Development of The Thrust Stand of High-Power Electric Propulsion Using a Tuning Fork Electronic Balance

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Abstract

This study is carried out for the purpose of development of the thrust stand to do 0 displacement measurement using an electronic balance in thrust measurement of large-power electric propulsion. Propulsion device used the Kyushu University of Hall thruster. Then, the performance of the thrust stand was acquired.

Keyword : Electric propulsion, Hall thrusters, Thrust stand

Nomenclature

T', T''	:	*tension*
M	:	*weight*
m	:	*calibration weight*
g	:	*acceleration of gravity*
N'	:	*normal force before actuation*
N''	:	*normal force after actuation*
L	:	*wire length from the pulley*
ΔL	:	*amount subduction of dish*
F	:	*force*
ρ	:	*linear expansion coefficient*
l	:	*arm length*
δ	:	*displacement*
θ	:	*displacement angle*
A	:	*cross-sectional area*
E	:	*elastic modulus*

Subscripts

1	:	*before actuation*
2	:	*after actuation*
3	:	*after calibration*
4	:	*wire for calibration*
m	:	*weight for calibration*
S	:	*thruster*
A	:	*arm*
t	:	*thrust*
h	:	*horizontal direction*
p	:	*pivot*

1. Introduction

1. 1 Background

A high specific thrust as a feature of the electric propulsion rocket engines, it has been applied to long-term missions required for deep space. Large transport missions between track the results of these practical application as the destination of future additional electric propulsion has been studied. In order to achieve the mission as orbital transfer techniques, it is necessary to develop a 5-50kW class large power electric propulsion. Electric propulsion is very low percentage of thrust against its own weight. Therefore, it is very difficult to develop a thrust measuring device of electric propulsion compared to thrust measurement of chemical propulsion unit with high accuracy. Thruster stand have different types were developed, one for measuring the thrust from the pendulum displacement is the mainstream. Since measuring the pendulum displacement, there is a drawback that becomes to include errors due to the interference of the piping and wiring of the thruster. Also, errors due to thermal drift become a problem. The thrust stand to be developed this time, it is considered a thrust measurement using the electronic balance capable zero displacement measurement to solve the above problems.

1. 2 Purpose of research

This study is based on a research plan of JSPEC, development of electric propulsion of 50kW class as a full success, has become the development of thrust measurement device using the electric propulsion of 5kW class as minimum success. In this study, we aimed to develop a thrust stand with new measurement principle corresponding to a power level at the minimum success. Then, to correspond to the power level of full success. The target performance as a thrust stand aims to 1% error.

2. Thurst stand design

2. 1 Summary

Thrust stand to be developed in this research is advanced than research plan JSPEC. Thruster uses a 5kW class of Hall thrusters have been developed by Kyushu University. Test environment to use the sub A tank of endurance test chamber of

Institute of Space and Astronautical Science. A sub-tank is the length of 0.6m, diameter 0.8m. As a proposal for a new measurement principle for application in high-power, 1) 0 displacement measurement order to disable the interference of the piping and wiring, 2) measures against influence of heat from the thruster, 3) I want to consider the simplified using an electronic balance. At present, it was designed with those incorporating 1) and 3). It will consider after checking the impact is actually carried out the measurement with respect to 2).

2. 2 Thrust measurement principle

Summary of the thrust measurement principle will be described more after activation and prior to actuation. Figure 1 shows the state before actuation.

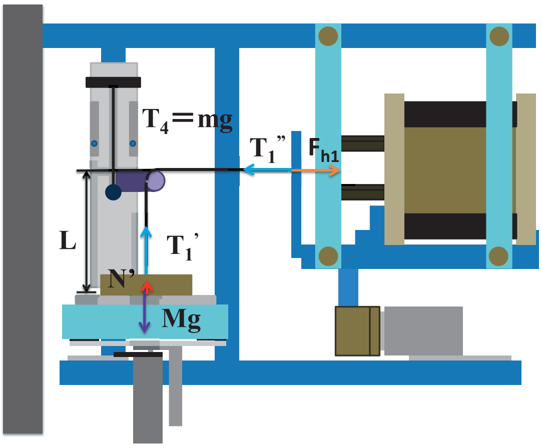

Figure 1 State before actuation

Before actuation

I think vertical direction of the balance equation of the weight, the horizontal direction of the balance equation applied to the pendulum, the balance equation applied to the wire, Respectively. Each it shows below.
Vertical direction of the balance equation of the weight

