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AERODYNAMIC CHARACTERISTICS OF MISSILES WITH TRIANGULAR CROSS-SECTIONS

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Abstract

An experimental investigation of schematic wingless missiles, with triangular body cross-sections and triform tail fins has been done. Sub- and supersonic aerodynamic characteristics are evaluated at angles of attack up to 23°. Comparisons are made with corresponding conventional designs (i.e. cruciform with circular section). It is found that the triangular body configuration has superior aerodynamic performance, but is not suited for skid-to-turn manoeuvring. An essential rounding of the triangle corners leads to a loss of this superiority, but results in a configuration somewhat more suitable for skid-to-turn. The triangular configurations have high roll stability when facing the wind with a flat body surface. This roll position also provides the highest lift-to-drag ratio. No significant lateral disturbances at symmetrical onflow are found.

Nomenclature

A non-rolling axis system is used, Fig. 1

$\bar{\alpha}$	Angle of attack (deg)
φ	Roll angle (deg)
M	Mach number
$C_{\bar{N}}$	Normal force coefficient
$C_{\bar{m}}$	Pitching moment coefficient
$C_{\bar{C}}$	Side force coefficient
$C_{\bar{n}}$	Yawing moment coefficient
C_l	Rolling moment coefficient
$C_{\bar{L}}$	Lift force coefficient
$C_{\bar{D}}$	Drag coefficient
$\delta_{\bar{e}}$	Elevator deflection
$\delta_{\bar{a}}$	Aileron deflection

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Introduction

Although not optimized regarding strength and wetted area, missiles with a triangular body cross-section are of interest for stealth and packaging reasons, among others (these reasons may also be related to each other when weapon platforms are considered).

The aerodynamic characteristics, which can be expected to be rather poor, especially regarding lateral characteristics, might be of decisive importance for a triform missile project, and are consequently well worth investigating. Of course, earlier investigations of missiles with non-circular cross-sections have been done, both with four(1) and three(2) fins, as well as of circular bodies with triform fins(3),(4).

In general, there are some different aspects of having three or four control surfaces (drag, weight, cost, control laws, control authority, etc.). For a missile with a triangular body cross-section, symmetry and mechanical design aspects contribute to the reasons for choosing three control surfaces. Aerodynamically they will probably do a better job if located at the corners, although there will be big gaps when deflected. It is most interesting whether or not enough control authority may be achieved in this case.

The present investigation is based on wind tunnel tests where schematic wingless missile configurations with triangular body cross-sections and triform corner located tail control surfaces (all-movable fins) are investigated. It is somewhat focused on the stability and control aspects in order to assess limiting factors for manoeuvrability, and attention is paid to the differences between sharp and rounded body corners. Comparisons are made with corresponding cruciform missile configurations with a circular cross-section.

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Wind Tunnel Tests and Configurations

A wind tunnel test of some schematic wingless missile configurations with equilateral triangular body cross-sections has been performed at the FFA S4 wind tunnel[5].

Two different cross-sections (sharp and rounded corners) in combination with different nose shapes, and two different sizes of triform tail control surfaces located in the corners have been tested. The configurations are depicted in Fig 1.

The shape parameter of the rounded section - as defined by unity minus the ratio of corner radius/ inscribed circle radius - is equal to 0.4, i. e. this section is geometrically a little closer to a circle rather than a triangle. (This is in some respects true also aerodynamically as will be shown.)

The large fins are double in (linear) size compared to the small ones. Deflections are only investigated for the small fins. Tests have basically been done with the tetrahedral (or rather trihedral) nose on the sharp-corner body, and with the spherical nose on the body with rounded corners. Conical nose, as well as large control surfaces, are tested less extensively.

In two earlier tests, corresponding "normal" configurations (i.e. cruciform configurations with circular body cross-section) with spherical and ogival noses have been investigated in the same wind tunnel[6],[7]. *The control surfaces are the same as for the triangular missiles* (but four instead of three panels are used) and have the same aft location. The cross-section is derived from the inscribed circle of the triangular sections. *The area of this circular cross-section is the reference area for all configurations and the corresponding diameter is the reference length.* Moment reference point is the same for all configurations as measured from the body base.

Six-component measurements for angles of attack up to 23° at different roll angles, and at Mach numbers from 0.6 to 1.93 - with a concentration on 0.6 and 1.42 - have been performed. All data in this paper are presented in a non-rolling coordinate system.

Reynolds number varies between 0.3×10^6 and 0.4×10^6 based on the reference length which equals 26 mm.

Tangential force has been "corrected" for base pressure with use of the base area of the circular body for all configurations. This approach makes it, at least to some extent, meaningful to compare drag between configurations using wind tunnel data.

Body Alone Characteristics

Since the bodies themselves constitute the most characteristic feature of these configurations - besides the triform fins - it is well motivated to take a closer look into the aerodynamic characteristics of the isolated bodies to begin with. Isolated bodies are tested almost as extensively as bodies with the smaller fins.

Longitudinal data

The most important advantageous aerodynamic feature for a triangular body is seen in Fig. 2, where drag is plotted vs. lift for the different bodies at some Mach numbers. The true triangular body (without rounded corners) exhibits quite outstanding high values of lift-to--drag ratio (except for very small angles of attack), and the best values are found when flying with a flat surface in windward position (φ=0). Rounding of the corners reduces the lift-to-drag ratio to almost the same as for the circular bodies. These are observations that are also found in earlier research on noncircular bodies. The differences in zero drag are of minor interest for a manoeuvring case. It is, however, interesting to notice that the sharp-corner body - with its slender but flat-surfaced tetrahedral nose - does not have lower supersonic zero drag than the body with rounded corners and a blunt spherical nose.

Drag vs. lift characteristics are reflected in those of normal force vs. angle of attack, which for M=0.6 are shown in Fig. 3. Normal force for the triangular body with sharp corners is highly dependent on roll orientation, except in the small angle of attack regime. Maximum normal force is achieved at zero roll angle. Then it is monotonously reduced as the roll angle is increased up to 60° (same as 180°), when a flat surface is on the leeside. The triangular body with rounded corners does not have a very significant roll dependence. (The circular ones have, of course, nominally none.) The sharp-corner body has more than double the normal force as the rounded body at all roll angles. These observed characteristics are very much the same also at supersonic speeds.

The differences in normal force is natural because of the differences in span and crossflow drag coefficients. It must, however, also be considered that strong three-dimensional vortices play a substantial role here. The span squared for the true triangular body (at zero roll angle) is three times that of the circular body. The corresponding normal force ratio exceeds this considerably except at very small angles of attack.

A study of pitching moment, together with corresponding normal force, tells us something about the distribution of the normal force. In Fig. 4, circular bodies are compared to the triangular ones at M=0.6 and zero roll angle. It is obvious that the circular bodies are rather dominated by the lift at the nose, whereas the triangular bodies are more dominated by the "crossflow drag" (moving center-of-pressure backwards with incidence). At the highest incidences, center-of-pressure for the triangular bodies is close to the reference point, which is located roughly at half the length of the body. Rounding of the corners makes the center-of-pressure travel forward, but not as far as for the circular bodies.

