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Pyrolysis Caused Tail-Off Thrust in a Solid Rocket Motor: A Semi-Empirical Model

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ABSTRACT

Knowledge of tail-off thrust characteristics of solid rocket motors used for an upper stage of satellite launch vehicle is essential for proper sequencing of stage separation. The phenomenon is highly complex and theoretical models accurately describing the tail-off thrust are not available. Only rough estimates can be made through ground testing. A semi-empirical model is derived by the authors using the Indian polar satellite launch vehicle (PSLV) flight data and is used for fixing the time of stage separation. The model has been validated using data over an extended duration from another flight of the PSLV. The method adopted for modelling is described.

1. INTRODUCTION

Solid propellant rocket motors finds application in a satellite launch vehicle, not only for the booster stage but also for many other functions[1,2]. When a solid propellant motor is used as an upper stage, its tail-off thrust has a major say in the design of the stage separation system. This is specifically so when there is concern about recontact of a spent stage with the ongoing part[3]. In general, there are limitations in designing/implementing separation systems which can impart very high separation velocities so as to overcome the effect of a large tail-off thrust. So, it is necessary to know accurately the tail off thrust characteristics, so that sufficient wait period can be provided for the tail-off thrust to die down to a sufficiently low value. But since the tail-off thrust is very small compared to the large thrust during the propellant burn time, its direct measurement during ground testing is extremely difficult[4,5]. Approximate estimates are made possible through monitoring of the chamber pressure history. Not much reliance can be had on such measurements because of the influence of atmospheric pressure during ground testing. The best means is surely flight measurements. The authors have generated a semi-empirical model for studying the tail-off thrust characteristics of solid propellant rocket motor used for the third stage of the polar satellite launch vehicle (PSLV) of ISRO using flight data. The data obtained from the second successful developmental flight of PSLV was used for this purpose. The model could be validated using data from the third developmental flight of PSLV.

2. TAIL-OFF THRUST PARAMETER IN PSLV THIRD STAGE SEPARATION

PSLV makes use of a solid propellant rocket motor for its third stage. After its burn out, it is separated from the ongoing stage using a ball lock mechanism and the relative velocity of separation is achieved through the actuation of a set of

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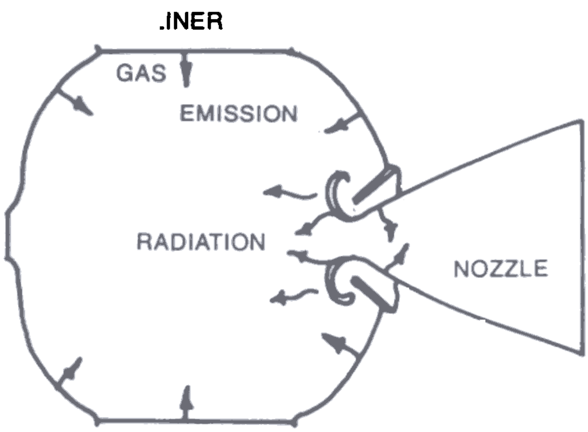

