Aerodynamic Analysis of Projectiles in Ground Effect at Near-Sonic Mach Numbers

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The behavior of projectiles at Mach 0.9, 1.1, and 1.2 when in close proximity to a surface were investigated using a synergy of live-range test firings, wind-tunnel experiments, and computational fluid dynamics simulations; the latter provided the majority of the insight into the problem. Building on work that previously indicated significant ground influence for a projectile at Mach 2.4 due to shock reflections, a similar projectile was investigated for ground clearances of height-to-diameter ratios from 0.25 to 8. It was found that at Mach 0.9 the projectile’s drag, normal force, and pitching moment coefficients changed predictably, and with significant increasing magnitude below \(h/d = 2\). Drag increased, a strong normal (suction) force acting toward the ground developed with increasing strength of the shock developing on the lower side of the projectile, and a nose-up pitching tendency was established. At the supersonic Mach numbers, the ground influence was present at higher ground clearances, and influential shock reflections occurred; at high clearances, the reflected shock increased the pressure on the lower side, and at low clearances (\(h/d < 1\)), the reflecting expansion waves lowered the pressure to produce a pronounced negative normal force. At the lowest investigated clearances, drag was approximately 30% higher, and the Mach 1.2 cases experienced more substantial fluctuations in the trends. The normal force and pitching moment behaviors would be unlikely to influence the projectile’s path over any realistic distance, but the ground proximity drag increase would significantly alter the projectile’s deceleration and therefore trajectory response.

\[ C_D = \text{drag force coefficient in the } x \text{ direction, based on projected frontal area} \]
\[ C_M = \text{pitching moment coefficient positive is nose up based on center of gravity, projected side area} \]
\[ C_N = \text{force coefficient acting normal to ground plane, based on projected side area} \]
\[ C_P = \text{pressure coefficient} \]
\[ C_Z = \text{side force coefficient in } z \text{ direction, based on projected side area} \]
\[ d = \text{projectile diameter, mm} \]
\[ h = \text{height above ground plane, mm} \]
\[ k = \text{turbulent kinetic energy} \]
\[ l = \text{projectile length, mm} \]
\[ M_{\infty} = \text{freestream Mach number} \]
\[ s = \text{shock standoff distance from tip, mm} \]
\[ \omega = \text{angular velocity} \]

1. Introduction

W\(\text{hen a ballistic projectile or lifting craft operates in close proximity to the ground, its aerodynamic properties can change substantially. At subcritical Mach numbers, this behavior is generally predictable, and pressure distributions change gradually at all but the most extremely low clearances (usually defined as being lower than 10% of the reference length of the object in question). Ground proximity can lead to a marked increase in lift for a wing, accompanied by a less pronounced increase in overall aerodynamic efficiency. These characteristics have led to interest in craft that can take advantage of this performance improvement as well as a need for better understanding of ground effects for vehicles that can only operate in this regime, such as high-speed trains and maglev transport}\([1]\).

However, when shock waves exist in the flowfield, the behavior becomes less predictable. Depending on the camber and incidence of said wing, a shock may first form on the lower surface before the upper one, destroying significant amounts of lift and influencing the wake\([2]\). Relatively small changes in the ground clearance can cause a rapid, shock-induced change from the enhanced lift to reduced lift and even downforce, making the transonic region a difficult one to navigate in the ground effect from a performance/stability standpoint. In addition, the critical Mach number of a body will be reached earlier when in the ground effect, potentially bringing forward any consequences for a buffet and marked drag rise\([3,4]\).

As a more bluff and preferably aerodynamically neutral body, a projectile will exhibit different behavior in the ground effect. The aerodynamic performance of projectiles has been the subject of many investigations since the advent of the firearm. Advances in the field of external ballistics with the aid of modern visualization techniques and increasingly more common and sophisticated numerical investigations have enhanced the understanding of stability, performance, and long-range accuracy. The influence of a proximal plane or immovable object has received scant attention, however, and few studies to date on this matter have uncovered the first real insight into the ground effect on projectile forces and coefficients. The only other
close analogy that has been studied in adequate detail in the literature is the rocket sled, albeit at a much larger scale. Studies on vaguely projectile-shaped geometries at transonic and supersonic Mach numbers and in the ground effect indicate that sudden changes in the lift and drag, and even lift reversal, may occur, depending on the strength and location of shock reflections relative to the body [1]. Additionally, there are data to suggest that acceleration or deceleration can also exaggerate the sensitivity of these forces to the Mach number, ground clearance, or both in combination [1]. As a possible scenario, the firing of rounds in an urban combat situation could involve projectiles travelling in close proximity to walls or other surfaces; successful impact upon a target would, of course, be the goal, yet changes to the aerodynamic force coefficients could potentially affect trajectories even over relatively short ranges.

