Flight Test Result of Kyutech Student's Experimental Rockets "Ninja-10" and "Sakura" in France

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Since 2006, small experimental rockets have been developed by students of the Kyushu Institute of Technology for an annual rocket launch campaign held in France. This paper introduces the design and flight results of two rockets. One of the rockets named Ninja-10 was developed in order to research and test point tracing while gliding using a parafoil. It reached a height of approximately 635 m, 12 s after ignition. In order to maintain the doors of the ejection system bay facing upward, the roll angle of the rocket is controlled by using ailerons. At the apogee, the door of the ejection system bay opens, and a drogue chute is ejected to deploy the parafoil. Unfortunately, although Ninja-10 had passed various qualification ground tests, it was not allowed to be launched because of strong wind conditions. The other rocket named Sakura was developed to achieve supersonic flight. Sakura's mission was accomplished successfully; the maximum Mach number the rocket achieved was 1.07. Further, Sakura was recovered safely by using a two-stage parachute system that was deployed after the rocket reached an apogee of approximately 3300 m.

Key Words: Rocket, Parafoil Recovery System, Guidance and Control, Roll Control, Supersonic Flight

1. Introduction

The CNES (Centre National D'Etudes Spatiales) and the French non-profit organization Planète Sciences have been conducting an annual experimental rocket launch campaign called "La Campagne Nationale de Lancement," since the 1960s, for amateur clubs comprising university students and young engineers [1).

The purpose of this campaign is not only to help participants realize their dream of launching a rocket but also to teach them how a project can be successfully developed. Amateur club members learn not only the technical aspects involved in launching a rocket but also team work and project management, particularly with regard to scheduling and budgeting. Such activities are important and necessary for the development.

Since 2006, a group of students from the Kyushu Institute of Technology have been participating in an annual French experimental rocket launch campaign [2-6). This paper focuses on the design, development, and test results of two rockets called Ninja-10 and Sakura developed in 2010.

Ninja-10 has two missions that include (1) controlling the roll angle of the rocket in order to maintain the doors of the ejection system bay facing upward during coasting flight and (2) point tracing while gliding using a parafoil. Sakura's mission is to cross the speed of sound and to study the transonic aerodynamic characteristics while flying from subsonic to supersonic speeds. The mission sequences of Ninja-10 and Sakura are shown in Figs. 1 and 2, respectively.

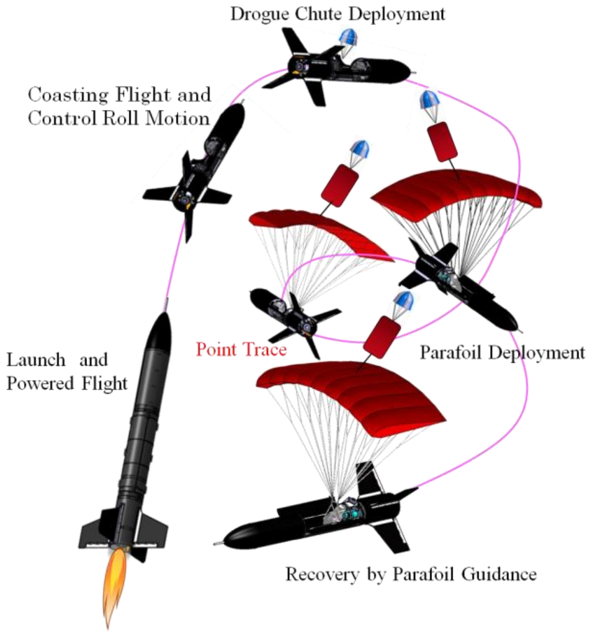

Fig. 1. Mission sequence of Ninja-10 [2).

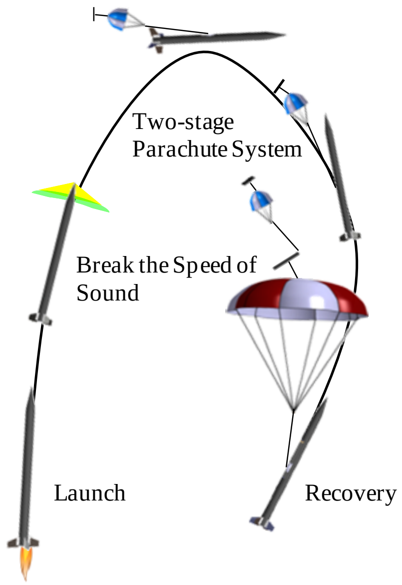

Fig. 2. Mission sequence of Sakura.

