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WIND TUNNEL INVESTIGATION OF A HIGH L/D PROJECTILE WITH GRID FIN AND CONVENTIONAL PLANAR CONTROL SURFACES

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The present wind tunnel investigation is part of a project studying the effectiveness of grid fin controls on missiles and projectiles. As part of this program, wind tunnel tests were conducted over a range of Mach numbers from 0.5 to 3.0, and aerodynamic coefficients were generated for various body configurations. A second model, with conventional planar surface controls, was also studied under the same conditions. Increase axial force, reduced normal force, and a marked reduction in static stability for the grid fins configuration over the conventional one were the results of this comparison. Another interesting result from the grid fin model, which was shown during the build-up component study, is that the two elevators generated almost 100% of the normal force of the complete body.

INTRODUCTION

To aid in the evaluation of the performance of a novel missile control under study (lattice controls), a baseline missile configuration utilizing conventional, planar controls has been designed. This missile is intended to represent a typical Tail Controlled Air-to-Air Missile (TCAAM). This configuration was developed as part of an international research program investigating what advantages lattice controls may offer over conventional controls when employed on highly manoeuvrable air-to-air missiles. Grid fins, also known as lattice control devices, are unconventional aerodynamic control devices that consist of an outer frame that supports a unique, internal grid of lifting surfaces. Aerodynamic advantages associated with this type of design are a near-zero hinge moment, resulting in reduced control actuator requirements, and favorable lift characteristics at high angles of attack and high Mach numbers (conditions typical of agile air-defence weapons). Absence of fin stall typical of conventional controls at high combined angles of attack and control deflection, and more linear control effectiveness, are representative of these interesting lift characteristics. However, a particular disadvantage for many applications is the generally high level of drag, which can be several times that of planar control surfaces.

This work is part of an overall international program and involves semi-empirical simulations, analytical development, wind tunnel experiments and finally free flight firings. The present phase of this project is composed of a wind tunnel experiment to measure aerodynamic coefficients on a scale version of this flight vehicle and assess the performance of lattice controls in comparison with conventional control surfaces. The experiments were carried out for a wide range of Mach numbers, from 0.5 to 3.0. Several roll positions and projectile pitch angles were also investigated.

BACKGROUND

Research projects on grid fin technology (lattice fins) have existed for more than a decade. The main objective behind this research is to study the possibility of enhanced dynamic stability and control capability at high angles of incidence shown by these structures. Figure 1 shows a close-up view of some of these fins on a cylindrical body. The unconventional structure of these fins comprising stronger outer frame supporting an inner grid system of intersection planar surfaces is well demonstrated in it. Various organizations have studied the workings of these fins using experimental testing [1,2,3], analytical methods [4,5] and more recently, computational fluid dynamics [6,7].

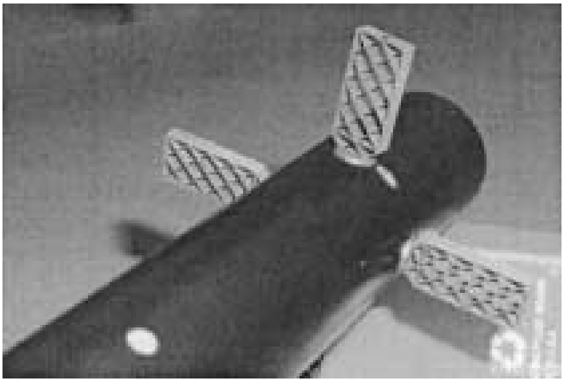

Figure 1. Lattice control.

These studies have confirmed some aerodynamic advantages of grid fins over their planar counterparts, but have also displayed some important disadvantages. The ability to maintain lift at large angles of attack is the major factor leading to grid fin investigations for short range air-to-air missile. Additionally, because of their short chord, a reduced hinge moment is required to actuate them, which leads to savings in volume and weight for the actuators. Their structure also allows them to be stowed along the body of a missile without causing an increase in storage dimensions, until they are needed in flight. However, because of their obvious structure (obstacle to the flow field), they tend to generate higher values of drag than the equivalent planar fins. Specific wind tunnel experiments [2] have shown that this problem can partially be solved by optimising the design process of the grid fin itself. Potential problems in the transonic regime have also been identified

Home
Table of Contents

through the various wind tunnel experiments during the last few years. Choking of the flow through the cells has been identified to explain this transonic behavior.

