Computer simulation methods for launch vehicle mission and control problems

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Abstract. The flight control system of a launch vehicle is the result of the right trade-off between different objectives, such as the interaction between the control, guidance and performance aspects of a mission with specified end conditions and the analysis of the mission trajectories and vehicle systems under a variety of normal and failure modes. Hence an evaluation of the design and performance of such a system is not feasible through purely analytical means even with simplified models. This, together with the necessity for step-by-step refinement of the models used for the vehicle and its environment, calls for the computer simulation approach The various considerations involved in developing and selecting the simulation model and implementing it on a computer are discussed. To illustrate the approach, a hybrid simulation evaluation of the performance of the first stage control system of a satellite launch vehicle and that of the controlled vehicle under different operational modes is presented.

1. Introduction

In recent years, computer simulation has emerged as the most powerful among the many systems analysis tools available to the designers of complex processes or systems. As the design of individual subsystems and the integrated system becomes more involved, simulation enables system designers to actually experiment with their models. Yet simulation modelling and experimentation have largely remained an intuitive process. Despite this lack of mathematical sophistication and elegance, simulation has come to occupy a special status particularly in aerospace sciences.

The one-shot nature of launch vehicle missions and the cost, difficulty and risk associated with controlled experimental flights have logically and inevitably prompted recourse to computer simulation. Since the aerodynamics of the vehicle configuration, performance of the individual rocket motors and other subsystems as well as their failure behaviour can be tested on the ground, these together with atmospheric and wind data allow a computer simulation assessment of the vehicle under different operational modes.

Simulation applications and approaches can be used at each stage in the design and development of a launch vehicle and its mission planning. Simulation plays a significant role in arriving at a control strategy which can keep the loads and trajectory dispersions low in the presence of disturbances and winds, conserve control

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fuel in limited fuel missions and increase the payload capacity. Simulation is resorted to in the design and evaluation of the contol system under different modes of operation. Range safety and mission monitoring considerations require the generation of controlled trajectories of the vehicle and its spent-up stages, under different conditions of equipment failure. Also, subsystem hardware can be tested for effectiveness and reliability through real time simulation of the rest of the vehicle. Furthermore, simulation is an inexpensive training device for mission check-out and emergencies.

One of the important steps in a simulation study is the construction of a simulation model which would include all the vital aspects pertaining to the investigation and would exclude the trivial details   One of the pitfalls of simulation is to include more detail than necessary in the hope that the computer will provide the solution (Shannon 1975). The pertinent aspects of simulation models in relation to launch vehicle studies are discussed in § 2. Multiple considerations arise in the choice of a computer for a simulation task and in matching the simulation model with the computer. A comparative account of analog, digital and hybrid computers as well as digital and hybrid computer simulations in the past, is presented in § 3. § 4 presents a specific case study of the hybrid computer evaluation of the first stage control system for a satellite launch vehicle for near-earth missions.

2. Simulation models

There are two distinct but related dynamic effects of a launch vehicle. Of these, the long-period dynamics refer to those factors that determine the capability of the vehicle to accomplish a specific mission, and deal with the relationship between guidance philosophy, control response and trajectory profile. Short-period dynamics, on the other hand, are concerned with those factors which influence the oscillations of the vehicle about its centre of mass and with the performance of the control system to attitude commands and disturbances. Effects such as non-spherical rotating earth, variable mass of the vehicle, eccentric centre of gravity (c.g.) and jet damping are relevant only to the long-period motion while higher-order dynamic effects such as fuel sloshing, bending modes, gyro and actuator dynamics have significance only on the short-period motion.

It is not practical to develop an all-purpose simulation model even for a single vehicle   Different long-period models (which emphasise long-period effects) enable studies on payload capacity, dispersions from the nominal trajectory, orbit capability, structural load profiles, aerodynamic heating, pogo oscillations (for liquid fuel vehicles) and control fuel requirements. Short-period models provide information on the stability of the vehicle attitude, structural vibrations, and fuel slosh modes (for liquid fuel vehicles), speed of response of the control system in alleviating gust-induced loads on the vehicle, accuracy of the system in following the guidance commands and the output stiffness of the system. Permissible simplifications and approximations of the equations of motion representing a simulation model depend upon the study, the parameters of interest and the degree of accuracy required. For example, long-period models differ depending upon whether we need an accurate trajectory relative to earth's surface or whether we need the load profile on the vehicle as it passes through the atmosphere or the orbital parameters of the payload a

burn-out. Similarly, two different short-period models exist depending upon whether the drift rate or angle of attack is of interest along with the attitude response. All these factors make the development of a simulation model often an art, based heavily on experience and engineering judgement, rather than a science.

Both long-period and short-period models can be constructed as deterministic or stochastic models depending upon the description of the vehicle parameters and disturbances. If they are specified to lie in deterministic bands, the outcome of the simulation can be interpreted deterministically. If, on the other hand, vehicle parameters and disturbances are specified using a statistical description as in Monte Carlo simulations, the results have to be interpreted probabilistically.

Many standard text books e.g. Greensite (1970), Etkin (1972) and Geissler (1970) are available describing the detailed developments of the six degrees-of-freedom and planar long-period models as well as short-period models in pitch, yaw and roll modes. We now illustrate the long-period and short-period models of only the launch phase where the performance of the vehicle and its control system and the resulting structural loads, trajectory drift from the nominal and control fuel requirements are of interest.

For the long-period model, we ignore the c.g. eccentricity and its motion relative to the vehicle. The earth is assumed to be as a spherical non-rotating inertial reference. With the origin of the body axes at the c.g., the force (translational) and moment (rotational) equations are as follows:

$$m \begin{bmatrix} \dot{u} + qw - rv \\ \dot{v} + ru - pw \\ \dot{w} + pv - qu \end{bmatrix} = \begin{bmatrix} -QA_1 C_D \\ L_\beta \beta \\ -L_\alpha \alpha \end{bmatrix} + m C_b^E \begin{bmatrix} g \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} T_s + T_c \\ -T_c \delta_y \\ T_c \delta_p \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} I_{xx}\dot{p} + \dot{I}_{xx}p + (I_{zz} - I_{yy})qr \\ I_{yy}\dot{q} + \dot{I}_{yy}q + (I_{xx} - I_{zz})rp \\ I_{zz}\dot{r} + \dot{I}_{zz}r + (I_{yy} - I_{xx})pq \end{bmatrix} = \begin{bmatrix} 0 \\ L_\alpha l_\alpha \alpha \\ L_\beta l_\beta \beta \end{bmatrix} + \begin{bmatrix} T_r l_r \delta_r \\ T_c l_c \delta_p \\ T_c l_c \delta_y \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{m}qr^2_{ex} \\ \dot{m}rr^2_{ex} \end{bmatrix}. \qquad (2)$$

In (1) and (2), u, v, w and p, q, r are the linear and angular velocity components, m is mass, I_{xx}, I_{yy}, I_{zz} are the moments of inertia and g is acceleration due to gravity. Further T_s, T_c, T_r are the fixed thrust, pitch-yaw control thrust and roll control thrust respectively with δ_p, δ_y, δ_r as the control variables. L_α, L_β are normal force slopes and the l's are moment arms.

