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Understanding Space Launch Vehicle Complexity: A Case Study in Combustion Instabilities

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Abstract

In rocket engine failures of F-1 and Titan-II, chamber combustion instabilities (CI) caused damage, reflecting behavioral complexities at the component level. Combustion chamber walls with embedded acoustic nodes self-excited by the heat released to cause amplification of acoustic oscillations, showed increases in the thermo-kinetic related pressure. Although the causes of the failed launch were determined decades after the accident, the problem-solving process identified the CI problem domain with information describing the internal representation of the problem. Rocket engine complexity may be described by the high number of component parts contained; alternatively, of the constituent processes occurring. Interactive behaviors not accounted for, occur at the interface between the parts or result from coupling of different processes within the combustion chamber. Unlike monolithic systems, rocket engines exhibit performance behaviors emergent, unpredictable and uncoordinated. Over half propulsion technologies of prospective mission competence have a Technical Readiness Level (TRL) less than 5. However, operational risk needs mitigation through increased development of technological readiness related to not only structural performance but to processes enacted of their functions. Increasingly complex propulsion technologies and the thousands of stakeholder requirements needed for analysis are important for framing problems to be solved. The purpose of this paper is to correlate complexity of propulsion technology at the subsystem level with development of technological readiness for performance reliability. Nonlinear performance behaviors connote system complexity.

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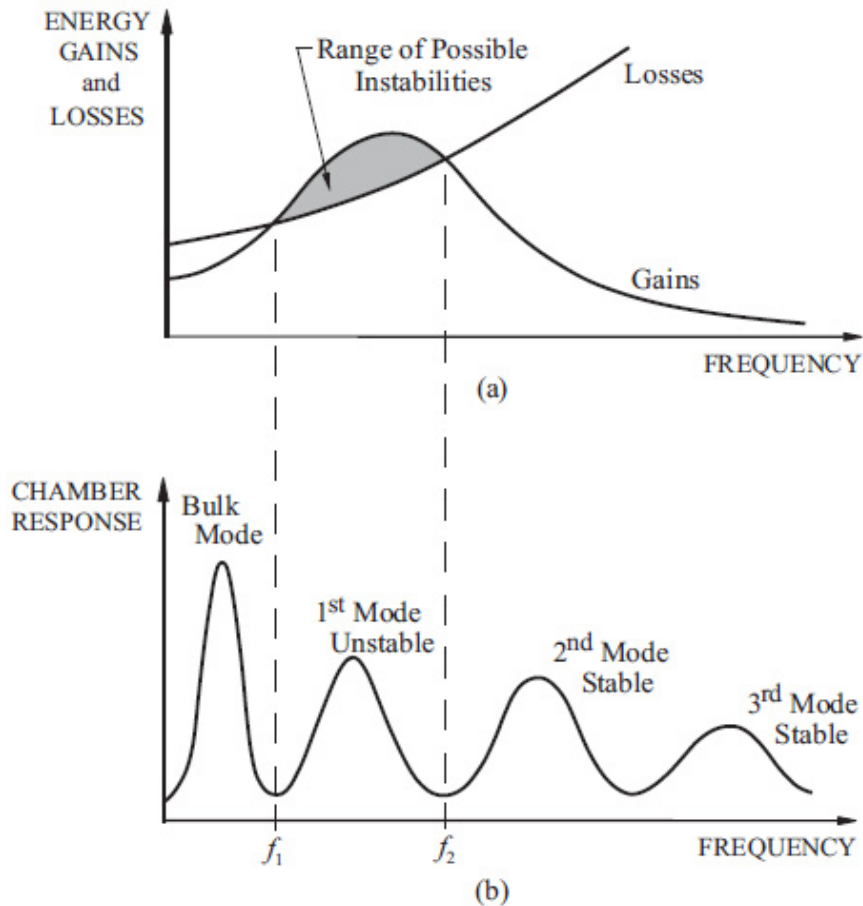
1. Introduction

