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PARAMETRIC STUDY OF THE QUADRATIC-YAW DRAG COEFFICIENT FOR PROJECTILES USING COMPUTATIONAL FLUID DYNAMICS *

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*** Dedicated to the memory of Major-General George Ruhlen, United States Army**

Six-degrees-of-freedom trajectory modelling which is used within the PHANTOM/MAN wound ballistics code and in-house GTRAJ6DOF exterior ballistics code requires accurately predicted aerodynamic coefficients to determine impact conditions. This paper describes a method of using CFD simulations to pre-determine aerodynamic coefficients for projectile configurations with varying ogive shape and length, meplat, afterbody length, and boattail length and angle at selected Mach numbers. Storing these matrix data in an aeroprediction database and in conjunction with ballistic range test data, the TRIPLE AP (A3P) engineering code can quickly determine aerodynamic coefficients, stability characteristics, trajectories, and other information for the projectile designer in a matter of seconds. This is illustrated with the quadratic-yaw drag coefficient for which experimental data are less abundant than for other coefficients such as the zero-yaw drag coefficient. By implementing the CFD results within the TRIPLE AP (A3P) database we were able to reduce the error in predicted static aerodynamic coefficients to about 5-8% for Mach numbers from 0.4 to 5.

INTRODUCTION

For more than 20 years we have developed a semi-empirical code for the prediction of physical properties and aerodynamic coefficients of spin-stabilized projectiles. This code, which is called TRIPLE AP - or A3P for short -, utilizes semi-empirical databases and models and is used as an input module for 6-degrees-of-freedom trajectory modelling within the PHANTOM/MAN and GTRAJ6DOF codes.

The PHANTOM/MAN model is a computerized mathematical representation of the human anatomy and physiology that was developed to simulate wound ballistics and the resulting incapacitation, lethality, and medical consequences caused by spin-stabilized projectiles (bullets). PHANTOM/MAN was independently validated [1,2] and is in use by organizations in NATO and TTCP countries. The GTRAJ6DOF is an exterior ballistics modelling code developed for simulating trajectories and the resulting ballistic dispersion of medium-caliber and artillery projectiles; the theory behind the six-degrees-of-freedom model is described elsewhere [3]. Most of the time the GTRAJ6DOF code is used to run standard projectiles, however, it has the option to link code modules for simulating special projectiles such as Base Bleed or liquid-filled shell.

Accurate estimates of impact yaw conditions are required for wound ballistic and vulnerability/lethality computer modelling if true fidelity is sought by the analyst. Furthermore, future artillery systems are required to engage the enemy at ever increasing ranges. For 155mm artillery systems, ranges may well be $\geq$ 65 km with times-of-flight on the order of 150 sec, requiring accurate (higher-order) aerodynamic coefficients for evaluation of promising shell concepts using engineering design codes.

It would be beneficial if computational fluid dynamic simulations (CFD) could sometimes be used in place of the aeroballistic range to determine the aeroballistics of standardized projectiles for which only a single geometric parameter - such as non-dimensional ogive-length - is varied. This allows the storing of aeroballistic data at fixed Mach number-Angle-of-Attack in a database thus permitting rapid estimation of the aerodynamic coefficients for engineering purposes. Whilst supercomputers allow CFD simulations to be run almost in real-time together with a 6-DOF projectile trajectory simulation [4-6] there is still a considerable savings in terms of money and CPU time when engineering or interpolation techniques are used to estimate the aerodynamic coefficients for a candidate design. Furthermore, with respect to accuracy there is not much to be gained using supercomputers for design purposes unless radical new projectile configurations are considered. TRIPLE AP (A3P) provides solutions in seconds and is used to quickly determine aerodynamic coefficients, stability characteristics, trajectories, and other information for the projectile designer in a matter of seconds. Other aerodynamic prediction codes developed over the last 20-years, using semi-empirical engineering models, include the MISSILE [7] designed by Onera and the American SPIN-73/98/04 [8] codes.