The inertial-to-body axes transformation matrix and the Euler angle rates are given by

$$C_b^E = \begin{bmatrix} c\psi c\theta & s\psi & -c\psi s\theta \\ -c\phi s\psi c\theta + s\phi s\theta & c\phi c\psi & c\phi s\psi s\theta + s\phi c\theta \\ s\phi c\theta s\psi + c\phi s\theta & -c\psi s\phi & -s\phi s\psi s\theta + c\phi c\theta \end{bmatrix}, \qquad (3)$$

$$\dot{\theta} = \sec\psi \, (q \cos \phi - r \sin \phi), \qquad (4)$$

$$\dot{\psi} = q \sin\phi + r \cos \phi, \qquad (5)$$

$$\dot{\phi} = p + \tan\psi \, (r \sin \phi - q \cos \phi). \qquad (6)$$

The aerodynamic velocity V_a, α, β are given by

$$V_a = ((u')^2 + (v')^2 + (w')^2)^{1/2},$$ (7

$$\alpha = \tan^{-1}(w'/V),$$ (8

$$\beta = \tan^{-1}(v'/V),$$ (9

with $$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} - C_b^E \begin{bmatrix} O \\ -W_N \\ W_E \end{bmatrix},$$ (10)

where W_N, W_E are wind velocity components.

The components of the vehicle velocity in the geocentric inertial system are

$$\begin{bmatrix} u_E \\ v_E \\ w_E \end{bmatrix} = \left(C_b^E\right)^{-1} \begin{bmatrix} u \\ v \\ w \end{bmatrix}.$$ (11)

The vehicle inertial velocity V, flight path angle γ and azimuth angle σ are given by

$$V = [u_E^2 + v_E^2 + w_E^2]^{1/2},$$ (12)

$$\gamma = \sin^{-1}[u_E/V],$$ (13)

$$\sigma = \sin^{-1}[v_E/V].$$ (14)

The components of the vehicle position vector are obtained by integration:

$$\int u_E\, dt = R_{ox} + C_1,$$ (15)

$$\int v_E\, dt = R_{oy} + C_2,$$ (16)

$$\int w_E\, dt = R_{oz} + C_3,$$ (17)

where C_1, C_2, C_3 depend on the launch point. The range angle and latitude of the vehicle are given by

$$\Gamma_1 = \cos^{-1}[R_{ox}/(R_{ox}^2 + R_{oy}^2)^{1/2}],$$ (18)

$$\Gamma_2 = \tan^{-1}[R_{oz}/(R_{ox}^2 + R_{oy}^2)^{1/2}].$$ (19)

The control deflections δ_p, δ_y, δ_r are generated through the autopilot dynamics and the attitude programs.

A welcome feature of launch vehicles is their strong stabilisation in roll leading to practically no coupling between the longitudinal and lateral motions. Essential

long-period motion features of the vehicle and its control system are still preserved in separate studies on the pitch and yaw plane motions. Blair and Lovingood suggest pitch plane motions for trajectories and yaw plane motions for loads in the case of large symmetric vehicles (see Geissler 1970, pp. 163–197). Rheinfurth discusses how statistical analysis techniques can be applied to study planar motion and loads pertaining to the wind-vehicle interaction in flight (see Geissler 1970, pp. 199–228).

Short period models are obtained by the time-slice approximation since the control system response is fast, compared to the trajectory variations. Thus the thrust, mass, inertia, c.g., c.p., and normal force slope L_α are assumed constant implying trajectory frozen conditions. Often the forward force equation is not written in the pitch or yaw plane short-period motion. Thus the rigid vehicle model reduces to

$$\ddot{z} = -\frac{T-D}{m}\,\theta - (L_\alpha/m)\,\alpha + (T_c/m)\,\delta_p, \qquad (20)$$

$$\ddot{\theta} = (L_\alpha l_\alpha/I)\,\alpha + (T_c l_c/I)\,\delta_p, \qquad (21)$$

$$\alpha = \theta + (\dot{z}/V) + \alpha_w. \qquad (22)$$

where $\alpha_w = (-V_w/V)$ is the gust angle of attack. In (20)–(22), T, D are the total thrust and drag respectively, $\dot{z}$, V are the lateral drift and total velocity respectively.

Bending is incorporated in the short-period model only in so far as it influences the vehicle structural loads and control interaction through sensors. Forward loop coupling of bending-to-vehicle response is often significant only in its effect on structural loads. Consequently, the bending moment at a distance x from the engine gimbal point is approximated by

$$BM(x) = M_\alpha(x)\alpha + M_\beta(x)\beta + \sum_{i=1}^{n} M_{\eta_i}(x)\,\ddot{\eta}_i(x), \qquad (23)$$

where η_i is the generalised co-ordinate of the ith bending mode for the vehicle. Each bending mode's dynamic response for $i = 1, 2, \ldots n$ is given by

$$\ddot{\eta}_i(x) + 2\,\zeta_i \omega_i \dot{\eta}_i(x) + \omega_i^2\,\eta_i(x) = f_i(x, t), \qquad (24)$$

where ζ_i, ω_i are the damping ratio, natural frequency of the ith bending mode with $f_i(x, t)$ as the forcing function resulting from aerodynamic and thrust effects. Feedback coupling of bending is accounted for by introducing additional terms into equations representing feedback variables. For example, if a rate gyro is located at station x on the vehicle, the rate gyro output is given by

$$\dot{\theta}_s(x) = \dot{\theta} + \sum_{i=1}^{n} \lambda_i(x)\,\dot{\eta}_i(x), \qquad (25)$$

where $\lambda_i(x)$ is the slope of the ith bending mode at x.

The models of other sensors and control actuators for use in short-period models are well documented in the literature. The control logic for a vehicle is rather specific to the vehicle and is given beforehand for simulation.

Atmosphere and wind models are important both in long period and short period simulations. There are three different descriptions of wind disturbances in use. The most desirable and complete description is that of the total wind profile (as obtained from balloon soundings and smoke trail techniques). This is resorted to in Monte Carlo simulations with a large number of representative profiles. This can lead to prohibitively large manpower and computer time.

