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Drag-free Satellite Simulator

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Summary: We have been investigating a possibility of launching a satellite in a planetary orbit to test the general theory of relativity. As a first step of it, we have fabricated a drag-free system model for a laboratory simulation in order to acquire the fundamental technique and find unexpected problems. It has been demonstrated that a two-dimensional drag-free simulator functioned successfully. It could continue operating faultlessly until the gas reservoir expired (4 hours), which is an important start for the realization of a drag-free satellite in future.

CONTENTS

1. INTRODUCTION

In the experiment of testing the general theory of relativity by using an artificial planet (artificial spacecraft in an interplanetary orbit) the most serious problem is the presence of various nongravitational surface-forces, for example, solar radiation pressure, solar wind and meteorite impact, namely what is called "drag". The largest one among these drags is the solar radiation pressure. It is about 1 mgw on an artificial planet in an earth orbit with its mass of 100 kg, its surface area of 1 m^2. The force of 1 mgw on it causes the acceleration of 10^{-8}g, where g is the acceleration of gravity on the earth's surface. This value imposes a severe load for testing general relativity.

In order to avoid this difficulty the use of "drag-free satellite" which has the system of cancelling these drags has been proposed [1] [2]. The concept of this satellite is shown in Fig. 1. A tiny spherical ball "proof mass" is completely enclosed and floated in a cavity of an outer satellite, so the proof mass is shielded from any drag. The outer

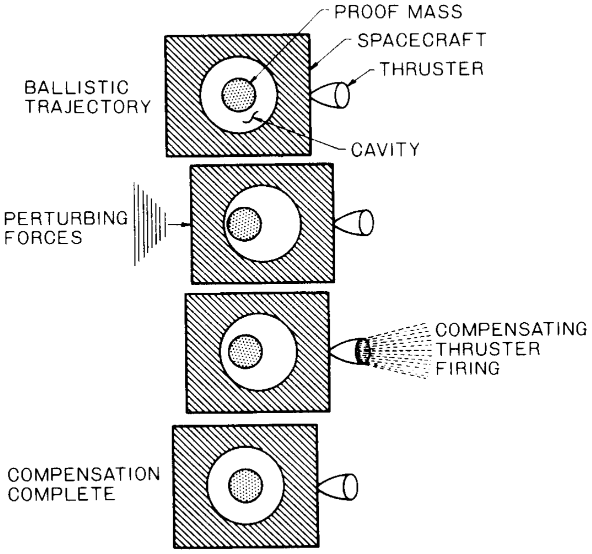


Fig. 1. Concept of drag-free satellite [3].

satellite which has the system of sensing the relative position of itself with respect to the proof mass is controlled by using small thrusters so that the proof mass should always be kept nearly at the center of the cavity. In the ideal case when other disturbing forces don't exist the orbit of the proof mass, hence, that of the satellite will be determined only by gravitational forces.

In reality, however, new disturbing forces instead of canceled drag arise on the proof mass. Among these new disturbances, mass-attraction from a non-uniform mass distribution of the outer satellite itself is the most difficult to eliminate. In order to reduce this force we have to make two efforts. One is to fabricate the outer satellite as spherically symmetrical as possible. The other is to reduce the relative fluctuation of the proof mass around $g_s=0$ point, where g_s is acceleration of gravity due to the outer satellite.

The first drag-free satellite ever flown is "TRIAD 1" [4] [5] and it was launched into the orbit around the earth by U.S. in 1972. In the gravity gradient around the $g_s=0$ of 10^{-11}g/mm and permitting the proof mass to move only ±0.9 mm from the $g_s=0$ point, the acceleration of the proof mass less than 10^{-11}g was accomplished.

We have been investigating a possibility of launching a satellite to test general relativity. As a first step of it, we fabricated the drag-free system model for the laboratory simulation in order to acquire the fundamental technique and find unexpected problems.

