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# Experimental Study of Cone-Derived Waveriders at Mach 5.5

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**We describe experimental studies of aerodynamics of a cone-derived waverider model. The experiment was conducted at a freestream Mach number of 5.5 and a Reynolds number based on the model length of 1.3 × 10^5. An on-design model and a comparison model are fabricated and tested, the latter having the same planform as the on-design model but with a flat lower surface. The results show that the on-design model has better aerodynamic performance and attains a maximum lift-to-drag ratio as high as 3.8 at zero angle of attack. The comparison model shows a lower ratio due to flow leakage out of the compression surface.**

## Nomenclature

$C_D$ = drag coefficient
$C_L$ = lift coefficient
$L/D$ = lift-to-drag ratio
$L_w$ = model length
$M_\infty$ = freestream Mach number
$R$ = curvature radius of upper surface
$\alpha$ = angle of attack
$\beta$ = conical shock-wave angle
$\delta$ = cone semivertex angle

## Introduction

WITH the growing interest in hypersonic flight, waverider configurations have become an important subject of experimental research.

The waverider[1,2] is a kind of high-speed aircraft that maintains a high-pressure layer below the body with a shock wave attached to the leading edge. The configuration attains high-$L/D$ flight at hypersonic speed. The original concept of the waverider was developed by Nonweiler[3] in 1963 as a caret wing. It was extended to a conical flowfield by Jones[4] in 1963. Waveriders are classified into two types according to the flowfields on their lower surfaces: the wedge-derived waverider (such as the wedge wing or caret wing, producing two-dimensional plane shock waves) and the cone-derived waverider (either idealized or general, generating three-dimensional conical shock waves).

Many researchers have studied waveriders, but most studies are concerned with numerical calculations[5–8] or experiments restricted to caret wings and idealized cone-derived waveriders.[9] Few experimental studies have been performed on general cone-derived waveriders; moreover, models of the general cone-derived waverider have been designed according to the hypersonic small-disturbance theory[10–12] (HSDT). Using a personal computer, our study group has designed a general cone-derived waverider for flight at low hypersonic Mach number, based on the Taylor–Maccoll (TM) equation[13] instead of HSDT, and has constructed the model with a numerically controlled milling machine. The results of various tests performed in the Tokyo Metropolitan Institute of Technology (TMIT) hypersonic wind tunnel at Mach 5.5 are reported herein.

The main contents of this paper are design and construction methods for the model, a verification test of the model as a waverider from oil flow pattern visualization and schlieren photography, and aerodynamic tests of the model. From these studies, the advantage of the cone-derived waverider is shown experimentally.

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## Cone-Derived Waverider

### Design Method

The design of the waverider configuration is performed according to the following steps. First, we established a method of aerodynamic design and construction of the general cone-derived waverider for a low-hypersonic flight. In designing the waverider, we define the $z$ axis in the freestream direction and assume a conical shock wave and its apex angle whose center line is on the $z$ axis, as shown in Fig. 1. At step 1, the upper surface of the model is parallel to the $z$ axis. To simplify the construction of the waverider model, we make the upper surface of the model cylindrical (step 2). Then the crossing line of the conical shock wave and the upper surface makes a leading edge of the model (step 3). We trace streamlines downstream from the leading edge. Here we use the TM equation[13] to find the streamlines. A set of the streamlines from the leading edge conforms to the lower surface of the model (step 4).

Usually, HSDT is applied to calculate the streamline behind a conical shock.[5] This theory is described in algebraic expressions, so it is easy to calculate with a computer. However, HSDT loses its accuracy at low hypersonic Mach numbers and for a model with large apex angle of the conical shock as shown in Fig. 2. So in the present study we use the TM equation, which is expected to be in good agreement with real phenomena, independent of Mach number. In this way, flowfields are numerically calculated at an on-design flow condition of Mach number 5.5. The pressure-distribution contour and the aerodynamic characteristics based on the TM equation are shown in Fig. 3 and Table 1, respectively.