2. Rocket Profile

Schematics of the side views of Ninja-10 and Sakura are shown in the upper and lower halves of Fig. 3, respectively. Their major dimensions and aerodynamic parameters are summarized in Table 1.

The nose cone of Ninja-10 is made of GFRP (glass-fiber reinforced plastic. It has a semi-monocoque body that consists of three CFRP (carbon-fiber reinforced plastic) tubes reinforced by aluminum alloy flanges and stringers. These tubes are fastened using bolts and flanges. In order to achieve static stability, Ninja-10 has four fins, which are made from a CFRP plate. The two fins on opposite sides of the rocket have ailerons.

Sakura has a nose cone and avionics bay made from GFRP, and a recovery system bay and engine bay made from CFRP. The four fins are made of aluminum alloy to prevent fin flutter while flying at the speed of sound.

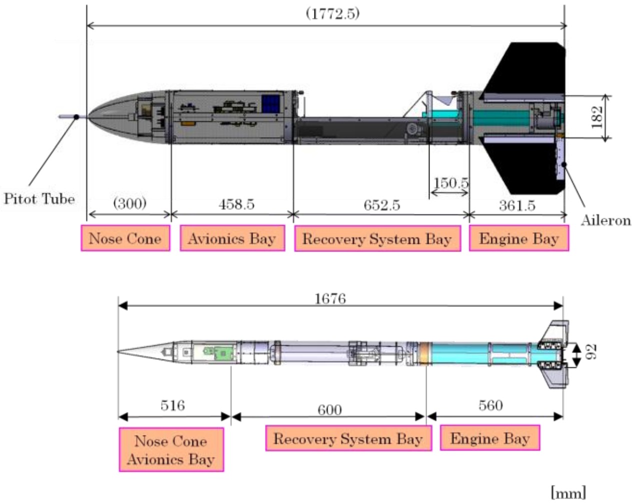

Fig. 3. KIT student's experimental rockets.

Table 1. Major dimensions and aerodynamic parameters.

Specification Issues		Ninja	Sakura	Requirement [8]
Total length L	[mm]	1772.5	1676	≤ 4000
Body diameter ϕ	[mm]	182	92	$40 \leq \phi \leq 200$
Mass M	[kg]	13.1	6.77	≤ 15
Lift derivative C_n	[-]	17.4	15.4	$15 \leq C_n \leq 40$
Moment derivative $C_m = M_S \times C_n$	[-]	40.5 44.3	48.3 66.5	$40 \leq C_m \leq 100$
Drag coefficient C_d	[-]	0.32	1.05 ~0.34	NA
Static margin M_S : in terms of body diameter	[-]	2.3 2.6	3.14 4.33	$2 \leq M_S \leq 6$
Launcher exit speed	[m/s]	21.7	35.5	≥ 20
Maximum altitude	[m]	635	3211	NA

where upper values are obtained at ignition, and lower values are obtained for the condition after combustion.

The drag coefficient of Sakura is calculated using the data of the Institute of Space and Astronautical Science (ISAS) rocket μ-5[8]. The fins attached to the body have a drag coefficient that is similar to that of the body (Fig. 4).

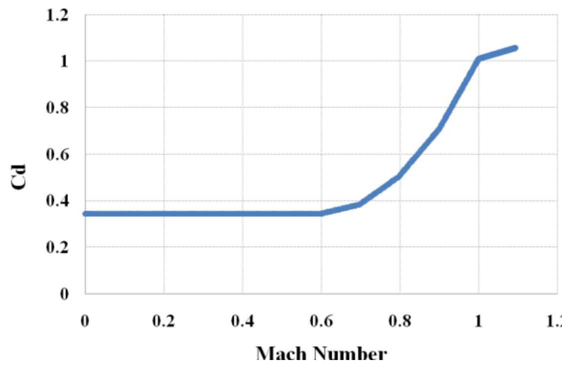

Fig. 4. Drag coefficient of Sakura.