The variation of pitching moment with roll angle is rather analogous to that of normal force. If roll angle increases from 0 to 60° (180°), center-of-pressure travels forward because the normal force behind the nose is decreasing. Examples of pitching moment for the sharp--corner body at different roll angles and Mach numbers can be seen in Fig. 5. Rounded corners mean drastically less roll dependence. Pitching moment characteristics are the same also for other Mach numbers.

Lateral data

While longitudinal data for triangular bodies in some respects (as shown) are beneficial, one can perhaps expect lateral data to be of nothing but trouble as compared to circular bodies who, when "clean", normally have no "laterals". However, the existence of lateral disturbances due to asymmetrical vortices at high incidences makes a comparison interesting.

For isolated triangular bodies it is interesting to compare the magnitude of side forces to normal forces, to study roll stability and the influence of rounded corners, but also to compare side forces and yawing moments with those of the stochastic ones of the circular bodies.

Within the measured angle of attack range there are, for the triangular bodies, no signs of any lateral forces and moments at symmetrical roll angles, which is very satisfying. However, with the body in non-symmetrical positions, the side force is very large and amounts, at the higher incidences, to roughly half the value of the normal force at the same incidence. This ratio is many times smaller for the circular bodies. Moreover, these side forces are very large already at a rather small deviation from zero roll angle. This sensitivity is reduced when flying in the opposite roll position. These characteristics are illustrated in Fig. 6, which is valid for M=0.6. Rounding of the corners results in essentially lower side forces, Fig.6. This is, however, true also for normal forces and consequently the unfavourable high ratio of side force to normal force remains, at least for higher incidences. This ratio is significantly reduced at lower incidences. All these side force features are the same also at supersonic speeds.

Maximum side force for the triangular bodies is much higher than for the two circular bodies. It is approximately six and two times the value of circular bodies for sharp and rounded corners respectively. This ratio is likely to be still higher for higher than measured incidences, since the side force values for circular bodies are rather limited for incidences over about 30°, whereas they may very well continue to increase for triangular bodies.

The nose contribution does not play as important a role for yawing moments as for pitching moments. A study of yawing moment together with side force data shows that side force center-of-pressure is, for the true triangular body, located approximately 3 diameters aft of the reference point, independent of Mach number, angle of attack, and roll angle. This means that yawing moment data behave similar to side force data.

For the body with rounded corners, suction forces in the corner areas have a great influence on the side force distribution. Center-of-pressure varies strongly, and the local side force evidently appears with both signs. Very roughly, this body develops between half and two thirds the yawing moment of the sharp-corner body (sometimes at moderate incidences with opposite sign).

Maximum yawing moments, as compared to those of the circular bodies, resemble the situation for maximum side forces. (Maximum yawing moment for the two circular bodies - ogival and spherical nose - differs considerably making a comparison more complicated.)

Rolling moments for isolated bodies are largest at roll angles of about 15° to 30° for all Mach numbers, and essentially lower if the corners are rounded, see Fig. 7 as an example. Both triangular body configurations are stable in roll at zero roll angle (φ=0), and unstable at the opposite position (φ= 180° or 60°). The counteracting rolling moment is produced primarily by a shift in the pressure distribution of the windward surface and is quite high already at φ=15°. The influence of the leeside vortices would be interesting to investigate though.

Body with Fins

Adding tail fins to the bodies does not change the overall main aerodynamic features of the different body configurations as compared to each other. Of course, fins do somewhat smooth out the characteristics of the different bodies, and this is naturally more apparent with large fins. Using three instead of four fins makes, of course, also sometimes a significant difference. But, as will be seen, the basic features of the isolated bodies will be recognized also for finned configurations, i.e. the body aerodynamics has a dominant influence on the total configuration.

Longitudinal data

The normal force increment due to fins of different sizes is roughly independent of the body cross-section, except for higher incidences where the advantage of triangular bodies over circular is somewhat diminished. Examples of this observation are shown in Fig. 8. In the linear regime (small angles of attack) there is no significant difference at all due to roll angle or body cross-section in this increment. The roll independence is in agreement with linear theory, and also with Ref(1) where fin-body interference has been investigated for triangular bodies with cruciform fins, among others, with different shape parameters. (Also circular bodies are included.) The cross-section independence means (in our case) that the loss due to dihedral is, for both triangular configurations, compensated by favourable body carry-over interference.

The overall picture of lift-to-drag ratio comparisons is not changed when fins are mounted. At small incidences, the lift-to-drag ratio for the "triforms" will be gained as compared to the cruciform configurations, because of less fin drag.

Since the incremental normal force due to fins is located at the same aft part of the missile, and is of roughly the same magnitude, it is evident that the different features of longitudinal stability, as compared between bodies, are not changed drastically because of the fins. Pitching moment is of course more sensitive than normal force, and it must be remembered that the choice of reference point significantly affects the view.

Since the additional normal force is roughly roll independent, the fins will somewhat reduce the variation of longitudinal stability data with roll angle. With the small fins on the sharp-corner body, the spread in pitching moment is, however, almost the same as for the isolated body (but corresponds to a smaller center-of -pressure travel because of higher normal force), Fig. 9. This shows the great impact of the body aerodynamics (as for isolated bodies, rounding of the corners reduces the roll dependence). Also with the larger fins, the variation with roll angle (with sharp corners) is still considerably large at supersonic speeds, Fig. 10. In this case, the roll dependence is exceptionally large as compared to the circular cruciform configuration with the same fins, which has almost zero roll dependence. For subsonic speeds with large fins, both triangular bodies provide almost the same moderate roll dependence of pitching moment.

Unfortunately, a decomposition of body-fin interference in carry-over and vortex interference has not been done. Body vortex interference with the fins has of course a strong influence.

Lateral data

Adding fins, small or large, does not essentially change the side force for any of the triangular bodies. This means that the side force related to normal force is somewhat reduced with fins, but is still about 20% or higher, also with the larger fins. This is several times higher than for the circular bodies with cruciform fins.

Also with fins, there seems to be no essential lateral disturbances at symmetrical flow (within the measured range) for the triangular bodies.

Nor the yawing moment changes drastically because of fins on the triangular bodies, see Fig. 11 as an example for M=0.6 (roughly the same also for other Mach numbers). Rounding of the corners makes maximum yawing moment considerably smaller as for isolated bodies, but unfortunately this effect has now much less impact at supersonic speeds, Fig. 12.

Maximum yawing moment for the "triforms" are, except with rounded corners at subsonic speeds, several times higher than for the corresponding cruciform configurations. (Circular body configurations always include the stochastic contribution within the investigated range.) The absence of stochastic "laterals" for symmetrical onflow is satisfying, but, unfortunately, high yawing moments will arise already at small deviations from zero roll angle, which provides the best aerodynamic performance.