### Construction of the Model

This waverider model is manufactured using a numerically controlled milling machine based on this design method. We shall call this model the on-design model. The shape and size of the on-design model are shown in Fig. 4, where the apex angle of the shock wave and other dimensions are determined under the constraint of the blockage ratio of our TMIT hypersonic wind tunnel. As a result, the model parameters of the on-design model became as follows: $L_w = 32.67$ mm, $\delta = 19.15$ deg, and $\beta = 23.5$ deg. No optimization (such as viscous optimization) is performed on the on-design model. For the purpose of comparison, a nonwaverider model with a flat lower surface, the same body length, and the same body width is made and used for all tests at the same flow conditions. We shall call this model the comparison model. The shape and size of the comparison model are shown in Fig. 5.

## Experiments

### Wind Tunnel

A hypersonic test section is attached to the TMIT supersonic wind-tunnel system. This system has a transonic test section and a hypersonic test section. The two sections have a common reservoir tank and a joint exhaust vent. The layouts of this wind-tunnel system and its test sections are shown in Figs. 6 and 7, respectively. We call the hypersonic test section of the system the TMIT hypersonic wind tunnel (TMIT HWT). Experiments are performed in the TMIT HWT

**Table 1 Estimated values of aerodynamic parameters**

| $C_L$ | $C_D$ | $L/D$ |
|---|---|---|
| 0.245 | 0.074 | 3.30 |

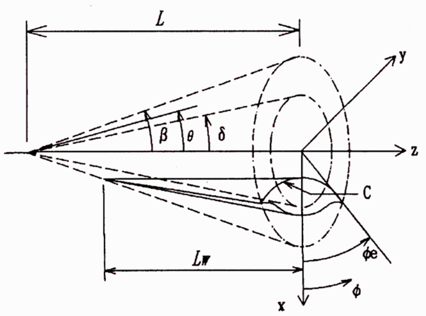



