Combustion Stability Characteristics of the Project Morpheus Liquid Oxygen / Liquid Methane Main Engine

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Abstract

The Project Morpheus liquid oxygen (LOX) / liquid methane rocket engines demonstrated acoustic-coupled combustion instabilities during sea-level ground-based testing at the NASA Johnson Space Center (JSC) and Stennis Space Center (SSC). High-amplitude, 1T, 1R, 1T1R (and higher order) modes appear to be triggered by injector conditions. The instability occurred during the Morpheus-specific engine ignition/start sequence, and did demonstrate the capability to propagate into mainstage. However, the instability was never observed to initiate during mainstage, even at low power levels. The Morpheus main engine is a JSC-designed ~5,000 lbf-thrust, 4:1 throttling, pressure-fed cryogenic engine using an impinging element injector design. Two different engine designs, named HD4 and HD5, and two different builds of the HD4 engine all demonstrated similar instability characteristics.

Through the analysis of more than 200 hot fire tests on the Morpheus vehicle and SSC test stand, a relationship between ignition stability and injector/chamber pressure was developed. The instability has the distinct characteristic of initiating at high relative injection pressure drop (*dP*) at low chamber pressure (*Pc*); i.e., instabilities initiated at high *dP/Pc* at low Pc during the start sequence. The high *dP/Pc* during start results during the injector /chamber chill-in, and is enhanced by hydraulic flip in the injector orifice elements. Because of the fixed mixture ratio of the existing engine design (the main valves share a common actuator), it is not currently possible to determine if LOX or methane injector *dP/Pc* were individual contributors (i.e., LOX and methane *dP/Pc* typically trend in the same direction within a given test).

The instability demonstrated initiation characteristic of starting at or shortly after methane injector chill-in. Colder methane (e.g., sub-cooled) at the injector inlet prior to engine start was much more likely to result in an instability. A secondary effect of LOX sub-cooling was also possibly observed; greater LOX-sub-cooling improved stability. Some tests demonstrated a low-amplitude 1L-1T instability prior to LOX injector chill-in.

The Morpheus main engine also demonstrated chug instabilities during some engine shutdown sequences on the flight vehicle and SSC test stand. The chug instability was also infrequently observed during the startup sequence. The chug instabilities predictably initiated at low *dP/Pc* at low *Pc*. The chug instabilities were always self-limiting; startup chug instabilities terminated during throttle-up and shutdown chug instabilities decayed by shutdown termination.

Ignition stability was greatly improved via a modification to the ignition sequence and the effects of this change are corroborated in the injector/chamber pressure relationship. Propellant conditioning was

refined for an operational startup box that that maintains “warm” methane (e.g., not subcooled). The startup sequence profile was also modified to include higher throttle setting. The combined changes for the propellant startbox temperatures and the higher startup throttle setting successfully demonstrated stable conditions for engine start.

To protect for the possibility of instability occurrence on the Morpheus vehicle, a high-speed redline cutoff system has been designed, tested, and installed. The instability redline circuit monitors chamber pressure via piezoelectric dynamic pressure sensors and determines the level of combustion stability based on the integration of the dynamic signal. If the Morpheus vehicle is still on the ground (pre-liftoff), then the engine enters shutdown mode. This mode of operation has been demonstrated successfully on the vehicle. In flight, instability would cause a “soft abort”, in which the vehicle is immediately commanded to land in place and shutdown the engine. In the SSC test stand configuration, an engine shutdown is commanded.