Complexity and Analogy in Science
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Complexity in Space Engineering

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I. Introduction

Space system design throws interesting challenges in complexity arising out of the need to bring together multiple disciplines of engineering and sciences. Indeed, a satellite launch vehicle provides a fitting example of the complexity involved in the design and control of such a near-cybernetic system – controlled essentially by real-time commands from the on-board computers, though there are necessarily some commands from the ground stations as well. We will address this problem of complexity later in specific terms relevant to the launching of a satellite. But first, let us see what a satellite launch essentially is all about.

Basically, launching an Earth (geocentric) satellite means placing an object (*i.e.*, a payload, of a high level of design complexity, called the satellite) in functionally intact condition in a prescribed orbit around, or a pre-assigned slot above the Earth, using a satellite launch vehicle (LV, essentially a powerful rocket) so as to ultimately serve a set of designed mission objectives. There are, however, many possible variations on this basic theme. Thus, for example, the object, or the payload, could be a communication satellite, a scientific satellite, a weather satellite, etc.; the orbit chosen could be a geo-synchronous, Sun-synchronous, equatorial, or a near-Earth polar; the rocket could be a single- or a multi-staged one.

What is, of course, essential is that the rocket engines must generate a thrust, far in excess of the weight of the launch vehicle at lift-off so as to take it to the designed orbital height in short time – of the order of tens of seconds. The rocket is propelled by a chemical fuel that could be liquid/solid, or a combination thereof. Now, the complexity involved in a satellite launch lies in the fact that the system comprises a number of interacting subsystems, components and their functions, and this number is very large. Most importantly, the interactions involved are non-linear, and interactions too interact. This can, therefore, exhibit a range of behavior often at the edge of instability. The on-board control system, therefore, necessarily involves enormous real-time processing of information generated by the sensors. Such systems are naturally unforgiving of any design errors as there is a sensitive dependence on the various conditions involved.

Clearly, the development of any space system calls for the definition of a systemic configuration resulting from the interplay of a number of disciplines including flight mechanics, aerodynamics and various mechanisms, structural and thermal sciences, navigation and guidance, control and propulsion, and so on.

Now, among the many critical phases, *the most* critical phase of a satellite launch is the *atmospheric phase.* During this phase the system is accelerated from rest to high velocities (high Mach/Reynolds numbers) in a matter of seconds, and is, therefore, subjected to excessive and hard-to-predict, randomly fluctuating aerodynamic stresses (mechanical as well as thermal) of great complexity. This could lead to, *e.g.,* a structural failure that may be catastrophic. This paper is intended to give some interesting insights into the role of various inter-related complexities involved by analyzing the possible anomalous behavior of a launch vehicle as illustrated by means of an example taken from our own experience (from a space mission of the Indian Space Programme), namely the catastrophic failure of a developmental Augmented Satellite Launch Vehicle (ASLV-D2), launched from the SHAR Launch Complex, in which the mission was terminated soon after the lift-off when the vehicle broke up catastrophically. This was indeed an object lesson for us in real complexity. Happily, the lesson so learnt led to a subsequent satellite launch that proved to be a great success.

II. Complexity of the Atmospheric Phase of a Launch Vehicle

Before we get to the specifics of the ASLV-D2 launch failure, let us get acquainted with the complexity of controlled flights of a multi-stage rocket system that reveals the extent of critical interactions that often dwell along the thin line between success and failure in meeting the final objective of spacecraft orbit insertion: The overall sizing of the vehicle dictated by the payload capability and consistent with the propulsion and structural technologies; the design of the trajectory and the sequence of events; the aerodynamic shaping, particularly of the bulbous heat shield, protrusions, joints and inter-stages and the internal thermo-fluid-combustion kinetics of the propulsion units are some of the major design considerations. All these have to take cognizance of a variety of optimization processes at each sub-system level. The trajectory design, based on the methods of optimal control of dynamical systems, determines the levels and the timing of the peak dynamic pressures encountered by the launch vehicle in the critical atmospheric phase. These dynamic pressures directly determine the aerodynamic load distribution and drag on the vehicle, which influence the vehicle performance in terms of velocities and altitudes achieved, as well as the structural loads acting on the vehicle. The load distribution is critically influenced by the prevailing wind conditions and the dispersions in propulsion and auto-pilot performances. This in turn can lead to the build-up of vehicle angles of attack and lateral deflections of the long and slender vehicle structure. Stage separation events are mission critical and should be designed to ensure the smooth transition of vehicle control and collision-free dynamics of the separating parts jettisoned under all possible conditions. The spent strap-on jettisoning generally occurs within sensible atmosphere, and hence is influenced by the nonlinear aerodynamic interactions of the separating bodies. An important parameter in the transfer of control is the tail-off thrust profile of the strap-on boosters, and the characterization of the control forces derived from them. The structural deflections, as determined by the vehicle mode shapes and frequencies, affect the vehicle performance and stability through the functioning of the auto-pilot control system. The vehicle attitude is controlled, by the lateral forces derived from the fluid injection thrust vector control system, or directly by nozzle gimballing, both of which depend primarily on the main thrust provided by the propulsion system. Proper functioning of the onboard electronics and computer logic systems depends on limiting the acoustic and vibratory environment created by the high speed jet flow, aerodynamic shock oscillations on the bulbous head shield, flow separations and the shock-boundary layer interactions, and the complex shockwave patterns created due to aerodynamic interactions of the strap-on and the core configurations and the influence of several local body protrusions. These critical parameters are the direct functions of vehicle aerodynamic angle of attack, which in turn is determined by the vehicle flexibility, control, trajectory and atmospheric winds. Thus several loops and sub-loops of mutual interactions determine the complex vehicle dynamics.