The second method is the use of ' synthetic ' wind profile. Synthetic profiles are constructed taking into account wind speed, wind shear and gust values at various altitudes of the entire wind field. Since only one forcing function is used, it is possible to conduct parametric studies on various launch vehicle systems with a minimum of computer time. The drawback is that the statistical properties incorporated in the profile do not completely define the aerodynamic loads over a large class of vehicle systems, so that the results have to be viewed with greater care.

The third approach to describing wind field consists of its strictly statistical re-presentation as a stochastic process. The idea is to circumvent the time-consuming Monte Carlo method. The statistical analysis of wind field is satisfactorily developed only upto first- and second- order statistics. This restricts the analysis essentially to a Gaussian stochastic wind process and a linear dynamical system. As the system is time varying, simulation is required for such analysis.

3. Choice of simulation computer

There are multiple considerations governing the choice of simulation computer, a detailed treatment of which is beyond the purview of this paper. However, to provide an insight into the considerations which have led to the use of the hybrid computer for the case study presented in the next section, we present briefly the strong and weak points of the analog, digital and hybrid computers, especially their comparative speeds. Also presented is a concise discussion on general-purpose digital simulation programs, the hallmark of which is flexibility, in contrast to the hybrid simulation implementations, which are generally tailor-made to obtain the best run time speeds.

Four factors affect the time and cost of the computer implementation of a simulation model These are programming, set-up, run-time, and data reduction. Of these, the run-time makes the most significant contribution to the time and cost per solution, because simulations that are run repeatedly are characteristic of many aerospace problems Thus, we concentrate our effort at comparing the run time requirements for launch vehicle simulations using analog, digital and hybrid computers.

It is well-known that analog computers have a tremendous bandwidth and speed of solution advantage over digital computers. They operate in ' parallel ' fashion so that the solution time is independent of problem complexity. Their output of data is available in easily assimilated graphical form, although the data collection and display requirements may cause the loss of some of their inherent computing speed advantage. The basic limitations of the analog computer are in respect of its precision and resolution. Also, discrete calculations and complex logic functions cannot be easily handled. Storage capacity and memory are extremely limited and automatic programming methods are not available More significantly, analog

computers suffer from the 'curse of dimensionality', which imposes a basic limitation on the size of the problem that can be handled.

A digital computer is an inherently sequential machine and as a consequence, the more complex the problem, the slower the solution time. Its main advantage over the analog computer stems from its unlimited precision and resolution of numerical variables and its floating point arithmetic which eliminates scaling problems. The key to digital simulation is the numerical integration method used and the results are sensitive to the integration step size. If it is too large, the accuracy deteriorates and the solution becomes unstable and if it is too small, the computational burden in terms of run-time goes up very rapidly. Through the choice of the integration method and the step size, the digital computer offers the well-known speed-accuracy trade-off.

When confronted with more severe problems which require high accuracy and computational speed, either computer used alone will not be adequate and a hybrid digital-analog combination is called for. Starting in the late 1950s, crude attempts were made to link analog and digital computers. During the ensuing years, the hybrid computer underwent a great deal of evolution. The modern hybrid computer is a sophisticated combination of a real time, interrupt-oriented digital computer with one or more parallel analog processors. Ideally, each of these units is used to its own best advantage, providing significant cost per solution advantages over either pure digital or analog computing methods. In distinct contrast to the earlier systems, current generation hybrid computers are fully automatic, pre-programmed, multi-processors. Problem set up on these machines is accomplished quickly and it is possible to insert new parameters and obtain results in milliseconds.

There have been several reports comparing the speeds of analog/hybrid and digital computers (Saucier 1975). Such a comparison is complicated by the inherent diversity in their basic operations. Present day analog computers are capable of a computation bandwidth of 1000 computations/s to an accuracy of 0·1%. Further, they can also display a variety of variables simultaneously at high speeds with a resolution equivalent to atleast 1000 points/computation.

A commonly accepted criterion for measuring digital computer performance is throughput, which is a measure of the rate at which useful output is obtained from the computer system. Since no two machines have identical architecture or software, the computer performance may be compared on the basis of specific job applications. In comparing digital and hybrid computer systems, selected scientific applications in which relatively heavy workload is performed by the central processor while the peripheral workload is light, are considered. When comparing various digital computers, it is usual to create a mix of instructions (e.g. Gibson Mix) to be the basis for a quantitative comparison. A figure of merit frequently used to describe the speed of a digital computer is millions of instructions per second (MIPS), which is based on the average number of machine instructions a digital computer can execute in one second. Typical second generation digital machines are in the 0·1 to 1·0 MIPS region and third generation machines are in the 1·0 to 5·0 MIPS region.

To provide a quantitative measure of the performance of hybrid and digital computer systems in a simulation environment, the WSP scientific mix has been developed. This is based on dynamic applications consisting of first order simultaneous differential equations with non-linear coefficients with arbitrary and fixed function

generators also included. The mix can be adjusted to suit the problem parameters and size and can be used as a standard bench mark in assessing dynamic computation capabilities of computers for scientific applications. The average hybrid computer system is claimed to have a digitally equivalent speed of more than 10 MIPS, giving a speed advantage of 20 to 100 times over that for digital-only solutions for dynamic models. In fact, in all such speed comparisons, it is the digital part of the hybrid computation that slows down the analog and prevents hybrid computation from being even more effective.

The lack of speed of the digital computer is compensated by the well-known trade-off between speed and user convenience in terms of program generality, flexibility, interchangeability and set-up of the digital computers. Thus the digital and hybrid approaches in a way complement each other—digital, where general purpose programs encompassing different vehicles and missions are required, and hybrid, where real time or faster than real time simulation runs are needed.

The early digital programs for trajectory simulation were conceptually quite simple and designed to simulate a specific vehicle and its mission. Obviously, such programs cannot be adopted rapidly enough for other situations. In order to accommodate the requirements of a variety of advanced vehicles and missions, it is essential that the programs be based on generalised systems concepts. Among the several programs that have been developed during the intervening years, mention must be made of the N-STAGE and SNS programs. Written in assembly language, the N-STAGE simulates ballistic and earth orbital missions, while SNS computes the extra terrestrial trajectories. Neither of these programs have the capability to simulate an entire mission due to computer systems and capacity constraints. The advent of the third generation computer system has sparked off the development of more sophisticated general purpose digital simulation programs. The Mission Analysis and Trajectory Simulation (MATS) program is an outstanding example of this breed. MATS written in FORTRAN IV, is claimed to embody the capabilities of its predecessors and to include new techniques in the control logic and data handling processes.