Among the foregoing conditions for reducing the mass-attraction force only the one condition of confining the proof mass relatively in a small region was taken into consideration in this simulator.

The detailed description and the operation of this simulator will be reported in detail below.

2. Detailed Description of Drag-Free Simulator

A whole view and its system configuration of the drag-free system model fabricated

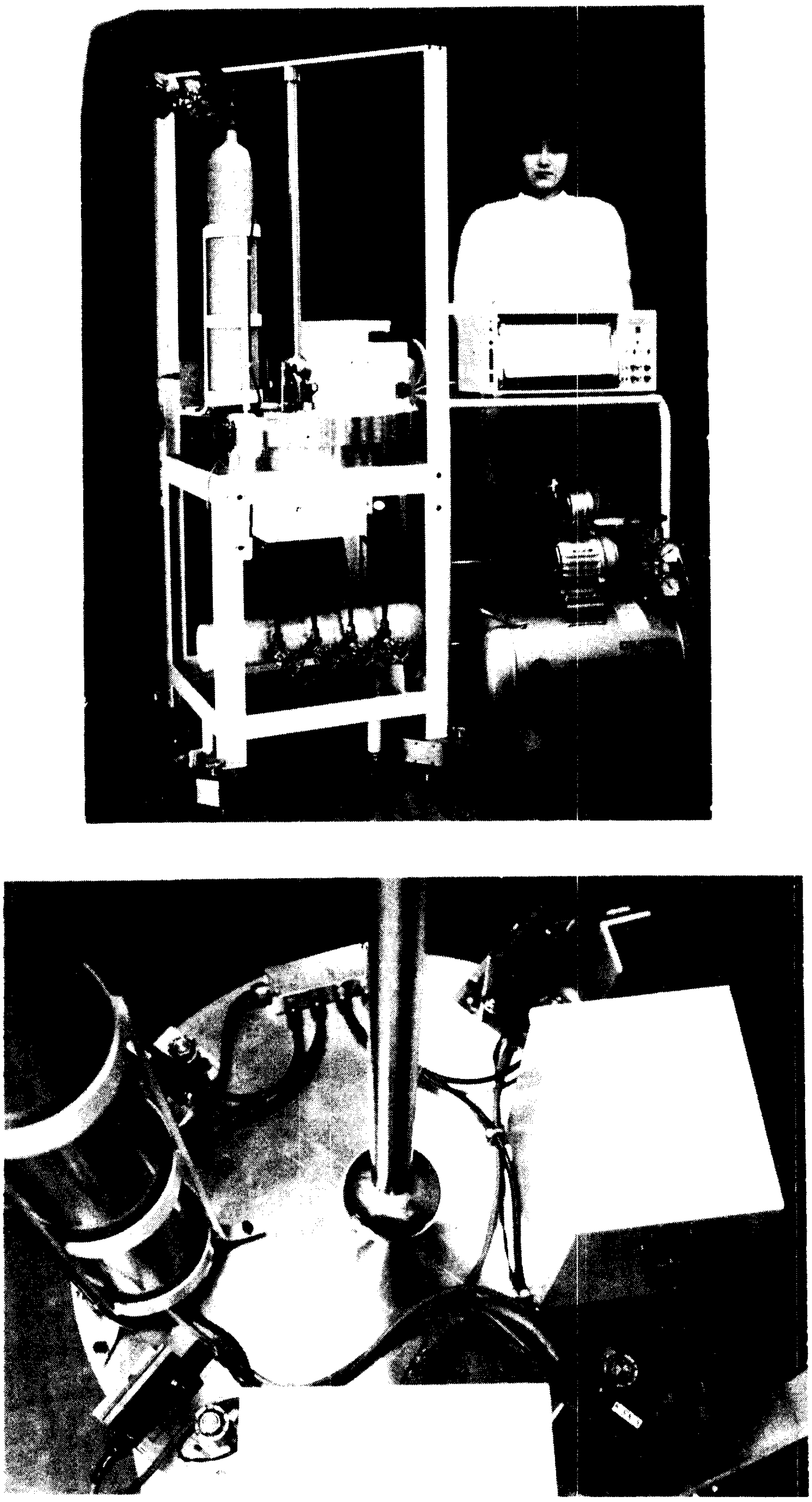


Fig. 2. Whole view of drag-free simulator.

