論 文 の 内 容 の 要 旨

論文題目　Numerical Modeling of Combustion Instability in Hybrid Rocket Motors
（ハイブリッドロケットモーターの燃焼不安定性の数値モデリング）

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Hybrid rocket propulsion is hailed as one of the candidates for the next generation chemical propulsion system that can cater to the increasing necessity for reliable, regular, safe and cost-effective access to space. However, one of the long-chronicled problems in hybrid rockets is the presence of intrinsic low frequency combustion instability. These combustion instabilities can cause unplanned thrust fluctuations that can result in a launch failure of the rocket. Before this problem can be eliminated, it needs to be studied carefully with an understanding of the underlying physical processes that result in the unstable behavior of the motor. Existing models to study this phenomenon are restricted in their capabilities to only prediction of linear characteristics such as frequency of oscillations. They cannot predict the non-linear effects such as the limit cycle amplitude which are seen in all experimental results. They also cannot predict if or not whether a motor would be susceptible to instability. Therefore, the aim of this thesis is to model this phenomenon using a numerical model. The numerical model is designed not only to study this phenomenon of combustion instability, but also to be able to be used by a potential hybrid rocket motor designer to design engines that are not susceptible to this phenomenon.

In this thesis, it is shown the steady state heat-feedback from the flame to the burning fuel surface can be modelled as a function of the boundary layer

properties by using the Reynold's analogy. A power law function form for the determination of ratio of skin coefficient frictions with and without blowing is assumed during this derivation. A novel method to model the unsteady heat-feedback from flame is proposed by the consideration of finite time delay for the wall heat flux to adapt to changes to the regression rate through the blowing effect. This delay is called the boundary layer delay and is a function of the boundary layer properties such as boundary layer thickness and the turbulent diffusion speed.

Using an analogous analytical modelling, it has been shown that the presence of such a delayed feedback can result in an unstable system due to the occurrence of negative damping. It has also been shown that depending on the magnitude of this boundary layer delay, which is the finite delay experienced by the convective heat flux to the changes in the mass flux and the regression rate in the boundary layer, different non-linear behavior can be extracted. An attempt is also made in this regard to model the oscillatory regression rate equation in hybrids and the limitations of such an approach have been elucidated.

The computational model that has been developed for the simulation of the transient internal ballistics in the rocket motor consists of the following four sub models: 1) a quasi-one-dimensional gas dynamics model using Euler equations for flowfield simulation, 2) an instantaneous chemical model using CEA, 3) an analytical heat-feedback model for transfer of heat from the flame to the burning solid fuel surface, 4) a one-dimensional thermal conduction model inside the solid fuel. All these sub-models have been individually constructed, verified and coupled together. The numerical model has been validated against experimental data for the prediction of steady state regression rates.

In the unsteady time-dependent simulation, it is seen that without the consideration of the delayed heat-feedback, the motor is always stable even upon external pulsing. However, upon the consideration of the proposed unsteady heat-feedback, at first an oscillating periodic increase in the regression rate and chamber pressure is observed, which then proceeds into a non-linear limit cycle. A positive DC shift in the chamber pressure is also observed. It is seen that all the natural modes of the system are excited. The FFT of the pressure oscillations show that frequencies of different natural modes (including the intrinsic hybrid oscillation mode) predicted by the model are found to be in good agreement with theoretical prediction. The frequencies of the regression rate oscillations also show the same peaks as that of the pressure oscillations showing that there is a coupling between the acoustics and the unsteady burning in the combustion chamber of the motor.

Parametric analyses have been carried out by varying the boundary layer delay values. It is seen that both the RMS amplitude and the magnitude of the DC shift of the limit cycle region asymptotically increases with increasing boundary layer delay in a logarithmic fashion. However, there exists a minimum delay value for the system below which, the system is always stable. This observation is important because it suggests that any mechanism that can alter the boundary layer delay values can alter the intrinsic stability characteristics of the system. As a natural corollary, it is seen that with increasing port diameter, the unsteady characteristics increases, which in turn may be attributed to the average boundary layer delay increase.

The limitation of using a power law functional form for the ratio of skin coefficient frictions in the derivation of the unsteady convective heat flux is explained using a sensitivity analysis. As an improvement, an analytical model utilizing a logarithmic functional form is adopted in the derivation of the unsteady heat-feedback from the flame.

Using this model, experimental comparisons for the prediction of limit cycle pressure amplitude were performed against two sets of experimental data. It is seen that the numerical results match well with the experiments.

The novelty of this numerical modelling approach is that by using the proposed unsteady convective heat flux, the normal unsteady characteristics of the combustion as seen in experiments such as limit cycle amplitudes can be obtained. These limit cycles are present even in the case of a stable motor due to it being a result of intrinsic hybrid rocket feature, however only by the treatment of the proposed unsteady heat-feedback, we can simulate these characteristics. Additionally, upon using this modelling methodology, the details about all the natural modes of the system can be extracted without the necessity of any external forcing. Therefore, the numerical model serves as a powerful tool to model and study the unsteady combustion in hybrid rocket motors. Within its limitations of Q1D flow field, the model additionally serves as an excellent engineering tool for a motor designer to parametrically study the effect of different motor configurations on the motor stability characteristics.