3. Recovery System

3.1. Ninja-10's recovery system

Ninja-10 has a parafoil to guide and recover the rocket safely and four servo motors to open the ejection door and control the movement of the parafoil. The parafoil is a wing-type parachute, which is lightweight and can be compactly folded in the body bay.

In 2009, the experimental rocket Ninja-09 was launched. However, the direction of the rocket could not be controlled with a parafoil because the release of the half brake, shown in Fig. 5, failed [7]. The half brake maintains the tension of the control line until the line is fully deployed. However, it is necessary to release the half brake after the parafoil is deployed completely. On launch, it was found that the half brake failed to release because the parafoil got caught around the fin which led to the control line getting twisted.

This year, Ninja-10 has an actuator whose sole function is to release the half brake. The parafoil is packed in a fabric container, which will be pulled outside the body by the drogue chute to be stripped and deployed when the lines are under tension.

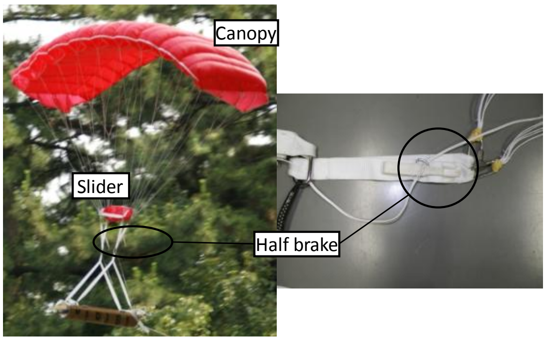

Fig. 5. Parafoil's canopy, slider, and half brake.

After the parafoil is fully deployed, Ninja-10 begins guidance and control to execute point tracing while gliding using the parafoil. The algorithm for point tracing for generating waypoints is shown in Fig. 6. The waypoints are calculated according to the position where the parafoil is ejected, the position of target point, and the gliding ratio of the parafoil. These position data are acquired by an onboard GPS (Global Positioning System). The guidance law described by Eqs. (1) and (2) is calculated using the velocity and target vectors as illustrated in Fig. 7.

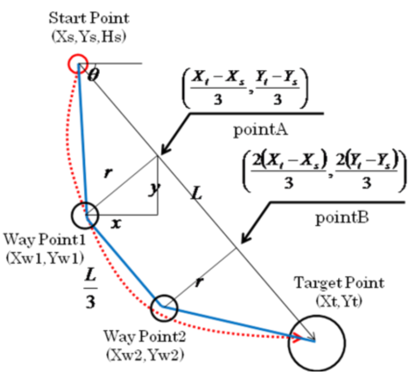

Fig. 6. Generation of waypoints.

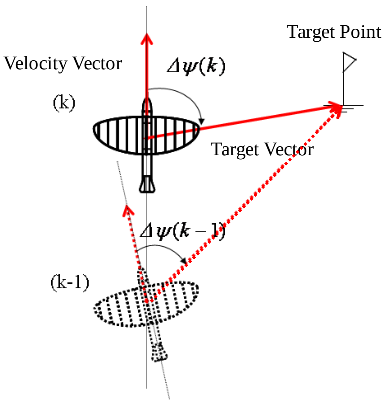

Fig. 7. Guidance law for parafoil.

$$\Delta\dot{\psi}(k)=\frac{1}{T}\{\Delta\psi(k)-\Delta\psi(k-1)\} \quad (1)$$

$$l = K_{\Delta\psi}\Delta\psi + K_{\Delta\dot{\psi}}\Delta\dot{\psi} \quad (2)$$

where $\Delta\psi$ is the directional angle, $\Delta\dot{\psi}$ is the angular velocity of the directional angle, T is the sampling period, l is the stroke of the control line, $K_{\Delta\psi}$ is the proportional feedback gain, and $K_{\Delta\dot{\psi}}$ is the rate feedback gain.

3.2. Sakura's recovery system

Sakura consists of a light body structure and a high thrust rocket engine. Hence, it can reach up to an altitude of 3000 m or higher. The main chute cannot be deployed at the apogee because the launch point is near the sea and area that is inhabited. After the deceleration chute is deployed at the apogee, the rocket descends at a speed of 40 m/s. Then, the main chute is deployed at an altitude of approximately 1000 m. Fig. 8 shows the launch point and predicted landing point, considering the wind direction and speed.