It is apt to recall here that the launch vehicle is *not* simply *a rigid body of six degrees of freedom – three rotational and three translational*. (In fact, even such a rigid body in motion can display a complex behavior inasmuch as some of the degrees of freedom (finite rotations) do not commute. In reality, in flight, it is deformable under aerodynamic stresses. The deformations may even subtend zero-angular-momentum turns). All these and more. Extensive six-degrees-of-freedom and flexible vehicle simulations with control-structure-aerodynamics-propulsion interactions of the complex experiment (the ASLV-D2 Launch and its failure) highlighted the need to introduce: (i) event-based ignition of the Core Stage motor based on Strap-on-Stages motor chamber pressure, (ii) appropriate characterization of the fluid injection thrust vector control model in the control of yaw, particularly during tail-off, (iii) extensive short-period, six-degrees of freedom and flexible body dynamics and hardware-in-loop simulations to detect the presence of any critical interactions due to the vehicle system and wind-profile uncertainties, (iv) increasing the inherent stability of the vehicle by providing fins in the pitch-yaw plane with stability coming from the strap on boosters themselves, and (v) reduction of the maximum dynamic pressure to be faced by the vehicle, if necessary by re-designing the motor thrust profiles.

III. Monte Carlo Simulations of Launch Vehicle (LV) Dynamics

When a highly complex system is comprised of (i) a number independent-disciplinary subsystems; (ii) these subsystems themselves are involved in complex physical processes; and (iii) the dynamics of these independent subsystems is dependent on the interactions with the other subsystems of the main process, then the probabilistic outcome of the main system cannot be easily described by a deterministic mathematical model. When the external processes that influence the main system are also random, for example in the context of launch vehicle dynamics amidst the random environmental (aerodynamical) processes of winds and atmospheric parameters, then the system performance is nearly impossible to describe by a deterministic mathematical model. The dynamics of such complex interactive systems can then be studied effectively by system engineers by a Monte Carlo simulation process, which enables the mission analysts to evaluate the mission success probability and make informed decisions on mission-go-ahead (launch-commit) criteria.

Such a process of Monte Carlo Simulations is depicted in a nutshell in the block diagram displayed in Fig.1, in which the main subsystems of a launch vehicle dynamic process are identified as blocks and their mutual interactions are indicated by arrows. As (i) the vehicle lifts off from the launch pad by the propulsive forces of the rocket engines, (ii) picks up a velocity defying gravity forces, and goes through the aerodynamic regimes of subsonic, transonic, supersonic and the hypersonic conditions (which characterize essentially the changes elliptic-to-parabolic-to-hyperbolic mathematical descriptions of the governing partial differential equations), (iii) the vehicle's structural modes are excited by aerodynamic, propulsive and control forces which are interactive, and also the autopilot functions are influenced by the nonlinear sensor dynamics of various actuators, (iv) the vehicle guidance system analyses the current instantaneous state of the vehicle as determined by the onboard rate-gyro and accelerometer packages and determines continuously the immediate attitude orientation changes the vehicle should adopt, and (v) all these processes are influenced by the instantaneous and dynamic wind and atmospheric variations, (vi) the dynamics of the vehicle comprises not only the six-dimensional space of rigid-body motion but also the multi-dimensional nonlinear continuum elastic

