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Longitudinal Stability Measurements of a Winged Biconic Configuration in Supersonic Flow

Andreas K. Flock†, Pascal H. Kringe, and Ali Gülhan
Supersonic and Hypersonic Technologies Department, Institute of Aerodynamics and Flow Technology
German Aerospace Center (DLR)
Linder Höhe, 51147 Cologne, Germany
†Corresponding author: andreas.flock@dlr.de

Abstract

In the present manuscript a biconic re-entry model was investigated in a blow down wind tunnel at Mach 1.5, 2, 3, and 4. The main focus was on studying the longitudinal stability and aerodynamic efficiency in this flying regime. In particular, the influence of wings near the rear part of the model, their wing dihedral, and of additional body flaps was investigated. While the purely biconic configuration was unstable, it could be stabilized with wings at a 20 deg downward pitch and with the additional body flaps. In general a larger dihedral angle improved static longitudinal stability.

Nomenclature

A	area, [m^2]
CFD	Computational Fluid Dynamics
COG	Center Of Gravity
CMY	pitching moment coefficient
L	length, [m]
LoD	lift to drag ratio
M	Mach number
p	pressure, [N/m^2]
Re	Reynolds number
T	temperature, [K]
TMK	Trisonic Wind Tunnel Facility Köln
x, y, z	spatial coordinates, [m]
α	pitch angle, [deg]
γ	wing pitch angle, [deg]
η	flap angle, [deg]
ϕ	dihedral angle, [deg]

Subscript

F	flight
M	model
ref	reference
t	total
∞	free stream condition

1. Introduction

To return payload from orbit to earth's surface certain space craft are designed as entry vehicles. These entry vehicles usually have special properties: For instance, they have a protection shield to withstand aerodynamic heating at high velocities, they have a recovery and/or landing system to secure touch down, and they are able to properly control the vehicle during the hypersonic, supersonic, and subsonic flight through the atmosphere. Historically, entry vehicles were designed as capsules, which are simple designs and which land with a parachute deployed at supersonic velocities. Examples are the Apollo or Soyuz capsules. However, their ability to increase range or to change the flight trajectory is limited due to their low lift to drag ratio (*LoD*) and lack of aerodynamic control surfaces. Newer entry vehicle designs, such as the U.S. Space Shuttle or the U.S. X37, have the ability to glide through the atmosphere, as they are winged. Therefore, they add flexibility and increase range.

One trade-off between simplicity and aero-assisted entry are lifting bodies,[1] which consist of relatively simple blunt geometries with wings or body flaps as aerodynamic control surfaces. Therefore, their *LoD* is in between the

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range of what is expected for capsules and winged configurations.[3] Weiland summarized aerodynamic data for several conical geometries, such as symmetrical ones (e.g. the Colibri or Slender Bicone) or even asymmetrical configurations (e.g. BENT-BICONE).[3] The slender biconic configuration, which is similar to our model, shows unstable behavior in longitudinal stability for the transonic and low supersonic Mach numbers. For higher Mach numbers, the behavior becomes neutrally stable. The center of gravity is located at $x = 57\%$ and $z = -6.7\%$. Weiland noted, that to stabilize the vehicle the center of gravity has to move to $x = 42\%$ and $z = -14.7\%$. However, he also noted that this is a rather optimistic location for COG.

Another similar configuration was investigated numerically and compared to a sharp edged configuration by Wartemann et al.[2] To achieve stable behavior, the vehicle had to be additionally truncated on its lee side where also spoilers were added. Furthermore, the nose radius was lower than in our configuration.

The present paper focuses on the static, longitudinal stability of a biconic configuration. The model was investigated in the trisonic wind tunnel of the German Aerospace Center (DLR) in Cologne. The main focus was on the influence of wings on the static stability. Further other variables, such as LoD or the influence of flaps as aerodynamic control surfaces are discussed. For the investigated angles of attack ($0\,\text{deg} < \alpha < 32\,\text{deg}$) the wings could impose an additional upwards force to decrease the $\partial CMY/\partial\alpha$ slope. Furthermore, the LoD was at approximately $1 - 0.9$ and therefore marginally larger compared to the purely biconic configuration.

2. Methods and Materials

In the present chapter, the biconic wind tunnel model is described in more detail. Next, the wind tunnel facility and the investigated conditions are summarized. Finally, the balance apparatus which we used for the aerodynamic measurements is described shortly.

2.1 Biconic Model

A biconic wind tunnel geometry was designed with a rounded nose and cylindrical rear end (figure 1). Overall length was 116.6 mm and various other dimensions are given in figure 2. The bottom side was flattened and a pair of body flaps was added. Body flap angle η was varied between -10 deg, 0 deg, and 14 deg; a positive flap angle indicated a pitch downwards as indicated in figure 2 (left). On the cylindrical portion two wings were installed with a dihedral angle of $\phi = 120$ deg. The wing cross section was a NACA 63-021 profile while the base length and height of the wing were 24 mm and 21.2 mm, respectively. The wing leading edges were swept (20 deg) and the wings themselves could be rotated, meaning their pitch relative to the biconic structure could be varied, between $\gamma = \pm 25$ deg. The axis of rotation was where the NACA profile had its maximum thickness. In the present work, a negative wing pitch angle indicated that the wing leading edge was rotated downwards. Only pitch angles ≤ 0 deg were investigated. The cylindrical part was manufactured exchangeable, to study different dihedral angles. A second rear portion with a wing pitch angle of -10 deg and dihedral angle of 90 deg was also investigated in this study.