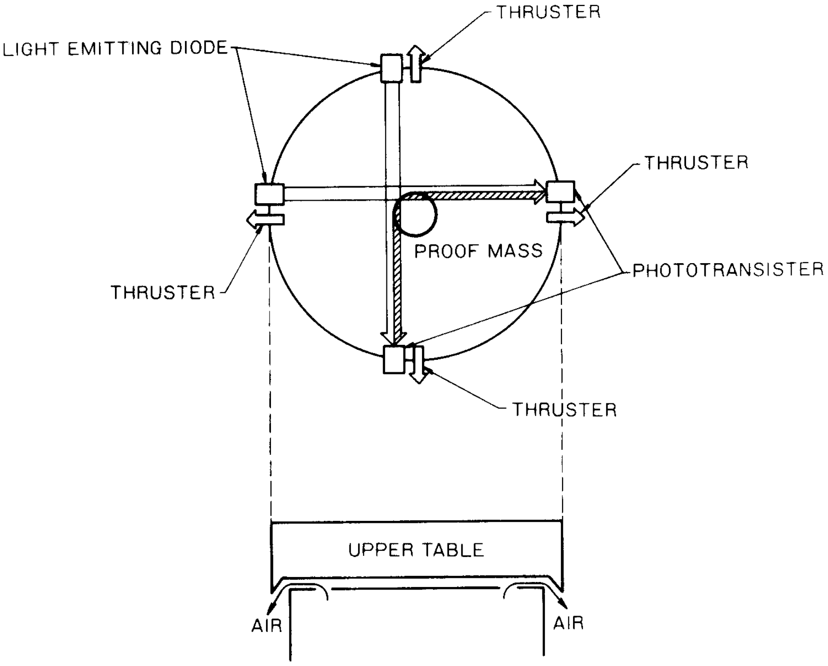


Fig. 3. System configuration of drag-free simulator.

this time is shown in Figs. 2 and 3, respectively. Though this model has only two-dimensional system, it is sufficient to simulate the drag-free satellite system.

The relative position of the upper table to the proof mass is sensed by two pairs of analog beam sensors which are orthogonal to each other on the upper table. These two independent singnals are used to turn on and off two corresponding pairs of solenoid valves of thrusters through a control circuit. The control circuit has a deadband in phase space within which all valves are closed. Roughly speaking if the table moves outside the deadband the corresponding valve is opened so that the table should return within the deadband again. Gas for the thrusters is supplied from a small bomb of N_2 through an ordinary two-stage regulator. As a power supply, a lead battery cell package (±24 V) are used. All devices described above are mounted on the upper table isolated both mechanically and electrically so that the upper table is suspended by air from the ground.

The relative position of the upper table with respect to the lower table is sensed by the other analog beam sensors, too. These sensors are fixed to the lower table stand so that their beams may graze the edge of the upper table. These signals are recorded on a strip chart recorder to monitor the relative position of the upper table with respect to the lower table.

i) Air Table

The mass of the upper table and all devices on it is altogether about 80 kg, which is expected to be of the same order of magnitude of the actual drag-free satellite weight. The lateral component of the gravity which corresponds to drag in space can be reduced to about 100 mgw by adjusting the length of four legs of the lower table stand deliberately. This value strongly depends on how solid the floor is. In our case one person standing by the side of this air table causes a lateral force of 1-2 gw on the upper table because of the horizontal level change of the floor. This value is more than a thousand times as large as the actual drag of solar radiation expected in space.