The nonlinear effects of combustion instabilities (CI) represent function values of the burning rate-dependent hardware response over a range of different pressure frequencies. And, they reflect many different harmonic modes simultaneously excited such that the propulsion system fails to linearize into discrete wave forms due to many different processes and factors that include chamber acoustics and geometries, propellant flow and pressures, propellant burning rate, flame characteristics. Very small fractions of available energy may cause excessive large unstable motions within combustion chamber as a consequence of internal coupling between combustion processes and unsteady motions. Since oscillations affect mean thrust unnoticeably, chamber instabilities go unnoticed. However, the cumulative changes in thrust relate to structural vibrations causing damage. For the past 60 years, dozens of solid rocket motors developed have experienced CI at increased costs to project development only to be cancelled or continued in spite of nondestructive oscillations. A prevalent factor for engine sub-performance, CI, requires technology development programs to both study and control the micro-dynamics of propulsion complexities. Quantitative characterization of combustion instability provides performance-based reliability requirements in early design for system durability and component selection. Since program contractors are not obligated to design for reliability, reliability issues, such as CI, go unnoticed. Observation of pre-engineering and manufacturing developed (EMD) prototypes of propulsion technology provides data to characterize system performance but fails to evaluate concurrent potentiating processes that undermine performance, such as CI. In efforts to mitigate CI risk, reducing combustion-generated pollutants (ie., NO_x and carbonaceous soot) with lean-burning combustion systems also changes unsteady heat-release patterns that when in-phase with acoustic pressure fluctuations inadvertently cause fluctuations to grow into high amplitude oscillations (100-500 Hz). Such oscillations cause flame extinction, reduce engine life and cause structural damage to the chamber. Methods used to analyze or predict CI describe (1) relations between flame-front perturbations about particular Mach numbers to solve for nonlinear CI eigen-frequencies; (2) relations between pressure perturbations and combustion heat release; and (3) computational fluid dynamics (CFD) simulations to evaluate both (1) and (2). Large eddy simulations (LES) model for propellant flow field and chemistry, as well as, fine-scale fluid contributions to flow field incorporating low order acoustic model to predict oscillatory instabilities. CFD provides modeling of pre-hardware testing of flow-induced pressure and temperature loads to diagnose potential problems of existing requirement engineering (RE) components and to develop optimum designs for RE components. Additionally, CFD provides prediction modeling of flow behavior and heat transfer to internal walls of RE injectors, combustion chambers and nozzles. CFD analysis is used to predict and simulate combustion flow behavior and heat transfer to internal walls of rocket engine injectors, combustion chamber and nozzles. Failure to analyze pressures, temperatures, and flow rates of propellants, pre-design and pre-manufacture, results in inadequate strength, thermal protection and operational control, thus increasing costs, excessive re-design and testing, with the potential for engine-, system-, or component-failures. The need for sensors to monitor engine behaviors provides both documentation and feedback for corrective re-design and –engineering. Whereas simulation models are data-driven, RE processes are model-driven to enable model refinement and transformative platform model generation. Advanced imaging techniques are of two types. First, combustion visualization includes adaptive mesh refinement tools that model chamber turbulence by imaging polygonal and embedded geometry representations; and endoscopic methods for soot residue analysis and chemical characterization of combustion species emissions. Second, optical non-destructive testing/ imaging includes chamber-embedded fiber optics, infrared thermography, endoscopic and terahertz technology to measure liquid level, chemical, pressure, electric field, vibration strain and temperature. Advanced Power System Visualization Tools integrated with propulsion modeling methods synthesize data informative of propulsion problems and identify corrective actions timely to assure system reliability.

2. Combustion Instabilities

Joseph Narelsky demonstrated how reliability and complexity of machines were inextricably linked. Rocket engine complexity may be described by behaviors of interacting processes that are emergent, unpredictable and uncoordinated, resulting in sub-par or failed performance. Linear behaviors show energy gains and losses proportional to energy exchanged from the coupling (See Figure 1.41), which is proportional to the square of initial,

small amplitude of the disturbance (Culick, 2006). Dependent variables of combustion instabilities show time-dependent amplitudes of acoustic modes used as the basis for series expansion of unsteady pressure (Culick, 2006). Such consideration relates to general problems of linear stability.



Qualitative dependence of (a) energy gains and losses; and (b) the frequency combustor.

Figure 1.41

Blomshield (2006) defined nonlinear instability (see Figure 1.42) as “oscillations containing many acoustic modes, characterized by steep fronted non-sinusoidal waveforms that cannot be linearized into discrete sin waves ... caused by injecta or debris passing through the nozzle which pulse the motor.” Combustion chamber processes are nonlinear, whereby a linearly stable system will respond unstably to large disturbances and show oscillations of limiting amplitudes (Culick, 2006). The unstable disturbance grows exponentially over time and without limit with the linear processes during the initial stages of instability of the self-excited chamber (Culick, 2006). The unstable chamber motion temporally starts to display a limiting motion, a periodic limit cycle (Culick, 2006). Culick (2006) underscored the need to understand properties of the limit cycle in order to know what variables determine nonlinear behavior and motion sensitivity. Burnley (1996) demonstrated that noise and interactions between random acoustical

motions related to flow separations, turbulence as well as combustion noise can cause departures from periodic limit cycles.

Recognizing the nonlinear behavior of combustion stabilities motivated NASA to develop bombing technique in the Apollo program (Harrje & Reardon, 1972). By triggering the chamber to display instability, the size of disturbance would show measurable sensitivity to chamber relative stability (Culick, 2006). Experimental activities were replaced by numerical simulations in early 1970s due to a need for deeper understanding of instabilities. Comparison of experimental data containing large uncertainties with approximate analyses of numerical simulations during the 1980s showed good agreement for nonlinear unsteady motions of combustion chambers. Wanbainen et al. (1967) used Helholz type acoustic damping devices to suppress high frequency combustion instability. Such experimental data contained large uncertainties that it was not until early 1970s when attempts for approximate analysis by numerical simulation for the same problem (See Figure 1.43) were made possible (Culick & Levine, 1974).