In a possible flight experiment with the biconic configuration, which was also considered during conceptual studies for re-entry vehicles, model length was assumed to be 2.2 m. Therefore, the scaling factor was approximately 19 : 1. Weight of the flight experiment was assumed to be on the order of 500 kg. The subsequent coefficients were scaled with a reference length and area of $L_{\text{ref}} = 116.6$ mm and $A_{\text{ref}} = 2091.36\ \text{mm}^2$, respectively.

2.2 Wind Tunnel Facility

Tests were performed in the trisonic wind tunnel facility (TMK - figure 3) at the German Aerospace Center (DLR) in Cologne. TMK is a cold flow, blow down wind tunnel, that operates in the sub-, tran-, and supersonic Mach number range, while the present study focused on supersonic Mach numbers. Mach number can be varied during an experiment with an adaptable Laval nozzle which is adjusted by hydraulic actuators. To further increase the Mach and Reynolds number range the facility can be run in ejector mode. The ejector guides a secondary airstream into the subsonic diffusor and ultimately decreases exit pressure. The test section is rectangular with $0.6 \times 0.6\ \text{m}^2$. The Reynolds and Mach number ranges for the normal and ejector modes are summarized in figure 4, in which total temperature was assumed to be 295 K. Testing times of approximately 60 s can be achieved, depending on the exact conditions. During one test, an alpha polar was performed for different discrete Mach numbers. Four different Mach numbers were investigated, namely 1.5, 2.0, 3.0, and 4.0.

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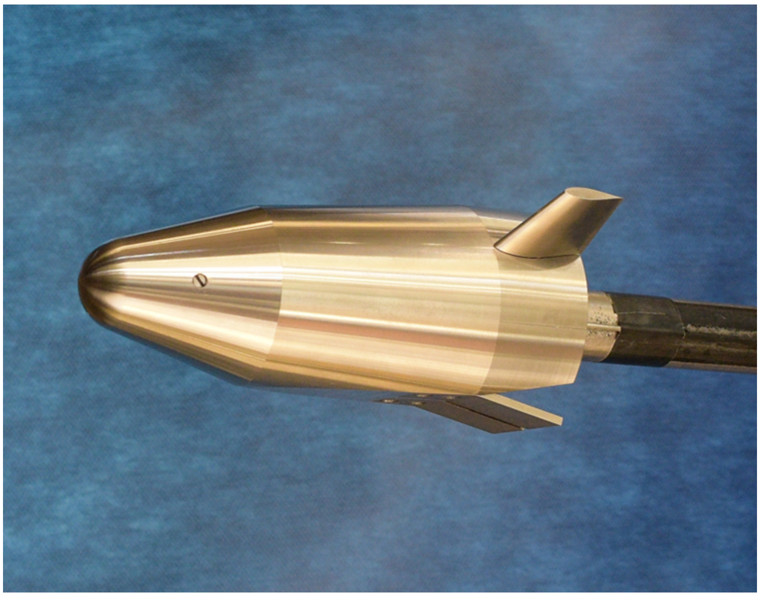

Figure 1: Biconic wind tunnel model mounted on sting.

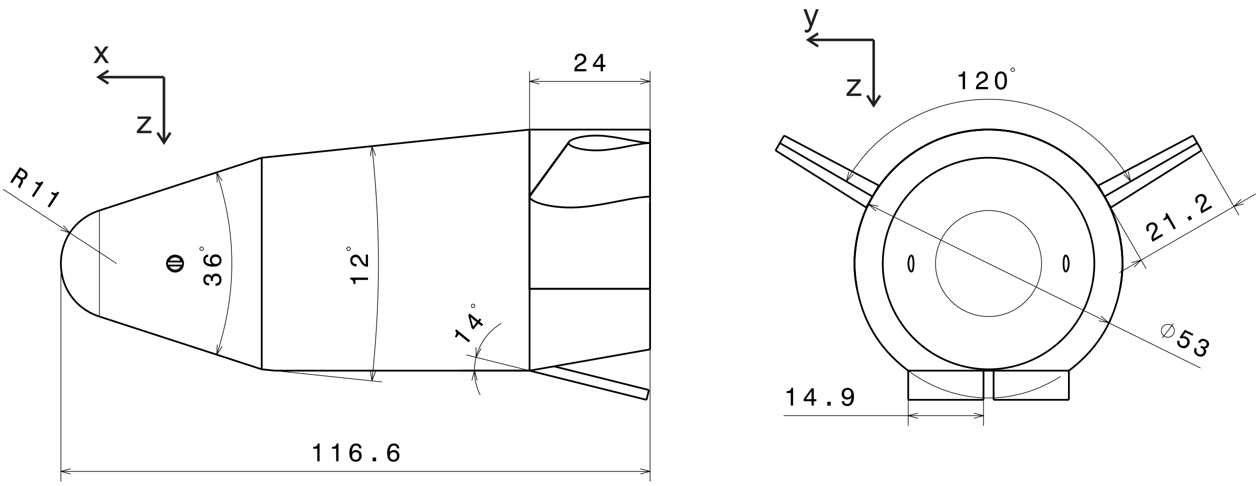

Figure 2: CAD drawing of biconic wind tunnel model.