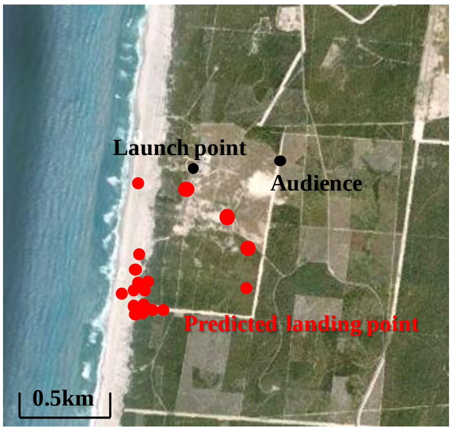

Fig. 8. Launch and landing points.

Sakura's recovery system bay is shown in Fig. 9, and the opening mechanism for the ejection doors is illustrated in Fig. 10. There are two ejection doors, one for the deceleration chute and the other for the main chute. The doors are activated by a servo motor with a link mechanism. The main chute door does not open under the shock load caused by the deployment of the deceleration chute.

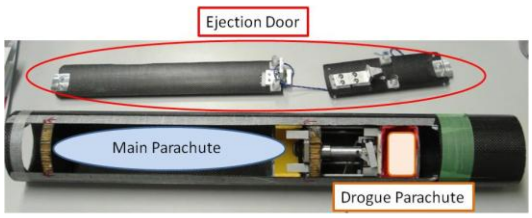

Fig. 9. Sakura's recovery system bay.

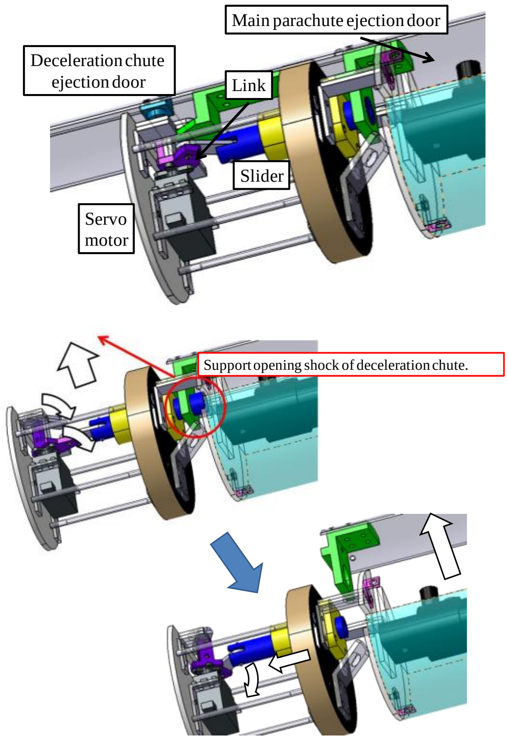

Fig. 10. Door ejection mechanism.

4. Avionics

Both the rockets, i.e., Ninja-10 and Sakura, have an onboard avionics system as shown in Figs. 11 and 12, respectively. The architecture of the onboard avionics for Ninja-10 is almost the same as that of Ninja-09 [6]. However, last year it failed to acquire any flight data. Therefore, the quality of the components of the power supply system and connectors has been improved to avoid the problem that occurred last year.

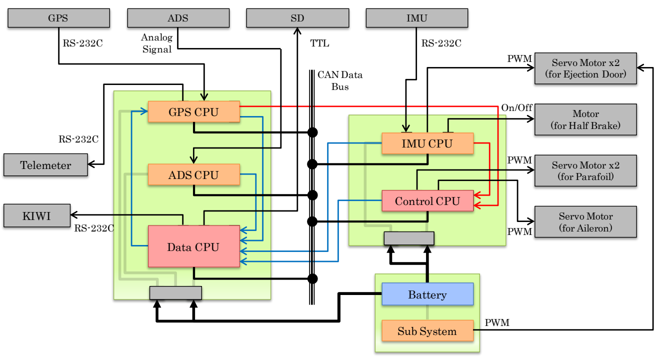

Fig. 11. Onboard avionics of Ninja-10.

Sakura's avionics consists of two microcomputers, two pressure sensors, a 3-axis accelerometer, a GPS receiver, a servo motor, and a data transmitter KIWI provided by CNES (Fig. 12) [9].