The aerodynamic performance of a projectile at Mach 2.4 has been previously reported for ground proximities ranging from height-to-diameter ratios \( h/d \) of 0.3 to 3. Incorporating a series of unique experiments using live ammunition on a firing range [5,6], wind-tunnel testing [7], and extensive numerical simulation [8–11], the study provided detailed information about how projectile trajectories may be affected by the influence of the ground effect, and a novel means of emulating the ground effect in the blowdown wind tunnel was also developed as part of the work [7].

A complex process of wave/ground interaction and reflection occurred as the projectile initially passed over the ground plane, swiftly reaching a relatively steady state in which the shock angles did not change and the reflections remained remarkably constant. The turbulent wave structures showed deflection and distortion, indicating the altered pressure fields caused by the ground proximity. The study identified three regimes of interaction that affected the aerodynamic properties of the body [10]; at a height-to-diameter ground clearance of greater than 1.3, the bow shock reflected from the ground plane into the far wake, and little to no effect on the forces and moments was observed. At lower clearances, the bow wave reflecting into the near-wake region reduced the drag by increasing the pressure near the base. Below \( h/d = 0.75 \), the shock reflected back onto the projectile one or more times. This produced a strong normal force away from the ground plane, and the wake was notably thickened and deflected downward. Because the projectile was spinning, it was inferred that this upward normal force would, in fact, cause a lateral movement due to the precession effect. The flowfields were shown to be highly three dimensional and complex, indicating that computational fluid dynamics (CFD) was required to properly understand the results in coordination with a multipronged experimental campaign. As a result, the same approach was applied for the present study for transonic Mach numbers.

Advanced numerical approaches to projectile problems, such as large-eddy simulation and detached-eddy simulation [12,13] and various refinements allowing a very accurate determination of the more complex coefficients and behaviors inherent in projectile flight, are increasingly common in projectile studies [14–24]. The study described in the present paper does not attempt to use the aerodynamic forces and moments predicted by computational modeling to undertake a full trajectory prediction analysis, although such a process has been proven as successful in comparison to experimental measurements. Such studies have shown that the motion of a spinning projectile at an angle of attack to the freestream depends heavily on the accurate prediction of damping derivatives and Magnus coefficients, though only the latter was considered in the simple form in the present investigation in which all simulations were conducted for a zero angle of attack. Magnus coefficients have been shown to be particularly sensitive to the periodic vortex shedding in the wake, though steady-state lift and drag force coefficients compare satisfactorily to experimental data when placed next to results from transient simulations [17].

Figure 1, which comprises symmetry plane density contours from CFD for visualization, introduces the salient flow features of the projectile at a) Mach 1.1 and b) 0.9 in free flight (symmetry model) and at Mach 1.2 in the ground effect. When supersonic, a strong detached bow wave sits forward of the nose, and there is a rapid recompression (and slight overcompression) of the flow as it transitions to the ogive-esque forebody. The second geometric transition, to the cylindrical main body, is relatively strong and produces a significant expansion wave. The base presents essentially a 90 deg corner, and the free shear layer that forms the bounding region of the wake encloses a strongly recirculating zone narrower than the projectile, causing another expansion wave, and also serves as the foundation for the trailing recompression shock that is required to turn the flow back to parallel. When in the ground effect (Fig. 1c), the flowfield exhibits multiple wave reflections; the bow shock interacts with the ground and forms a semiregular reflection, distorted by interactions with the secondary compression waves and expansion waves from the forebody. At this particular clearance, the reflected shock impinges on the projectile at the origin of the first main expansion wave; evidence of its propagation around the projectile and onto the top surface can be seen in the new wave downstream of the expansion zone at the forebody–cylinder junction. The multiple expansion wave reflections lower the pressure on the ground side and draw the wake downward. The Mach 0.9 case exhibits a strong normal shock over the cylindrical main body, behind the center of gravity of the projectile. The boundary layer thickens but does not separate at the shock foot, and the shock itself is strongly influenced by its close proximity to the rapid expansion from the forebody to the main body that accelerates the flow to supersonic.

Stillss from the high-speed schlieren video of the experiments, in Fig. 2, show the Mach 1.1 projectile passing over the leading edge of the ground plane, and both preliminary numerical and experimental analyses of the shock behavior in that situation confirmed that the flowfield took time to change and reestablish to a new state. This is in contrast to previous testing at Mach 2.4 where the new flowfield was established almost instantaneously. Figure 2a shows a case at

![Fig. 1](image-url) a) Flow features around the Mach 1.1 projectile in free flight (no ground); b) at Mach 0.9 in free flight; c) in ground effect at \( h/d = 2 \) and Mach 1.2.
\( h/d = 1.5 \) (approximately), and the bow shock reflection was still adjusting at one projectile length past the ground leading-edge encounter, eventually forming a continuous structure with the small overcompression shock on the forebody. At \( h/d = 0.5 \) (approximately), the bow shock did not reflect, but gradually adjusted to be nearly perpendicular to the ground plane, and the wake became increasingly asymmetric. Although this behavior is itself of interest, the flowfields rapidly arrived at a quasi steady state after a few projectile lengths of travel over the ground, and therefore the present study focused on this condition; changes to forces, moments, and underlying pressure coefficients from free-flight cases to clearances as low as \( h/d = 0.25 \) were examined using CFD, as validated against experimental data.