Figure 1. Residual thrust mechanism

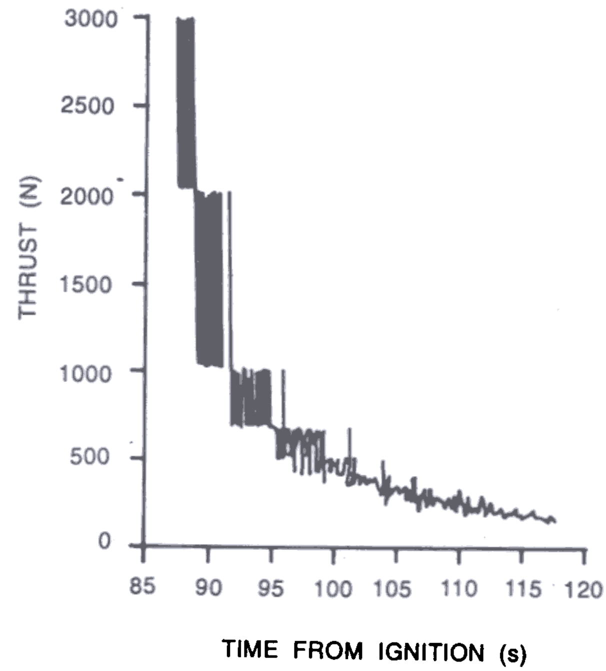

Figure 2. Plot of tail-off thrust

compressed springs. Due to space and mass constraints, the jettisoning spring system is designed to provide a relative separation velocity of nearly 0.7m/s only. Naturally, the separation time must be such that the tail-off thrust does not accelerate the spent stage to a velocity, sufficient enough, to establish recontact with the ongoing stage at any time during the coasting phase. This condition necessitates knowing the tail-off thrust characteristics of the third stage motor.

3. THEORETICAL MODELLING

Theoretical modelling of the residual thrust is not easy because of the complex geometry of the system, insufficient data on parameters which controls outgassing from the liner material, exact nature of the heat sources, etc. But attempts have been made in this direction considering the fact that the main source of heating of insulation is the submerged nozzle itself, which has a sufficiently large thermal mass and gets heated during the action time of the motor. Since the motor itself is an adiabatic system, the thermal mass of the submerged nozzle and the heat required for decomposition of the liner material determine the history of heat flux to the insulator surface (Fig.1). With this background information, and the valid assumption that insulator thickness is small compared to the dimensions of the motor, there have been attempts to model the outgassing in a one-dimensional half space[6,7]. Some quasi-experimental procedures have also been adopted[8,9] for estimating the tail-off thrust due to pyrolysis. The experiments use subscale models, and depend heavily on extrapolations to flight environments.

Though such theoretical and quasi-experimental models can help to have a rough understanding of the total phenomenon of outgassing due to pyrolysis, these do not provide sufficient accurate information on the tail-off thrust to work out the separation sequence with necessary level of confidence.

4. SEMI-EMPIRICAL MODEL USING FLIGHT DATA

Data on vehicle acceleration due to the tail-off thrust is obtained till the stage of separation. By knowing the mass of the vehicle during this flight regime, the tail-off thrust, which is the product of mass and acceleration, can be estimated. From the second developmental flight of PSLV, tail-off thrust data on the third stage solid rocket motor could thus be generated for a duration of nearly 40 s. A plot of the thrust data is shown in Fig. 2. Therefore a flight regime where the acceleration is due to low residual thrust alone, is dealt with. The acceleration values are very low, so that

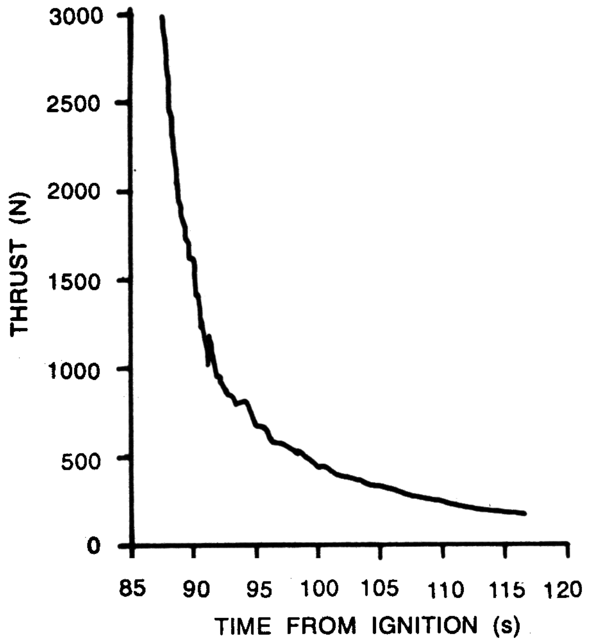

Figure 3. Plot of averaged tail-off thrust

considerable fluctuation are caused by different noise sources. To minimise the impat of this, we first subject the data to moving average and then this averaged data is used for generating a model. A plot of the thrust data after averaging is shown in Fig. 3. The curve suggests an exponential decay of the thrust. So an attempt on exponential model has been made. The best means for achieving an exponential curve fitting is to fit a straight line first to the logarithm of the thrust function, and then convert it to the exponential function.