On the Indian scene, the program SIMSPACE, which has the capability of computing the trajectory based on the propulsive, aerodynamic and gravitational forces and moments has been developed in the late 1960s. This program has been extensively used by ISRO in its launch vehicle development projects and the program itself has undergone constant modifications to enhance its capabilities   Yet another program acronymed OMTATSAT meant for the simulation of rigid body long period flight dynamics of multi-stage satellite launch vehicles has recently been announced. In particular, this program carries out preflight analysis of the vehicle's trajectory performance and orbital capability with a view to fixing the specifications of critical design parameters for achieving the mission objectives.

While the emphasis in digital computer programs is on generality and versatility, the emphasis in hybrid computer simulation has been on speed. Since the tasks are divided between the digital and analog portions, substantial effort is necessary to recast the model in a proper form to match the speed and accuracy requirements of the interfaced variables.

Important computer requirements such as accuracy and speed are dependent on the choice of axis system for solving the translational equations of motion and the method of generating the multivariable aerodynamic functions on the computer.

It is well known that a direct body axes integration of the translational equations places unnecessary demands on the computer because the rapidly changing angular velocity components get coupled into the slow changing trajectory variables thereby generating large artificial accelerations. Since flight path or wind axes do not exhibit rapid rotations like body axes, Fogarty & Howe (1968) suggest the former for the solution of the translational equations for atmospheric flight. Howe recommends the modified flight path axes (H-frame) for orbital flights outside the atmosphere (see Bekey & Karplus (1968, pp. 363–389). Higuchi & Koshiishi (1968) use the H-frame for the complete flight of a launch vehicle upto orbital injection of the payload.

Digital generation of multivariable aerodynamic functions introduces phase errors which seriously affect the fidelity of the simulation. To keep the errors down, at least the main variables α, β should have a small sampling period. Mitchell *et al* (1966) present a redundant analog mechanisation of α, β, with two extra integrators. The digitally generated α, β, correct the integrator outputs at a low sampling rate. The analog α, β, are sampled faster to reduce the phase errors in digital function generation (figure 1). The problem is so serious that Rubin (1976) introduces the hybrid multivariable function generation approach for combating effectively the phase error problem.

Planar and short period simulation models are comparatively easy for computer implementation.

Hybrid simulation of short period models allows an easy introduction into the computer set-up of actual physical components, such as hydraulic and electric servos,
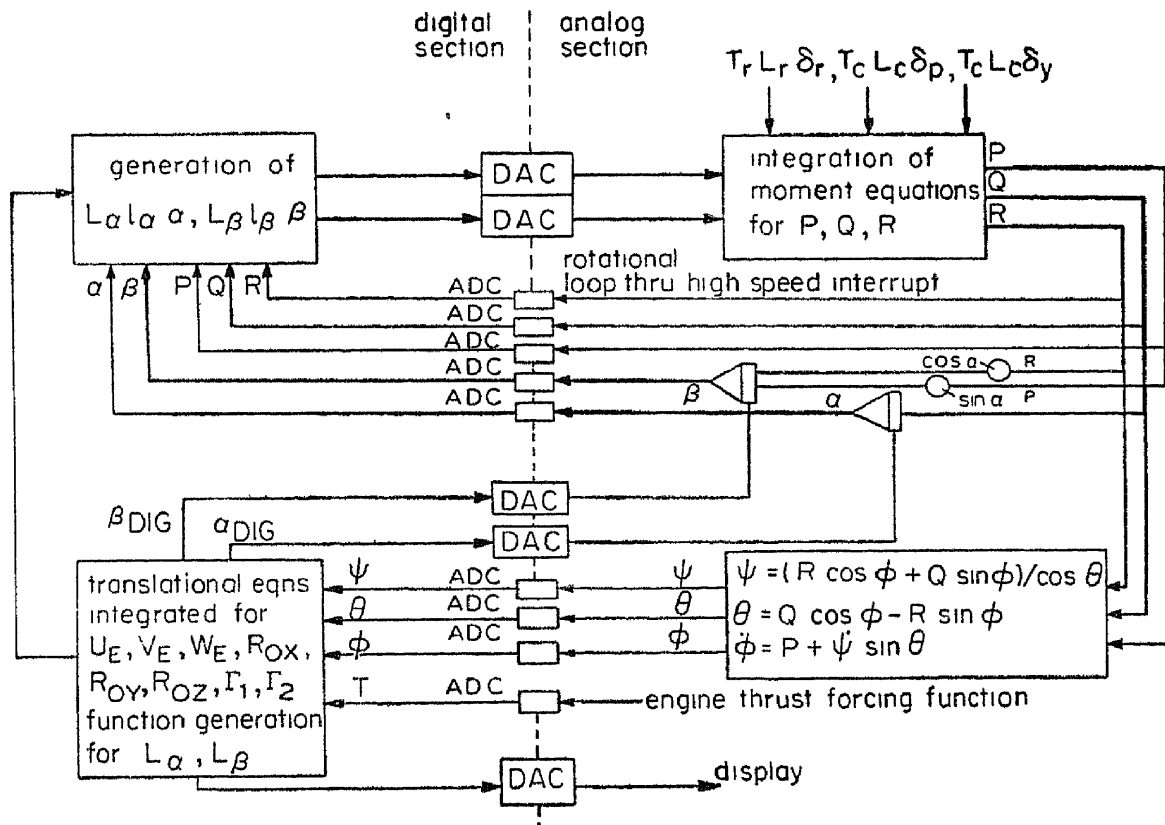

Figure 1. Use of redundant integrators to complete α and β loops around rotational equations

control surfaces, autopilots and human operators. This technique is superior to any analytical representation of the dynamic characteristics of these elements especially if non-linearities, back lash, dry friction etc., are involved Problems involving statistical analysis requiring repeated solutions of the model lead to hybrid computation.

4. Case study

The case study presented here deals with the first stage of a satellite launch vehicle for a low earth orbit mission. The control objective is to accurately steer the vehicle along a reference trejectory, without violating the structural load constraints and range safety limits on the flight azimuth. To achieve this, the vehicle is commanded in pitch and stabilised in yaw and roll. Two different forms of control, namely aerodynamic fin tips (FTC) and thrust vector control (TVC) are both provided (figure 2). While both fin tips and TVC are useful for control in pitch and yaw axes, fin tips alone are effective in roll control.