EXPERIMENTAL SITE AND INSTRUMENTATION

The DREV wind tunnel, shown schematically in Fig. 2, is an intermittent, in-draft wind tunnel with a 0.6 m x 0.6 m test section. Because of its in-draft characteristics (air flowing from an atmospheric pressure tank to a vacuum tank), values of Reynolds numbers are lower than the free-flight values during tests at high Mach numbers. The range of Reynolds numbers for this test series varied between 9.50 x 10^6/m (for Mach number = 0.5) to 6.0 x 10^6/m (for Mach number = 3.0). Tests were performed at 7 Mach numbers (0.5, 0.75, 0.9, 1.15, 1.5, 2.0, and 3.0). The useful duration of testing for these conditions was around 7 seconds.

The testing sequence consisted in performing a series of force and moment measurements using wind tunnel balances. For these tests, the model was swept (in pitch) over a range of angles of attack varying between –12° to +12° for the seven Mach numbers under investigation. The model was also tested at two roll indexation angles (0° and 45°). Finally, fins were canted in pairs (rudders or elevators) at 10°, 20° and 30°. No roll configurations were tested. Simultaneously, the base pressure was measured to allow the data analysis system to calculate the base drag and provide the forebody drag component of the total drag.

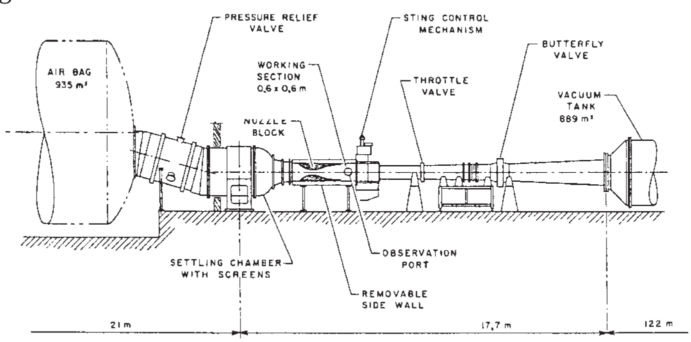

Figure 2. DREV intermittent in-draft wind tunnel.

Thereafter, aerodynamic coefficients were derived from the test results. It should be mentioned that the Moment Reference Point is measured from the base of the model.

MODEL AND TEST CONDITIONS

The model used for this experiment is based on a modalar concept (developed for a previous series of tests [8]), with a 30 mm diameter main body, and a total length of 480 mm (1/d of 16). The body geometry consists of a 3D tangent-ogive nose attached to a 13D cylindrical body. This model is composed of 3 modules: one for the nose, one for the mid-section, and finally, one for the tail section of the model. The complete wind tunnel model is held in the tunnel test section by the strut hub – sting support – balance combination system. Two types of fins were also developed for this experiment. These fins were developed with the objective of having a similar pitch control at a specific Mach number (Mach 3.5). The first series of fins is of a clipped delta shape, with a height of 0.90 calibers. The truncated delta planform has been chosen to typify the type of conventional fin used on air-to-air missiles, this planform combining the small travel of delta fins with the greater normal force properties of rectangular fins. The second set of fins is of a grid fin design, and is 0.67 calibers high. The number of cells used in this fin design and the thickness of the various webs are presented in Fig. 3.

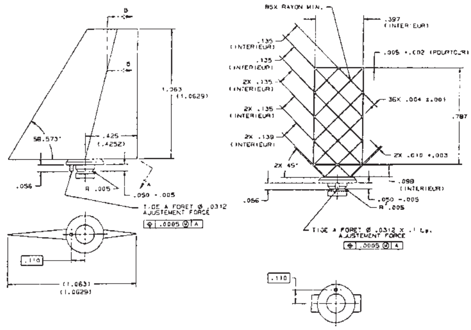

Figure 3. Fins of TCAAM.

The next figure (Fig. 4) shows pictures of the actual wind tunnel model for each one of these control systems.

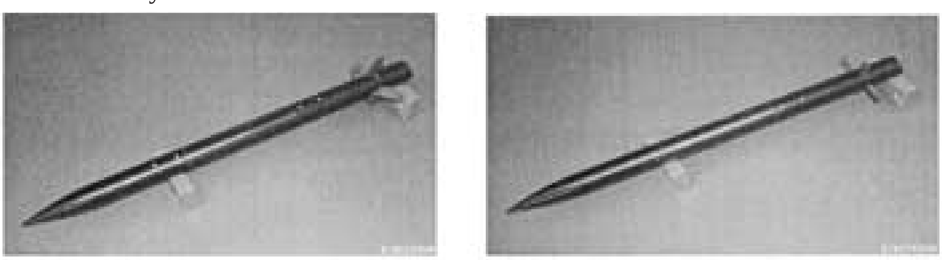

Figure 4. Planar and grid fin control models.