**Fig. 1 Construction of the cone-derived waverider.**[1]

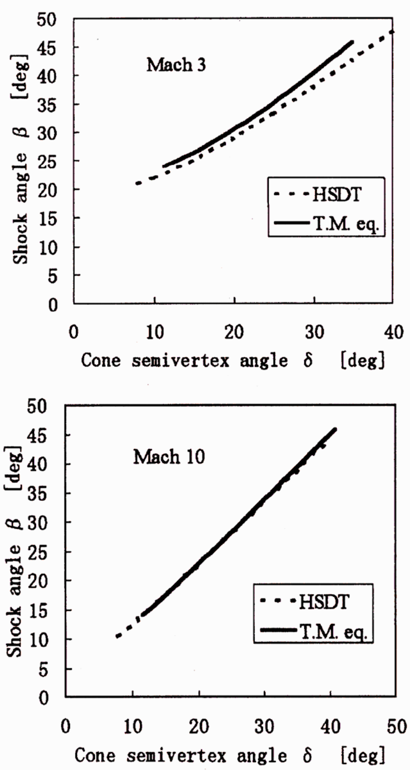



**Fig. 2 Taylor–Maccoll equation and HSDT.**

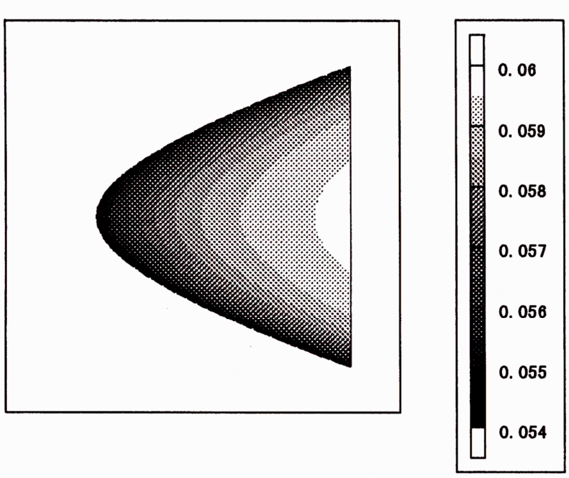



**Fig. 3 Pressure distribution on the cone-derived waverider.**

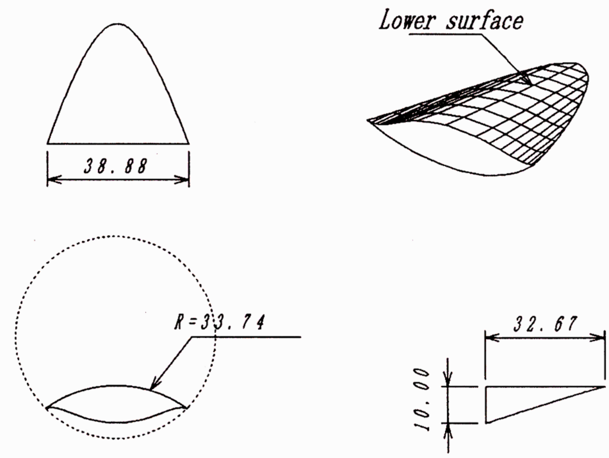



**Fig. 4 On-design model (dimensions in millimeters).**

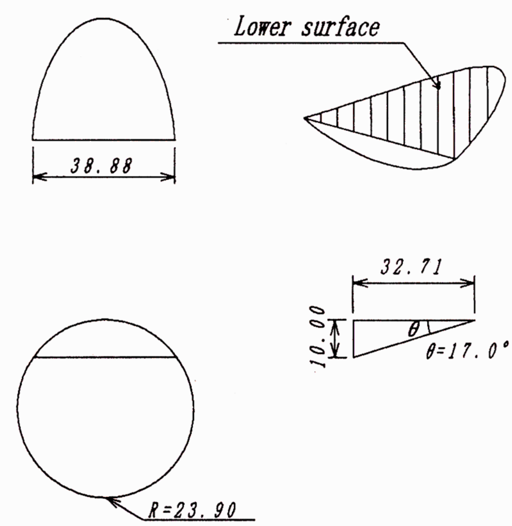



**Fig. 5 Comparison model (dimensions in millimeters).**

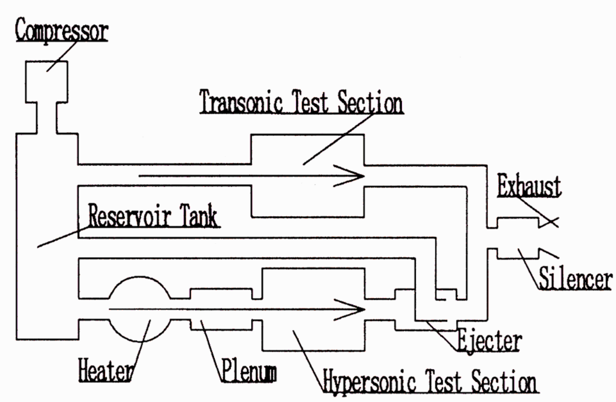



**Fig. 6 Layout of TMIT supersonic wind-tunnel system.**

with a freestream Mach number of 5.5. The freestream unit Reynolds number was $4.34 \times 10^6$/m, and the maximum duration of steady flow was about 22 s. Other specifications of this wind tunnel are shown in Table 2.

### Observation of Flow Fields

The shape of the shock wave and flow pattern of the lower surface was observed so as to investigate the flowfields around the waverider models. The shock shape was observed with a schlieren system using a 75-W xenon lamp. The flowfield on the lower surface of the model was observed by the oil flow visualization method. The ingredients of the oil are silicone oil (1000CS) as a main solvent, titanium dioxide as a pigment, and oleic acid as an additive. The proportion of these ingredients by volume is 5:1:trace.

**Table 2 Specifications of TMIT HWT**

| | |
|---|---|
| Type | Blowdown |
| Diameter of nozzle at the exit | 120.0 mm |
| Diameter of nozzle at the throat | 18.4 mm |
| Stagnation pressure | 860 kPa |
| Stagnation temperature | 850 K |
| Maximum mass flow | 0.3 kg/s |
| Exhaust | Air ejector |