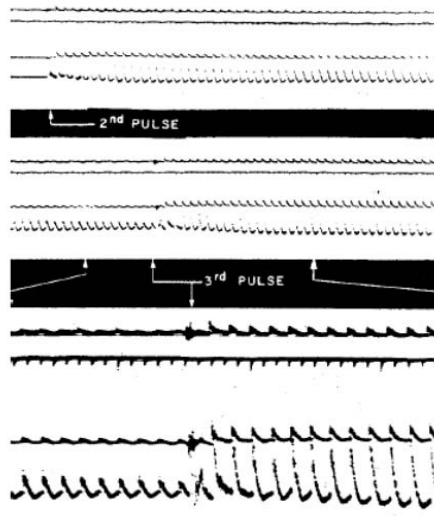


FIGURE 1.42. Steep-fronted waves observed in solid propellant rocket motors (Brownlee 1964).

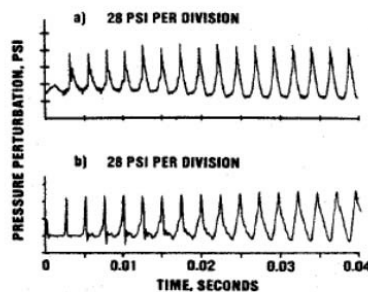


FIGURE 1.43. A comparison of observed and simulated steep-fronted waves in a solid propellant rocket motor. (a) observed; (b) numerical simulation (Baum and Levine 1982).

Culick (2006) showed numerical simulation applied to nonlinear problems of a single case, for which generalization was not possible. Integration of the three investigative methods—experimental testing, analytical approximation and numerical simulation—resulted in the capability to understand, interpret and predict combustion instabilities.

3. Technological Readiness

Key propulsion parameters for engine chamber pressure, area ratio, and oxidizer fuel ratio, are optimized and plotted to show impacts to engine mass and overall vehicle mass (GAO, 2009). Factors characterizing technology risk include uncertainty that technologies constituting sub-system technology portfolio will not reach maturity for subsystem integration and that technical performance measures will not be met (Wilhite & Weisbin, 2004). The need for sensors to monitor engine behaviors provides both documentation and feedback for corrective re-design and -engineering. Therefore, co-development of propulsion and sensor technologies indicates an additional need for compatible, requirements engineering.

The probability of project failure indicates technical failure of performance, as well as programmatic failure of costs and schedule (Wilhite, 2006), all of which manifest from both observed and unobserved structures and inter-structural relations. Unobserved structures and inter-structural relations relate to subsystem complexity. The inability to adequately measure uncertainty when technology matures and integrates into the larger system (Mankin, 2002) points to the need for exploring component level integration, interoperability, and sustainability. Effective integration studies at the component level may require greater rigor and different tools. Nilsson, Nordhagen, and Ofredal (1990) recommended an Integration Maturity Metric (IIM) to determine integration maturities of nested component configurations and a metric to examine different levels of sub-system architecture. The latter would require (1) access to a user interface integrating the components; (2) access to data of one component to access data of another component; and (3) access to the integrating components executing internal functionality (Nilsson et al., 1990). More than one component would store the data but the overall data would be controlled centrally (Nilsson et al., 1990). There is greater demand for data describing inter-operability of two or more components (Rezael, Chiew, Lee, & Aliee, 2014).

Developing and incorporating sensor technology, especially with complex systems, entail distinct validation of technological readiness and reliability (Bartzoudis, 2007). Propulsion data derived from either sensor-visualization methods or from testing provide the basis for developing a model to simulate real-world propulsion operational processes. Whereas sensor-visualization simulation models are data-driven, requirements engineering processes are model driven to enable model refinement and transformative platform model generation. Advanced power system visualization tools integrated with propulsion modeling methods synthesize data informative of propulsion problems and enable identification of timely corrective actions to ensure system reliability (Rezael, Chiew, Lee, & Aliee, 2014). Solution of multi-objective optimization problems in aeronautical and aerospace engineering has become standard practice. The high technical risks involved, present opportunity to consider the problem domain of component-component interactions and identify requirements needed during the engineering process.

4. Conclusion

Combustion instabilities represent a category of causes for sub-par rocket engine performance not structurally related. Energy of heat release due to combustion processes causing chamber vibrations (motions) represented in terms of frequencies correspond to acoustic frequencies described from concomitant noise due to combustion processes. The chamber walls described as having embedded acoustic nodes cause amplification of acoustic oscillations that increases thermo-kinetic related pressure amplitudes when excited by the heat released. The cumulative effects of such limiting cycles cause damage as shown in F-1 and Titan-II launch accidents. Failure to analyze pressure, temperature, flow rates of gases/fluids in propulsion systems using CFD techniques prior to design and manufacture will result in inadequate structural strength, thermal protection, operational control of liquid rocket propulsion system and component parts.

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