SOLID MOTOR & LIQUID ENGINE VIBRATION COMPARISON

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Introduction

The purpose of this paper is to present an overview of the vibration characteristics of solid motors and liquid engine systems. Further details and case histories are given in the references.

Broadband Random Vibration

Solid motors and liquid engine systems both generate broadband liftoff acoustic noise. The resulting sound pressure levels depend on the number of nozzles, nozzle exit diameter, thrust, exhaust velocity, launch pad configuration, use of flame trench or water suppression, etc. Current empirical acoustic prediction techniques do not otherwise differentiate between solid motors and liquid engines, per Reference 1.

Solid motors and liquid engine systems both generate structural-borne, broadband vibration during liftoff and ascent, which can propagate throughout the vehicle. But the resulting vibration levels tend to be less than those due to liftoff acoustics and aerodynamic flow excitation during the transonic and maximum dynamic pressure phases.

Both solid motors and liquid engine systems have localized exceptions:

1. The forward and aft domes for solid motors may have high vibration levels due to the proximity of the propellant burn surface

2. Liquid engine turbopumps produce high vibration levels

The high vibration levels for each localized case may be broadband random, sinusoidal, or a combination thereof.

Sinusoidal Excitation

Sinusoidal oscillations are important characteristic of each system. These oscillations have several potential consequences:

1. Vehicle control problems
2. Resonant excitation of structural modes
3. Over-stressing payloads or critical components
4. Degraded propulsion performance

The remainder of this paper focuses mainly on sinusoidal vibration sources.

Solid Motor Vibration Sources

Solid rocket motors have combustion cavities. The cavities for elongated motors typically have an organ pipe shape, although other geometries may be used.

The hot exhaust gases may form standing pressure waves inside these cavities. The standing waves may be driven by vortex shedding within the cavity.

The standing wave oscillation occurs at a sinusoidal frequency per Reference 2. Integer harmonics may also be present.

Furthermore, these frequencies tend to shift downward with time as the cavity enlarges due to propellant expenditure.

This effect is called *thrust oscillation* for the case of the solid rocket boosters used on the space shuttle system. It is also known as *resonant burn* for smaller motors.

This pressure oscillation drives structural-borne vibration particularly in the vehicle's longitudinal axis.

The extent to which the oscillation occurs varies according to motor design and may also vary by lot number.

Liquid Engine Vibration Sources

The pressure, temperature, propellant flow rate, and exhaust velocity each experience fluctuations in a liquid engine, per References 3 and 4.

Propellant pump cavitation and gas entrapment in propellant flow may contribute to these fluctuations.

The pressure fluctuation can interact with the natural frequencies of the propellant feed system or the combustion chamber acoustic volume. This interaction causes instability oscillations.

A rocket with "smooth combustion" has pressure fluctuations that do not exceed $\pm$5% of the mean chamber pressure, during steady operation.

There are different types of combustion instability as summarized in Table 1.

Table 1. Types of Combustion Instability in Liquid Engines

Type	Frequency Range (Hz)	Cause Relationship
Low frequency called chugging or system instability, Pogo	10-200	Linked with pressure interactions between the propellant feed system and combustion chamber. May excite longitudinal vibration mode of entire vehicle.
Intermediate frequency, called acoustical, buzzing, or entropy waves	200-1000	Linked with mechanical vibrations of propulsion structure, injector manifold flow eddies, fuel/oxidizer fluctuations, and propellant feed system resonances.
High frequency called screaming, screeching, or squealing	Above 1000	Linked with combustion pressure waves and chamber acoustical resonance properties.

Combustion instability problems can be attenuated by adding an accumulator in the propellant feedline.

Engine shutdown transients are another concern. The Delta II had a main engine cut-off oscillation (MECO) event at 115 Hz, per Reference 5.

In addition, liquid engine tanks have slosh modes which can be mitigated via baffles, per References 6 and 7.

Conclusion

Sinusoidal and broadband random vibration effects for both solid motors and liquid engines are difficult to predict analytically for a new propulsion system design.

Careful static fire testing must be performed with proper instrumentation to characterize these effects.

The resulting levels will affect avionics, payload, and control system design and testing.

References

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