Fins have a much stronger influence on rolling moment than on side force and yawing moment. Fig. 13 shows an example of rolling moment for the sharp-corner body with small fins. Corresponding graph for the isolated body is found in Fig. 7. The triangular bodies without fins have, for all tested Mach numbers, more than half the maximum rolling moment as compared to that of the corresponding bodies with small fins. Rounding of the corners results in less than half the values for rolling moments, but they are still more than double the values of a circular cruciform configuration. This is shown in Fig. 14 where rolling moment is plotted vs. roll angle at α=20°. (The circular body here has an ogival nose, and significant stochastic rolling moments start to develop just *above* this incidence.)

With the larger fins the effect of rounding is eaten somewhat by the span (primarily), and the max rolling moment is still more than double that of the corresponding circular cruciform configuration.

As for the isolated triangular bodies also the finned ones are stable in roll for zero roll angle, and unstable in the opposite position. This is observed also in Ref(2) (supersonic), and is of course a very satisfying quality since zero roll angle is the preferred flight orientation. It is also advantageous that the counteracting moment is large already at small roll deviations, (i.e. the roll stability derivative is large at zero roll angle).This is very helpful if this roll position wants to be kept. The unwanted "cross-talk" is rather large also for small deviations from zero roll angle.

Control effectiveness

Effects of control surface deflection are only investigated for the small control surfaces (fins). The most interesting purpose with the present study is to assess and compare what can be achieved in trimming and manoeuvring for different configurations. i.e. to see if the three control surfaces possess enough authority to control the missile. Therefore, only maximum deflection is paid attention, here supposed to be 25° and 15° for elevator and aileron respectively.

Elevator effectiveness for M=0.6 and M=1.42 is shown in Fig. 15. (Tested roll angles are quite limited.) It is shown that rounding of the corners has no dramatic effect here. Gaps are reduced, but so also the effective body span. The configurations with triangular bodies exhibit elevator effectiveness close to that of circular cruciform ones (in "+" orientation and up to moderate incidences). This is not surprising, considering what was earlier observed regarding incremental normal force due to fins, although the interference situation is not the same here as in the angle of attack case. For higher angles of attack, it is most interesting to notice that the triangular configurations, for subsonic speeds, have essentially higher elevator effectiveness than the circular ones for "normal" deflections, i.e. negative for positive angle of attack. For the highest incidences the "triforms" can provide about the same control force as the cruciform configurations in "x" position where all four control surfaces are engaged. This must partly be the result of favourable body interference in these flow situations. The results are less remarkable at supersonic speeds where flow separations do not play the same significant role.

Although elevator effectiveness is not measured at several roll angles, we may conclude that it seems possible to trim all the configurations longitudinally (center-of-gravity assumed to have about the same location as our reference point) with the small control surfaces, within almost the entire tested envelope. One exception is when flying with the sharp-corner missile at high incidences with a flat surface leeside, here we have to counteract large nose up moments with very poor control effectiveness.

The performed test program for the triangular missiles was rather sparse regarding control surface deflections, consequently rudder effectiveness has not been investigated. However, to get a very rough idea about the ability to trim in yaw, we may look at elevator effectiveness with some "sense" and together with information from the more extensively tested cruciform configurations. By doing that it is found that the available trim force for the triangular body configurations with small fins is marginally too small to achieve trim for all roll angles and all (measured) angles of attack and Mach numbers. Note that this conclusion assumes that a deflection of 25° is reserved solely for rudder! At subsonic speeds the rudder effectiveness seems to be adequate for the configuration with rounded corners. The cruciform configurations are far from rudder authority limitations.

Aileron effectiveness is of course highly dependent on the span. The aileron moment arm is for the triangular configurations approximately 17% and 57% higher (rounded and sharp corners respectively) than for the circular body if the small control surfaces are used. So, unlike elevator effectiveness, the aileron effectiveness is substantially reduced due to the rounding of the corners. In Fig. 16 it can easily be seen that aileron effectiveness - at subsonic speeds and small incidences - is related between the different configurations with the same figures as the moment arm, in spite of the fact that the triangular bodies have only three surfaces. Consequently, the beneficial body carry-over interference (of which circular bodies have none) compensates alone for the reduction in the number of fins. This beneficial effect is not as regular for higher incidences, and is essentially reduced at supersonic speeds, also Fig. 16. Aileron effectiveness for the circular cruciform configuration in "x" position (not included in the graphs) is very much the same as for the "+" position.

If roll trim capability is required for all roll angles (with the small control surfaces and aileron deflection limited to 15°), the angle of attack for the triangular missile with sharp corners must be limited to about 17°, even though no other deflections are superimposed. The other configurations have a better situation here, but the configuration with rounded corners does only marginally achieve this for all tested angles of attack.

Influence of nose shape

Configurations with triangular body cross-sections and small fins, have also - to some extent but only subsonically - been investigated with a conical forward part of the nose. Besides a minor influence on drag, the only essential influence of this change has been found for pitching moment. This is quite interesting and tells us that all "laterals" are not sensitive to nose design, an observation that is not self-evident bearing in mind the influence of body vortices originating from the nose.

The largest influence on pitching moment was found when flying with a flat surface in leeward position, Fig. 17. It is noteworthy that the influence is largest for the sharp-corner body, whereas the geometrical change for the other body is more drastic, since a shorter blunt nose is replaced with a longer pointed one. The sharp-corner body exhibits almost the same nose influence on pitching moment also for other roll angles, for which the other configuration exhibits much smaller influence.

Discussion and Conclusions

Triform wingless missiles with triangular body cross-section, without any rounding of the body corners, have tremendously better aerodynamic performance (as measured by the lift-to-drag ratio) than corresponding cruciform missiles with circular cross-section. Rounding of the corners (to a considerable extent, as in the present investigation) will reduce this performance to be significantly no better than for circular bodies.

The most stealthy design (except for laser signature) has sharp body corners. This design is also well suited for the folding of fins (while rounded corners provide better location for axis bearings, among other mechanical design aspects). However, its longitudinal stability is very strong dependent on roll angle, making it very hard for the control system to manage skid-to-turn manoeuvring. This problem is reduced if the body corners are rounded.

Aerodynamic "cross-talk" at non-symmetrical onflow, as measured by the ratio of side force to normal force, is much higher for configurations with triangular rather than with circular bodies, and is essentially the same whether or not sharp corners are used. This is of considerable concern for the missile guidance, and hence also makes skid-to-turn manoeuvring less attractive.

Yawing moments are much higher without the rounding of the corners. However, for some reason they are still very high with rounded corners at supersonic speeds. There is no drastic change in yawing moments when fins are added.

The tested configurations with triangular bodies do not have any (stochastic) "symmetric laterals" at all for the tested angle of attack range. They are highly roll stable at zero roll angle (flat surface windward). This is also the roll angle for max lift-to-drag for the sharp-corner body (rounding of corners implies rather insignificant lift-to-drag roll dependence).

All these above mentioned qualities speak for bank-to-turn flying at zero roll angle.

Skid-to-turn is normally only interesting for missiles with high manoeuvrability. Flying true skid-to-turn requires the ability to trim all three moments at all roll angles within the whole angle of attack and Mach number range. This can, with the smaller control surfaces, only be achieved for the cruciform configuration with circular body cross-section. It might be possible (but not particularly good) for the triangular body with rounded corners if it is limited to subsonic speeds. With sharp corners it is impossible. The main obstacle is that the control authority will not be enough for all three moments at the same time. This is emphasized for the sharp-corner missile, for whom it is impossible to keep the longitudinal stability at a suitable level (requiring "adequate" elevator deflections) for all roll angles.