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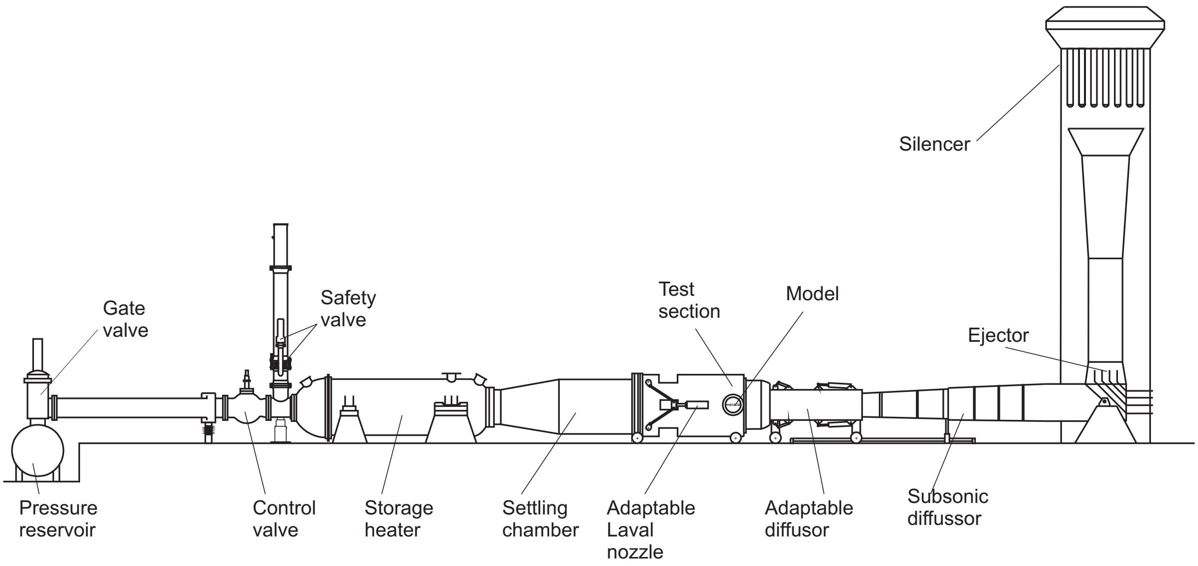

Figure 3: Schematic set-up of TMK wind tunnel.

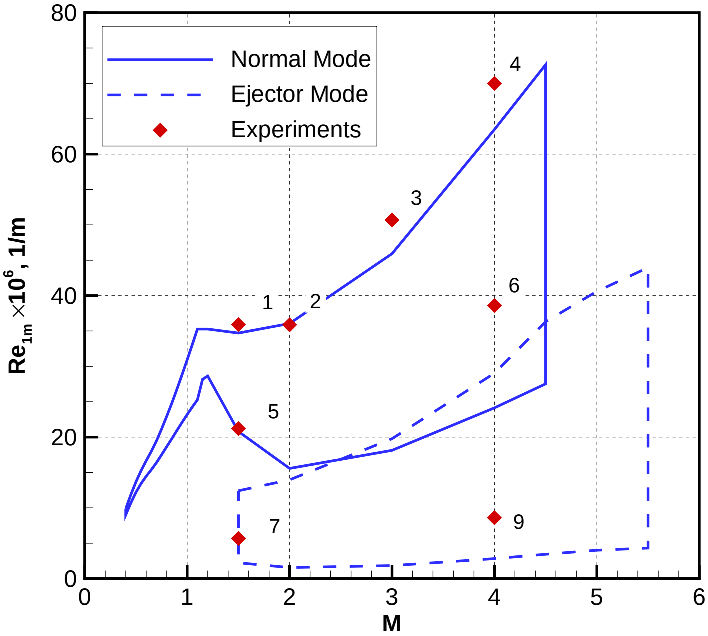

Figure 4: Performance map of TMK wind tunnel.

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Table 1: Wind tunnel conditions; total temperature for all tests was at $T_t \approx 275$ K.

M_∞	p_t, bar	$Re_M, \times 10^6$	h, km	$Re_F, \times 10^6$
1.5	2.2	4.19	20	5.63
2.0	2.6	4.18	21	6.61
3.0	6.0	5.91	23	7.28
4.0	14.0	8.17	25	7.15

2.3 Wind Tunnel Conditions

An overview of the investigated wind tunnel conditions is given in table 1. The purpose of the wind tunnel campaign was to measure the aerodynamic behavior during the supersonic glide phase. Therefore, four supersonic Mach numbers, namely 1.5, 2, 3, and 4 were investigated. Total pressures were adjusted so that model Reynolds numbers Re_M approximately matched flight Reynolds numbers Re_F. Flight altitudes were estimated from preliminary trajectories provided by DLR-SART. Furthermore, the wind tunnel conditions are summarized in figure 4. Note that due to the very cold outside weather conditions (testing time was in December/January) the total temperature was lower ($T_t \approx 275$ K) than was was used to calculate the normal mode and ejector mode ranges. Thus, the large Mach and Reynolds number conditions (No. 3 and 4) lie above their nominal Reynolds numbers.

2.4 Balance Measurement System

A 3/4 inch six component balance from the TASK corporation was used to measure aerodynamic forces and moments. The balance was mounted onto a sting and was aligned with the x-axis of the biconic configuration. All six components were calibrated before the tests to determine the calibration and correction factors. Before the run the angle of attack was varied in the same matter as during the experiment to subtract out the effect of the model weight.

3. Results

The center of gravity for all following results was at $x = 60\%$, measured from the nose, if not stated otherwise. The center of gravity in y- and z-direction was on the symmetry line of the biconic model. Except from the data in section 3.5, all results presented are for the largest Reynolds numbers possible in TMK (see 1. - 4. in figure 4).

3.1 Pure Biconic Configuration

The biconic configuration without wings showed an unstable behavior in nearly all investigated flight regimes (figure 5). Only for large flap angles and angles of attack larger 28 deg stable behavior, i.e. $\partial CMY/\partial\alpha < 0$, started to emerge. Moving the center of gravity forward to 58% only marginally improved the behavior (figure 5(b)).