II. Experimental Methods

Extensive details of the live-range and wind-tunnel experiments have previously been covered in the literature \([5–10]\) and therefore are only described in short here for the sake of brevity.

Live-range rifle experiments, devised at University of New South Wales (UNSW)–Canberra at the Australian Defence Force Academy, were intended as a way of using time-resolved schlieren photography to examine the effect of the ground proximity on a projectile fired from a rifle in controlled circumstances \([1]\). A Shimadzu camera was able to operate at 500,000 frames/s with a sufficient pixel count (312 \times 260) to ensure clarity in the waves and their reflections, as well as to approximate any trajectory changes (which were measured to be negligible in the small field of view).

The initial firings were conducted using a NATO round at Mach 2.4 as the test subject as well as a blunt, hollow-tipped projectile at Mach 1.1. The latter, with its more complex geometry, proved less preferable for both trajectory repeatability and later CFD investigation, and subsequent tests were conducted with a Nosler 50-grain Shot projectile (length 16 mm unfired). This was much more similar in shape to the NATO round and thus facilitated an equivalent comparison between the two Mach numbers when all results were collated.

Since the live-range tests could only provide limited quantitative information, wind-tunnel testing was conducted using scale models that were 7.5 times the diameter of the originals and approximately Reynolds scaled, although the spin of the projectiles could not be reproduced in this way. The Mach 2.4 tests were conducted at the blowdown wind tunnel at UNSW–Canberra, with Mach 1.1 and 1.2 tests at the supersonic tunnel facility of the Institute of Space and Astronautical Science of the Japan Exploration Agency. Since it is unfeasible to implement a moving ground for supersonic tests, as would technically be the correct way to model the ground plane, the use of mirror image symmetry models provided results that were nearly identical to those that could be obtained if a moving ground were possible \([1]\). The latter condition is easily simulated in CFD \([7]\), although similar studies on wings indicated that when there were areas of subsonic flow this technique introduced minor discrepancies due to the lack of a ground boundary layer \([3,4]\). Tests were not conducted at Mach 0.9, though the flow condition was of interest for the present study; it is anticipated that a symmetry ground plane or elevated ground would produce potentially unacceptable results in that regime \([11]\).

Pressure distributions around the nonspinning wind-tunnel projectile model were obtained (along with schlieren images). The data were used as validation for CFD when all tunnel scales and conditions were reproduced, allowing the numerical methodology to be applied with confidence to the real-world spinning projectile at different ground clearances. Such a process proved successful in the previous similar study of a Mach 2.4 projectile and other recent high-speed ground effect studies \([9,10]\), although higher-resolution multivariable validation data would be required to accurately determine CFD turbulence model behavior, as will be highlighted in the following section.

III. Numerical Method

A. Outline of Numerical Method

ANSYS Fluent was used to produce all the results described here; the software has previously been shown capable for reproducing projectile flowfields \([10]\). All simulations were run on 64 bit clusters using a pressure-based, coupled solver. Additional solutions with Fluent’s density-based solver were found to offer no significant difference in predicted forces and moments (<1%), but solution times were markedly longer, and the iterative process featured greater instability in the early stages before a settled path to a steady-state solution could be established. According to software documentation, it is likely that the coupled solver offered a slight damping of mild unsteadiness in the flow \([25]\), which in this instance was viewed as beneficial as the transient behavior was not a focus. The pressure-based solver makes use of a background algebraic multigrid (AMG) solution procedure (using progressively coarse grids), and in this instance, the default Gauss–Seidel smoothing algorithm was substituted in favor of an incomplete upper–lower smoothing technique. This reconstitutes the solution matrix such that elements can be calculated and stored in memory as the AMG grid levels are being constructed, and this stage is then followed by a series of sweeps similar to the Gauss–Seidel approach. The AMG technique has some inherent limitations in that it ignores nonlinearities on coarser grids, which is pertinent when dealing with shock waves; these are fully resolved on the fine (original) grid, and this process may affect the damping of instabilities in arriving at a steady-state solution.

For all solutions, convergence criteria were deemed to be met not only when the mass and momentum scaled-residual errors ceased to change by more than approximately 0.03% over 1000 continued iterations but also when the aerodynamic forces on the body ceased to change by more than 0.03% over 1000 further iterations on top of a nominally converged 3000 iteration solution. A second-order cell-
Based upwinding discretization scheme was applied, as was a standard three-coefficient Sutherland viscosity model (though viscosity changes in the flow would be relatively insignificant).