The method of trying to fit a straight line to the logarithm of the thrust function revealed a very important characteristic of the tail-off thrust. As the plot of the logarithm of thrust given in Fig. 4 shows, the whole curve does not fit into a single straight line, instead, it has two distinct slope regions: One initial region, where the fall is quite fast followed by a second region, where the fall is comparatively slow. Obviously, the former region represents thrust due to burning of propellant silver, which is normally referred to as the tail-off thurst, and the second region represents the residual thrust due to pyrolysis of the motor liner material. In fact, it is this second region where the stage separation and the subsequent motion of the separated stage happens. So, curve fitting is done for the second region. The change-over from the silver burning region to the pyrolysis region cannot be very sharp. So, in order to make the model represent the pyrolysis-caused tail-off thrust region closer to the true situation, a small portion of the data towards the start of the second slope region is discarded and the rest is used for curve fitting. A model of the

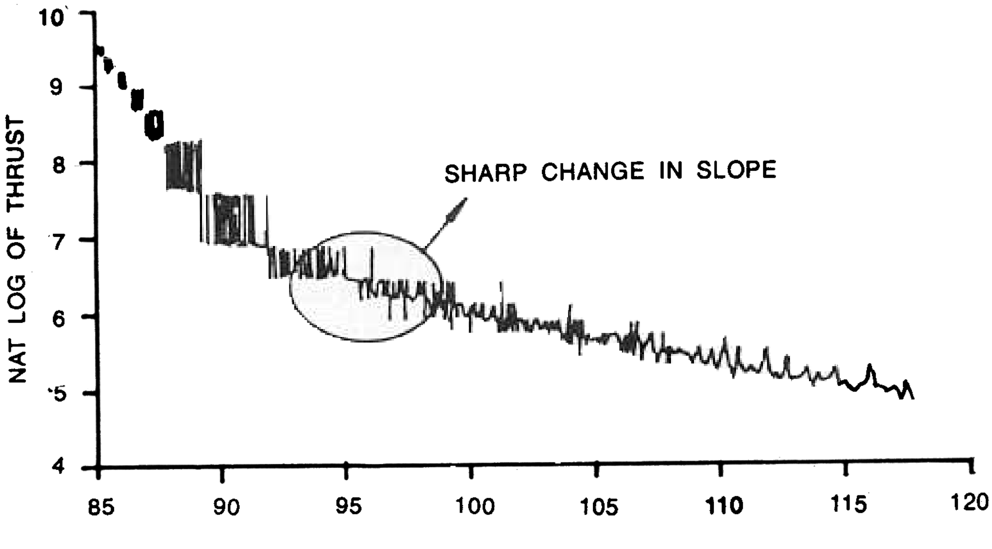

Figure 4. Plot of log thrust

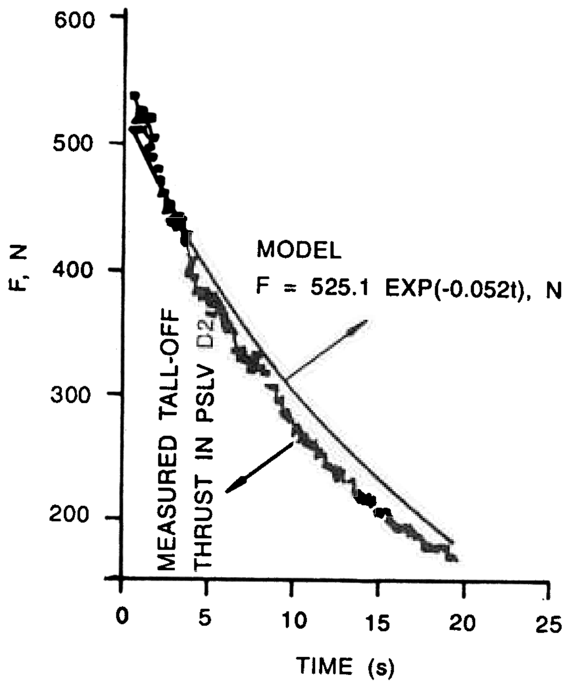

Figure 5. Over-plot of tail-off thrust model and D2 data

pyrolysis-caused tail-off thrust region along with the mathematical representation is shown in Fig. 5

