Chapter 1
Introduction

In the present era of space exploration, there is an increasing demand for reliable, economical and efficient means of space transportation. Diverse and stringent requirements with emphasis on low cost access to space; and the tight international competition are the major challenges before the launch vehicle community. Extensive research activity is in progress the world over, in all aspects of expendable and reusable launch vehicle design, to achieve reliable performance over a wide spectrum of variation in the flight environment. The system models are uncertain in the sense that the structure and parameters of the model are known to lie within some boundaries but are not known exactly. A design is robust if the performance of the system stays within tolerable limits for a given uncertainty level.

Stabilization and control of the rotational dynamics of the launch vehicle is critical to the success of any launch vehicle mission. This is achieved by the launch vehicle autopilot. The function of launch vehicle autopilot is to stabilize the short period rotational dynamics, and to control the vehicle in order to follow the commanded trajectory, while providing adequate noise and disturbance rejection and robustness to parameter perturbations. Launch vehicle autopilot design is a challenging task involving modeling, design and validation. In this thesis, the problem of robust autopilot design and analysis for space transportation systems with unstable aerodynamics, lightly damped structural and slosh dynamics and rapidly varying uncertain parameters is taken up for study, with focus on the evolution of accurate, efficient and robust autopilot strategies for both expendable and reusable launch vehicles.

1.1 Motivation

The current autopilot design methodology for space transportation systems the world over is based mainly on classical methods, which use gain as well as phase information to yield a minimal order controller. These controllers are best suited for single input single output systems with small uncertainty levels and slow variation in parameters. The order of the controller has been an important consideration in the current launch vehicles due to
the limited memory size and computation capability of the on board computer. With the powerful on board computers planned for the advanced launch vehicles, however, more complex algorithm with higher order controllers can be implemented. Moreover, space transportation systems are becoming increasingly complex, with highly coupled pitch/yaw/roll dynamics, Multi Input Multi Output (MIMO) plant, control through aerodynamic surfaces, and very high uncertainty levels over the flight envelope. Conventional design techniques are inadequate for such systems.

To cater to the demands of such systems, it is necessary to have design techniques which can replace classical controllers totally and provide flexible, robust designs for complex space transportation systems, with minimal design effort. The present work is motivated by the need to develop practical robust design and analysis techniques which can overcome the limitations of the classical methods, and can be applied to the autopilot design of advanced space transportation systems with high levels of parametric uncertainty.

1.2 Present State-of-the-Art in Launch Vehicle Autopilot

The launch vehicle characteristics, which pose a challenge to autopilot design, are briefly described in this section, followed by a summary of the state-of-the-art in autopilot design.

1.2.1 Launch Vehicle Characteristics

The launch vehicle plant is time varying in nature and has both translational dynamics, which correspond to the motion of the vehicle as a point mass along the trajectory, and rotational dynamics, which correspond to the motion about its centre of gravity. The dominant rotational dynamics consists of rigid body rotation about the pitch, yaw and roll axes. The movement in the three planes is normally treated as decoupled, but may be coupled through higher order dynamics as well as through control in certain problems. The higher order dynamics consisting of propellant slosh and vehicle flexible modes, which are often lightly damped, also influence the rotational dynamics. Liquid propulsion tanks mounted on the launch vehicle give rise to slosh oscillations, which affect the
attitude motion. In addition, the large length to diameter ratio leads to a highly flexible configuration and the existence of low frequency dominant modes.

In the atmospheric phase, there is a strong interaction between aerodynamics, structure and control dynamics, which needs to be taken care of in autopilot design. The launch vehicle dynamic model takes inputs from the different subsystems / dynamics as depicted in Fig 1.1.

![Fig 1.1 Inputs to Launch Vehicle Dynamic Model](image)

Launch vehicles are often aerodynamically unstable; i.e. the centre of pressure is ahead of the centre of gravity. Any increase in the angle of attack due to a disturbance will be further aggravated and can lead to high loads on the vehicle which can result in the break up of the vehicle, unless properly stabilized by closed loop control. The overall configuration of a typical aerodynamically unstable ascent phase launch vehicle is given in Fig. 1.2.