RESULTS

As a large amount of infornnation was generated through this wind tunnel experiment, only significant results were selected for presentation in this report. The absolute accuracy of the wind tunnel results has been estimated through previous run campaigns. Likely errors to be encountered in axial force, in normal force and in pitching moment coefficients are of the order of ± 5%, ± 3% and ± 1.4% respectively with a 0.03 caliber error in the location of the center of pressure [9].

Axial Force Data

Figure 5 shows the axial force coefficient in terms of the body angle of incidence for the grid fin and planar fin models, over the range of Mach numbers tested.

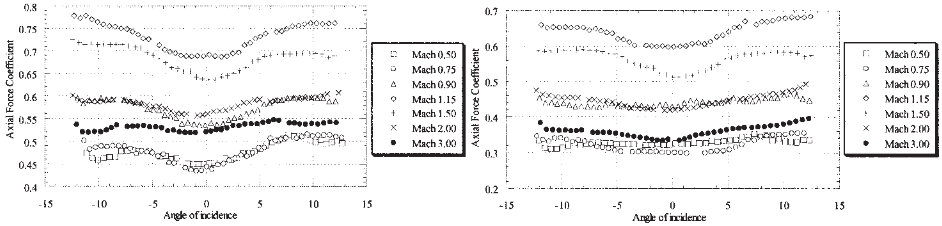

Figure 5. Axial force coefficient for the grid and planar fin models.

The data on both of these figures present the same general trends. First, the axial force coefficient on the models is fairly constant through the subsonic region. Then, a large increase is seen through the transonic region, from Mach 0.9 to 1.15. This is followed, in the supersonic regime, by a slow decrease, as expected through this region. Also shown by these curves, for both models, is a decrease over the range –5° to +5°. It is known that the shape of the leading edge of a body can influence the boundary layer flow and hence the overall drag at low angles of attack [10]. For an ogival nose section like the present body, transition on the leeward side of the body is not observed until higher angles of attack (compared to immediately upon departure from zero angle of attack for a sharp nose). This results in an axial force coefficient curve with a distinct region of reduced drag around 0° (often referred to as a “drag bucket”). Finally, as expected, are the larger values of axial force for the grid fin cases, when compared to their respective planar fin cases.

A build-up method was used to install the grid fin model in the wind tunnel, and various configurations were tested to provide an exhaustive database on this body. Figure 6 shows some of these results, for one Mach number only (Mach 3.0). Results for a clean body (no fins), a body with only 2 elevators (horizontal grid fins), a body with only 2 rudders (vertical grid fins), and a complete model (4 grid fins) are presented in this figure. The increase in axial force generated by the addition of the various components (fins) is very obvious from this figure. One interesting result is the small axial force difference at large angles of attack (above 5°) between the two fin cases (rudders and elevators). The case with only rudders generates a larger axial force than the case only with elevators. One possible explanation for this behavior is that the grid fin on the leeward side of the model (rudders only) starts choking because of its position on the model, thus generating a larger axial force than a completely functional fin. The windward fin sees the non-disturbed flow field during the whole run. Similarly, for the case with elevators only, the two fins always see the same non-disturbed flow field during the whole run.

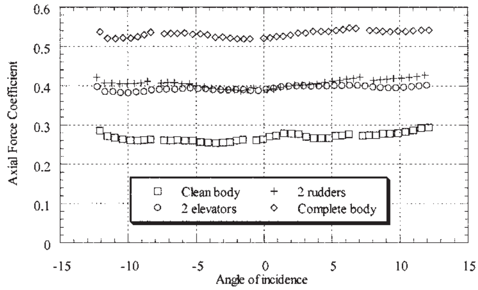

Figure 6. Axial force coefficient for build-up grid fin model.

The next figure (Fig. 7) shows the axial force coefficient at 0° angle of incidence (CA_0) through the Mach number range tested. All four cases show the same general trend through this Mach number range. Again, it is easy to note that the axial force coefficients for the planar fin model are substantially lower than the values for the grid fin model. AB range data [11] have been generated on this projectile (grid and planar fins). The second graph of Fig. 7 shows zero yaw axial force coefficients versus Mach number for these 2 cases, compared to their wind tunnel counterpart.