The need for the TVC arises from two reasons. The FTC is not effective from lift-off until sufficient dynamic pressure builds up. The magnitude of the over-turning disturbance moments on the vehicle may be lower than the moment provided by the FTC, during some portion of the flight trajectory (according to preliminary design). Since TVC fuel impulse requirement may become exceedingly large if used singly, incorporation of the FTC becomes indispensable. Therefore, a logical control design objective is to first utilise the FTC when available and augment this effort by switching in the TVC after the fin tips saturate. By adopting such a control strategy, the TVC fuel impulse is conserved The principal features of the feedback loops incorporated to implement such a control logic arc depicted in figure 3 The
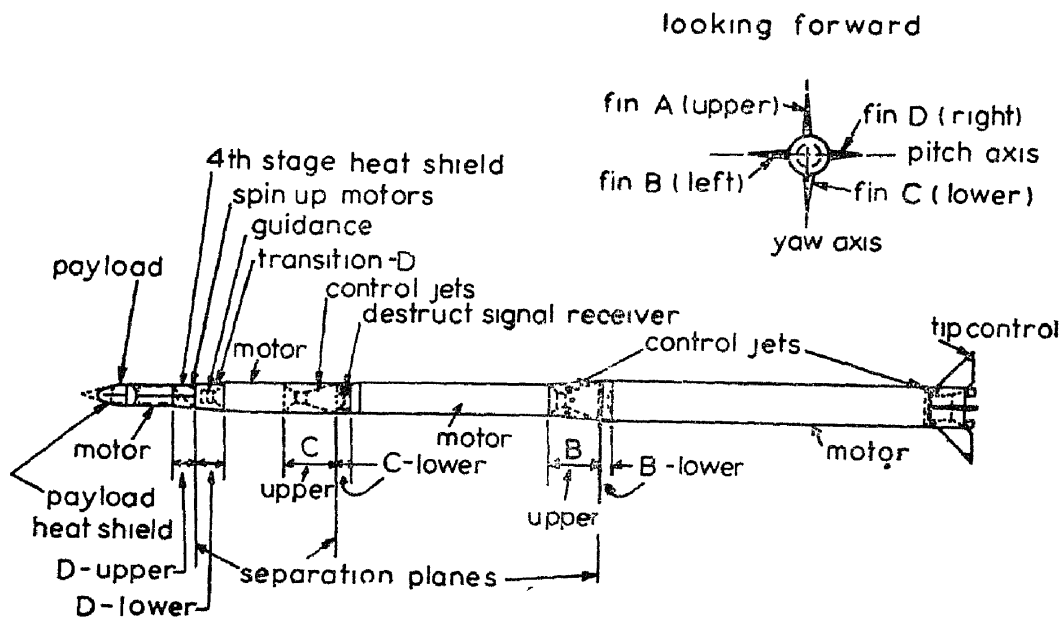

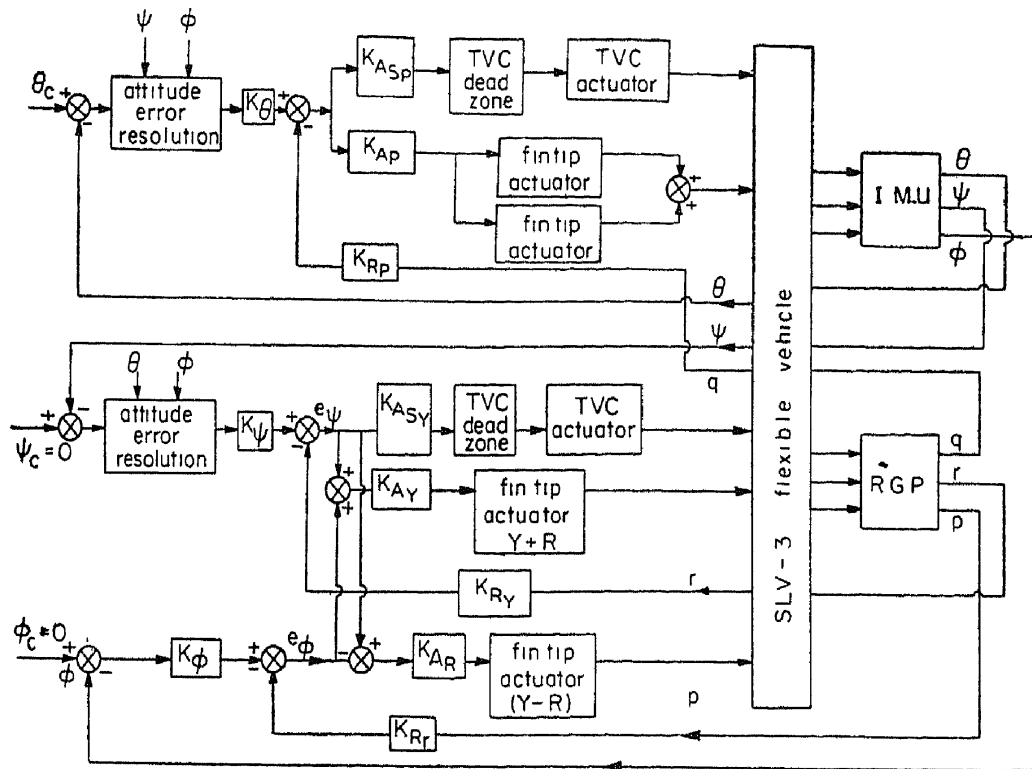Figure 2. General arrangement and assembly of a launch vehicle

Figure 3. Block diagram of the first stage control system of a launch vehicle

feedback signals for loop stabilisation consist of a weighted combination of the body rates produced by the rate gyro package (RGP) and the angular positions given by the inertial measurement unit (IMU). The physical location of these sensor units is to be determined from considerations of the vehicle bending modes and their interaction with the control loops.

With the winds and gust profiles undergoing rapid changes and the fin tip effectiveness also drastically varying along with other vehicle parameters, dynamic scheduling of the individual loop gains is essential to ensure satisfactory operation of the control system. Quite often, appropriate bending filters may also be required to minimise control-structure interaction. Thus, the two principal aspects of system design from the control standpoint encompass:

(i) selection of gains for the various control loops such that they provide adequate measures of relative stability, speed of response to pitch commands and accuracy of tracking and stabilisation. These requirements must be met at all points along the reference trajectory;

(ii) selection of gyro locations such that the bending modes do not interact with the control loops and design of suitable bending filters to gain or phase-stabilise the bending modes, if considered necessary.

In carrying out the above design tasks, it is common to initially take recourse to extreme simplifications, since the more exact models are much too complicated for analytical handling. However, extensive simulation studies are later conducted not only as a means of design verification and improvement, but with several other objectives in mind. These simulation objectives can be briefly enumerated as follows.

(i) Dynamic response of the control loops in the presence of thrust misalignments and wind gusts, which constitute the major disturbances.

(ii) Sensitivity analysis of the control loops for specified dispersions in the aerodynamic coefficients, actuator time constants, location of the gyros, variations in the natural frequency and damping ratio of the sensors, etc.

(iii) Effects of vehicle bending modes on the control loop performance and interaction with respect to dispersions in the structural damping ratio and bending mode natural frequency.