With larger control surfaces, about the size used in the present investigation, it seems possible to manage skid--to-turn for all configurations. This is mainly due to the fact that yawing moments do not increase very much because of larger fins (but rudder effectiveness does), but also that the roll dependence of longitudinal stability (for the sharp-corner configuration) is evened out and the elevator effectiveness is improved. Aileron effectiveness will remain adequate.

Triform controls have, in most cases, larger secondary effects of control deflection (e.g. rolling moment due to rudder deflection) than cruciform controls, and the control system has only three surfaces to command in order to handle this problem together with the other mentioned problems. As a consequence of skid-to-turn, a considerable part of the available control capability must be engaged for lateral trim, hence leaving a substantially reduced authority for manoeuvring. So, even though skid-to-turn means *quicker* manoeuvres, these may be quite *weaker* than what can be achieved with bank-to-turn, and therefore might end up with a less satisfying performance.

Considering this, it might be too challenging to design a skid-to-turn manoeuvring missile with a triangular body cross-section, also with larger triform fins. Such missiles are very well suited for bank-to-turn manoeuvring when flying with a windward flat surface. A true triangular body (with sharp corners) possesses much better aerodynamic characteristics than a body with rounded corners when flying bank-to-turn. Rounded corners though alleviate problems with skid-to-turn, especially for subsonic speeds.

Future research should include a detailed computational aerodynamics study of these configurations, as a complement to the experimental investigation, in order to obtain a better understanding of the exhibited interesting aerodynamic characteristics.

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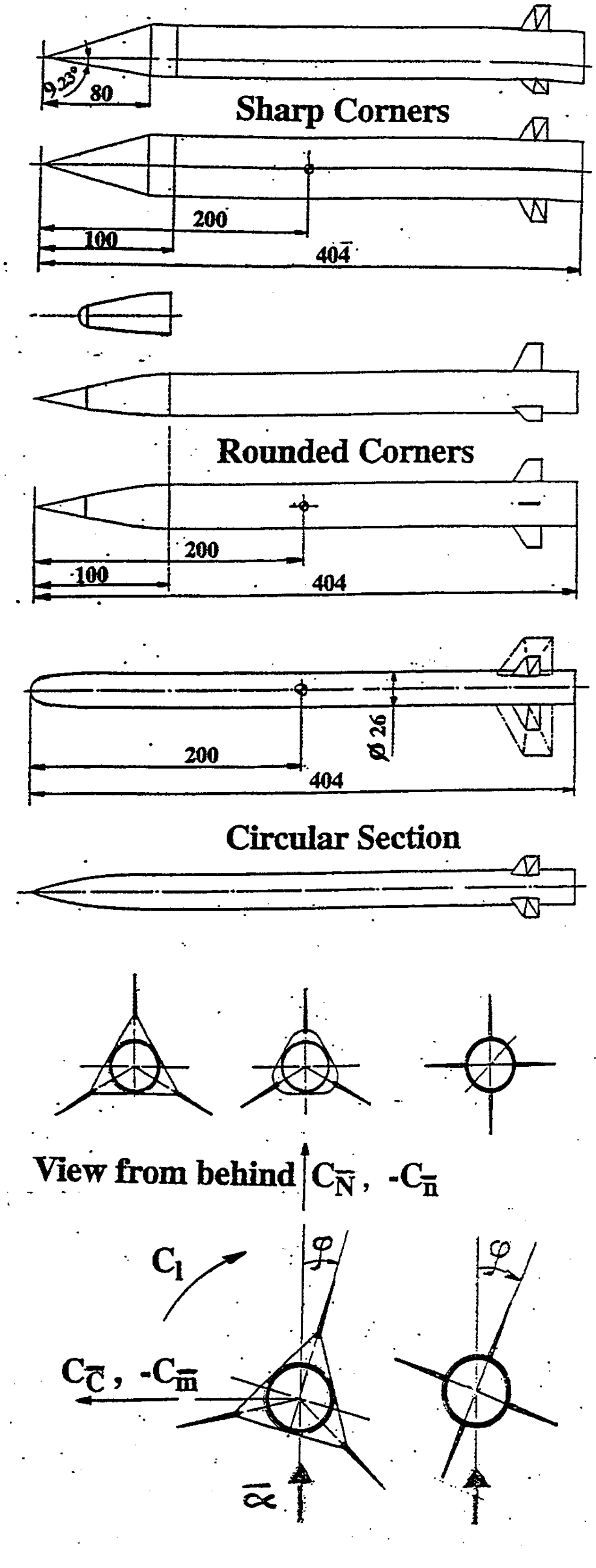


Fig. 1: Models geometry and definitions.

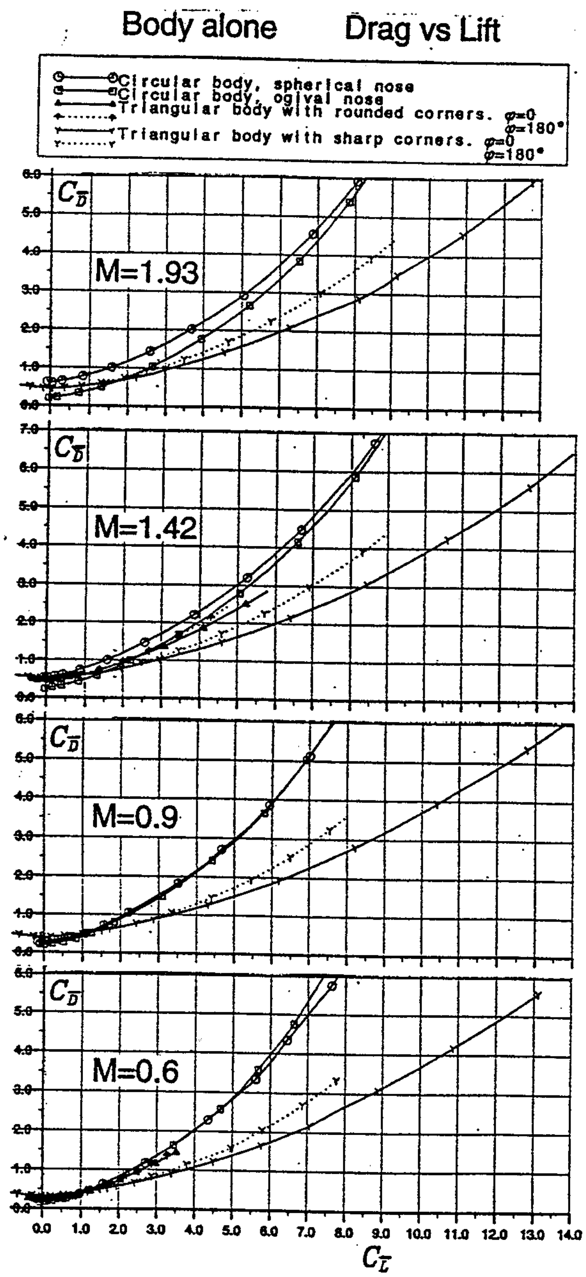


Fig. 2: Drag vs. Lift. Body alone.

