equations. Detailed test-validated 2D or 3D models can capture losses and geometric effects. Transients can also be measured via instrumented subsystem tests.

Fast-moving transients induce a dynamic structural response. Localized stress peaks are created whose magnitudes are influenced by the component geometry, material properties, and pressure wave (velocity, amplitude, and shape). A ratio called Dynamic Amplification Factor (DAF) provides a quantitative measure of structural response via structural dynamics analysis. A parametric study performed by varying the mean radius (r), wall thickness (t), modulus of elasticity (E), and density (ρ) of a pipe subjected to a half-sine traveling pressure wave showed that the ratio (ω^*) of pressure wave frequency (ω) to the ring natural frequency (ω_n) of the pipe was a key parameter in DAF calculations.

$$\omega^* = \omega/\omega_n = r\omega/\sqrt{E/\rho} \quad \text{(rad/s)}$$

Three outcomes are possible:

$\omega^* << 1 \rightarrow$ similar to static pressure load, DAF = 1
$\omega^* = 1 \rightarrow$ resonance, response is amplified, DAF ~ 3
$\omega^* >> 1 \rightarrow$ structure responds slower than the load, DAF ~ 0

Pressure Vessels vs. Pressure System Components

The transient pressure wave entering fluid storage vessels, such as tanks and pressurized structures, dissipates due to relatively large volume compared to that of the connecting pipe. In these cases, DAF is zero and the magnitude of the pressure transient is added to the steady state pressure to define MEOP. Pressurized components, such as pipes and valves, may show a minimal dynamic response (DAF~0.0), a quasi-static response (0.0 < DAF < 1.0), or an amplified response (DAF ≥ 1.0).

Verification Process

Establish a MEOP that mimics a localized maximum stress at the critical location, which is equivalent to that of steady state pressure plus pressure transient. A damage tolerance approach with lower proof and burst factors can result in weight-savings, especially when pressure transient magnitudes are significant.

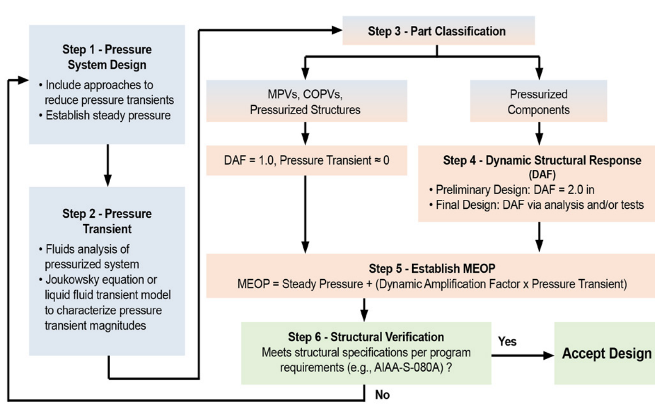

Figure 2: Workflow for Transient Pressure Evaluation

References

1. K. Imtiaz, V. Goyal, P. Babuska, E. Barbour, and J. Smith, *Treatment of Transient Pressure Events in Space Flight Pressurized Systems* NASA Engineering and Safety Center, NESC, NASA/TM 2021-0022275, https://ntrs.nasa.gov/citations/20210022275, 2021.

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