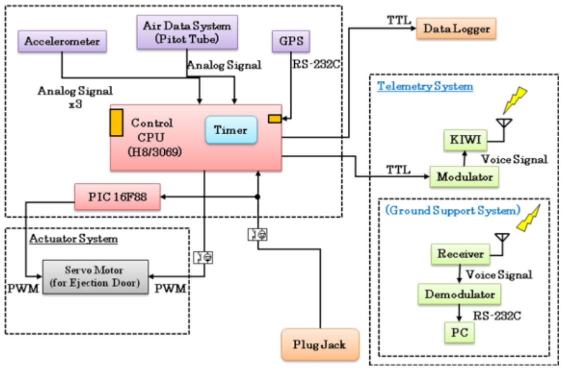

Fig. 12. Onboard avionics of Sakura.

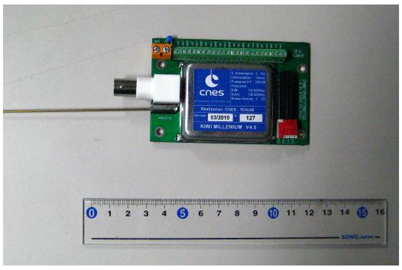

Fig. 13. KIWI transmitter.

The pressure sensors are employed to measure Sakura's flight Mach number in order to verify the aerodynamic drag coefficient. Air compressibility based on the isentropic flow relation, given in Eq. (3), and the Rayleigh Pitot tube formula, expressed by Eq. (4), must be considered when calculating the Mach number for supersonic flight. Then, the dynamic pressure and drag are calculated using the Mach number.

$$\frac{p_t}{p} = \left(1 + \frac{\kappa - 1}{2} M^2\right)^{\frac{\kappa}{\kappa - 1}} \tag{3}$$

$$\frac{p_t}{p} = \left(\frac{(\kappa+1)^2 M^2}{4\kappa M^2 - 2(\kappa - 1)}\right)^{\frac{\kappa}{\kappa - 1}} \frac{(1-\kappa) + 2\kappa M^2}{\kappa + 1} \tag{4}$$

where p_t is the total pressure, p is the static pressure, κ is the specific heat ratio, and M is the Mach number.

5. Ground Test

Ninja-10 and Sakura needed to be subjected to many tests before launch. For example, they were tested in the wind tunnel to check the control of aileron, and the ejection mechanism for the parachute or parafoil was also tested. Data transmission by KIWI was also checked in an anechoic chamber.

Fig. 14. Wind tunnel test to check aileron controllability.

Fig. 15. Telemetry data transmission test in an anechoic chamber.

6. Qualification Tests

The rockets are permitted to be launched if they pass the various qualification ground tests in the campaign, such as the flight simulation, stiffness, and static load tests.

Fig. 16. Static load test.

7. Flight result

Although Ninja-10 had passed the tests, it was not allowed to be launched because of strong wind conditions.

Sakura reached a maximum Mach number of over 1.0 and was recovered successfully using a two-stage parachute system after it reached its apogee.

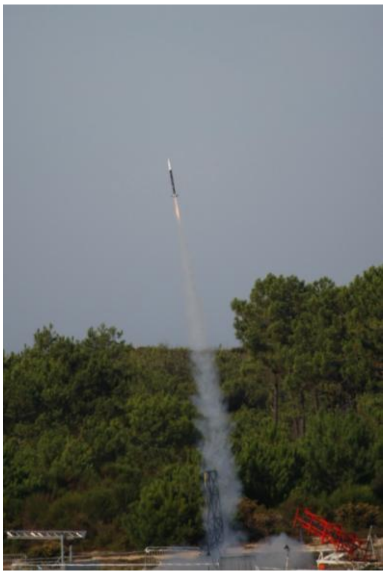

Fig.17. Flight test of Sakura.

The rocket reached Mach 1.07, 5.2 s after ignition. The Mach number was calculated by substituting the pressure sensor data in Eqs. (3) and (4) (Fig. 18).

Fig. 19 shows data measured by the acceleration sensor. This figure indicates the opening time of the deceleration chute and the main chute. The deceleration chute was deployed 23.0 s after ignition, and the main chute was deployed 41.4 s after ignition.