The return from orbit is characterized by unpowered glide flight, controlled by aerodynamic surfaces. The overall configuration of a typical reentry vehicle is shown in Fig. 1.3, and the return mission profile from orbit is given in Fig. 1.4. During return from orbit, the reentry phase is most critical. During this phase, the vehicle has to fly over a wide variation in the environment and wide range of Mach numbers.
The next section summarises the state-of-the-art in flight control design and highlights the areas where further research is necessary.

1.2.2 State-of-the-art in Autopilot Design

The field of automatic control has undergone continuous development for the last seventy years. The majority of flight proven autopilots for space transportation systems have been
designed using the classical control techniques, which form the benchmark for most of
the advanced control design and analysis algorithms that are currently being reported in
literature. Greensite\textsuperscript{1} and Ringland\textsuperscript{2} have described the various aspects of launch vehicle
control design and analysis using the classical methods. Classical design is carried out for
the nominal plant. Robustness is not explicitly addressed in the design procedure, but is
addressed indirectly by providing phase and gain margins for the nominal plant. Flight
loads in the atmospheric phase are alleviated by a combination of phase stabilization of
the lowest-frequency flexible modes, extensive antislosh baffling, and preprogramming
of the vehicle boost trajectory to compensate for the winds. In the exo atmospheric phase,
response to guidance commands is the controlling requirement. The attitude and attitude
rate gains are generally scheduled as a function of flight time to compensate for the
changing vehicle characteristics as propellant is consumed. Some of the other parameters
of the control system may have to be changed during flight to satisfy stability criteria.

Classical theory is essentially restricted to single-input-single-output time-invariant
systems and is not suitable for MIMO problems that contain a high degree of cross-
coupling between the axes\textsuperscript{3}. Considering the control requirements of large MIMO
systems with high levels of uncertainty and the need for performance optimization, as
well as the advancement in computing power, recent research is focused towards
developing better and more advanced control algorithms. These include improvements in
classical control methods and efforts to incorporate robustness in the design, optimal and
robust control schemes, and adaptive control schemes to enhance robustness of highly
uncertain MIMO systems. Those advanced control algorithms that have reached a
reasonable level of maturity have been applied to some extent in flight control design.

The two modern techniques which have been applied most often to flight control design
are the Linear Quadratic Gaussian (LQG) optimal design technique\textsuperscript{4} and the $H_{\infty}$ robust
design technique\textsuperscript{5,6}. Each of the methods is advantageous for a particular class of
problems. LQG controller design is most suitable in those phases of flight where
disturbance rejection and tracking performance requirements are paramount, such as the
exo-atmospheric phase of flight. $H_{\infty}$ optimization is generally suitable for handling
unmodelled dynamics and disturbances with uncertain spectra. These techniques often do
not adequately address practical implementation problems for aerospace applications. For example, phase stabilization (active stabilization) of the dominant bending mode in the atmospheric phase is a prerequisite for keeping the structural loads low; however, since H∞ optimization is a norm based approach, the phase information is ignored. This can also lead to conservative design.

The other robust method under active investigation is the Quantitative Feedback Theory (QFT)⁷, which may be regarded as an extension of classical design techniques to systems with parametric uncertainty. QFT produces robust design, with low order controllers. This method, however, has a serious disadvantage in that there are no analytical methods available for arriving at the exact plant templates for design; the current practice is to vary each parameter in small increments while keeping the others constant at different values over the interval of the specified bound on the parameter variation, so that all possible combinations are covered. This practice of gridding of the set of uncertain parameters leads to a very large set of plants for the class of systems with large number of uncertain parameters and a complex uncertainty structure. The launch vehicle belongs to this class of systems.

The robustness analysis of systems with parametric uncertainty requires the evaluation of the entire family of systems and is usually carried out by one of two methods. The first is to evaluate all possible combinations of parameter perturbations with the candidate controller in loop, which is extremely cumbersome for complex systems. The second method is to choose appropriate combinations of parameter perturbations to generate worst case bounds and evaluate this set of systems. Since the choice of the combination of perturbed parameters is left to the designer's judgment, there is a possibility of missing the worst case due to the large number of uncertain parameters.