Aerodynamic efficiency, which we expressed via the lift to drag ratio (*LoD*), peaked at 0.95 for the largest Mach numbers and decreased to 0.85 when approaching sonic speed (figure 6). Except for $M = 1.5$, the angles of attack where maximum *LoD* occurred were constant at 22 deg for $\eta = 0$ deg and decreased to 20 deg for $\eta = 14$ deg. Deeper insight into why the level of *LoD* is lower for Mach 1.5 can obtained when observing the schlieren images. For the lower Mach number and at 20 deg angle of attack, a shock (see arrow in figure 7 left) is present in the wake region of the model. This shock increases the pressure on the lee side an therefore decreases lift. For larger Mach numbers this shock was not observed (figure 7 right). Furthermore, for the two largest Mach numbers the change of the lift to drag ratios and momentum coefficients was only marginal, which indicated Mach number independence. Flap angle had little influence on lift to drag ratio.

To maximize the gliding range in the supersonic regime a trimmed location, i.e. $CMY = 0$, near angles of attack at which maximum *LoD* occurred is desirable. As the pure biconic configuration showed unstable longitudinal behavior, in the next subsections the influence of other aerodynamic surfaces on static stability is outlined.

3.2 Influence of Wings

The symmetrical wings were added as described in section 2.1 and pitching moment coefficients for the different Mach numbers are shown in figure 8. The individual plots represent the four Mach numbers which were investigated. Overall the wings decreased the $\partial CMY/\partial\alpha$ slope. For Mach 3 and 4, however, no stable behavior could be realized even with

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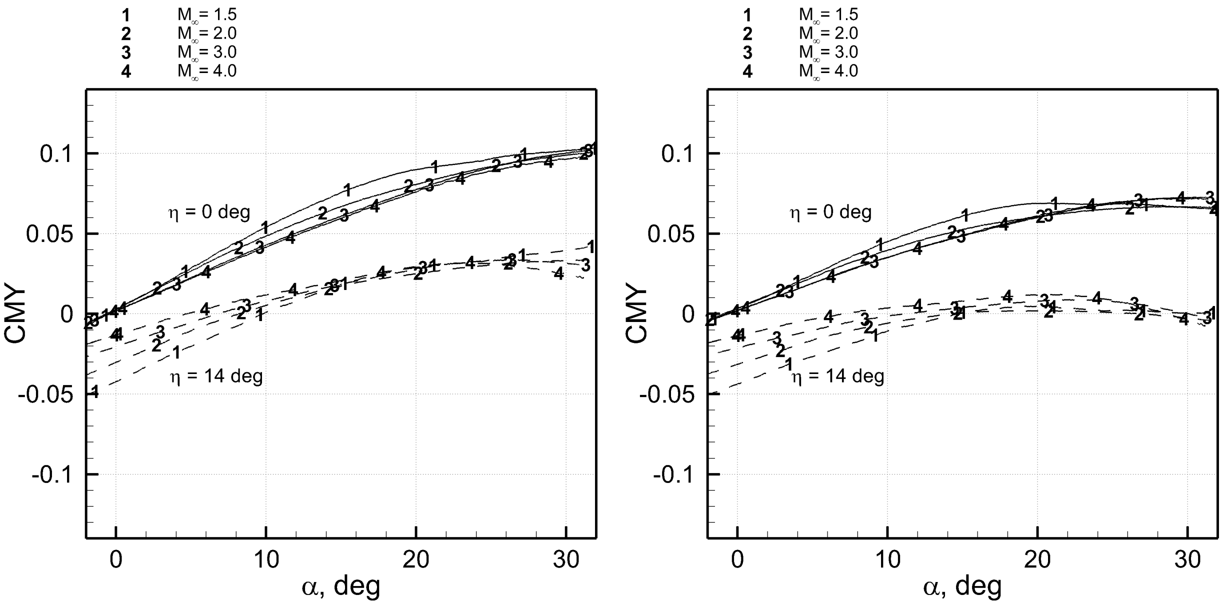

(a) COG at 60 %

(b) COG at 58 %

Figure 5: Pitching moment coefficient for unwinged biconic configurations.