### B. Mesh and Boundary Conditions

For all simulations, the projectile was simplified geometrically by removing the shallow rifling striations imprinted on the projectile as it was turned traveling down the barrel. This was done for ease of meshing and to negate the need to run transient simulations to establish the resulting small-scale but complex flow behavior due to unsteady rotational effects. Flow disturbances caused by these features were weak relative to the major waves in the flowfield, judging by observations from the live-range schlieren and experience with the Mach 2.4 projectile [10], though the dynamic derivative and roll damping coefficients are known to be more sensitive to the striations [15,16]. Since these derivatives and coefficients are not considered in the present study, the modeling choices are justified.

All simulations were run for the projectile at an angle of attack of zero deg, although the experiments also featured several shots that produced a noticeable angle of incidence to the freestream, usually less than 2 deg.

Whether matching the wind-tunnel experiments or the live-range experiments, the numerical model was designed to replicate the real scenarios as best as possible in terms of geometry, flow conditions (such as Reynolds number), and other pertinent parameters. However, properties such as turbulence intensity, which is very influential in determining the dissipation of shock structures in the mesh, were not known and therefore were set to be at what is potentially an artificially low level (0.05%) to aid in capturing the shock reflection and interaction phenomena. Higher intensity levels were tested and reduced shock sharpness but did not notably alter the resultant pressure distributions other than at the lowest ground clearances where shocks reflected back onto the projectile.

A quarter-model with two symmetry planes was used for the free-flight (no-ground) case that was the focus of the initial work to establish an appropriate mesh density. For further comparisons to the wind-tunnel tests, a nonspinning half-model was implemented for the no-spin case with the ground proximity. For all scenarios constituting the main body of the study, a full rotating model was implemented, with a moving ground as required for reproducing ground effect experiments in a changed frame of reference where the projectile is stationary and the air is oncoming with the appropriate Mach number. The frame of reference for the projectile is indicated in Fig. 3, as is the computational domain. Although the projectile’s rate of spin would begin to decrease immediately upon leaving the barrel, the angular velocity $\omega_z$ of the projectile at the target area was calculated to be 7108.9 rad/s, subsequently applied as a simple boundary condition to the CFD model.

Fully structured multiblock meshes were generated for all cases. Extensive grid-refinement studies were conducted for a quarter bullet (free flight with symmetry) model then at the other primary validation point of $h/d = 0.5$ (results are not plotted here but are consistent with free-flight findings). The general meshing approach can be gleaned from Fig. 3, both in the main image and for the projectile surface in the inset.

As Fig. 3 indicates, the unrestricted (non-wind tunnel) domain extends for 10 projectile lengths above and to the side (z direction) of the projectile nose and for approximately 8 lengths upstream and 12 downstream. A sensitivity study was conducted that indicated that extending the domain in all directions by a further 6 projectile lengths had a negligible influence on the lift and drag forces (<0.01%). Although a domain two chord lengths shorter in each aspect only exhibited a 0.1% difference, the larger domain was preferred to assist with a smoother convergence in the more challenging Mach 0.9 runs.

Over both the projectile surface and ground plane for all simulations, the wall $y^+$ value was between 1 and 3 to facilitate effective resolution of the boundary layer, particularly in the regions of shock interaction. Literature describing projectile research conducted using Fluent indicates that $y^+$ of less than 1 may even be preferable to predict the Magnus effect of a spinning shell [19]; however, the present study is primarily concerned with the static force coefficients, and thus the $y^+$ here was acceptable. The projectile surface mesh featured 240 circumferential cells (if extrapolated to a full projectile), and this aspect of the mesh was not altered during the refinement studies.

Two meshes were constructed, a standard and fine version with 135 and 270 lengthwise ($x$) cells on the projectile surface, respectively. This resulted in overall mesh sizes of $14.58 \times 10^6$ and $24 \times 10^6$ cells for the full projectile and no-ground cases. Because of the additional mesh required between the projectile and the ground for the ground effect cases, the largest standard mesh run was $40.4 \times 10^6$ cells for the $h/d = 8$ cases. Cells were clustered close to the nose and base regions, where influence waves originated and where high pressure gradients were anticipated.

To capture the shock waves effectively, local mesh adaptation (cell splitting) in regions of a high local pressure gradient was performed. This procedure added a third mesh to the mesh convergence study, though the number of cells refined was limited in each case so as to add not more than $2 \times 10^6$ to the overall cell count; the effect of this increased local resolution was an increased sharpness of waves similar to that observed for the fine mesh but without the more considerable increase in total cells and therefore processing time. Adapting the mesh typically altered the drag values by less than 0.1%.