Fig. 20 shows the change in altitude with respect to time. The altitude data, which is measured by the GPS, was unstable because the rocket had high acceleration and high speed. From the pressure data recorded, the maximum altitude achieved was calculated to be 3351 m at 23.2 seconds after launch, which is very close to the value calculated in the simulation. The main chute was ejected either (1) 83 s after launch or (2) if the GPS altitude at 40 s after launch is less than 1000 m. However, the GPS measured the altitude incorrectly; it indicated that the rocket altitude was only 400 m at 40 s after launch. Therefore, the main chute was ejected without the rocket descending, and the rocket landed 2.5 km away from the launch site.

Fig. 21 shows the plot of the drag coefficient against the Mach number. The bar indicates the error margins of the pressure sensor and the acceleration sensor. The error margin of the sensors increases with a decrease in the Mach number because the sensors are configured to acquire data around Mach 1. However, when the Mach number increases, the drag coefficient increases rapidly.

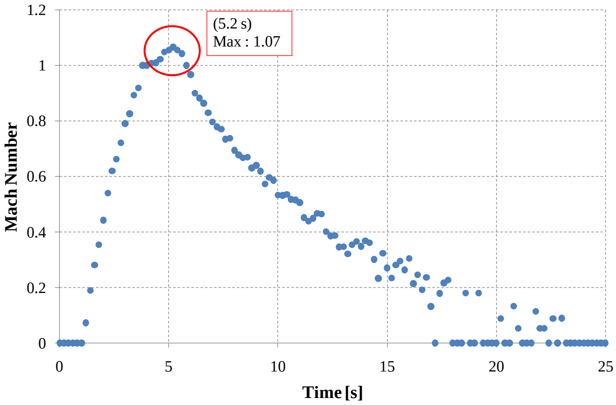

Fig. 18. Mach number change.

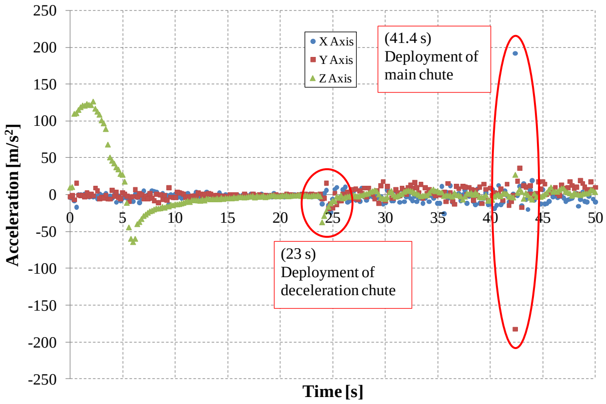

Fig. 19. 3-axis acceleration change.

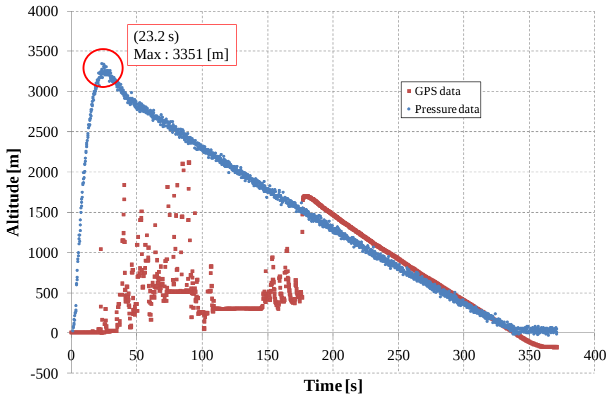

Fig. 20. Altitude change.

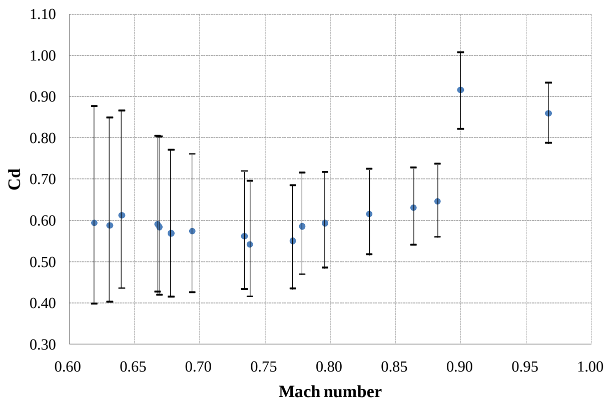

Fig. 21. Calculation of drag coefficient.

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