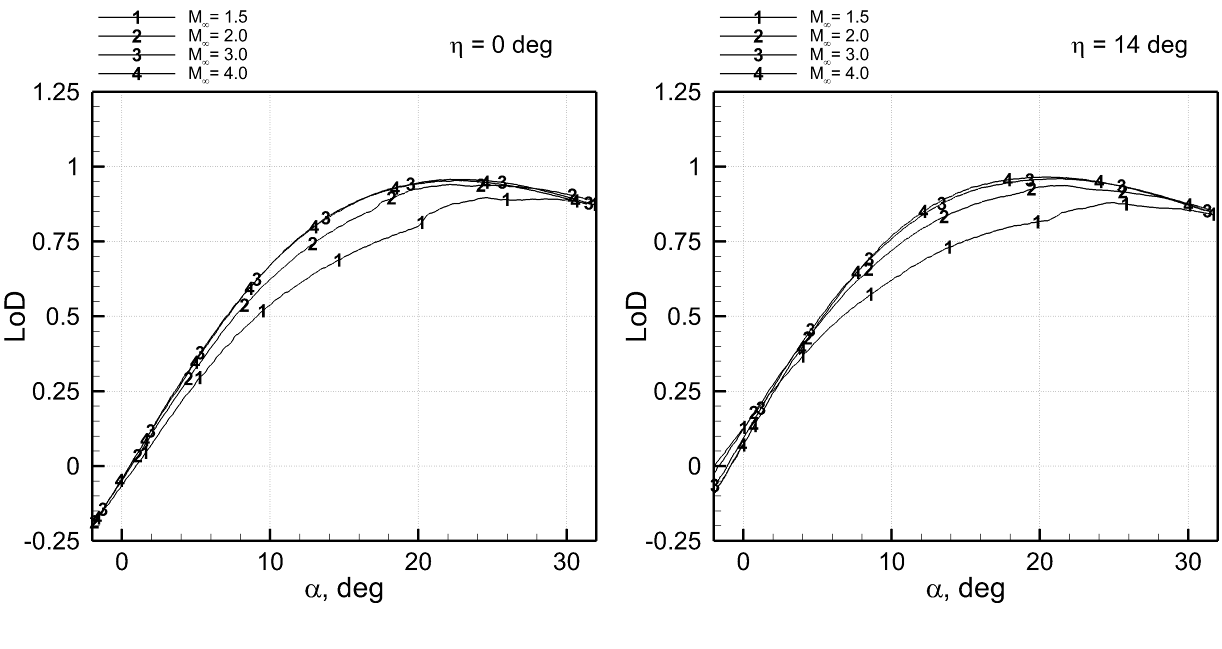

Figure 6: Lift to drag ratio for 0 deg (left) and 14 deg flaps.

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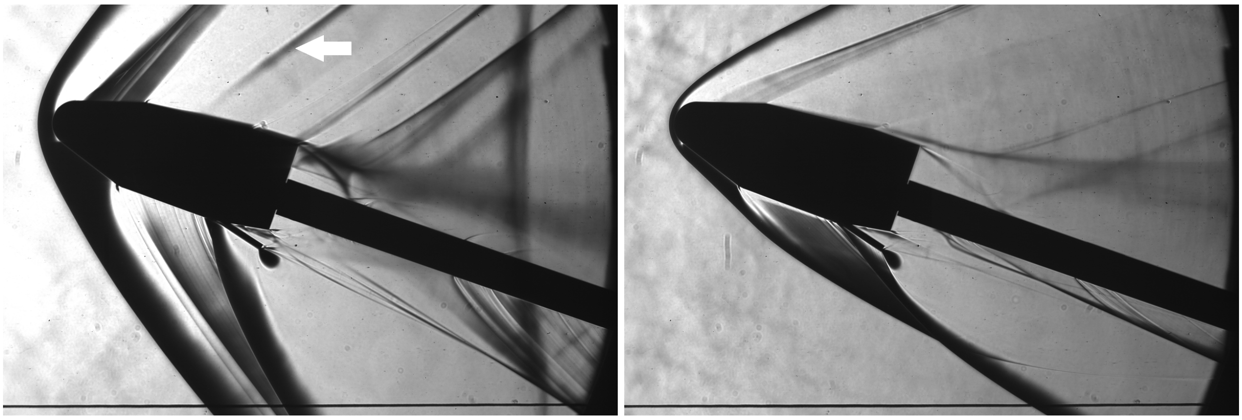

Figure 7: Schlieren images at $\alpha \approx 20$ deg for Mach 1.5 (left) and Mach 3 case.

the wings at $\gamma = -20$ deg. The general trends were again similar, which indicated Mach number independence. For Mach 2 and 1.5 wing pitch of ≤ -12 deg and ≤ -7 deg, respectively, were needed to create at least neutral behavior. These conditions were interpolated from the results for $\gamma = -10$ deg and $\gamma = -20$ deg. No trim conditions were detected which indicated the need for other means to trim the vehicle.

Lift to drag ratios were marginally affected by the additional wings (figure 9). For $\gamma = 0$ deg maximum LoD was again at ≈ 1 and at $\alpha_{\max} \approx 22$ deg. Inclining the wing pitch to -20 deg only slightly reduced LoD; the angle of attack $\alpha_{\max}$ remained unchanged.

3.3 Influence of Flaps

As second aerodynamic surfaces the flaps (see section 2.1) were added to the vehicle. Results are shown in figure 10 and the layout is similar to the previous section. As a reference the $\gamma = -10$ deg wings were used and for comparison the unwinged configurations for $\eta = 0$ deg are shown.

Similar to the wings, flaps also decreased the $\partial CMY/\partial\alpha$ slope and were more effective for the lower Mach numbers. For Mach 3 and 4, the largest flap angle (14 deg) generated neutral behavior, while for lower flap angles $\partial CMY/\partial\alpha$ was still positive. For Mach 2 flap angles of ≥ 5 deg showed at least stable behavior and a trim condition with stable behavior was detected for $\eta = 14$ deg and at $\alpha \approx 18$ deg. For Mach 1.5 the -10 deg flaps already stabilized the vehicle. A trim condition near $\alpha = 18$ deg can be estimated for 10 deg flaps. At the two largest Mach numbers, the largest flap angle together with a $\gamma = -20$ deg wing pitch could stabilize the vehicle (figure 11).

A positive flap deflection was more effective than a negative one. For Mach 1.5, for example, and at an angle of attack of 10 deg, the negative flap deflection caused a change of $\approx 0.0025\,\mathrm{deg}^{-1}$ in CMY; this value increased to $\approx 0.0036\,\mathrm{deg}^{-1}$ for positive flap deflections.

3.4 Influence of Dihedral Angle

The second rear portion with a dihedral angle of 90 deg was also used in the experiments to study the effect of dihedral angle. A lower dihedral angle decreases the effective wing surface area that acts in vertical direction. Consequently, the wing force in vertical direction also reduces and longitudinal stability should become more similar to the purely biconic case. Thus, the vehicle behavior should become less stable. This is confirmed in figure 12 which shows the pitching moment coefficients representatively for Mach 2 and 4 at a flap angle of 14 deg.

3.5 Influence of Reynolds Number

As the model Reynolds numbers only approximately matched the flight Reynolds numbers, several tests were run in ejector mode to lower the Reynolds number. Overall, the influence of Reynolds number on the results was low. For Mach 1.5, the pitching moment coefficient was slightly displaced for the lower Reynolds number (figure 13 left). For Mach 4, the influence of Reynolds number was even lower (figure 13 right).