5. LIMITATIONS OF SEMI-EMPIRICAL MODEL

The data used for generating the model do have finite error. This error need not be negligible, especially because the acceleration data used for estimating the thrust fall towards the very low end of the dynamic range of measurement. The influence of this error on the model has been reduced by finding the moving average.

There can be minor variations in the physical dimensions and thermal properties of the liner material as well as in the thermal condition of the submerged nozzle. All these can cause small variations in the residual thrust. But these are not accounted for in the model, since it is based on one set of flight data alone.

- Pyrolysis alone is considered in such modelling. Any spontaneous outgassing due to abnormalities cannot be accounted. But since we are dealing with a long duration phenomenon, the influence of such outbursts could itself be smoothed out to negligible levels by the process of finding the moving average of the data.

6. APPLICATION OF SEMI-EMPIRICAL MODEL

On applying the derived model to the actually obtained tail-off thrust, the root mean square deviation is about 15 per cent. But since we are interested in the tail-off thrust basically with regard to deciding a safe time of stage separation, we ought to have a conservative figure for the thrust. So, instead of fixing the upper bound at + 15 per cent, the decay rate is purturbed by a factor of two and the tail-off thrust is estimated to decide the upper bound. The lower bound is set by the estimated model.

In the third developmental flight of PSLV, separation of the third stage was delayed by an additional 100 s based on the tail-off thrust model. This could achieve an improved margin with respect to the clearance between the separated and the ongoing stages. This also helped to get valuable data on the tail-off thrust for an extra 100 s, as compared to the previous flight.

The tail-off thrust model is validated using this data. The predicted upper and lower bounds, along with the actual data from the third flight of PSLV are shown in Fig. 6.

7. NEED FOR IMPROVING SEMI-EMPIRICAL MODEL

A closer look at the curve showing the logarithm of the tail-off thrust as a function of time shows that the pyrolysis-caused residual thrust does not exactly obey an exponential fall; instead, it appears that the decay constant itself has some sort of time dependence. This calls for some improvement in the model. A theoretical model has to be first worked out to assess the time dependence of the delay constant based on which the empirical model can be improved.

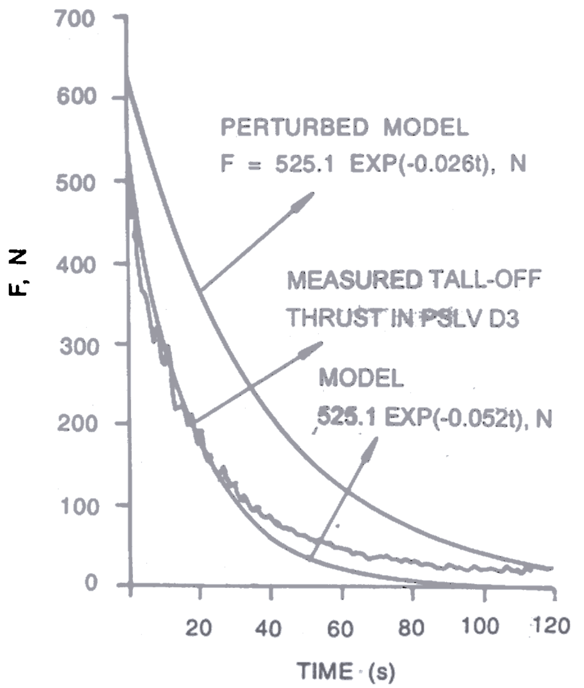

Figure 6. Over-plot of predication (lower & upper bounds) and D3 data.

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