(iv) Determination of structural load profiles in terms of the oft quoted ($Q\alpha$) measure and ensuring that it does not exceed the specified maximum along the trajectory.

(v) Estimation of the secondary injection fuel requirement under the worst conditions of disturbances to determine the total tankage including the reserve margins.

(vi) Assessment of failure mode behaviour of the vehicle for failures in the control logic and gain sequencer to catalog the conditions for salvaging the mission without violating the range safety requirements.

The first three objectives can be achieved through computer simulation studies on the short-period models at different critical points along the flight trajectory. The remaining objectives need a long-period simulation of the pitch plane trajectory.

4.1 *Short-period simulation*

In the present study, short-period simulation runs are conducted at the following initial trajectory points:

(i) a point during initial vertical rise,
(ii) the point at which pitching is initiated,
(iii) maximum pitch rate condition,
(iv) the point when the FTC and TVC dead zone are switched in,
(v) gain switching points,
(vi) transonic Mach number condition,
(vii) first stage burn-out.

At each of these points, the operational mode conditions listed below are simulated and the control system performance investigated:

(i) normal mode,
(ii) change or rate gyro location,
(iii) change of actuator time constant,
(iv) control effectiveness variation,
(v) aerodynamic effectiveness variation,
(vi) gain switching failures.

Since there is a natural decoupling, the pitch loop and the yaw and roll loops are simulated separately.

In the case of the pitch loop, the dynamics introduced by the pitch attitude (short period) of the vehicle, the rate gyro, FTC and TVC actuators and the vehicle flexibility effects are all included. The variable dead zone non-linear element is introduced in the TVC channel so that the channel is switched on only when the load demand is not fully met by the FTC. A thrust misalignment moment and a step wind gust angle of attack constitute the disturbances injected into the loop, which is tested for a step command.

On the other hand, since the yaw and roll control systems share the same fin tips, the performance of these loops is studied in the fin-sharing mode. Figure 3 provides details of the fin-sharing feature, where the sum of the error signals e_φ and e_ϕ is fed to one fin tip and their difference is fed to the other. Considering that the yaw and roll loops are merely stabilised, these two loops are studied for their behaviour relative to initial roll and yaw offsets, as also corresponding rate offsets if applicable. The disturbance inputs to these loops are:

(i) a moment due to the fin misalignment caused by fin canting,
(ii) a moment due to main thrust misalignment, and
(iii) a step gust angle of attack.

In view of the coupled nature of the yaw-roll loops, the simulation has been carried out under two conditions: one, by assigning FTC for roll and TVC for yaw, the yaw and roll loops are intentionally decoupled and then investigated for their behaviour, and the other by yaw and roll loops coupled as depicted in figure 3, this being the normal mode of operation. The variables monitored for the assessment of performance in the above short period studies are tabulated in table 1.

Typical response plots for the pitch and yaw-roll loops are presented in figures 4 and 5. For a step command in pitch, the normal mode response of θ is found to be quite satisfactory, whereas under two of the failure mode conditions (extreme reduction in FTC channel gain and TVC actuator time constant reduction to a low value), the response exhibits an unacceptable oscillatory behaviour. The generalised co-ordinate associated with the first bending mode attenuates rapidly. In the case of the yaw-roll loop studies, the error profiles of yaw and roll angles for initial offsets in these variables are shown in figure 5. It may be observed that the fin tips get first allocated to the

Table 1. Variables monitored for performance assessment in the short period simulation

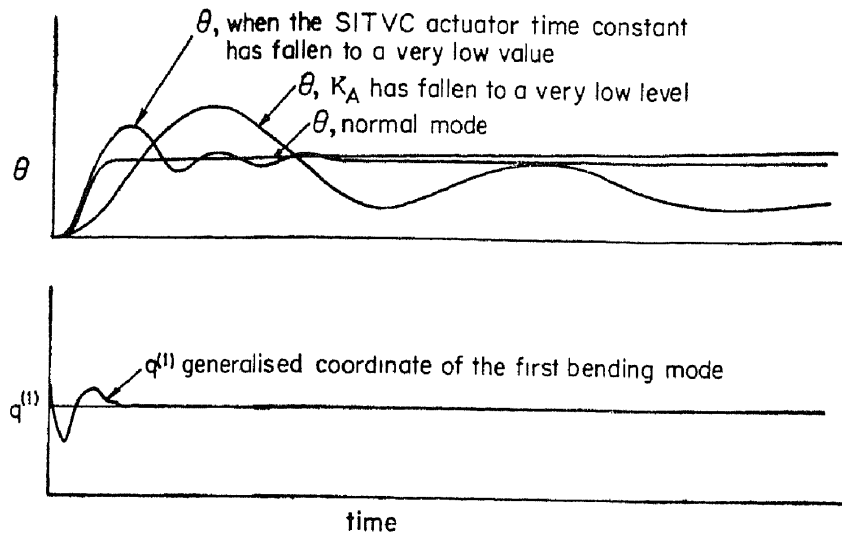| Pitch loop	Yaw-roll loops
Pitch attitude	Yaw attitude and rate
Pitch rate	Roll attitude and rate
Angle of attack	Yaw angle of attack and rate
Generalised co-ordinate of the first bending mode	Generalised co-ordinate of the first bending mode
FTC and TVC force levels	FTC force level for yaw and roll TVC force level for yaw

Figure 4. Typical pitch loop responses for different conditions
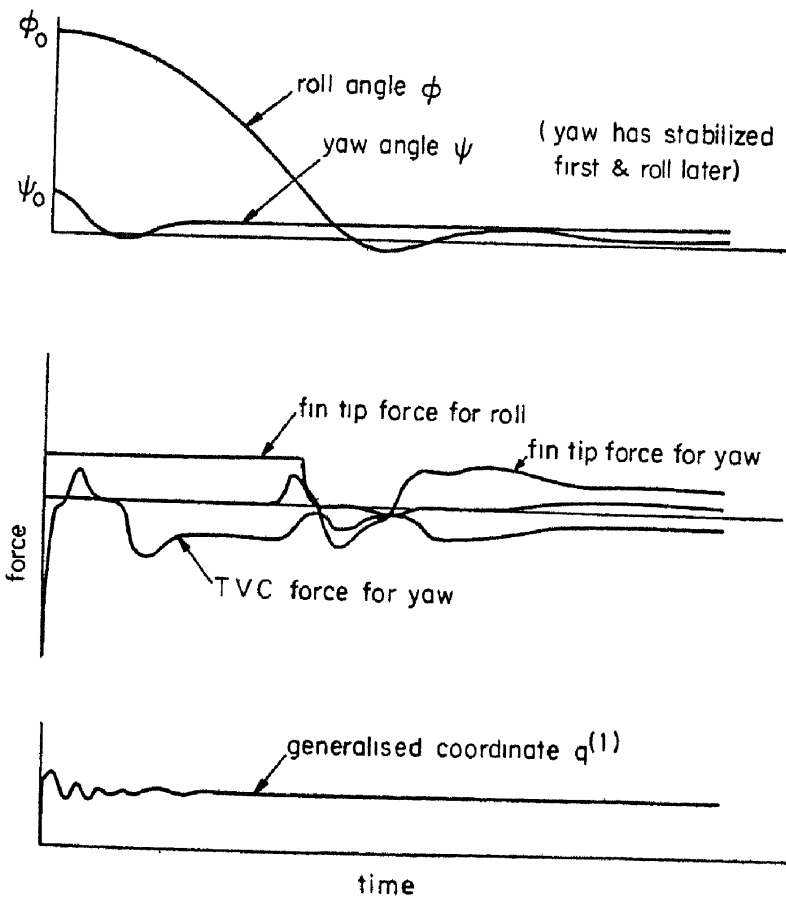