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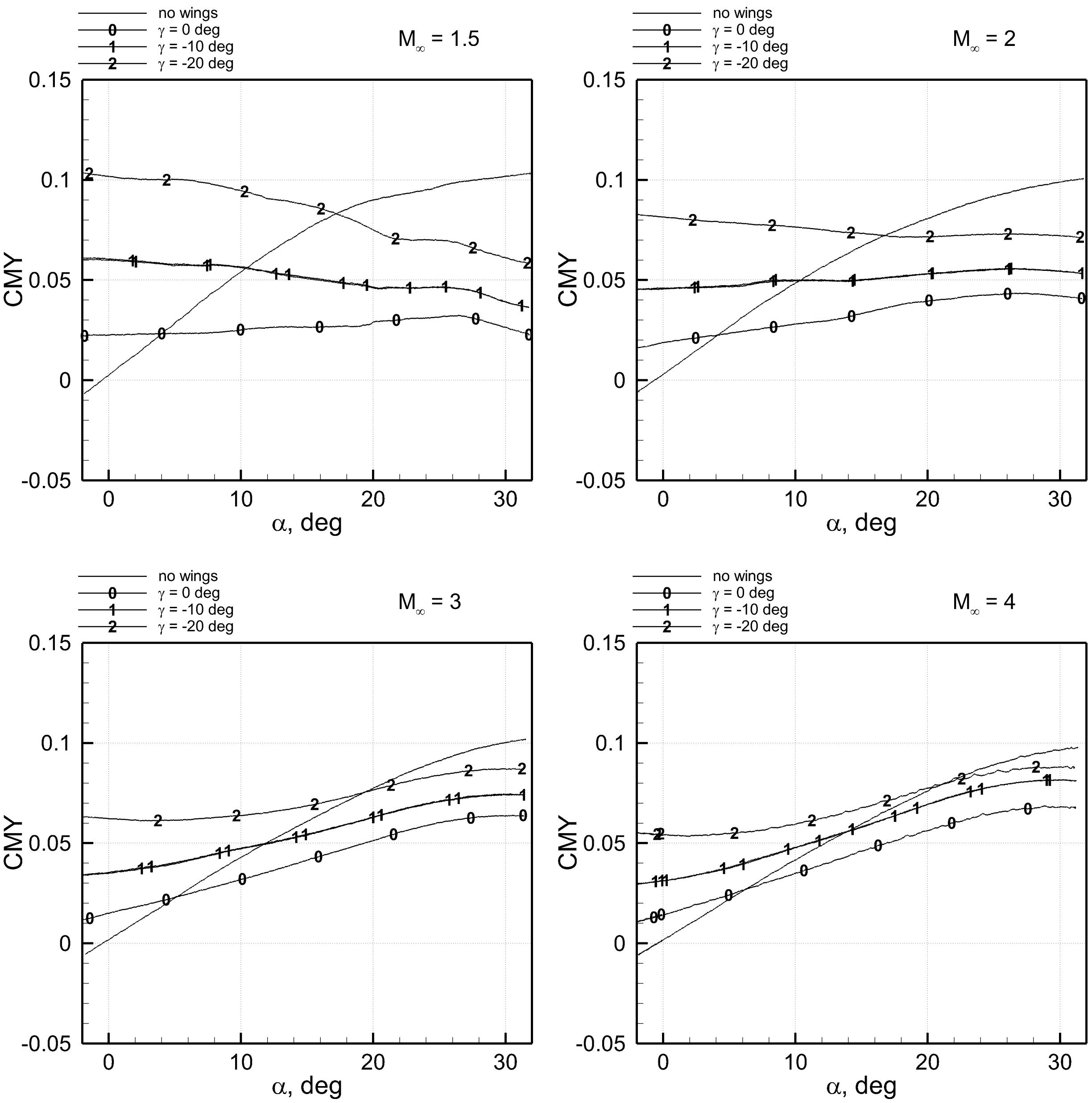

Figure 8: Pitching moment coefficient for different wing angles and Mach numbers; flap angle 0 deg.

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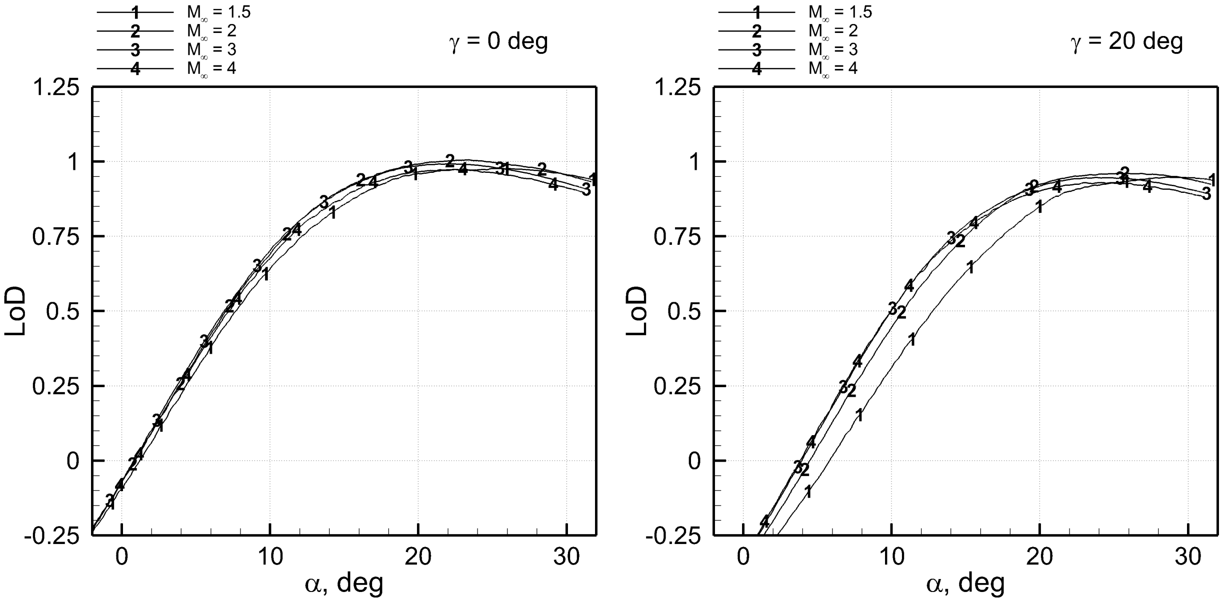

