

The Role of Guidance, Navigation, and Control in Hypersonic Vehicle Multidisciplinary Design and Optimization

Abstract

Airbreathing hypersonic systems offer distinct performance advantages over rocket-based systems for space access vehicles. However, these performance advantages are dependent upon advances in current state-of-the-art technologies in many areas such as ram/scramjet propulsion integration, high temperature materials, aero-elastic structures, thermal protection systems, transition to hypersonics and hypersonic control elements within the framework of complex physics and new design methods. The complex interactions between elements of an airbreathing hypersonic vehicle represent a new paradigm in vehicle design to achieve the optimal performance necessary to meet space access mission objectives.

In the past, guidance, navigation, and control (GNC) analysis often follows completion of the vehicle conceptual design process. Individual component groups design subsystems which are then integrated into a vehicle configuration. GNC is presented the task of developing control approaches to meet vehicle performance objectives given that configuration. This approach may be sufficient for vehicles where significant performance margins exist. However, for higher performance vehicles engaging the GNC discipline too late in the design cycle has been costly. For example, the X-29 experimental flight vehicle was built as a technology demonstrator. One of the many technologies to be demonstrated was the use of light-weight material composites for structural components. The use of light-weight materials increased the flexibility of the X-29 beyond that of conventional metal alloy constructed aircraft. This effect was not considered when the vehicle control system was designed and built. The impact of this is that the control system did not have enough control authority to compensate for the effects of the first fundamental structural mode of the vehicle. As a result, the resulting pitch rate response of the vehicle was below specification and no post-design changes could recover the desired capability. [Dr. Gunter Stein, "Respect the Unstable," IEEE Control Systems Magazine August 2003]

Dynamic analysis is the study and determination of the fundamental time-dependent physics and characteristics of a vehicle and subsystems. Dynamic analysis is an element of most subsystem design processes utilized in an airbreathing hypersonic vehicle configuration.

However, this dynamic analysis is often subsystem specific, e.g., wing flutter stability limits, and often the design impact of this analysis does not propagate to other design areas until much later in the vehicle configuration integration process. Since airbreathing hypersonic vehicles exhibit highly-coupled dynamical interactions, the impact of these interactions will require much earlier application and consideration of vehicle dynamic analysis.

An example of the potential impact of early system dynamic analysis in the hypersonic vehicle configuration design process is the effect of structural flexibility on propulsion system performance. In hypersonic configurations where the vehicle forebody serves as the external compression surface to a ram/scramjet systems, the angle of the forebody leading edge will determine the bow shock location. Ideal design conditions place this bow shock at the lower lip of the propulsion system cowl (i.e., shock on lip). This ensures maximum airflow to the propulsion system to achieve desired thrust levels. In vehicles with overall lengths greater than one-hundred feet, the vehicle forebody will likely exhibit large flexural deflections. These deflections alter the positioning of the forebody shock with direct impact on propulsion system inlet flow. This will in turn impact propulsion system thrust impacting vehicle accelerations impacting vehicle surface forces impacting vehicle structural deflections.

Vehicle structural designers will design to meet certain structural dynamic flexibility criteria. However, this criteria may not typically consider propulsion system performance in its formulation. If, for example, the vehicle forebody is too flexible, then variations in propulsive thrust may impact the ability of the vehicle to fly an optimal trajectory. This may require excessive vehicle control surface configurations and/or deflections requiring complex thermal protection systems ultimately impacting vehicle weight. Conversely, if structural dynamic flexibility criteria are over-conservatively developed to be too stringent in order to prohibit forebody shock variations, excessive vehicle structural weight may result. In addition, the boundary layer on the surface of the vehicle transitions to turbulence which coupled with the airframe oscillations produces further interference with the airflow inlet and the shock interactions. Therefore, it will be important to understand the impact of forebody structural flexibility on propulsion system and overall vehicle performance in determining the desired vehicle structural dynamic flexibility. This vehicle dynamic analysis should be undertaken early in the vehicle design process to be able to assess its impact on vehicle structural design criteria.

Another example of the need for early GNC analysis is in computing the vehicle's nominal mission trajectory or trajectories. This is a critical step in the conceptual design process, in which the vehicle's performance is matched to the requirements of the mission that it is to perform. If the vehicle can satisfy all of the constraints that define the mission, that particular phase of the conceptual design is declared a success. Typical trajectory analysis is often based

on a single point-mass models that may assume certain vehicle trim states without specification of the vehicle control surface characteristics to achieve this trim state. Due to the complex interactions present, trimming a hypersonic vehicle so that useful control forces and moments can be exerted about trim is not straightforward. The engine generates very strong pitch moments, deflection of control surfaces imposes serious localized heat loads, and the operating margin of the vehicle is too small to ignore the effect of trim on performance. Therefore, it is necessary that trim be optimized as part of the trajectory, and subject to constraints that assure that the vehicle can safely generate additional control forces and moments. Early application of GNC analysis will provide the necessary information and guidance to this process.

This paper will describe the research efforts undertaken and sponsored by the NASA Fundamental Aeronautics Program Hypersonics Guidance, Navigation, & Control team to apply dynamic analysis and control design early in the multidisciplinary design and optimization process for an airbreathing hypersonic space access vehicle. This effort will identify the impact of the tightly coupled dynamical elements of the vehicle on the both overall vehicle and subsystem design processes, and to provide appropriate early guidance to vehicle configuration and subsystem designers. We will provide details of our approach to develop dynamic models for early design concepts with the right mix of fidelity and tractability in areas such as aero-thermo-elasticity and scramjet propulsion for use in dynamic analysis and control design. We will describe an integrated design environment in which dynamic models can be quickly generated for dynamic analysis, control design, and evaluation for rapid vehicle configuration changes. Special areas such as dealing with model uncertainty, enhanced models for trajectory and configuration analysis, and highly integrated design approaches will be covered. Finally, we will introduce a new NASA sponsored model resource center that will provide access and configuration control for dynamic hypersonic models developed under this effort and elsewhere. This paper forms the foundation, rationale, and approach to implement early application of guidance, navigation, and control to hypersonic vehicle multidisciplinary design and optimization.