ii) Position Sensing

A commercial analog beam sensor is used for sensing the relative position of the upper table to the proof mass. This beam sensor consists of a light emitter and a collector. The former has a light emitting diode inside and the light beam width is fairly large. The latter has a collecting lense of about 2 mm in diameter, which determines the effective beam diameter of less than 2 mm. This value is too small to sense in the whole range because the upper table can be moved about 2 cm in the direction of its plane. Therefore by means of inserting two convex lenses between the emitter and the collector the effective light beam diameter was set as 1 cm in diameter. The output of this beam sensor changes from 1 V to 9 V continuously according to how the beam is interrupted by the proof mass, hence according to relative position of the upper table to the proof mass.

The configuration of beam sensors and the proof mass is shown in Fig. 3. The configuration was chosen so that the light reflected by the proof mass may not travel to the other pair's collector.

In the actual drag-free satellite the power of the light must be small enough in order to avoid the light pressure effect. It should be 10^{-7} W or less.

iii) Thrusters

In general the thrust F from a thruster is expressed in the following equation:

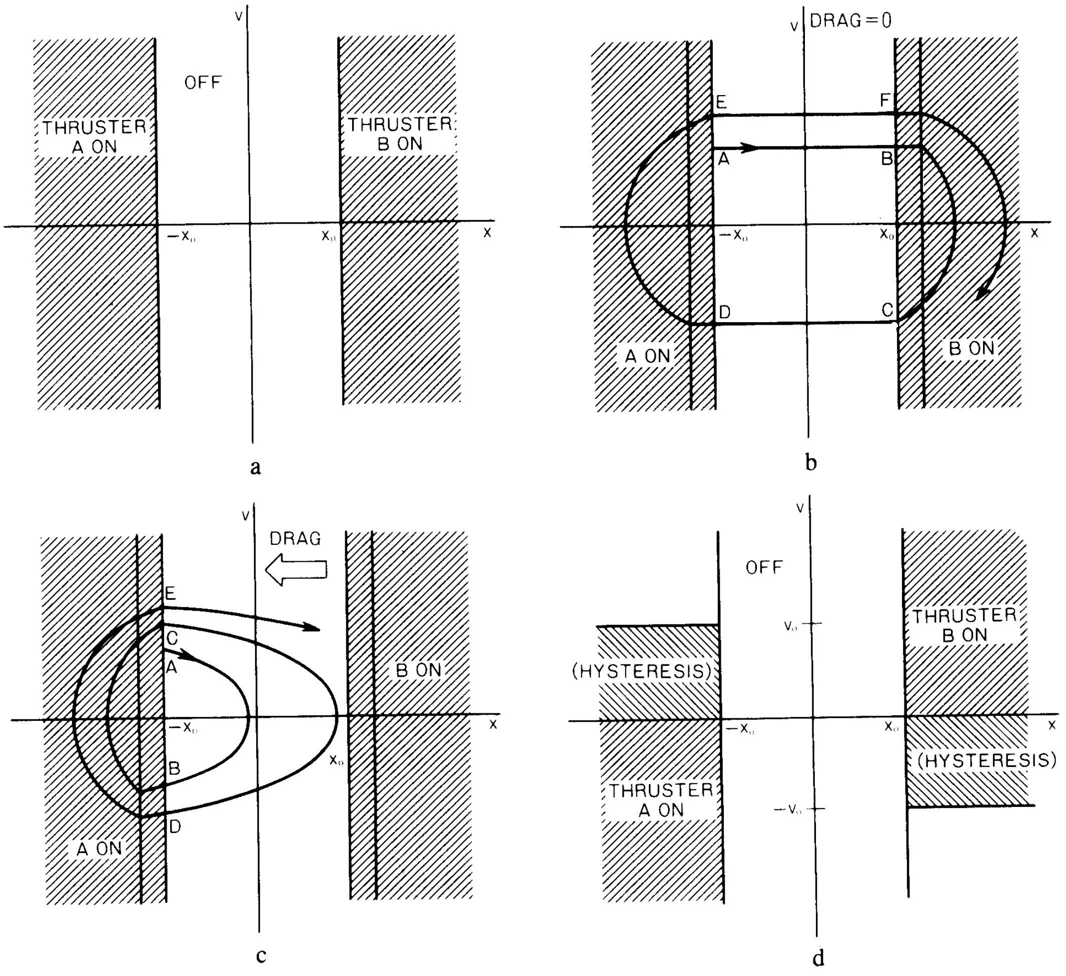
$$F=pAC_F$$

where p is the pressure of the gas reservoir, A the cross section of the nozzle throat, and C_F the thrust coefficient which changes according to the ability of the nozzle. Usually the value of C_F is 1-2. As we chose 1 mm-diameter nozzle throat and the pressure was adjusted at 2 kgw/cm^2 by the regulator, the thrust of 15-30 gw was acqired. This vaue is sufficient for the residual lateral gravitational force of 1-2 gw.

iv) Control Circuit