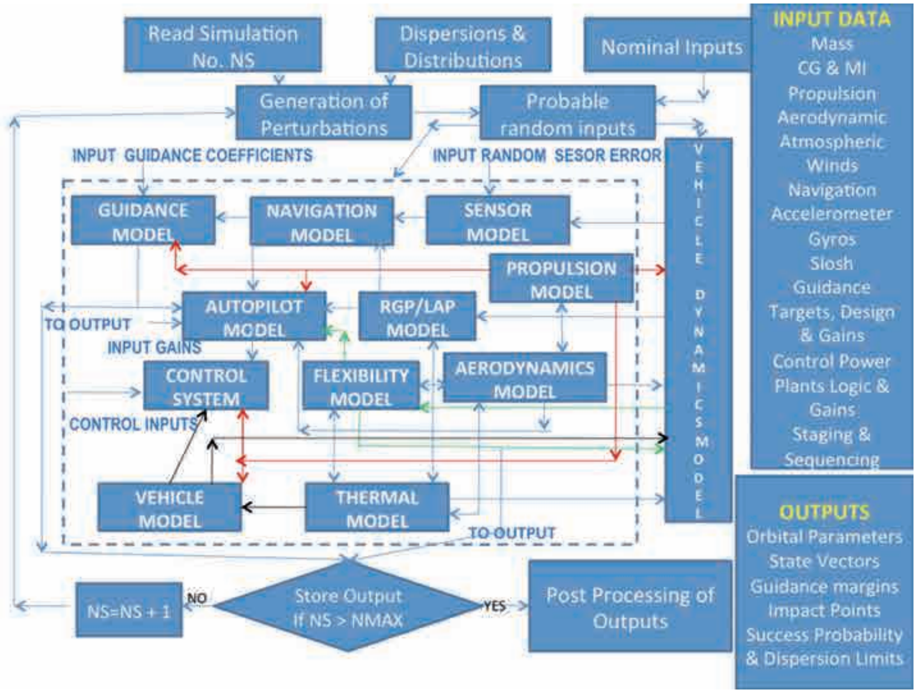

Figure 1. Monte Carlo simulations of L/V dynamics.

deformations and structural modes which modify the aerodynamics and autopilot functions, then the outcome and behavior of such system is not deterministic but becomes stochastic.

Monte Carlo simulation is the right tool for analyzing such systems and making launch decisions that ensure a high mission success probability.

This is done first by a systematic engineering analysis of the dispersion-levels and statistical distributions of all possible parameters (of all the subsystems already mentioned) that influence the vehicle dynamics. This difficult task is usually carried out by a number of ground experiments on the respective subsystems, and then adding any un-modeled uncertainties. A high-fidelity mathematical model of the linked-subsystem processes is made, which reflects the current state of knowledge of the physical processes involved. A random sample of the input-parameters is selected following the statistical distribution determined earlier, and the complete vehicle dynamics is simulated with this set of input parameters. The resulting output parameters of the vehicle state at each important instant (like stage ignition and burnout instants, separation events, satellite injection event) are captured and stored. Then a different set of parameters (as per the dispersion statistics) is randomly generated and the full vehicle dynamics is captured and stored as before. A large number of such simulations are done, the number being determined by the condition to reach statistical stability of the output parameters so that one gets stable mean and statistical distributions of the output parameters at all critical points up to launch. Usually the number of simulations can be of the order of a few thousands. All specific cases in which the vehicle fails to reach a final orbit as desired are carefully analyzed and the reasons for failures understood and ascertained. From a statistical analysis of the output parameters, the mission analyst can ascertain the mission success probability.

IV. An Analysis of the ASLV-D2 Failure

As mentioned in passing in the Introduction, the four-stage all-solid launch vehicle, designated as ASLV-D2, failed after 50 seconds into the flight.

After a detailed analysis of the flight telemetry and tracking data, film and video records of the launch and the flight, specifications and design documents of the vehicle systems, post-flight analysis documents, detailed simulation studies and the analysis of failure modes, it was found that the increase in the angle of attack occurred as the vehicle, which was aerodynamically unstable in the yaw plane (*i.e.,* in the plane containing the strap-on boosters), with a time-to-double-amplitude of about 0.5s, did not have adequate control during a period of about 3-4s, resulting in flight loads exceeding structural limits, and ending in vehicle break up.

Noting that the control forces were derived entirely from secondary fluid injection into the rocket nozzles, this period of inadequate control occurred in three phases of the tail-off region of the strap-on rocket motor. The factors that contributed to the rapid build-up of the vehicle incidence were that the autopilot gain implemented in the flight was lower than the design gain and was not compensated for the tail-off phase of the motor thrust. The Core motor, which was soon ignited, could not provide the required control force, although helping to reduce the yaw rate. The resulting increase in the yaw error at a time when the vehicle was experiencing the maximum dynamic pressure during the flight, led to a continuous increase in the flight loads on the vehicle that exceeded the structural limits and ended eventually in the disintegration of the vehicle.