$$Mg = T'_1 + N' \tag{1}$$

Horizontal direction of the balance equation applied to the pendulum

$$T''_1 = F_{h1} \tag{2}$$

According to wire the balance equation

$$T''_1 + \rho L g = T'_1 \tag{3}$$

The T'_1 given in lowering the position of the electronic balance. Thruster mounted pendulum in this case tilts slightly. This position is the initial position. Equation (1) is deformed for the N ". Then, when substituting equation (3)

$$N' = Mg - (T''_1 + \rho L g) \tag{4}$$

Substituting equation (2) into equation (4)

$$N' = Mg - (F_{h1} + \rho L g) \tag{5}$$

N 'is the display value of the electronic balance before actuation.
Figure 2 shows the state after actuation.

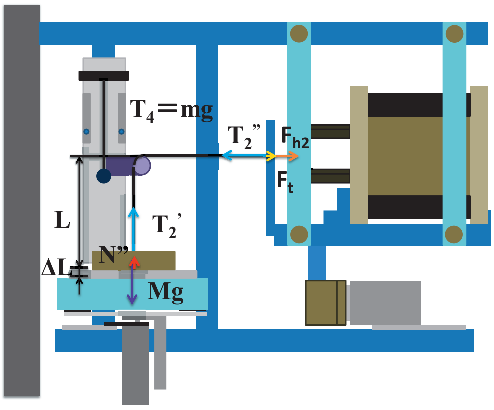

Figure 2 State after actuation

After actuation

I think vertical direction of the balance equation of the weight, the horizontal direction of the balance equation applied to the pendulum, the balance equation applied to the wire, Respectively. Each it shows below.

Vertical direction of the balance equation of the weight

$$Mg = T'_2 + N'' \tag{6}$$

According to wire the balance equation

$$T''_2 + \rho(L+\Delta L)g = T'_2 \tag{7}$$

Horizontal direction of the balance equation applied to the pendulum

$$T''_2 + F_t = F_{h2} \tag{8}$$

Equation (6) is deformed for the N ". Then, when substituting equation (9)

$$N'' = Mg - \{T''_2 + \rho(L+\Delta L)g\} \tag{9}$$

Substituting equation (8) into equation (9)

$$N'' = Mg - \{F_{h2} - F_t + \rho(L+\Delta L)g\} \tag{10}$$

N” is the display value of the electronic balance after actuation.

Difference of equation (10) and equation (5) is thrust.

$$N'' - N' = F_t - (F_{h2} - F_{h1}) - \rho\Delta Lg \tag{11}$$

The thrust is the right-hand side first term of equation (11). After second term becomes error.

The conditions order to achieve zero displacement measurement (no displacement from the initial position)

$$T''_2 \geq 0 \tag{12}$$

$$T''_2 = F_{h2} - F_t \geq 0 \tag{13}$$

$$T''_2 = F_{h2} \geq F_t \tag{14}$$

Therefore, it is possible to measure the thrust only changes in tension without displaced if giving the tension of more thrust.

2. 3 Thrust calibration

2. 3. 1 Calibration principle

During thrust measurement, the pendulum of position changes by expansion and contraction of the wire. In addition, also vary with subduction of electronic balance of dishes. And, also generates external force by pivot. These errors are displayed on the electronic balance. Therefore it is necessary to calibrate. Calibration gets from the relationship of a known load and display value of electronic balance. Figure 3 shows a summary of the thrust calibration principle. Calibration principles also described using an expression.