The Kharitonov method⁸ is a promising analytical approach for generation of the worst case systems, consisting of plant and controller, for stability analysis of interval plants. However, direct application of the method to the launch vehicle class of systems, where the presence of several uncertain transfer functions in the forward path leads to a multi-linear uncertainty structure, gives conservative results.
There is a need to develop practical robust analysis and design procedures which give a significant improvement over the currently adopted techniques, and which are suitable for the future complex MIMO launch vehicle systems. The present dissertation addresses this problem. The next section gives the problem definition and scope of this thesis.

1.3 Problem Description and Scope of the Thesis

A typical expendable launch vehicle controller has to satisfy multiple gain and phase margins at various frequencies of interest. The widely used, flight proven autopilot is based on classical linear control techniques, with design carried out for the nominal plant, and robustness evaluated subsequently by identifying and assessing a set of worst case systems. This approach is adequate for single input single output systems with few uncertain parameters and a narrow band of uncertainty. However, advanced aerodynamically unstable launch vehicles have large number of uncertain parameters and a complex multi-linear uncertainty structure. For this class of plants, the set of worst case systems (i.e. those combinations of plant with controller giving the least stability margins) for robust stability analysis cannot be directly identified. Hence the practice currently followed is to obtain the set of all possible systems by gridding the set of uncertain parameters so that the worst cases are covered. The response of the full set is analyzed and the design retuned if required. If the grid size is not fine enough, there is a possibility of missing the systems with the extreme response, which dictate the worst-case behaviour of the control system.

In the exo-atmospheric phase, the lightly damped lateral slosh oscillations of the fluid in the partially filled fuel and oxidiser tanks can create significant disturbance on the vehicle due to the small inertia of the launch vehicle and the relatively large slosh mass. The plant dynamics are relatively slow varying in this phase. However, in the terminal stage, structural hardware mass has a direct impact on the payload mass. Hence it is desirable to optimize the structural mass in this phase, to gain maximum payload.

During return from orbit, the aerodynamic control surfaces in the reusable launch vehicle act to provide control in pitch/yaw and roll. The effectiveness of the aerodynamic surfaces as well as the disturbances depends on the mission profile and the flight
condition. These vehicles are characterised by a high degree of coupling between the pitch/yaw and roll as well as the MIMO nature of the plant, which makes a decoupled single input single output design approach inadequate.

The continuous evolution in the field of automatic control over the past several decades has been only partially reflected in the autopilot design of launch vehicles. Practical application of modern control techniques in launch vehicle control has not kept pace with the development in the theory. This is partially due to the limited capability of the on-board computers and partially because many of these techniques have not been adequately studied for complex real life problems. It is necessary to bridge this gap between theory and practice.

The increasingly complex requirements of the advanced launch vehicles need to be met by adoption of suitable techniques. Performance assessment of autopilot design is based mostly on the performance for worst-case combinations of the perturbed parameters, which are heuristically decided by the designer. For complex plants with wide variation in the system parameters, the evaluation becomes complicated. Hence there is a need to define the worst-case behaviour of the system for a given controller. Historically, control failure due to lack of robustness has caused several launch vehicle mission failures. Hence there is a need to increase system reliability by improving the robustness of the autopilot design and evolving systematic design and analysis methods.

This thesis is aimed at the development of practical robust analysis and design procedures which give a significant improvement over the currently adopted techniques, and which are suitable for the future complex MIMO launch vehicle systems.

1.4 Original Contributions of the Thesis

The following are the original contributions of the thesis:

(i) This work explores a technique for conducting robustness analysis for a system with multiple uncertainties without resorting to Monte-Carlo or exhaustive gridding techniques. A Kharitonov approach along with the Mapping theorem is used to define a small number of perturbed plants that collectively define the worst-case stability margins given the bounds on the uncertainties. A realistic
assessment of the robust stability of the system is obtained with very little conservatism. This approach eliminates the need for tedious checking of all possible combinations of perturbed parameters to ensure design robustness and also ensures that the true worst case gets evaluated. The feasibility of this approach for real-life problems with multi-linear uncertainty structure and multiple minimum gain and phase margins is demonstrated, possibly for the first time (Chapter 5). The results are published in Ref. [A1] and Ref. [A2].