Other Insights: Oscillation in YAW

The behavior of YAW attitude in ASLV-D2 flight during the period of T+43s to T+52s was extensively simulated, studied and the factors contributing to the flight failure were identified. In this process there were so many other features and aspects of the complex flight behavior that one had the real opportunity to understand and explain the event. The ASLV-D2 flight data indicated that the YAW history shows an oscillation of about 0.3 Hz, which was not appearing in any of the pre-flight simulations. The oscillations in yaw rate have amplitude up to ±0.5 deg/s. Attempts to simulate these oscillations through wind-profile oscillations and the thrust-misalignments have not been successful. The flight SITVC (Secondary Fluid Injection Thrust Vector Control) pintle-opening telemetry data show an on-off behavior that corresponds with the observed YAW-rate oscillations. Simulations show that a dead-zone in SITVC pintle opening until the requirement reached 0.18 mm explains the complex flight behavior in a fairly reasonable manner.

Future Trends

At this moment, the space-faring world is looking ahead towards new frontiers of space science and technology. The main parameters of the new space challenge are low-cost access to space, reaching inter-planetary as well as deep space for scientific exploration, resource utilization, human habitat, and possibly also defending the planet Earth from the disaster of any possible major impact from Near Earth Asteroids.

The future new challenges will be in the area of hypersonic flow research, vehicle control and guidance in severe aero thermal environments, and development of supersonic combustion air breathing propulsion technology, etc. In this context, a number of complex viscous and shock interactions, high temperature boundary-layer transition effects become important. One of the most important factors to be handled in the development of hypersonic technology is the high temperature due to aero heating during re-entry. Some of the important aspects to be considered are: thermal and chemical non-equilibrium, wall catalyticity, communication black out and radiating shock layers. With such systems, the dimensionality of the system-interaction complexity increases – from typical aero-servo-elasticity interactions to aero-thermo-servo-elasticity systems. With the man-in-the-loop space systems, and with long-term space travel and habitation involved, the complexity extends further to include astro-biological and other environmental factors.

In design problems, load analysis, measurements results, material properties, etc., all have inherent uncertainties. Conventional design practices, including engineering design optimization techniques, take these uncertainties into account while designing systems in a very conservative manner, *i.e.,* the worst combination of errors is taken and the design is expected to meet the worst-case scenarios. Explicit factors of safety are considered at all stages of design. This makes the designs sub-optimal. Reliability based techniques need to be applied in design, where the uncertainty distribution is transformed through various sub-system and system analyses.

In addition to Multi-Disciplinary Design Optimization (MDO), substantial effort is now focused also on building algorithms for Reliability Based Design Optimization (RBDO), where input and constraint uncertainty distributions are taken into account, especially in multi-disciplinary scenarios, to obtain reliable optimal designs. The algorithm should optimize the objectives while ensuring that failure probability of constraints remains within acceptable limits. In typical problems, inputs like material properties, etc., are non-deterministic and the optimal designs need to respect these constraints. Future system and sub-system design optimization exercises will necessarily have to be RBDO exercises reflecting the non-deterministic nature of various inputs and constraints. One should also pursue Robust Design Optimization (RDO) where the objective is to minimize the sensitivity of the system performance to input uncertainties. In a complex and uncertain world, these tools permit the scientists and technologists to build systems that evolve and survive. Heuristic development of algorithms should be supported by formal mathematical analysis of their functionality. Thus, this field will continue to provide exciting opportunities for research both in the development of methods and in their application to aerospace technology.

It is tempting to compare the complexity of Space Engineering, epitomized by the design and launch of a near-cybernetic, but will-free space vehicle carrying a satellite, with that of Biology, epitomized by a living organism, evolved through adaptive responses to selective natural pressures over some three billion years, such as a willful human being. Indeed, both are highly complex though in a qualitatively different sense and contexts both possess complex hardware and software, but biology has the `a-ware in addition, and the information is stored in the inheritable genes.

But, really one should resist the temptation to compare these two any further. Instead, it would rather be a reasonable and fruitful, though somewhat distant possibility, namely that biology may, and indeed will get incorporated deeply into the complex Space Engineering Programmes of the future: A remarkably serious example of it would be the Dyson Tree as proposed by Freeman Dyson, developed through nano-biogenetic engineering that could support a natural habitat for living organisms including humans in a spaceship, or on an asteroid!

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