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**Fig. 3** Domain extents, important parameters, orientations, and mesh snapshots for the projectile in ground effect.
All results for this stage were generated using the k-ω shear stress transport (SST) turbulence model. Turbulence modeling is discussed in more detail in the following subsection.

As shown in Fig. 4, the CFD match to the free (no-ground) projectile wind-tunnel tests was satisfactory, including effective prediction of the forward stagnation pressure at the tip and the pressure recovery region following the expansion over the forebody as it blends to the rearward cylindrical section. The results are presented on the vertical (0/180 deg) plane, though here upper and lower surfaces are identical. There was some slight underprediction of the experimental $C_P$ for the tapping locations on the surface downstream of the mild recompression, which is a result of the overexpansion of the flow around the tight curvature near the tip and some “wobbles” in the distribution attributed to the influence of this small shock on the boundary-layer state immediately downstream, which then propagated. The instability starting at $x/l$ of approximately 0.15 damped out to a smooth profile again by $x/l = 0.25$. Changes in mesh density and structure in this region did not have a major influence on the pressure behavior observed.

Both the standard and shock-adapted meshes produced results that were essentially identical; however, the finest mesh produced a result that has a slightly lower pressure at the near-tip recompression and a slightly higher pressure over the cylindrical rearward portion. While potentially offering improved accuracy with regard to the numerical model in isolation, the finest mesh actually provided a less effective correlation to the experimental results, indicating there were some issues with either the CFD or experiments, or both, that may require closer investigation. The higher resolution of the entire forebody region had a subsequent effect on the shear-layer separation and base pressure at the rear; the shear layer was seen to dip more notably for the fine mesh, as seen in Fig. 4b. Without any detailed wake information from the experiments, the accuracy of this remains unquantified. However, the standard mesh appeared to be sufficient for the subsequent simulations, and the shock-adapting local refinement procedure was maintained for the purposes of ensuring shock resolution particularly for ground reflections and shock/ boundary-layer interaction regions.

C. Turbulence Modeling

Three Reynolds-averaged Navier–Stokes (RANS) turbulence models were evaluated for their ability to reproduce the experimental data: the Spalart–Allmaras (SA) one-equation model [26], the realizable k-ε model [27], and the SST variant of the k-ω model [28] (in this instance, the comparison was made for the more challenging $h/d = 0.5$ case, as shown in Fig. 5a). All three models had previously been examined for the Mach 2.4 study [1, 10], and in that instance, the SA model provided a preferable comparison to wind-tunnel data although all three models had significant differences in predicting the wake extent and behavior, as well as the pressure distribution in the presence of strong regular shock reflections.

The upper surface distribution, closely related to that seen for the projectile in the no-ground case, was well captured by all three

![Fig. 4](image1.png)

Fig. 4  a) Effect of increasing mesh resolution on correlation to Mach 1.1 wind-tunnel pressure coefficient distribution for a free-flight (no-ground) case (nominally symmetric pressure distribution); b) contours of density showing mesh resolution effect on shock-capturing and shear-layer behavior.

![Fig. 5](image2.png)

Fig. 5  a) Predicted pressure distributions from turbulence models for ground clearance $h/d = 0.5$ vs Mach 1.1, wind-tunnel test results; b) contours of velocity magnitude to highlight differences in wake structures in the base region and downstream (Vel., Velocity).
models; indeed, on both surfaces, there was negligible difference in the predicted pressure coefficients at any point on the projectile surface. However, this means that all three models had difficulty in reproducing the experimental points at \( x/l = 0.17 \) and 0.25. The wind-tunnel data imply that there was a strong fluctuation in the pressure here, perhaps as an exaggeration of the previously discussed recompression wave and resultant influence on the boundary layer downstream. However, without sufficient additional resolution from the experiments to confirm this behavior, the numerical results can be viewed as acceptable as the match to other points on the surface is good and any discrepancy is not specific to any one model.

While the predicted lift coefficients expectedly differed by less than 1%, there was a large spread in the drag coefficient values, from 0.39 (SA) to 0.43 (SST) to 0.53 (realizable k-ε). Figure 5b indicates the discrepancies in the predicted wake profiles in the vicinity of the projectile base, with the extent of the main recirculation cell correlating directly with the drag values from each model; shear layers, wake thicknesses, and recompression waves were all affected by the perceived stretching of the wake with the two-equation models. Intuitively, one would expect these models to be more competent in resolving the flow in this region, though the features are challenging to recreate accurately with any RANS model, and unfortunately no additional experimental data were available to elucidate further on the ranking of model performance.

The k-ω SST model was therefore selected for the remainder of the study, based on the good correlation to experimental \( C_p \) on top of its well-proven ability in predicting transonic flowfields and in particular its perceived advantages in modeling separation and free shear layers as well as a significant rotation in the flowfield causing high shear rates [28].