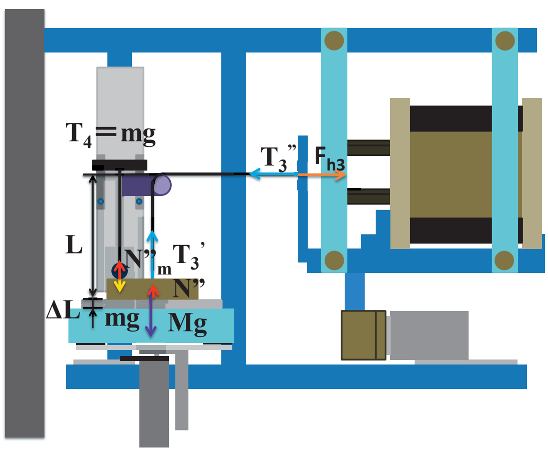

Figure 3 a summary of the thrust calibration principle

The balance on the measurement for weight of vertical direction

$$N''_m = mg \tag{15}$$

The balance of the vertical direction in the electronic balance of dishes

$$Mg + N''_m = T'_3 + N'' \tag{16}$$

According to wire the balance equation

$$T''_3 + \rho(L+\Delta L)g = T' \tag{17}$$

Horizontal direction of the balance equation applied to the pendulum

$$T''_3 = F_{h3} \tag{18}$$

Substituting equation (15) into equation (16). And I deform for N ". Substituting equation (17) becomes equation (19).

$$N'' = Mg + mg - \{T''_3 + \rho(L+\Delta L)g\} \tag{19}$$

Substituting equation (18) into equation (19)

$$N'' = Mg + mg - \{f' + \rho(L+\Delta L)g\} \tag{20}$$

It is the value of the electronic balance to be displayed at the time of calibration.
Load applied the calibration weight is the difference equation (20) and Equation (5).

$$N'' - N' = mg - (F_{h3} - F_{h1} - \rho\Delta Lg) \tag{21}$$

Equation (21) even after the second term on the right is displayed as an error. However, it is possible to measure only the F_t in equation (11) is to obtain the relationship between the known load and display value of the electronic balance.

2. 3. 2 Calibration method

Shown in Figure 3, use the actuator to change the height of the wire with a weight. And, I will add a load to the measurement for weight on the electronic balance dish. Weight that applies a load is one per 2.5g. Because assumed thrust is 100mN, I use five of the weight. As described above, I record the display value of the electronic balance when changing the height of the wire attached to weights (varying load). And, I get the relationship between the display value of electronic balance and the known load.

3. Approximation for 0 displacement measurement

Error had appeared as a term about measurement principle and calibration principle in Section 2. However, I thought the error is related to hysteresis. This chapter examines the amount of displacement to the study, it was estimated error.
Error factors that are considered in the measurement principle of the thrust stand is developed in this study is as follows.

1) Displacement of expansion and contraction of the wire
2) The amount subduction of electronic balance dish
3) External force by a pivot

I was examined, respectively.

3. 1 Displacement of expansion and contraction of the wire

Table 1 shows the physical properties of the wire used.

Table 1 Physical properties of the wire to be used

		Zylon HM
Diameter	[mm]	0.48
Density	[g/cm³]	1.57
Elastic modulus	[GPa]	270
Linear expansion coefficient	[ppm/℃]	-6
Specific heat	[J/ kgK]	700
Melting point	[℃]	650

The material of the wire is a fishing line of Zylon HM.
Wire contracts when the thrust is worked wire. In addition, the wire is contracted by the heat from the thruster. The displacement is considered to work in the horizontal direction component of the gravity applied to the pendulum. A summary

is shown in Figure 4.

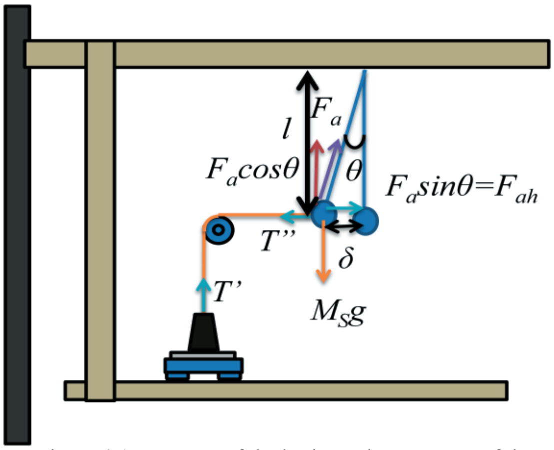

Figure 4 A summary of the horizontal component of the

Gravitational force applied to the pendulum.

The balance of the vertical direction in the mass point of the center of gravity

$$F_a \cos\theta = M_S g \tag{22}$$

The balance of horizontal direction in mass point of the center of gravity

$$T'' = F_{ah} = F_a \sin\theta \tag{23}$$

$$F_{ah} = M_S g \tan\theta = M_S g \frac{\delta}{l} \tag{24}$$

Therefore, I can be seen that the pendulum of displacement is affected as an error.