(ii) A systematic method based on the Kharitonov theory to obtain the worst case design set for a class of multi-linear parametric uncertain systems, which includes the atmospheric phase launch vehicle plant is developed in this thesis. The approach produces a small set of plants, which corresponds to the worst case behavior of the uncertain system with controller. The method hence provides a powerful tool for robust controller design, without sacrificing the phase information. The extremal plant set corresponding to a Proportional Integral Derivative (PID) controller design is obtained. An LQG controller has been designed with the weight tuned for this worst case design set. The extremal plant set for the LQG controller design has then been used to design a QFT based controller. The Kharitonov based approach, which is a robust stability analysis tool, is thus converted into a robust design tool. To the best of the author's knowledge, no such method for determination of the worst case plant templates for multi-linear parametric uncertain systems has been developed elsewhere (Chapter 6).

(iii) One reason for the limited usefulness of the LQG method in the launch vehicle autopilot design has been the lack of physical insight in the design procedure. At the same time, the method provides close control over the system states through manipulation of the weights. A new Two Phase LQG approach (TP-LQG) has been developed which combines the physical insight of the frequency domain methods with the advantages of the time domain methods, to provide a robust LQG design. Throughout the thesis, this approach has been used to obtain robust LQG controller design. The results are published in Ref. [A3].
One of the major inadequacies of QFT has been the inability to define exact plant templates, which has been addressed in this thesis. With the systematic method evolved for definition of the plant templates, QFT has become a viable method for robust control of launch vehicle autopilot. A robust low order controller is designed to meet the system specifications, which have been translated into QFT bounds (Chapter 6). The results are published in Ref. [A4] and Ref. [A5].

Aerodynamically controlled, unstable launch vehicles are extremely sensitive to parameter uncertainties. High degree of aerodynamic instability along with high parameter uncertainties severely constrains the achievable margins with linear autopilot design. This thesis has successfully evolved an adaptive gain tuning method which modifies the linear autopilot gain online, based on the estimate of the parameter uncertainty, and greatly increases the robustness to parameter perturbations (Chapter 4).

Conventional autopilot design achieves slosh stabilization with the help of mechanical baffles in the liquid tanks, which provide passive damping. Active stabilization of slosh modes through control would enable removal of these baffles, resulting in weight saving, and improved payload, especially in the final stage. This thesis addresses controller design for active slosh stabilization over the entire stage duration, while accounting for parametric uncertainty. The relative merits of LQG and $H_\infty$ controllers are assessed, based on all aspects of control system performance (Chapter 3). The results are published in Ref.[A6] and [A7].

1.5 Layout of the Thesis

The thesis begins by introducing the subject and defining the aim and scope of the present work. The perceived contributions arising out of the present work are also highlighted. The introduction is followed by a literature survey on the subject in Chapter 2, which establishes the current state-of-the-art as well as provides a basis for the work undertaken in the present thesis. The summary of work related to the launch vehicle autopilot published in open literature and the limitations of the methodologies with respect to the aim of the thesis are given in this chapter. The gaps that need to be filled in this research area are also emphasized. Chapter-3 evaluates the state-of-the-art controller
design techniques for a practical launch vehicle problem by application to the robust controller design for the final stage of a typical launch vehicle, with the aim of active stabilization of the slosh dynamics over the entire stage duration, while accounting for the parametric uncertainty. Chapter-4 proposes an adaptive gain tuning method to improve the robustness of the linear autopilot in the face of high uncertainties for two launch vehicle configurations of increasing complexity. Chapter-5 gives the methodology for robust stability analysis of parametric uncertain systems and its adaptation for robustness analysis of flexible, aerodynamically unstable launch vehicle autopilot in the atmospheric phase. The methodology developed in Chapter-5 for worst case system identification for robust stability analysis is extended in Chapter-6 to the robust controller design problem, and a systematic approach is evolved for robust controller design of systems with multi-linear parametric uncertainty, including the launch vehicle plant. Chapter-7 concludes the work, and indicates the scope for future work.