Let's consider a simple control circuit in one-dimension: x being the relative position of the upper table to the proof mass and v the relative velocity. First only a deadband in x is introduced. The control circuit in one dimensional phase space is shown in Fig. 4 (a). For $x>x_0$ the thruster B is on and for $x<-x_0$ the thruster A is on, where the thruster B is such that its thrust vector is in the direction of $-x$ and that of the thruster A in the direction of x. For $-x_0<x<x_0$ both of thrusters are off, so this region is called a deadband. The actual trajectory in phase space for such a control circuit is shwon in Fig. 4 (b) and (c) for drag=0 and drag$\neq$0, respectively. Due to the presence of a time lag when thruster turnes on or off and the lack of damping in space, the trajectory goes along ABCDEF . . . finally diverges in either case of drag=0 or drag$\neq$0.

In order to avoid the divergence of the trajectory, the control circuit must have some



a b

c d

restriction with respect to v in addition to the deadband in x. The control circuit used this time is shown in Fig. 4 (d). It has a restricting line with hysteresis in v other than the deadband in x. Actually the output of the analog beam sensor is used as x directly and the differentiation of it as v. For $x>x_0$ and decreasing v the thruster B is on for $v>-v_0$ and off for $v<-v_0$. For $x>x_0$ and increasing v the thruster B is on for $v>0$ and off for $v<0$. For $x<-x_0$ the thruster A is on or off in the same way. For $-x_0<x<x_0$ both of thrusters are off irrespective of v. The trajectory for this control circuit is shown in Fig. 4 (e) and (f) for drag=0 and drag$\neq$0, respectively. Due to the restricting line the trajectory doesn't diverge in spite of a time lag. It goes along ABCDEF.... In the case of drag=0 a limit cycle is GDEFG. Though in the case of drag$\neq$0 the trajectory is somewhat complicated, it becomes finally to the limit cycle of ABCDA as shown in Fig. 4 (g).

The presence of the hysteresis in the control circuit prevents the system from a chattering. Without hysteresis, that is, if the restricting line were simply $v=v_0$ for $x<-x_0$ and $v=-v_0$ for $x>x_0$, the thruster A would turn on from off and off from on repeatedly. (Fig. 4(h)). This phenomenon is called a chattering, and it is undesirable for the control system. In order to avoid it the hysteresis has been incorporated into the control circuit.