To estimate use the values in Table 1. I estimate in the case of expansion and contraction due to thrust and in the case of heat due to shrinkage.

3. 1. 1 In the case by the expansion and contraction of the thrust

M_S=23kg, L=400mm, F_t=0.1N, A,E demand from Table 1

$$\delta = \frac{F_t L}{AE}$$

$$\delta = 0.819[\mu m]$$

In terms of this displacement in error by the equation (24)

$$F_{ah} = 0.461[mN]$$

This error is not a problem because perform calibration. However, this amount of displacement might relate to hysteresis at the time of calibration. Therefore, it is necessary to be observed by performing experiments.

3. 1. 2 In the case of heat due to shrinkage

It is necessary to consider the influence of heat.

However, since heat is radiant heat by plume of thrusters, might not be a problem because it attaching the wires to the back of the thruster. I don't know the actual temperature is because it does not measure the temperature. But temperature in the vicinity of the wire for the same power scale of thruster of the laboratory did not change 1 ℃. Therefore, I thought that there is no problem if the heat shield.

3. 2 Amount subduction of electronic balance dish

Amount subduction of electronic balance of the dish as a zero displacement measurement is also a problem. Electronic balance is three. It is an electromagnetic type and load cell type and the tuning fork type. Electromagnetic can't measure the magnetic circuit is formed from the external magnetic field of the Hall thruster. Since it can't be used, I examined the amount of subducted by the load each load cell type and the tuning fork type.

Figure 5 shows the results.

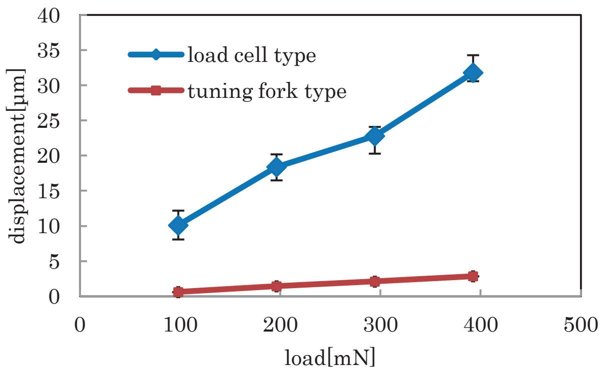

Figure 5 The relationship between the load and displacement

As a result from the load cell type has a larger amount of displacement and the variation compared to the tuning fork type. Therefore, I was adopted tuning fork type. The tuning fork type of displacement I was converted to the error of thrust. In the case of thrust is assumed F_t = 100 [mN] displacement is δ = 0.607 [μm].Thus, from the equation (24)

$$F_{ah} = 0.342[\mathrm{mN}]$$

This error is not a problem because perform calibration. However, this amount of displacement might relate to hysteresis at the time of calibration. Therefore, it is necessary to be observed by performing experiments.

3. 3 External force by pivot

Figure 6 shows a summary of the external force by a pivot.

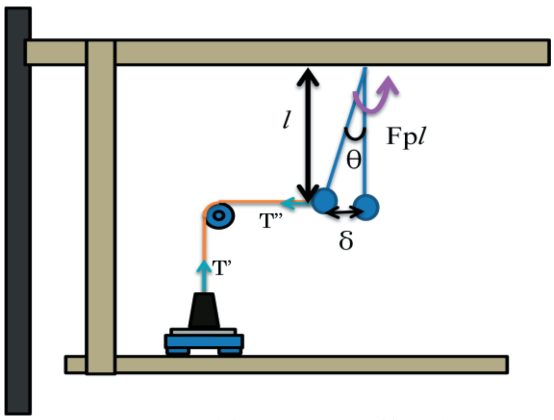

Figure 6 External force summary of by a pivot.

Table 2 shows the summary of pivot.