Figure 9: Lift to drag ratio for 0 deg (left) and 20 deg wings.

4. Conclusion

In the current paper we presented experimental results of aerodynamic measurements of a biconic model in the TMK wind tunnel. Experiments were performed for the supersonic regime, i.e. Mach numbers of 1.5, 2, 3, and 4. The main focus was to study the longitudinal static stability and aerodynamic performance in this flying range, as herein the pure biconic configuration is expected to be unstable. The influence of additional wings near the model rear side, their dihedral angle, of flaps as additional aerodynamic surfaces, and of Reynolds number was investigated. The main findings were:

1. With a dihedral angle of 120 deg and for a COG at 60% measured from the nose, the model could be stabilized for low supersonic Mach numbers, but still showed unstable behavior at larger Mach numbers.

2. If flaps were used in addition to wings, the vehicle could be stabilized even at larger Mach numbers.

3. A lower dihedral angle decreased the effective wing area that acted in vertical direction and therefore downgraded stability.

4. For low supersonic Mach numbers Reynolds number had little influence on the pitching moment coefficient; for large Mach numbers this influence further decreased.

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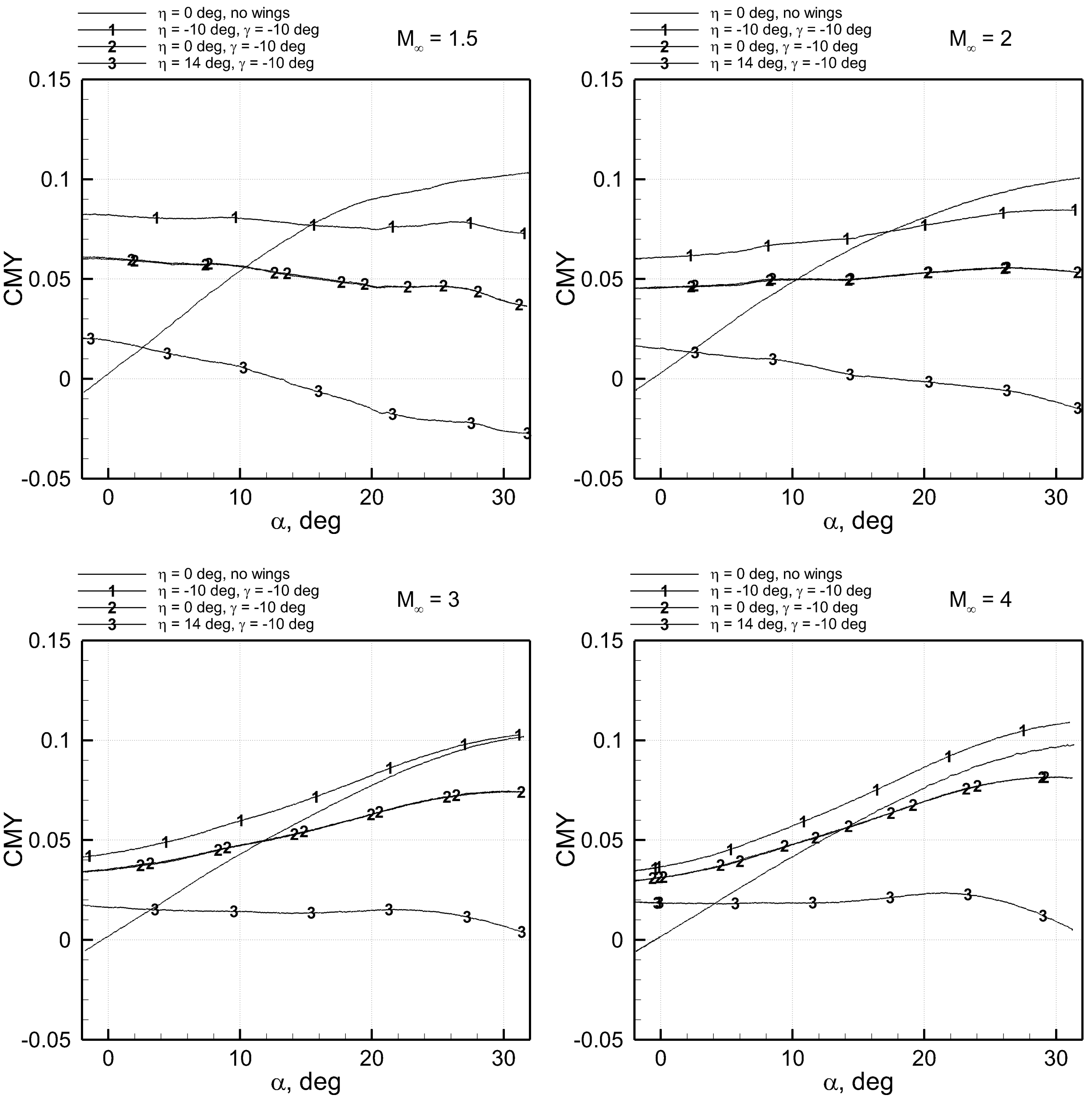

Figure 10: Pitching moment coefficient for different flap angles and Mach numbers.