Figure 5. Typical yaw roll loop responses for different conditions

roll channel and saturate calling in the TVC for the yaw axis. Fin tips become effective in yaw after the roll error is reduced. This initial time sharing of the fin tips is due to the fact that the fin authority limits for yaw and roll stabilisation functions have not been defined *a priori*. This situation points to an alternative design strategy of using the fin tips exclusively for the roll channel and the TVC correspondingly for the yaw stabilisation. Since the pitch and yaw axes requirements are different, such a strategy may eliminate yaw-roll interaction and achieve better response times for yaw and roll by meeting their individual performance requirements.

4.2. Long-period simulation

Since the vehicle is stabilised in yaw and roll and steered in pitch alone, the pitch and yaw loops are decoupled and therefore simulation of the vehicle trajectory in the pitch plane is considered adequate to monitor all vital features of the vehicle behaviour. However, in the presence of small uncorrected roll drift, it becomes necessary to resolve the pitch loop error function along the inertial axes, when the pitch error function gets coupled to the yaw attitude. To cover this situation, an approximate simulation of the yaw loop is needed and this can be achieved through the use of the nominal value of a_y.

For the above reasons, a five degree of freedom simulation model has been implemented for conducting the long period studies. This model includes both the trajectory dynamics and the control system dynamics. Since the variations in the trajectory variables are much slower compared to the variables associated with the control system, the logical choice of task allocation on the hybrid computer is to implement the control dynamics on the analog processor and the trajectory dynamics on the digital computer. In the present study, the trajectory equations have been solved on the digital computer using a fourth-order Runge-Kutta routine with 0.1 s step size. The parameters of the control loops and the pitch command are set through DCU's and DAC's so that their time variations can be controlled easily from the digital processor.

The specific investigations carried out using this model cover the following modes of vehicle behaviour:

(i) normal mode,

(ii) complete failure of roll control,

(iii) mechanical failures in pitch and yaw channels,

(iv) failure of control electronics of FTC channels (pitch and yaw),

(v) failure of gain sequencer after FTC gains are initially set,

(vi) gain schedules with reduced number of switchings

In all the above cases, the variables whose time histories have been monitored for assessing the vehicle performance are:
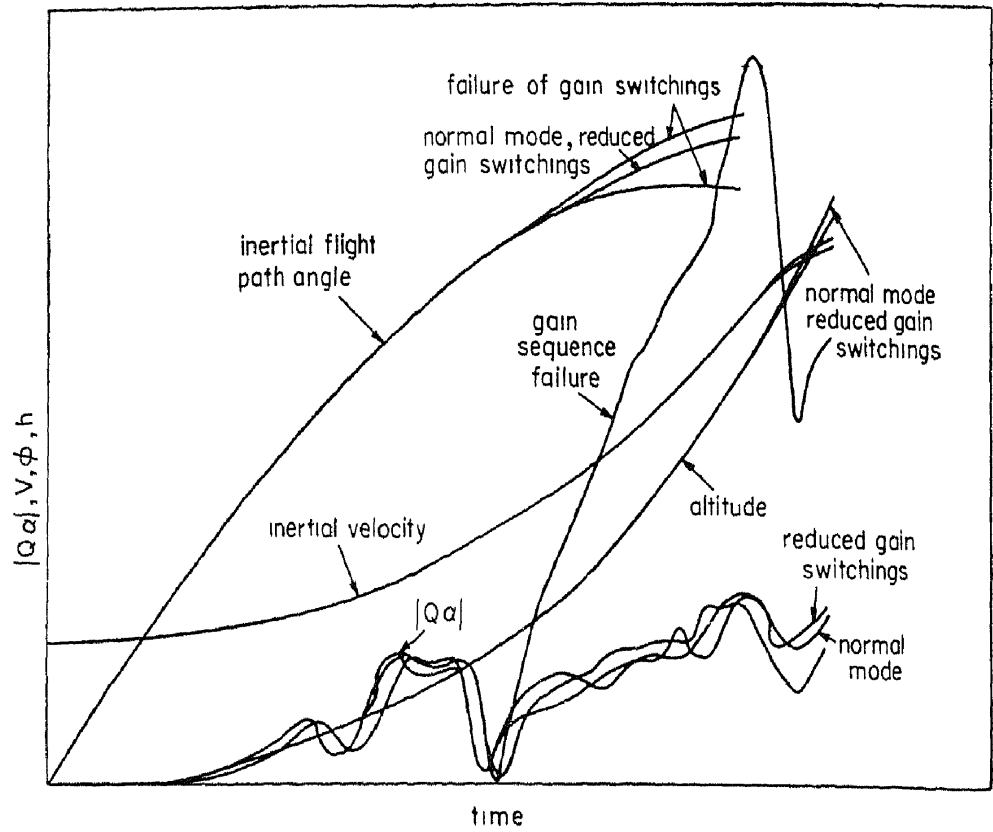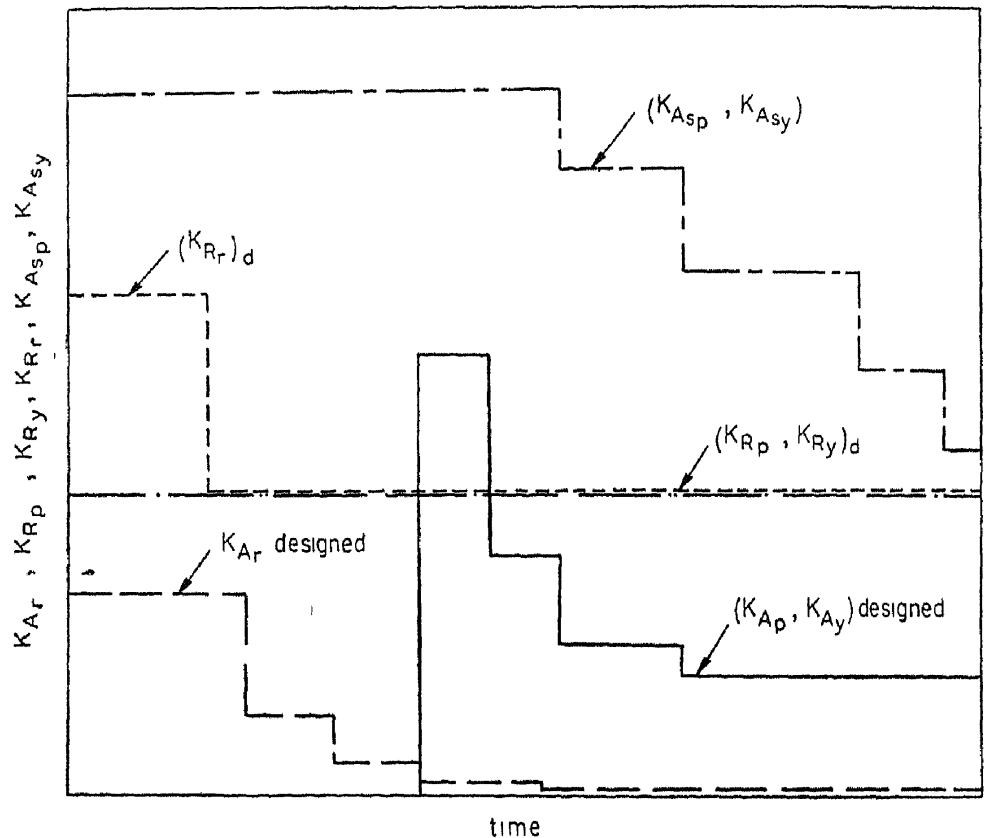
Figure 6. Trajectory variables: nature of variation