Table 2 A summary of pivot

Type number		5160-600
Diameter[mm]		12.7
Torsional Spring Rate	a [mm・kg/deg]	1.30
Radial Load Capacity	Vc [kg]	63.8
	Vt [kg]	91.5
Axial Load Capacity	Pc [kg]	88.8
Length	L [mm]	20.32
Fixed end length	A[mm]	9.652

External force of approximation by pivot can be determined by the following equation.

$$\theta[°] = sin^{-1}\frac{\delta}{l} \times \frac{180}{\pi} \tag{25}$$

External force by eight pivots

$$F_P l = 8 \times a \times g \times \theta \tag{26}$$

By using the values in Table 2,and the displacement is δ = 0.607 [μm] (amount subduction of electronic balance)

$$\theta = \sin^{-1}\frac{0.000607}{400} \times \frac{180}{\pi} = 0.0000869[^\circ\ ]$$

Therefore,

$$F_p = \frac{1.30 \times 9.81}{400} \times 8 \times 0.0000869 = 0.0222[mN]$$

This external force is dependent on the pendulum of the amount of displacement. Therefore, it is also related to hysteresis during calibration. However, it can be said that it is negligible levels from the above calculation results.

3. 4 Conclusion

Error is no problem to perform the calibration. But, it is better not subduction of electronic balance and the expansion and contraction of the wire because Given the hysteresis at the time of calibration, Thrust error also subsided in the goal error. Therefore, it would be able to be used. However, it is necessary to consider an experiment the effect of the hysteresis.

4. Thrust stand structure

Photo of the fabricated thrust stand is shown in Figure 7.

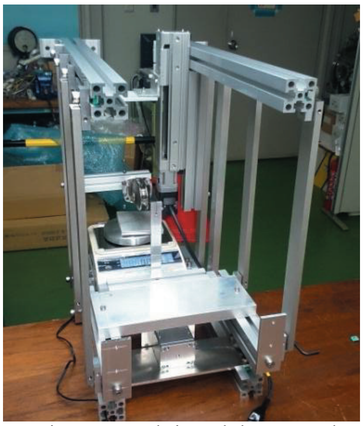

Figure 7 Fabricated thrust stand

Figure 8 pivot

Thrust stand to be developed in this study will be use eight pivots. Figure 8 shows a pivot.
Four arms used in this pendulum was adopted SUS304 because it is excellent in that the heat resistance and it is not magnetized. Other frame used a basic frame of aluminum. In addition, nuts and bolts used SUS.
Figure 9 shows the actuator for the raising and lowering of the electronic balance.
Figure 10 shows the actuator used in the calibration.

Figure 9 Measurement for actuator

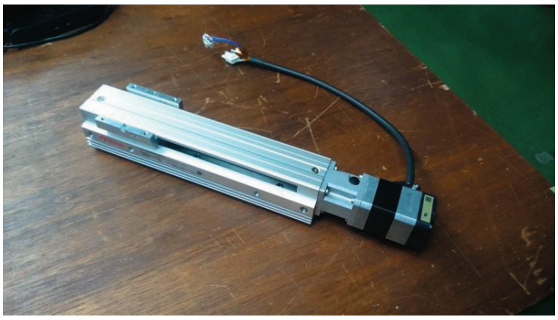

Figure 10 Calibration for actuator

There is a possibility that the pivot of damage when accommodating the thrust stand in sub A tank. Therefore, I was using an electric gripper. Figure 11 shows the electric gripper. Figure 12 shows bearing pulley. This material is SUS

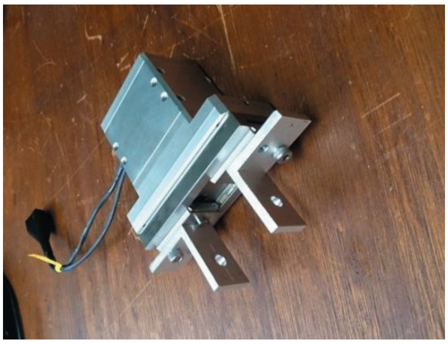

Figure 11 Electric gripper

Figure 12 Bearing pulley

Figure 13 shows a Zylon. It characteristic is strong expansion and contraction.
Electronic balance as the core as measure mechanism is shown in Figure 14.

Figure 13　Zylon

Figure 14 Electronic balance

5.　Thrust calibration experiment

5. 1　Calibration result

In this chapter, I describe the calibration result.

Experiment used a dummy weight. Dummy weight of the mass is the same as the Hall thruster. Figure 15 shows the calibration results.