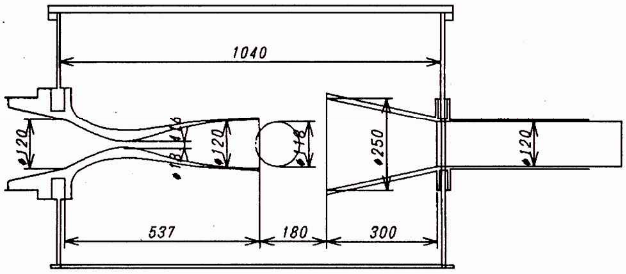
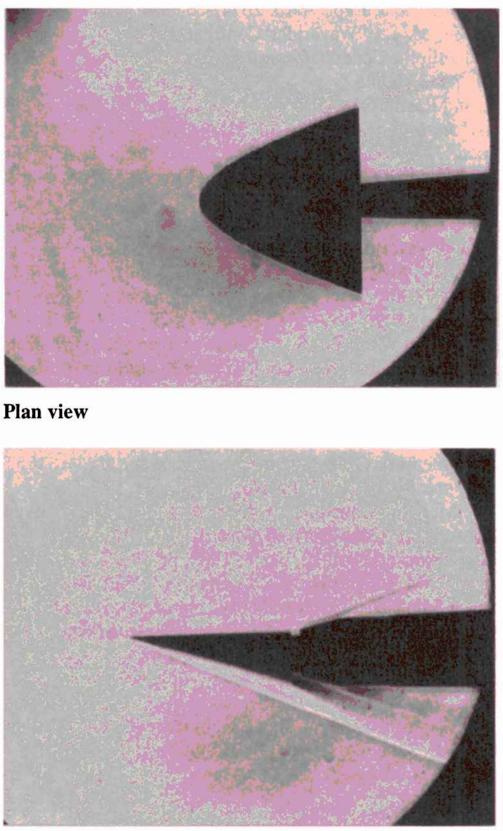



**Fig. 7 Hypersonic test section (dimensions in millimeters).**



Plan view

Side view

**Fig. 8 Schlieren photographs of the on-design model.**

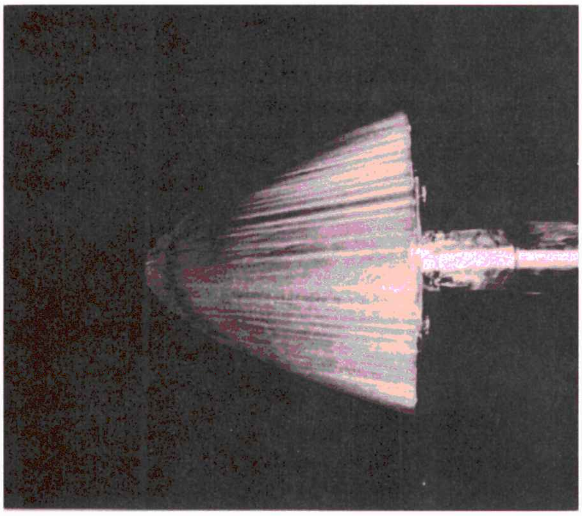
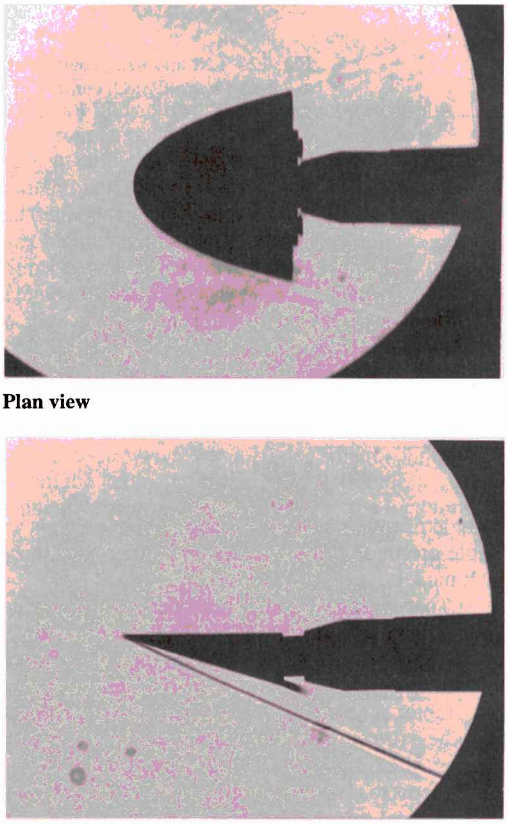


**Fig. 9 Oil flow photograph of the on-design model.**



Plan view

Side view

**Fig. 10 Schlieren photographs of the comparison model.**

From the schlieren photographs shown in Fig. 8, it is found that, from the plan view photograph, the shock wave is well attached to the leading edge of the on-design model at zero angle of attack. The side view in the photograph also shows that the shock-wave angle coincides with design angle. Moreover, an oil flow pattern photograph in Fig. 9 shows that the streamlines on the lower surface of the on-design model are conical, which coincides with design streamlines, and that no crossflow is observed. From these two observations, it is concluded that the on-design model works as a waverider around zero angle of attack. On the other hand, Fig. 10 shows, in the plan view and side view photographs, that the shock wave detaches at the rear of the leading edge of the comparison model; the shock-wave angle is 25 deg. This angle equals the plane shock-wave angle corresponding to a deflection angle of 17 deg at a Mach number of 5.5. Also, Fig. 11 shows that the streamlines on the lower surface of the comparison model are not conical because of the growth of crossflow. From these results, it may be said that the comparison model behaves like a three-dimensional wedge.