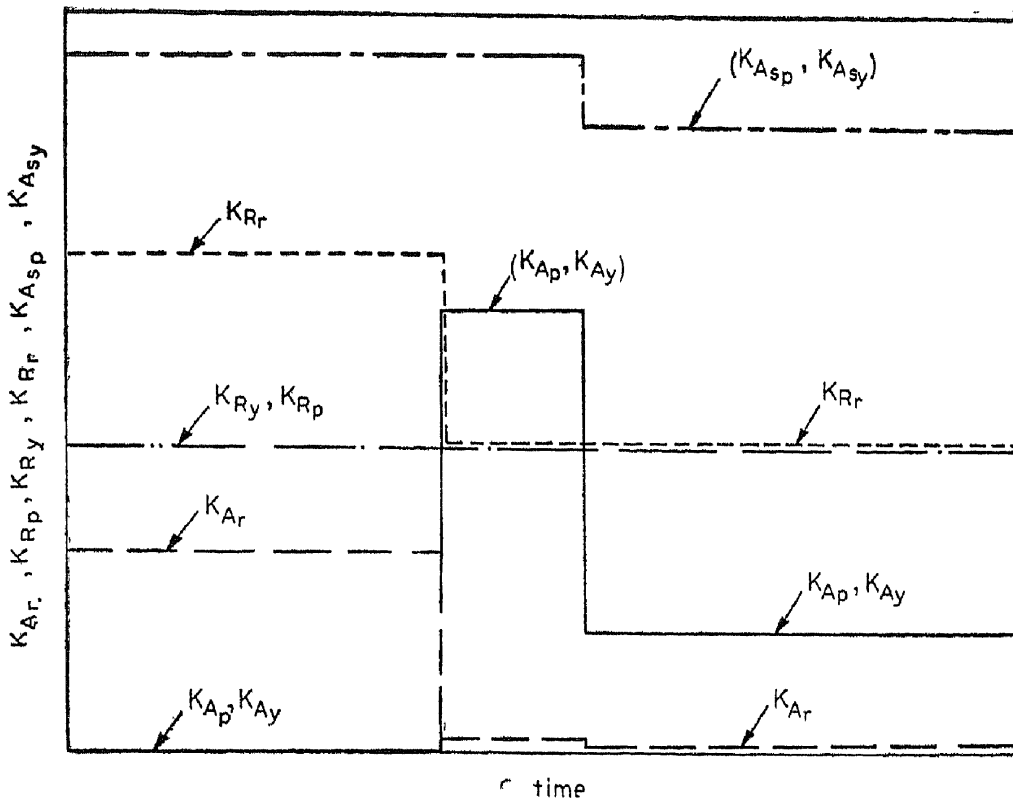Figure 7. Designed gain schedules of the control loops

Figure 8. Simulation derived gain schedules of the control loops

(i) inertial pitch plane velocity,	(vi) Mach number,
(ii) inertial flight path angle,	(vii) dynamic pressure,
(iii) altitude,	(viii) $Q\alpha$,
(iv) range angle,	(ix) pitch and roll angles,
(v) pitch angle of attack,	(x) TVC force level for pitch loop.

Representative plots of the trajectory variables such as inertial velocity, altitude, flight path and range angles and load profiles shown in figure 6 indicate that the trajectory variables are not very sensitive to changes in the control system parameter values. However, the load profiles single out a failure mode which generates an acceptable trajectory but violates the design structural load limit. Figure 7 shows the gain schedules designed using short period models. During the course of the trajectory simulation studies, an attempt has been made to obtain a schedule with reduced number of switchings, while retaining the trajectory profile within acceptable limits, (the violation of the structural load constraints being the critical element in this case). Figure 8 shows the improvised gain schedule. In actual practice, its performance has to be revaluated again by reverting to the short period analysis and simulation models. This iteration with the design process towards simplification and refinement of the system is an inherent trait of the simulation methodology.

5. Conclusions

The final orbit achieved by a launch vehicle exhibits considerable dispersion. The impact points of the discarded stages of the vehicle also show dispersion, which is due to uncertainties in the vehicle's aerodynamic data, thrust profiles of stages and atmospheric winds. These can only be determined by a simulation approach after much of the design of vehicle stages is completed to an advanced level. The paper presents the necessary modelling and choice of computer to accomplish such tasks.

The digital and hybrid approaches are both contenders for the simulation evaluation of vehicle subsystems or the integrated vehicle performance. The general purpose digital approach is applicable for non-real time applications which do not involve a large number of repetitive runs, viz. vehicle nominal trajectory and pitch program development, preliminary design of the vehicle configuration, vehicle systems and mission definition. For real time applications and/or those with a large number of simulations such as control system performance assessment, hardward testing, operator training or Monte Carlo techniques, the hybrid has runaway advantages both in respect of cost and speed of simulation.

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