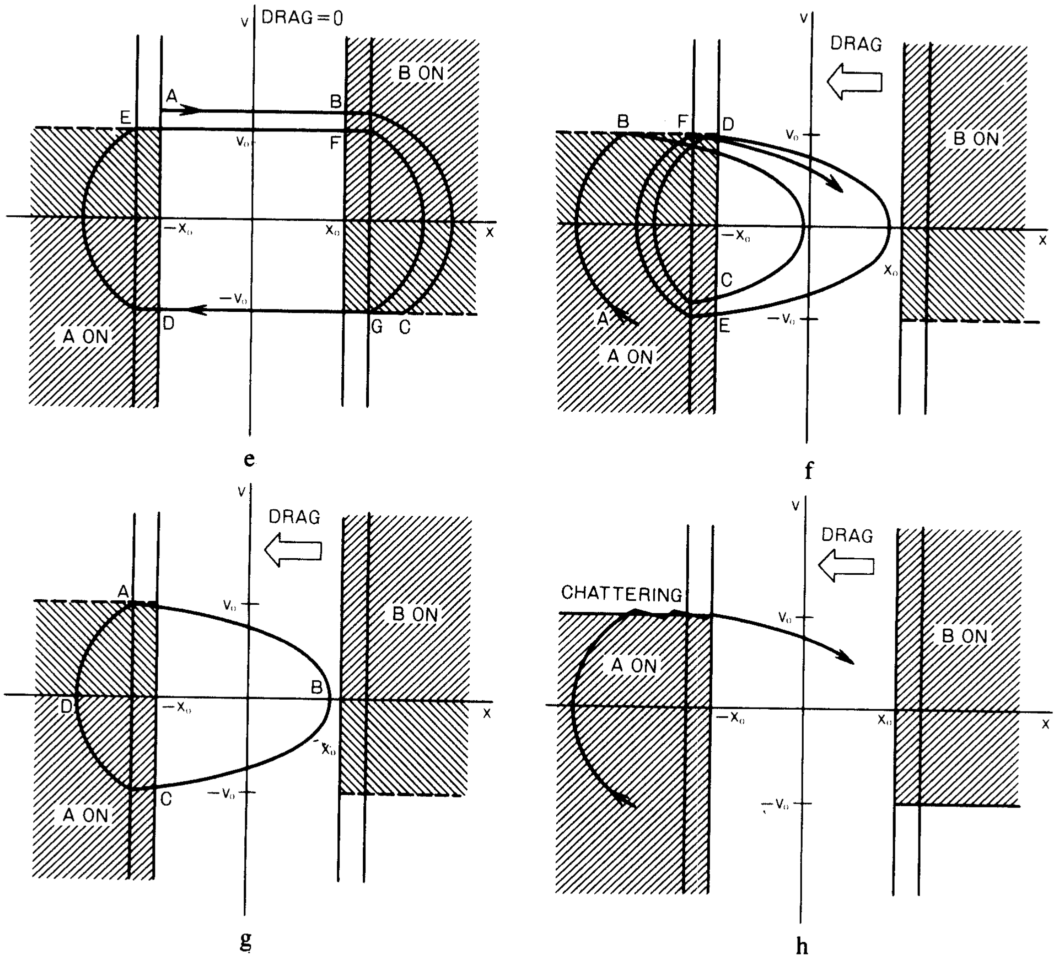


Fig. 4. Control circuit and trajectory in phase space.

3. OPERATION

The drag-free simulator with the control circuit mentioned above was operated with a deadband of 1 mm and a restricting line of 0.2 mm/s. It continued operating faultlessly for 4 hours until N_2-gas in the small bomb (0.5 m^3) was all exhausted.

The relative position against time was recorded by the sensors on the body of the table (Fig. 5(a)). It was recorded when the coordinate axis on the upper table nearly coincided to that on the lower tables so that we can regard this signal as the one used for the control circuit. We can estimate the magnitude of drag from the parabolic curve. In X-axis it is 100 mgw and in Y-axis 300 mgw.

The process of capture into the limit cycle is shown in Fig. 5(b). This large disturbing force was made by pushing the upper table. Within only a few cycles the capture was almost accomplished. This capture mechanism is necessary in the initial configuration of the drag-free system after the satellite is placed into the orbit.