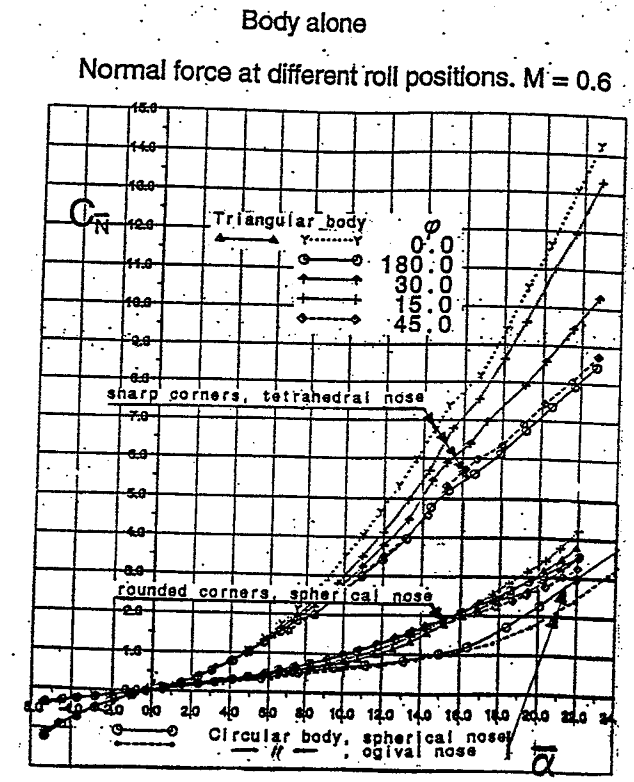


Fig. 3: Normal force of different isolated bodies. M=0.6.

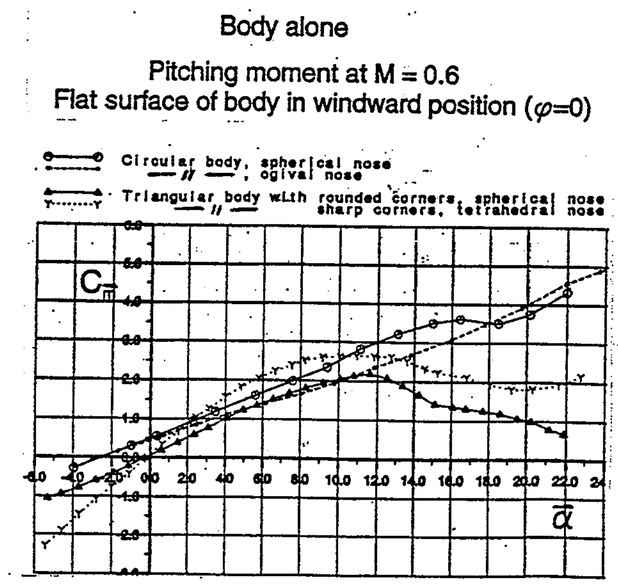


Fig. 4: Pitching moment of different isolated bodies. M=0.6.

Triangular body with sharp corners, tetrahedral nose
Body alone

Pitching moment at different roll positions

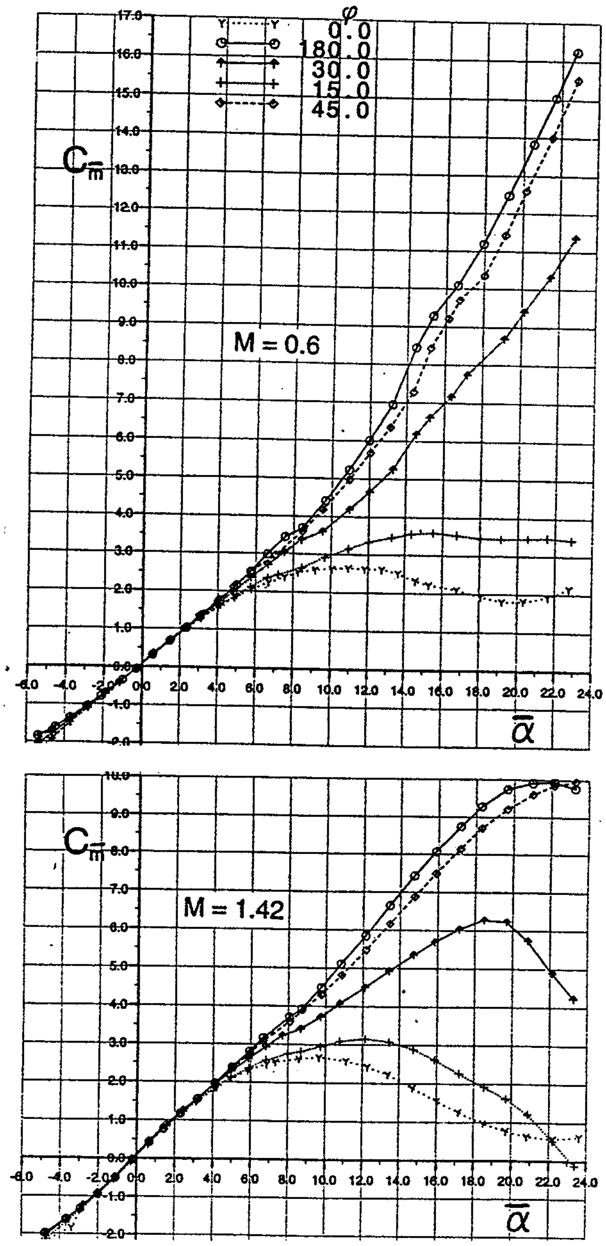
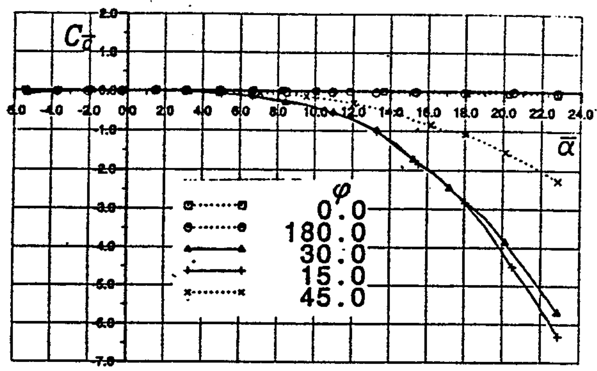


Fig. 5: Pitching moment of the isolated triangular body with sharp corners.