D. Additional Comparison to Experiments

The bow shock standoff distance could be measured with relatively high accuracy from the wind-tunnel schlieren images, and a plot of this parameter against the ground clearance for \( h/d = 0.5, 0.75, \) and 1 is shown in Fig. 6, indicating a correlation to the CFD results. Although the trend match is satisfactory, the absolute values could be interpreted as having a systematic offset of approximately 0.02d, which in the case of the tunnel model equates to approximately 0.8 mm. A variety of factors on both sides may have been responsible for this; however, the reproduction of the trend is encouraging and indicates that the experiments were producing valid behavior with the symmetry method and that the CFD methodology described above was able to reproduce that behavior, allowing increased confidence in the comparisons made in the following section for the flowfield response to an increased ground proximity.

IV. Results

A. Force and Moment Coefficients

Normal force and pitching moment coefficient data for the Mach 0.9, 1.1, and 1.2 cases are presented in Figs. 7 and 8, respectively, for...
the range $h/d = 0.25$ to 8. Free-flight (no-ground) results are not presented as the normal force, and moment coefficients in those cases were zero, which they essentially were at $h/d = 8$ (shown) for all cases, too. This indicates that any ground influence, in particular, wave reflections for the supersonic cases, only influenced the far wake and to a negligible extent.

The Mach 0.9 projectile force barely responded to the ground until the clearance was less than $h/d = 3$, at which point a negative normal force (toward the ground) established and developed exponentially as clearance was further reduced. The trend was relatively consistent and predictable throughout the range, with increasing suction at each increment. Accordingly, the pitching moment coefficient followed a similar trend, with increasing magnitude of a nose-up tendency as the clearance reduced; at low clearances, small changes had a larger effect on the magnitude, but the coefficient remained relatively slight.

In examining the Mach 1.1 data, it is clear that by $h/d = 5$, the ground influence was already exerting itself on the projectile, with a mild increase in the normal force coefficient that appeared to reach a peak at close to $h/d = 3$. With a continued decrease in the ground clearance came a reversal of this trend, followed by a reversal in the overall sign of the force such that between $h/d = 1$ and 0.75 the normal force then acted downward (towards the ground). This force intensified with the ground proximity to a coefficient maximum of ~0.047. While remaining a relatively small force coefficient, this represents approximately 15.6 N.

The pitching moment, while relative to an approximation of the center of gravity from what was known about the projectile mass distribution, followed broadly the same behavior as the lift coefficient; however, it changed from a negative (nose-down) moment to a positive (nose-up) scenario earlier than the lift coefficient changed sign; this latter condition indicated that either there was lower pressure acting on the lower rear of the projectile, higher pressure acting on the forward upper portion, or a combination of both effects. The trend for the increasing magnitude of the negative moment was nonlinear, with close ground proximity being an exaggerating factor as for the lift coefficient.

The respective plots for the Mach 1.2 case exhibit more unusual behavior that indicates the flowfield here may have been more sensitive to the wave reflections from the ground plane; the waves here were slightly more oblique and therefore more prone to reflecting back onto the projectile itself, and there was less subsonic flow around the body.

The normal force followed the Mach 1.1 trend of increasing from $h/d = 5$, but the peak positive force was reached at a lower $h/d$ of 2, and the increase in force here was abrupt and notable in magnitude. From here, the force dropped off and changed sign, again at a lower ground clearance (between $h/d = 0.75$ and 0.5) than before. Therefore, the behavior was similar between the two Mach numbers, with the higher-velocity case experiencing the same trends, albeit at an offset that must be directly attributable to the different wave/ground interaction phenomena.

The pitching moment, shown in Fig. 8, stayed essentially neutral until $h/d = 2$, and then followed the general trend to increasing positive as the ground clearance was reduced.

The drag coefficient plots presented in Fig. 9 highlight a significant increase in the retarding force as the ground clearance was reduced, particularly below $h/d = 2$. As with the lift and moment coefficients, the Mach 1.2 case followed the Mach 1.1 case with a slight delay, further indicating that an increasing Mach number resulted in a decreasing ground influence, at least until the closest proximities were achieved. For both Mach number cases, a slight decrease in drag compared to the free-flight (no-ground) case was observed before the marked drag rises appeared; at Mach 1.1, this occurred at $h/d = 5$, and at Mach 1.2, this occurred at $h/d = 3$. In the latter case, the drag reduction was approximately 10%, while in both cases, the maximum drag rise at the lowest ground clearance was in excess of 30%.