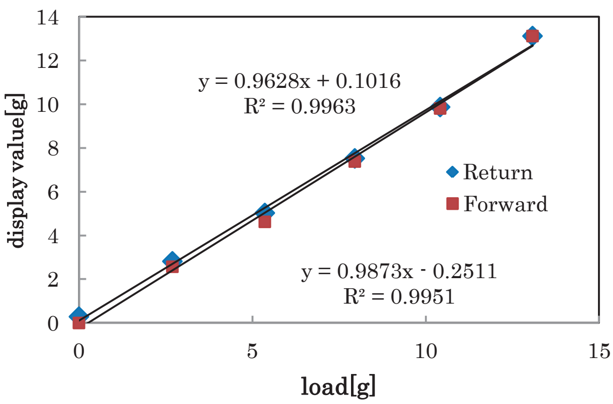

Figure 15 Calibration result

From calibration result, hysteresis appeared in the forward and return. In addition, the variation is not large. But, calibration results I will be thrust results. Therefore, errors due to this variation has to be within 1%. However, the error of the calibration curve at a point is appeared at 8.25% maximum.

5. 2 Consideration

This chapter describes the discussion of calibration result. For first hysteresis when it is added to the same load in the forward and return, it can be seen that the display value of the electronic balance indicates a large value during the return. Figure 15 consider the above. Figure 16 shows the drift of the display value in the time history of the electronic balance.

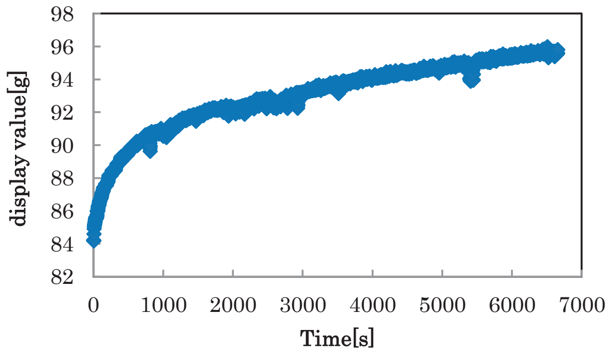

Figure 16 Drift of display value in the time history

Drift of display value of electronic balance has continued to appear even beyond the 6000s. Drift is appeared linearity from 1000s, I considered to appear the same change in the future. I think that is due to be wire is stranded wire. Because stranded wire have the property of stretching. It is necessary to consider using a displacement sensor for Elongation of the wire. Calibration result in Figure 14 is a result of the forward and return continuously. Therefore, the results may have been affected drift in time history. This drift is a serious cause of the hysteresis. Figure 17 is an enlarged view of Figure 16. Figure 17 can be seen that the noise is appeared.

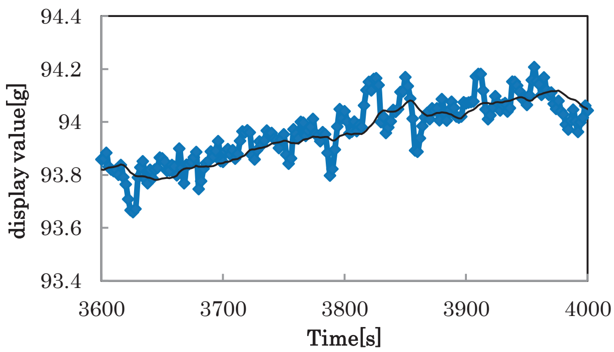

Figure 17 Consideration of noise

The cause of this noise is the impact of the thrust stand of the pendulum to vibration and wind. This noise is the cause of the variation. Therefore, this thrust stand is necessary mechanism to suppress the noise.

6. Conclusion

It was possible to manufacture the thrust stand. However, the thrust measurements are not performed. Therefore, I do not know whether it is possible to thrust measurement of 5kW class. However, the measurement principle is no problem because it is performed calibration is the same principle. It was possible to obtain a problem with the calibration to be directly related to the thrust measurement. From this knowledge, we want to continue to promote the development of the thrust stand in consideration of the re-examination of the wire and vibration measures.

7. Future plans

I want to do a performance acquisition of the thrust stand using the Kyushu University of Hall thruster in April. In addition, it is going to do the temperature measurement of the observation and the thrust stand of the thermal drift. I want to consider the thermal management from the results obtained in this test.

Acknowledgments

I want to tell thanks to all of the people who were involved in this study.

References

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