Body alone

Side force at different roll positions. M=0.6

Triangular body with sharp corners, tetrahedral nose



Triangular body with rounded corners, spherical nose

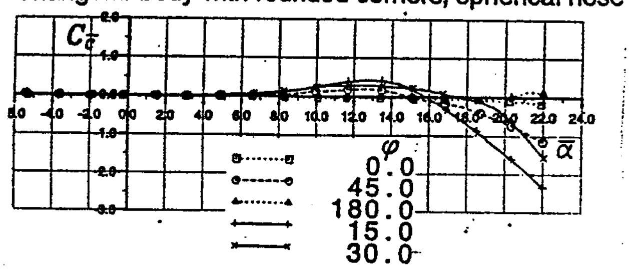


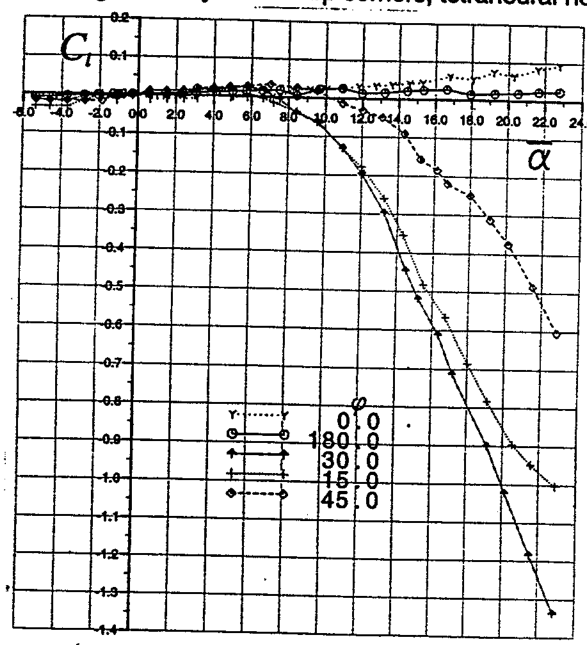
Fig. 6: Side force of the isolated triangular bodies with sharp and rounded corners. M=0.6.

Body alone

Rolling moment at different roll positions. M = 0.6

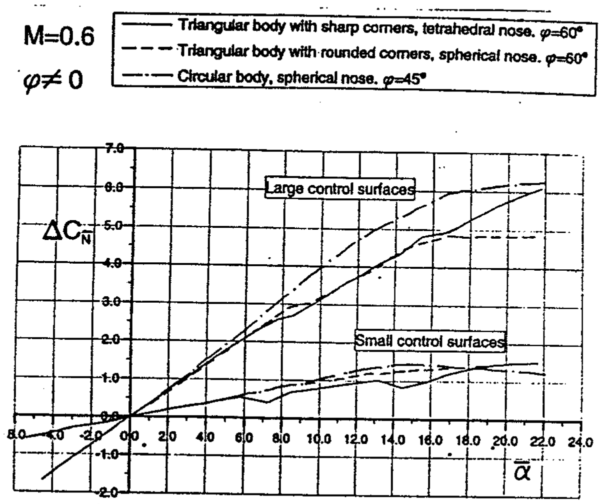
Normal force due to control surfaces (δ=0)

Triangular body with sharp corners, tetrahedral nose



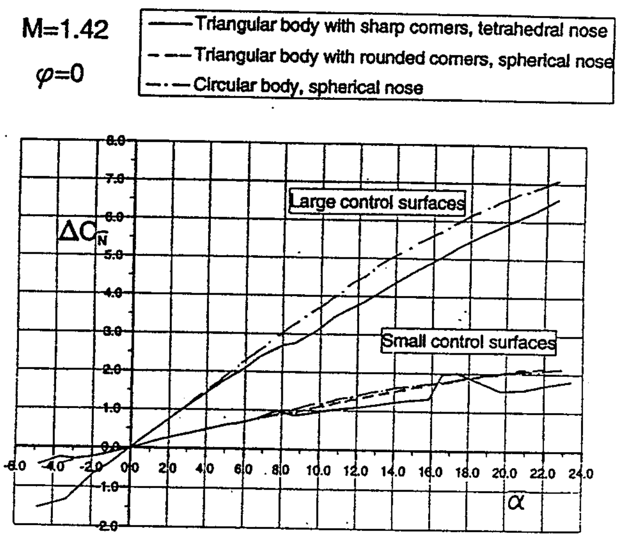
M=0.6

φ≠ 0



M=1.42

φ=0



Triangular body with rounded corners, spherical nose

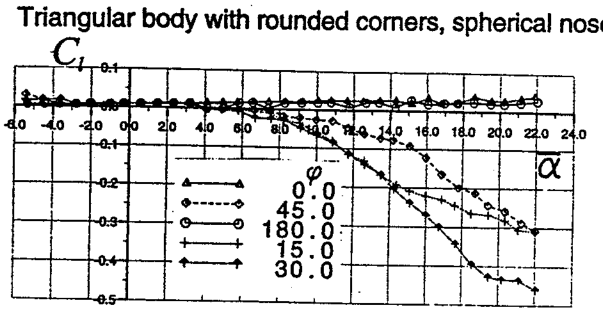


Fig. 7: Rolling moment of the isolated triangular bodies with sharp and rounded corners. M=0.6.

Fig. 8: Normal force increment due to control surfaces (at zero deflection).

Triangular body with sharp corners, tetrahedral nose

Body with small control surfaces

Pitching moment at different roll positions. M=0.6

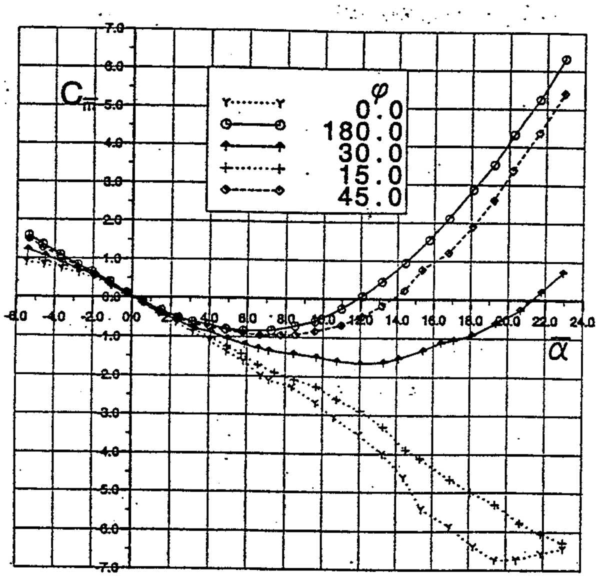


Fig. 9: Pitching moment of the triangular body with sharp corners and small control surfaces. M=0.6.

Triangular body with sharp corners, tetrahedral nose

Body with large control surfaces

Pitching moment at different roll positions. M=1.42

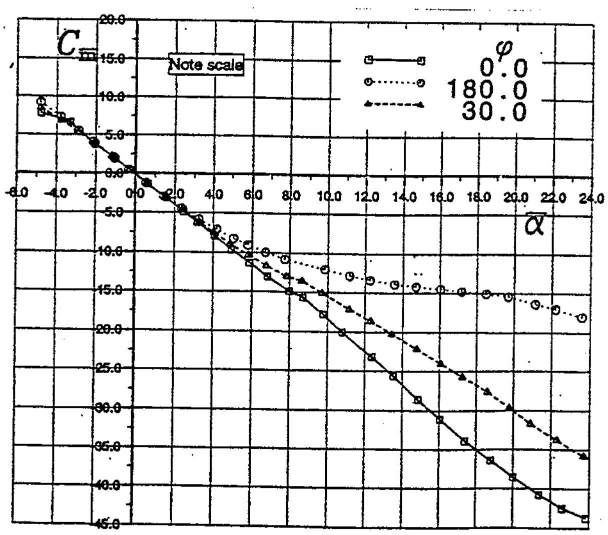


Fig. 10: Pitching moment of the triangular body with sharp corners and large control surfaces. M=1.42.