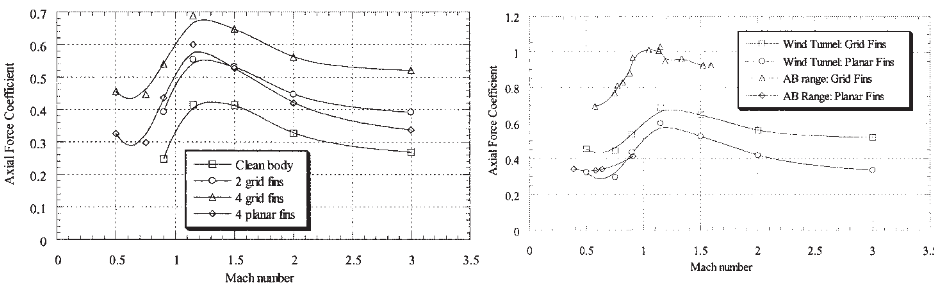

Figure 7. Zero yaw axial force coefficient versus Mach number.

The wind tunnel results follow the trends shown by the AB range results very well, for both models. Differences between the respective curves can be explained by several factors including base drag corrections and differences in boundary layer conditions between the two facilities. The major difference between grid fin results between the two facilities is generated by a physical difference between the models: the web thickness to cell size ratio. Due to gun launch conditions, the grid fin cell walls were thicker for the free-flight model (between 0.125 and 0.175 mm), when compared to the wind tunnel cases (0.100 mm). Thus, larger axial force components were generated by these multiple obstacles, which led to this large axial force difference between these models.

Normal Force Data

The second section of results is covering the normal force data generated in the wind tunnel. Figure 8 shows this coefficient at one specific Mach number (3.0) for both planar and grid fin models. As expected, the normal force coefficient increases as the angle of attack increases, for both models. The overall design philosophy behind these two models was for the grid fin model to impart an identical level of longitudinal static stability to the baseline body as the conventional fin, that is $d(C_M)/d(\alpha)$ should be the same for both fin variants. Approximately, this is the same as designing the grid fins to have identical incremental normal force slopes than the planar fins.

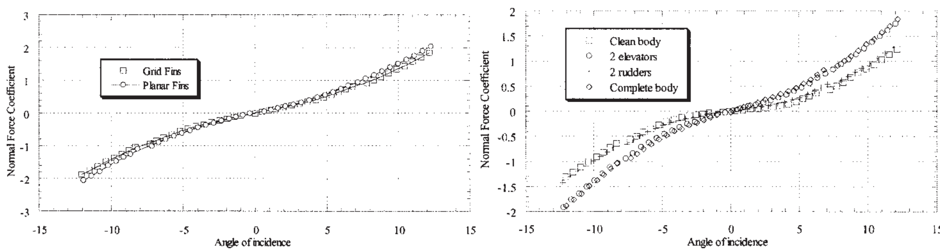

Figure 8. Normal force coefficient for planar and grid fins at Mach 3.0.

The figure shows that this objective was mostly accomplished (baseline Mach number of 3.5 was selected in the design). The second graph of this figure presents an interesting fact about grid fin models. Again, these results are for a Mach 3.0 case, for various grid fin body configurations. For the purpose of generating normal force, the two rudders (vertical fins) have a near zero efficiency, as the clean body and the two rudders curves are almost similar. This was not expected as we originally thought that the rudders would generate a small fraction of the normal force, thus presenting a curve between the clean body and the complete model. Therefore, for the present cases and configurations, two elevators generate almost 100% of the normal force for this body (same pattern seen at other Mach numbers).

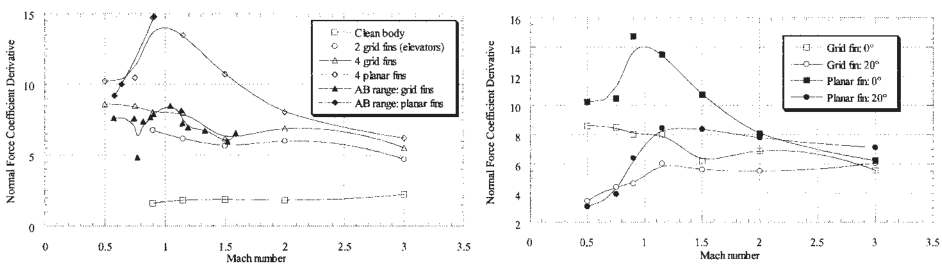

Figure 9. Comparison of the normal force coefficient slope.

