Design and Performance Evaluation of an Ion Thruster Simulator

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Theme

THE development and evaluation of an analog simulator for predicting the performance of a mercury ion thruster is described. The design, which applies a model-following concept, allows for the interactive coupling between the discharge power supply and the thruster, and between the multi-variable parameters of the thruster system both in the steady state and dynamic modes of operation. This is achieved by automatic regulation from inputs computed from the analogue model, the basic design of which relied on the application of experimental data obtained from an early version of the RAE T^4 mercury ion thruster.[1] The work is claimed to represent the most realistic attempt, thus far, at simulating the normal performance of an ion thruster. Previous simplified simulation has been accomplished only using fixed resistive loads.[2,3]

A number of possible applications have been sighted,[1] but probably the most immediate aim of importance is its use in the independent and economical check-out of the power processing and control circuits. There has been no attempt to combine simulated electrical breakdown of the accelerator-system grids. This can be considered as a separate performance study aspect.

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Analogue simulation was chosen because of both the ease of hardware manipulation and the application of thruster static performance characteristics offered by this method. The value of the hollow cathode keeper potential V_K used in the simulation was 13.5 V, which corresponds to the mean measured value. The keeper current was maintained throughout the tests at 400 mA, a value previously established as being a good compromise between miminizing power dissipation and maximizing the range of stable thruster operation. The boundaries which define the unstable regions[1] are fundamental to the performance prediction and were therefore also included in the simulation.

For simplicity, all data were obtained using a hot wire ion beam neutralizer, and normal operating conditions were established at constant values of screen grid voltage V_B, and accelerator grid voltage V_{AC}. The level of total extraction voltage $V = |V_B| + |V_{AC}|$ chosen was high enough to ensure operation beyond the value corresponding to the maximum space charge limited ion emission, to guarantee that operation was well within the flow limited region. This was judged on the basis of allowing a wide flow rate excursion while maintaing low levels of accelerator impingment current.

The essence of the circuit design principles used in the simulator model may be illustrated by the example of Fig. 1, which shows the method of representing the combined characteristic relating to the main propellant flow $\dot{M}_{MF}$, the hollow cathode mass flow rate $\dot{M}_{HC}$, and the magnetic field current I_M, associated with the main discharge.

A major aim in the data collecting was to ascertain the effects of the various input parameter changes on the mean plasma potential difference $\bar{V}_P$ between the coupling and main discharge chamber plasmas. A knowledge of this and the input conditions uniquely defined the value of beam current by reference to the combined thruster operating characteristics which are presented and discussed in Ref. 1. Following previous work,[4] $\bar{V}_P$ was chosen as a dominant parameter because it is approximately the difference between the discharge voltage, V_D and V_K, and is therefore fundamental through its influence in determining the energy of the primary electrons.[5] $\bar{V}_{PO}$ is used to define the value of $\bar{V}_P$ at the normal constant operating discharge current I_{DO}.

A block diagram of the analogue simulator is shown in Fig. 2. For easier understanding of the concept, it is subdivided into three distinct sections. Section 1 computes the appropriate values of $\bar{V}_P$ as the function of the variables, the total mass flow rate $\dot{M}_T$, the ratio of the separate mass flows, $\dot{M}_{MF}/\dot{M}_{HC}$, the field current I_M, and the discharge current I_D. Starting with the propellant mass flow, the function generators G_1 and G_2 describe the main flow and by-pass flow vaporizer characteristics, simulation of which is accomplished in the following steps: a) the vaporizer temperature T_v is determined as a function of the heat input current I_V, b) T_V is related to the mass flow, and c) the dynamic response is introduced in the form of a first-order time lag representing the thermal time constant for heating and cooling, where this is the predominant time lag in the thruster system. The functional equivalent of propellant flow is then fed into G_3, the output of which represents the plasma potential as a function of $\dot{M}_T, \dot{M}_{HC}/\dot{M}_{MF}$, and I_M as determined at the reference point I_{DO} and defined as V_{PO}. The information pertaining to the relationship between the slope of the discharge characteristic $\Delta\bar{V}_p/\Delta I_D$ and $\bar{V}_{PO}$ at I_{DO} is stored in the function generator G_4, which is driven from G_3.

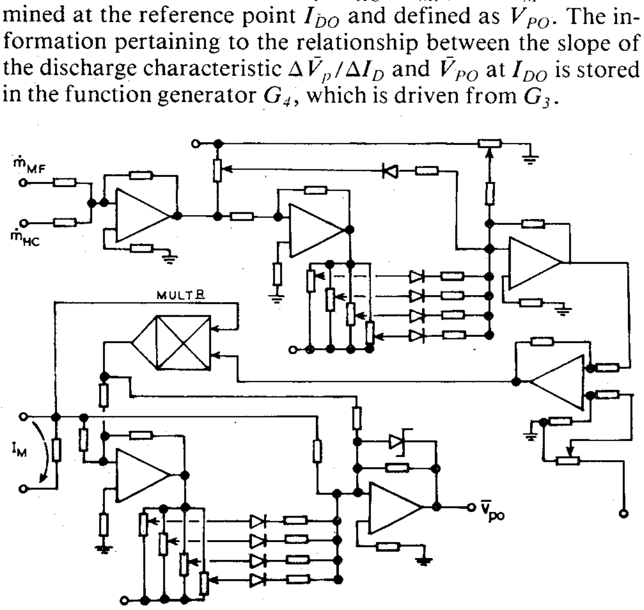

Fig. 1 Circuit design for generating $\bar{V}_{PO}$ as a function of the propellant flows and the magnetic field current.