Triangular body with sharp corners, tetrahedral nose

Yawing moment at φ=30°, M=1.42

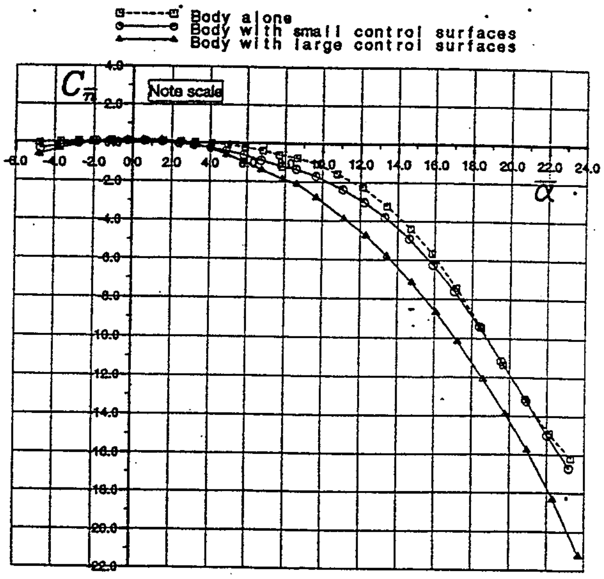


Fig. 11: Yawing moment of the triangular body with sharp corners. Effect of different control surfaces. M=1.42.

Body with small control surfaces

Effect of different body cross section forms

Yawing moment

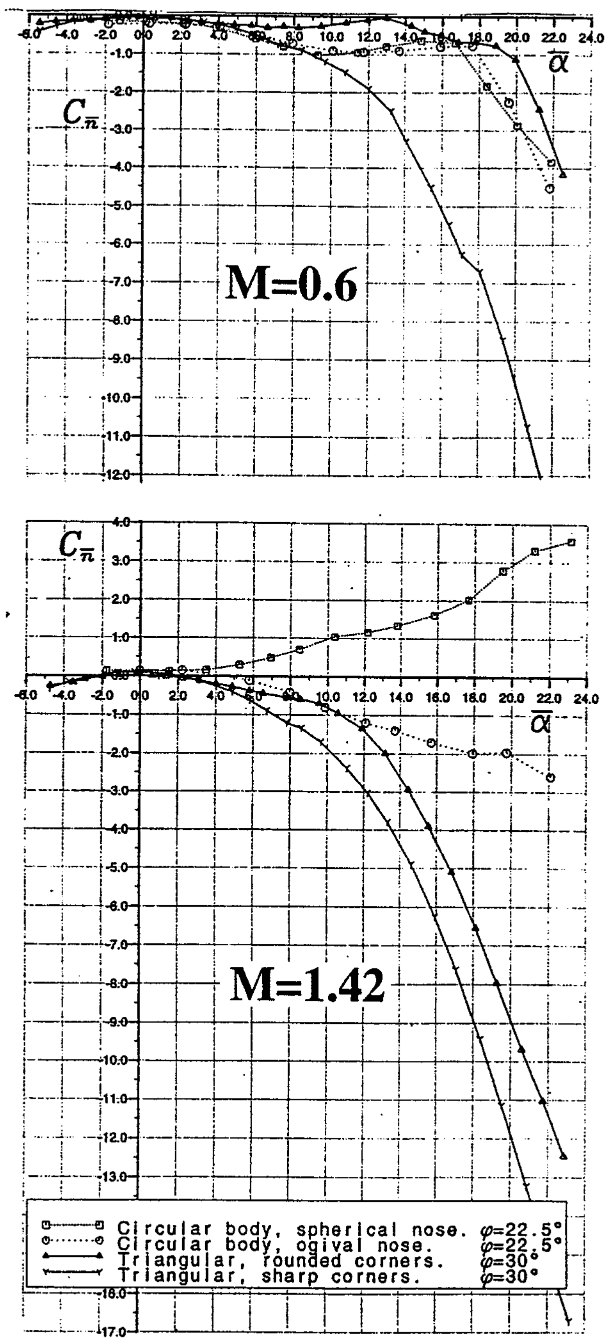


Fig. 12: Yawing moment of configurations with small control surfaces and different bodies.

Triangular body with sharp corners, tetrahedral nose

Body with small control surfaces

Rolling moment at different roll positions. M = 0.6

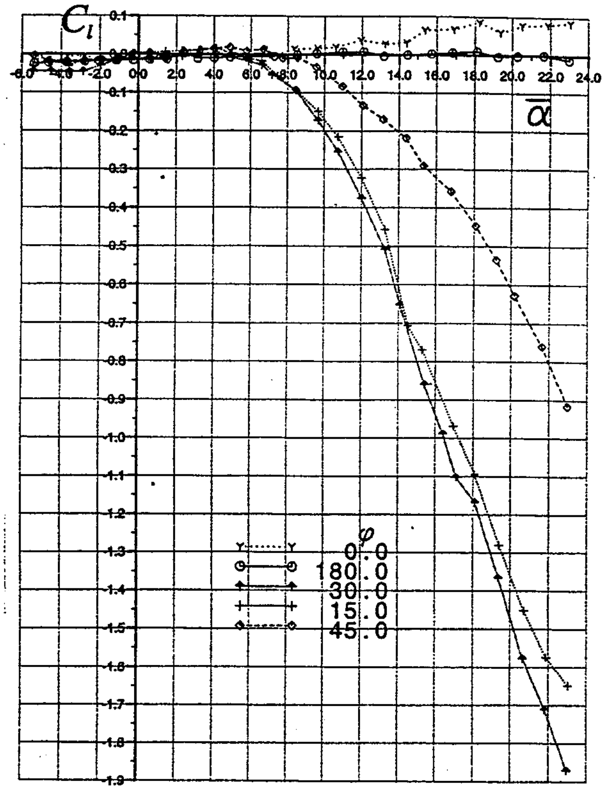


Fig. 13: Rolling moment of the triangular body with sharp corners and small control surfaces. M=0.6.

Body with small control surfaces

Rolling moment at a=20°. M=0.6

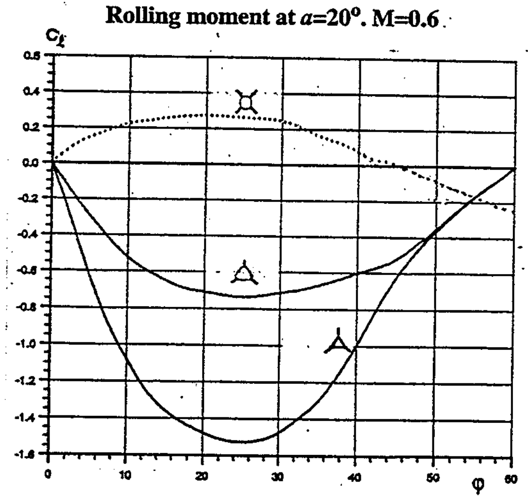


Fig. 14: Rolling moment vs. roll angle. Different configurations at α=20°. M=0.6.