4. CONCLUSION

It has been demonstrated that a two-dimensional drag-free simulator functioned

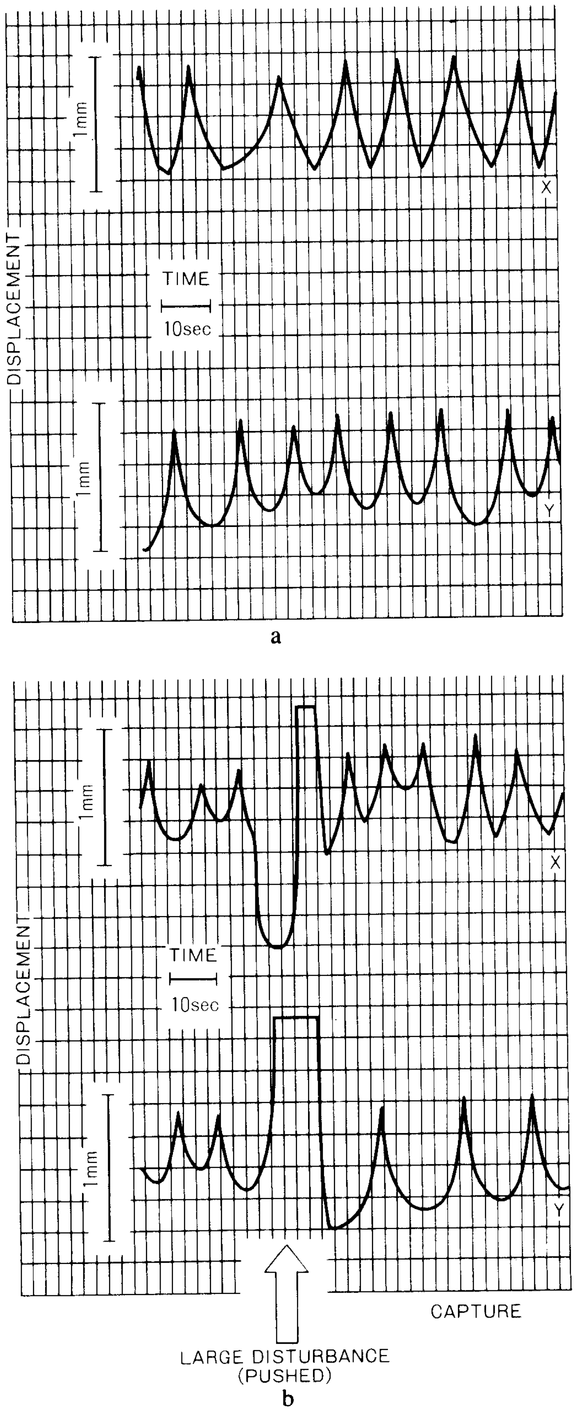


Fig. 5. Operation and capture process of drag-free simulator.

successfully. It turned out that the technique of drag-free system was rather easy. The fact that this model could continue operating faultlessly for 4 hours is the important start for the realization of the drag-free satellite in future.

The lateral force in this simulator which corresponds to drag is much larger than that expected in the actual satellite. At a first glance, it might seem that this simulator did not simulate the actual satellite correctly. From the standpoint of control, however, if the lateral force (drag) decreases, the time constant of control becomes longer and it makes the control much easier. In this sense, we have tested a more severe situation and it can be said that the success of this simulation has overcome one of difficult technical problems in the drag-free satellite system.

REFERENCES

[1] B. Lange, AIAA J. 2, 1590 (1964).
[2] 中井 豊，河島信樹，宇宙科学研究所報告 第13号 1983年
[3] R. F. C. Vessot, Center for Astrophysics Preprint series No. 1030.
[4] John Hopkins Apply Phys. Lab. & Stanford univ., J. Spacecraft 11, 637 (1974).
[5] J. C. Nicklas and H. C. Vivian, Transactions of the ASME, D 84, 54 (1962).