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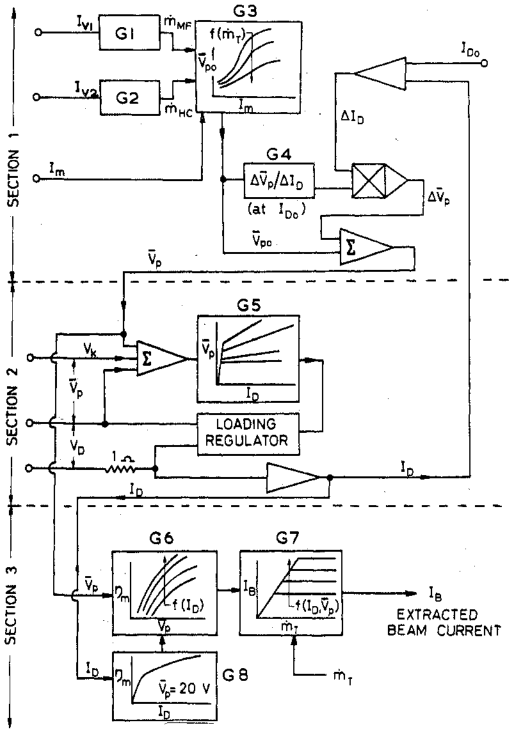

Fig. 2 Block diagram of analog simulator.

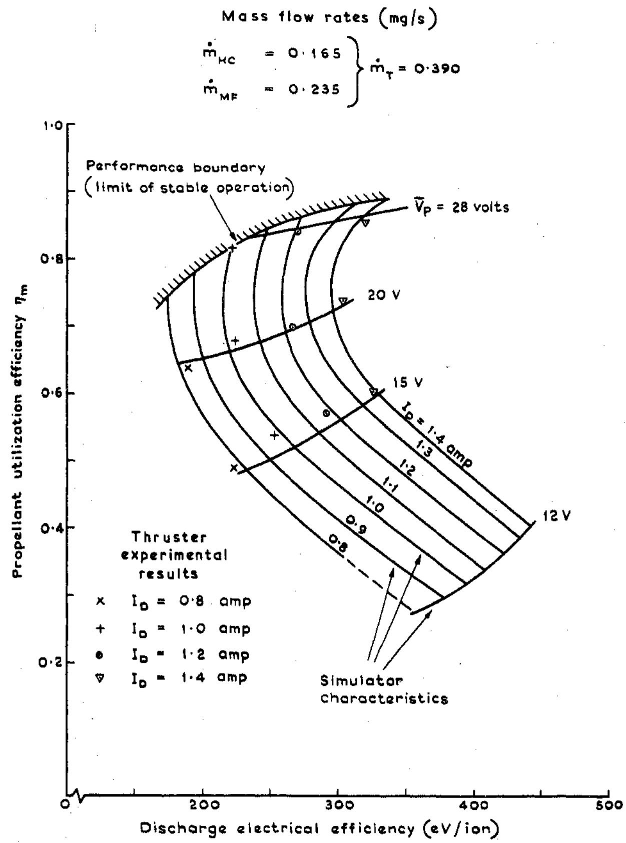

Fig. 3 Comparison of predicted performance with experimental data.

The output of G_4 is multiplied by any current change ΔI_D, which is obtained by comparing the measured value of I_D with the reference level I_{DO}, using a differential amplifier to produce the equivalent plasma potential perturbation $\Delta\bar{V}_P$. This is then added to $\bar{V}_{PO}$ to produce the final value of the plasma potential.

Section 2 uses the computed value of $\bar{V}_P$ to provide the appropriate loading to the discharge power supply which, in this case, is operated in a typically current limited mode. The loading regulator is driven until the difference between the applied values of V_D and V_K is equal to $\bar{V}_P$ for a range of fixed values of I_D. Hence both V_D and I_D may be 'slaved' to the combined model variables, as previously described,[1] resulting in the discharge characteristic[1] mechanised at G_5.

Section 3 generates the ion beam current I_B as a function of the parameters $\dot{M}_T$, I_D, and the previously established value of $\bar{V}_P$. The propellant utilization efficiency η_m is separately expressed in terms of $\bar{V}_P$ and I_D by G_6 and G_8, respectively. These are driven by their appropriate inputs and combine with $\dot{M}_T$ to produce a unique point on the thruster operating characteristic, simulated by G_7, thus defining the total extracted beam current, I_B.

The thruster efficiency, as predicted by the simulator, is presented in the usual form in Fig. 3. A comparison with the experimental data taken at $V_P = 28$, 20, and 15 V, for a range of I_D, indicates an overall accuracy in either η_m or eV/ion of better than 5%. In view of the fact that these errors also include setting-up inaccuracies, the good agreement with measured thruster data gives confidence in the concept and design of the simulator, and in the experimental procedure used to obtain basic design information.

References

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