Elevator effectiveness, small control surfaces

Non-rolling axis system

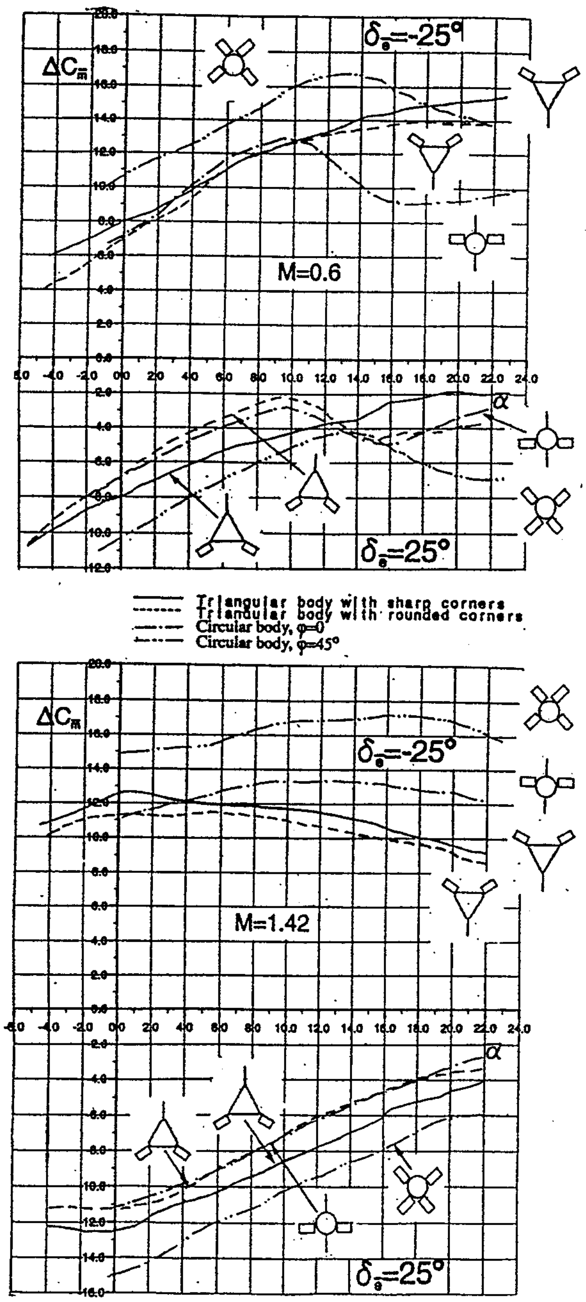


Fig. 15: Elevator effectiveness of different configurations with small control surfaces.

Aileron effectiveness, small control surfaces

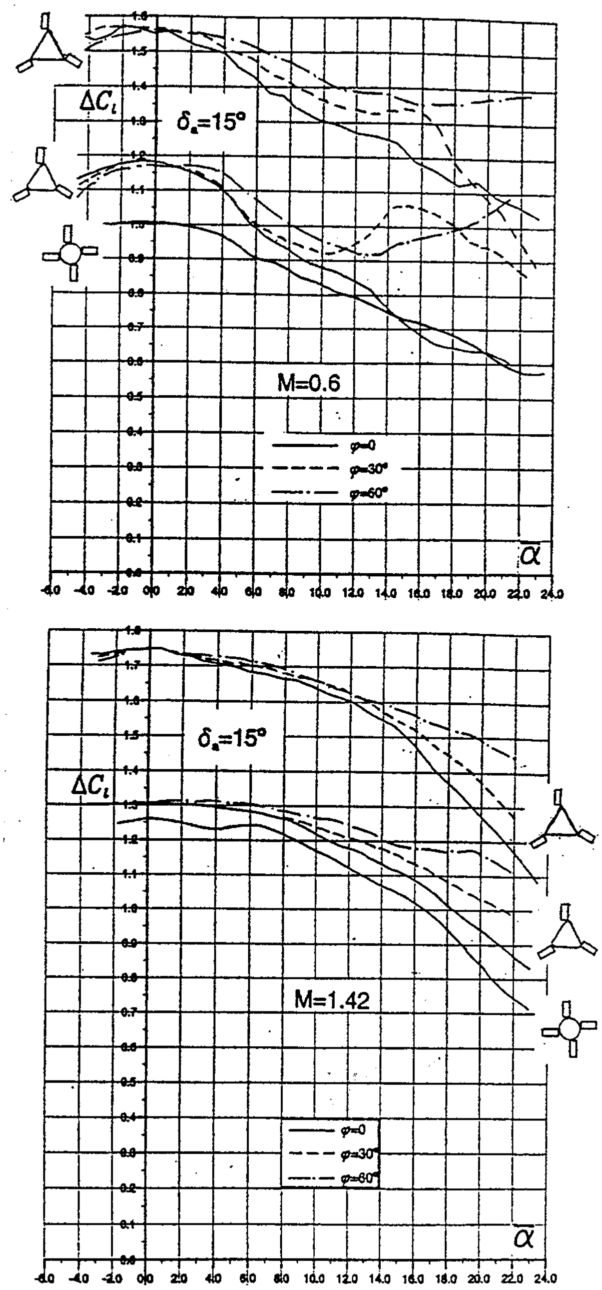


Fig. 16: Aileron effectiveness of different configurations with small control surfaces.

Pitching moment at φ=180°, M=0.6

Effect of nose shape

Body with small control surfaces

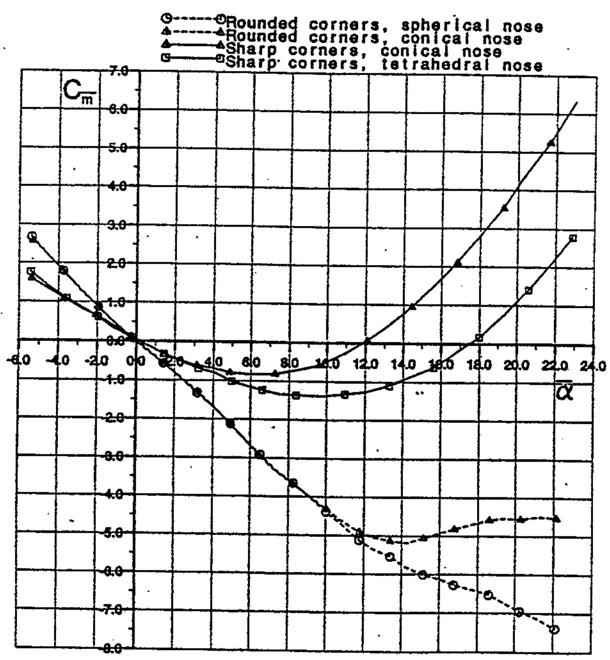


Fig. 17: Effect of nose shape on pitching moment. M=0.6