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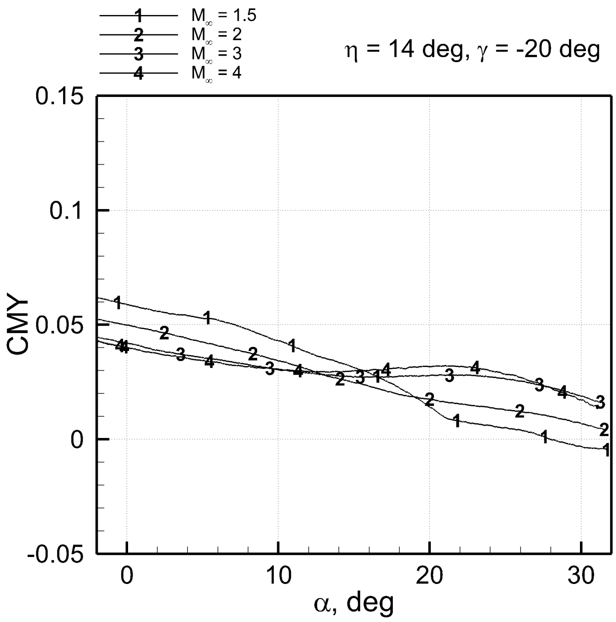

Figure 11: Pitching moment coefficient for largest flap and wing pitch deflection.

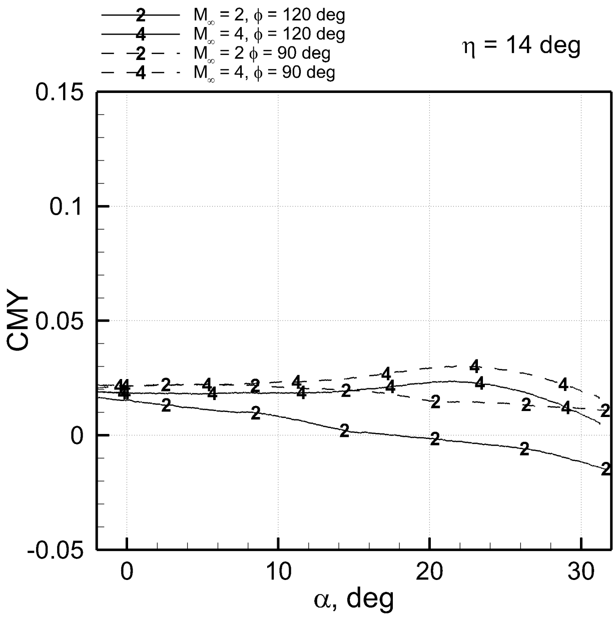

Figure 12: Pitching moment coefficient for different dihedral angles and Mach numbers; $\gamma = -10$ deg.

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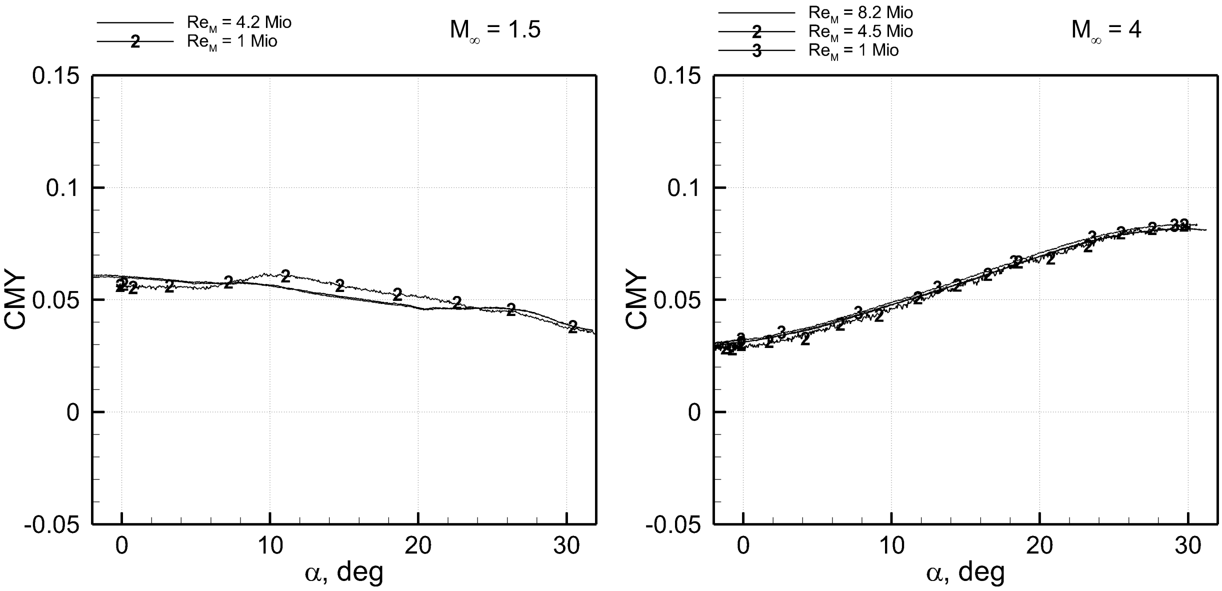

Figure 13: Influence of Reynolds number on pitching moment coefficient; $\gamma = -10$ deg, $\eta = 0$ deg.