At Mach 0.9, the drag coefficient, starting from a considerably lower free-flight level of 0.214, exhibited the same behavior, albeit in a less pronounced fashion. Without shocks reflecting into the wake or causing boundary-layer separation, and with a relatively small normal shock instead of the significant detached bow shock at the higher Mach numbers, the increase was modest and peaked at $h/d = 0.5$. $C_D = 0.25$. A slight decrease at $h/d = 0.25$ was observed, as flow underneath the projectile was relatively constrained and the strength of the shock was slightly reduced due to more flow being forced away from the region.

It is worth providing a comparison to the Mach 2.4 projectile study previously reported in the literature [6]. At the higher Mach number, with shock waves reflecting regularly from the ground plane and interacting one or more times with the projectile at low ground clearances, the normal force increased significantly once the projectile was within one diameter of the ground. No negative normal force was produced, with the shock behavior beneath the projectile and its resultant pressure rise on the lower part of the body ensuring that an escalating normal force was the only result. Drag, however, followed a very similar trend to the new results, with decreasing ground clearance producing a slight rise, then a slight dip, and then a significant rise in the retarding force. This was primarily due to the increase and distortion of base drag in the immediate vicinity of the rear of the projectile and the thickened wake that was deflected downward at the lowest clearances. In broad behavior then, the Mach 1.2 projectile exhibited a strong similarity to the Mach 2.4 projectile, whereby the bow shock reflecting into the wake or onto the very rear of the projectile may have slightly decreased the drag; with a further decrease in the ground clearance, the drag will markedly increase, though the onset of this effect depends on the shock angles (and therefore projectile Mach number) and no doubt the particular shape of the projectile.

Clearly, at a Mach number higher than 1.2 but lower than 2.4, a transition in the flowfield occurred, whereby the regular oblique reflection of waves started to exert a more predictable influence on the projectile. Therefore, at the low-supersonic Mach numbers, the trajectory of the body when close to the ground was both more sensitive to small changes in the velocity and ground clearance in that force and moment reversal could occur but less likely to be altered to any meaningful extent due to the relatively small magnitude of the forces involved compared to those occurring at the much higher Mach number. This sensitivity was reflected in the large-scale rocket sled tests touched upon in the Introduction and further demonstrates the difficulties in operating in transonic ground effect.

B. Flowfield and Pressure Coefficients

It is clear from the graphs of normal force and pitching moment that there were some subtle effects occurring over a relatively narrow range of ground clearances, particularly with the force and moment reversals seen at Mach 1.1 and 1.2. Pressure coefficients around the projectile surface on the vertical (0, 180 deg) midplane were extracted.
at each ground clearance and matched to qualitative and quantitative visualization provided by the CFD; these plots are shown in Figs. 10, 11, and 12 for Mach 0.9, 1.1, and Mach 1.2, respectively.

The Mach 0.9 projectile experienced only one particular state of interaction, whereby the lower portion of the circumferential shock wave on the main body experienced first a slight shift rearward due to increased flow acceleration in the gap, followed at lower clearances \((h/d < 1)\) by a lateral spread and further rearward movement. At \(h/d = 2\), shown in Fig 10a, the initial ground influence served to increase, slightly, the high pressure on the lower forebody and the low pressure to the rear behind the shock. This effect was exaggerated at lower ground clearances, and at \(h/d = 0.5\) (Fig. 10b), the pattern remained the same, albeit with the added complexity of a reflecting expansion wave from the forebody, which sustained the lower pressure over the rear of the projectile and drove the nose-up pitching moment previously described. The wake was thickened and drawn slightly downward, but remained largely symmetric with the flow effectively turned back to normal by the singular shock system.

For the Mach 1.1 case in Fig. 11, it is immediately apparent that the slight increase in normal force at \(h/d = 5\) was caused by the reflection of the bow wave from the ground to impinge on the rear of the projectile on the lower surface. The pressure coefficient indicates that the top surface was essentially unaffected by this, and therefore the pressure differential from the spike of the impinging wave caused the positive normal force and also the slight nose-down pitching moment that was noted. The density contours in the inset also indicate that the expansion and recompression waves (in particular) reflected from the ground and interacted with the far wake, but as the flowfield was supersonic at this downstream stage, the influence was not felt back at the projectile.

At \(h/d = 3\), the bow wave curved notably to normal instead of forming a Mach stem and a clear reflection as at the higher clearance,
and therefore there was not the defined wave reflection and interaction of the previous case. Rather, since the flow was subsonic for a large region around the projectile forebody, the entire flowfield adjusted to the new pressure regime, and this includes marginally higher pressure acting over the lower surface and therefore sustaining the positive normal force. At the ground, the bending of the shock to normal indicated the presence of subsonic flow behind, and this region became larger and more influential as the decreasing ground clearance further constricted the flow.

From $h/d = 1$ and lower, to the minimum clearance $h/d = 0.25$, a clear pattern was established whereby the pressure on the underside of the forebody was raised higher than the top surface, and on the rear of the body, the lower surface pressure was notably lower.