### Aerodynamic Characteristics

Aerodynamic characteristics were measured over the range of $-2$ to 3 deg in angle of attack with a three-component sting balance. Figures 12 and 13 show the experimental results on the lift and drag coefficients and on the $L/D$, respectively, as functions of angle of attack. The experimental error is smaller in size than the plotted points. For the comparison model, the angle of attack was limited to $-2$ deg $\leq \alpha \leq +2$ deg by the blockage ratio of the wind tunnel. It is seen that the comparison model has larger values of the lift and drag coefficients than the on-design model. On the other hand, the $L/D$ of the comparison model are lower than those of the on-design model, as shown in Fig. 13. The maximum $L/D$ is found to be about

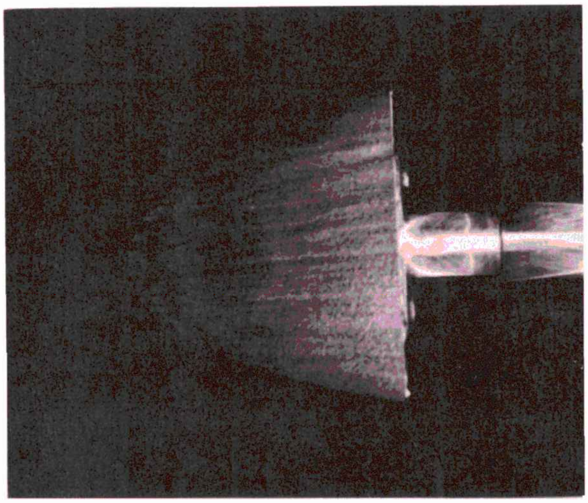


**Fig. 11 Oil flow photograph of the comparison model.**

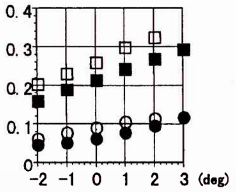



**Fig. 12 Lift and drag coefficients vs $\alpha$: ■, on-$C_L$; •, on-$C_D$; □, comp-$C_L$; and ○, comp-$C_D$.**

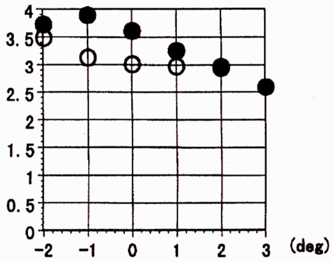



**Fig. 13 $L/D$ vs $\alpha$: •, on-$L/D$ and ○, comp-$L/D$.**

4.0 at an angle of attack around −1 deg, and its value is about 3.8 at zero angle of attack. These values are higher than those of the comparison model.

In a recent paper, Jones et al.[14] have designed waveriders having general shock geometries based on the Euler equation, which is equivalent to the Taylor–Maccoll equation for a cone at zero angle of attack. They designed some configurations derived from axisymmetric and elliptic cones at $M_\infty = 4.0$. Case 3 of their design corresponds to the axisymmetric conical waverider at $\delta = 20.9$ deg. It gives a theoretical $L/D$ of 3.76. Our experiment at $\delta = 19.15$ deg and at $M_\infty = 5.5$ seems to give a reasonable value of $L/D$ in comparison with their numerical calculation.

## Conclusion

Some important results from the present schlieren photographs, oil flow pattern visualization, and aerodynamic force and moment measurements are as follows.

1) From the schlieren photographs and oil-flow visualization, it was found that the on-design model designed with the TM equation works well in low-hypersonic flow as a general cone-derived waverider. The comparison model having a flat lower surface behaves like a three-dimensional wedge.

2) From the aerodynamic measurements, the present waverider attains a high $L/D$ at small angle of attack; in other words, the waverider has high $L/D$ with low drag at the on-design point.

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