Home
Table of Contents

Figure 9 shows the normal force coefficient derivative through the Mach number range tested, for various configurations (build-up method) and against AB range data [11]. As the Mach number increases (above Mach 2.0), planar and grid fins produce around the same normal force. However, between Mach 0.75 and Mach 1.5, the grid fins generate significantly less normal force then the planar fins. This difference in normal force generation between these fins can be explained by choking and internal shock reflections inside the various grid fin cells. In general, the trends shown by the AB range results are well followed by the wind tunnel data. However, the sharp decrease in the normal force coefficient derivative around Mach 0.77 is not reproduced by the wind tunnel data. The final figure of this section (second graph of Fig. 9) on normal force coefficient is to present some results with fins canted at various angles (0° and 20°) for both configurations. Subsonically, and for large fin cant angles (20°), the grid fins generate a larger component of the normal force than the planar fins. However, over all other testing conditions, the grid fins show lower normal force than the equivalent planar fin cases.

Pitching Moment Data

The two graphs of Fig. 10 are presenting some overall pitching moment data for the complete grid fin and planar fin models. These graphs show the same general trend for both grid and planar fins with respect to Mach number. Additionally, it clearly shows a switch in the static stability of the grid fin configuration in the high supersonic flow regime. It also shows the effect of canted fins on the models. Both planar and grid fin models show a decrease in static stability with increasing Mach numbers, and with increasing fin deflections.

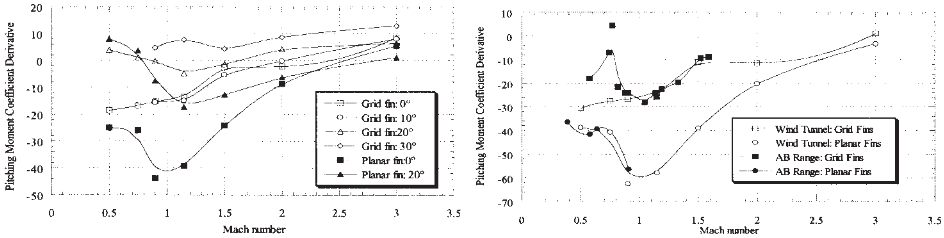

Figure 10. Pitching moment coefficient derivative for grid and planar fin cases.

The Moment Reference Point (MRP) for the data in the second graph of Fig. 10, and for Fig. 11 has been modified to correspond to the location used in [11], to allow for easy comparisons. The second graph of Fig. 10 shows pitching moment coefficient derivative over the full range of Mach numbers, for both planar and grid fins models, from both facility (DREV wind tunnel and AFRL AB range). Again, the overall trends from the free flight tests are very well followed by the wind tunnel data, and a loss in static stability for both models in the supersonic regime is shown by the results. These results also show that the grid fin model is less stable than the planar fin model through the whole Mach number range of this experiment. However, the discontinuity around Mach 0.77 for the grid fin AB range results is not reproduced in the wind tunnel data.

Center of Pressure Data

Figure 11 summarizes the center of pressure results over the range of Mach numbers. Additionally, free flight results have been added for the purpose of comparison [11].

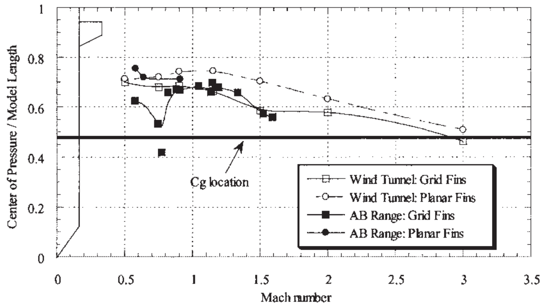

Figure 11. Comparisons to aeroballistic range results.

The location of the center of gravity of the model (and the MRP) has also been added to the picture. Again, the general trends demonstrated by both wind tunnel and free flight results are very similar. As indicated previously, the discontinuity in the free flight results around Mach 0.77 was not picked up by the wind tunnel instrumentation. The reduction in static stability (difference between the location of the center of gravity and the center of pressure) for both planar and grid fin models as the Mach number increases is well supported by this figure. These curves also show that the planar fin model is always slightly more statically stable than the grid fin model.

CONCLUSIONS

The present wind tunnel investigation is part of an international project studying the effectiveness of grid fin controls on missiles and projectiles. As part of this program, wind tunnel tests were conducted over a range of Mach numbers from 0.5 to 3.0, and aerodynamic coefficients were generated for various body configurations. A second model, with conventional planar surface controls, was also studied under the same conditions. Increased axial force, reduced normal force, and a marked reduction in static stability for the grid fins configuration over the conventional one were the results of this comparison. Another interesting result from the grid fin model, which was shown during the build-up component study, is that the two elevators generated almost 100% of the normal force of the complete body.

Very good agreement was demonstrated between the present wind tunnel results and actual free flight data on the same two projectiles. The information generated through this wind tunnel experiment constitutes an important dataset in the framework of this international collaboration for CFD validation and semi-empirical/analytical code development.

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