While this kept the overall force relatively low, it was the combination of these two levers that caused the significant effect on the pitching moment, as the rear was effectively sucked downward and the front was pulled up. The expansion waves produced by the blend from the forebody to the conical section drove the pressure drop on the lower rear of the body, and so when the ground clearance was low enough ($h/d = 1$ or less) for a reflection back onto the projectile, the pressure differential between the lower and upper portions of the body became increasingly exaggerated. At the lowest two ground clearances, a double reflection occurred that further distorted the pressure distribution and enhanced the nose-up pitching behavior.

The Mach 1.2 case first experienced a change to the pressure distribution due to the ground at $h/d = 3$; however, the clear point of interest occurred at $h/d = 2$, where previously a sharp jump in normal force was observed. The density contours and pressure distributions revealed that this was the product of the impingement of the bow shock reflection at a point just upstream of the primary point of flow expansion over the geometry transition from the forebody to the cylindrical section. This produced, in the sense of force development, a constructive interference as the high pressure of the reflected shock also reduced the extent of the expansion that would normally produce a large region of low pressure locally. As a result, the net normal force in the upward direction was augmented.

A flow feature that was observed in experiments but not noted at the specific ground clearances examined for the Mach 1.1 case is the joining of the reflection of the bow wave and the small wave caused by the overexpansion of the flow as it turned the sharp corner from the nose onto the more gentle curve of the forebody. The structure was most notable at $h/d = 1$ where it was well-established, and then it began to break at $h/d = 0.75$ before being negated by the significantly changed flow conditions under the projectile at $h/d = 0.5$ and below. While this behavior is interesting, it is fleeting in the context of the changing ground clearance and thus has little influence on the force and moment trends.

When viewed in terms of a real-life scenario, a long enough regular surface were available, it is clear that the projectile would be subject to significant ground influence as its trajectory changed due to gravity and drag, less so if it were fired close to a vertical wall, where the shock behavior would be the same but the clearance from the surface may be less changeable. As hypothesized previously for the Mach 2.4 projectile [6], the normal force would cause a lateral movement due to the precession effect caused by the projectile spin. The side force was not plotted here due to it being generally two orders of magnitude lower than the normal force and therefore essentially negligible; as a result, the primary change to the trajectory would be a lateral movement accompanied by changes in pitching behavior that would, eventually, destabilize the projectile into a more complex motion not considered in the present study.

V. Conclusions

Reynolds-averaged Navier–Stokes (RANS) computational fluid dynamics simulations of a projectile at near-sonic Mach numbers in close ground proximity were validated against experimental data and used to predict changes to aerodynamic performance. Mach numbers of 0.9, 1.1, and 1.2 were investigated at ground clearances from 0.25 to 8 diameters, with forces, moments, and pressure distributions analyzed.

At Mach 1.1, the influence of the ground was felt at over 5 projectile diameters from the ground, with the normal positive force
(caused by the shock reflection from the ground) slightly increasing, before changing sign and becoming increasingly negative with ground clearances less than 1 diameter. This was due to increased high pressure on the forward lower surface and increased low pressure on the rear lower surface. As a result of this effect, the pitching moment also increased rapidly in the nose-up sense. The side force and side moment changes were extremely small. At Mach 1.2, the trends were similar, but all effects were exaggerated, and the projectile felt the influence of the ground at a much lower ground clearance of 3 diameters and below. Results at a clearance of 2 diameters highlighted the potential for spikes in force if shock reflections interacted with specific points on the geometry such as where an existing significant flow expansion existed. Because the projectile was spinning, the normal force would manifest itself as a lateral force due to the precession effect, but the actual forces involved were of sufficiently small magnitude to have nowhere near the influence that the ground effect was previously observed to have for a projectile traveling at a much higher Mach number.

At Mach 0.9, the aerodynamic behaviors were more predictable, with a milder exponential increase in negative normal force and nose-up pitching moment being established at clearances of less than \( h/d = 2 \). The lower portion of supersonic flow ahead of the midbody shock was restricted by the ground and elongated rearward, producing the same nose-up pitching of the higher Mach numbers by a different mechanism.

Three obvious avenues for continuation of the work could be pursued. First, an experimental determination of the extent of trajectory deflection over a sizeable distance would be extremely useful in identifying the actual extent of destabilization and target alteration that could occur. In concert with such experiments, a series of transient simulations with the projectile allowed to move in six degrees of freedom would provide greater insight into this issue, as well as the flow-establishment phase when the projectiles first pass over the ground plane. Lastly, it is clear that, while RANS is capable of capturing the basic flow features well, the wake behavior and the exact nature and influence of shock/boundary-layer interactions are not necessarily being well captured, and a move to large-eddy-simulation-based methodologies would be preferable.

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References


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