By implementing the CFD results within the TRIPLE AP (A3P) database we were able to reduce the error in predicted static aerodynamic coefficients to about 5% for Mach numbers from 0.4 to 5. The work presented here is focussed on the numerical analysis of the quadratic-yaw drag coefficient $C_{D\alpha^2}$ at selected Mach numbers.

NUMERICAL APPROACH

The commercially available VisualCFD code [9], version 3.02, was used in this study. The VisualCFD code can simulate a range of fluid dynamic phenomena, ranging from incompressible to hypersonic flow. The 3-D axisymmetric, steady and unsteady inviscid Euler equations are solved using the finite volume method. Automatic grid generation and mesh distribution allow a rapid setup of the computational domain for a wide range of fixed body geometries, including fins. VisualCFD is designed for the Microsoft Windows operating environment.

CFD simulations were used to predict the aerodynamic coefficients and flow field over axisymmetric bodies (Fig. 1). The primary objective of the investigation was to determine the aerodynamic coefficients at selected Mach numbers and angles of attack (AOA). The Mach number range investigated was from 0.4 to 6.0. Steady state CFD calculations predicted the drag, normal force, pitching moment, normal force center of pressure, and roll damping very well.

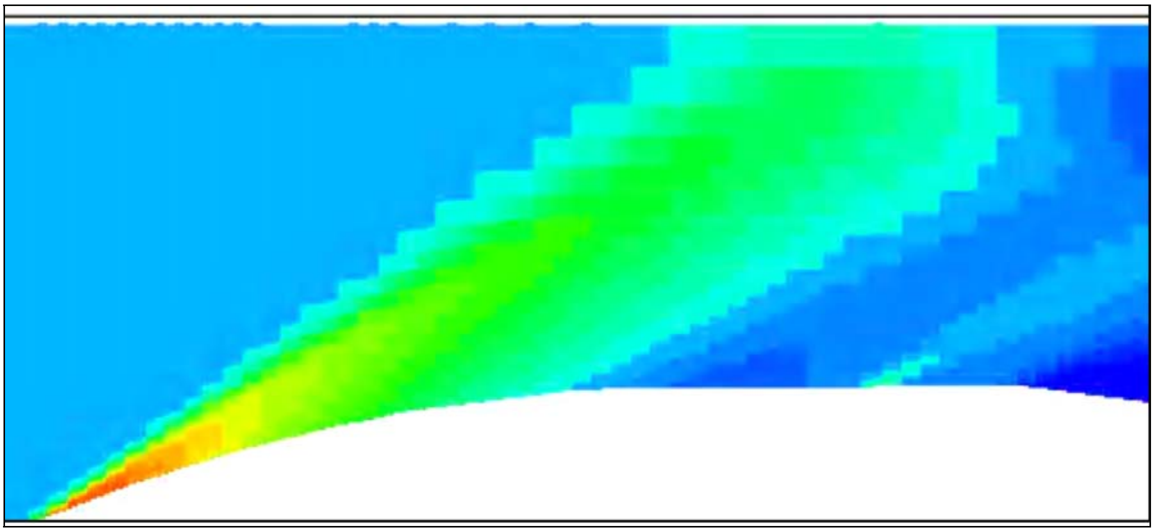

Figure 1. Free field pressure contour plot for a 155mm shell at Mach 3. Alpha = 0 deg.

The CFD simulations carried out with the VisualCFD code took about 25 hours of CPU time for each projectile.

Over 100 projectile configurations were chosen with different nose shapes and forebody lengths ranging from 1 to 5 calibers. Midsection lengths varied between 0 and 5 calibers. Afterbody geometry was fixed to conical boattail sections only, varying in length between 0 and 2 calibers with angles less than 15º. These configurations reasonably constitute the currently available projectile designs.

RESULTS AND DISCUSSION

Comparison of CFD results for the static coefficients show good agreement with experimental data from ballistic range tests for some standard projectile configurations. It is usually desired to predict the aerodynamic coefficients to within at least 10% of the experimental data.

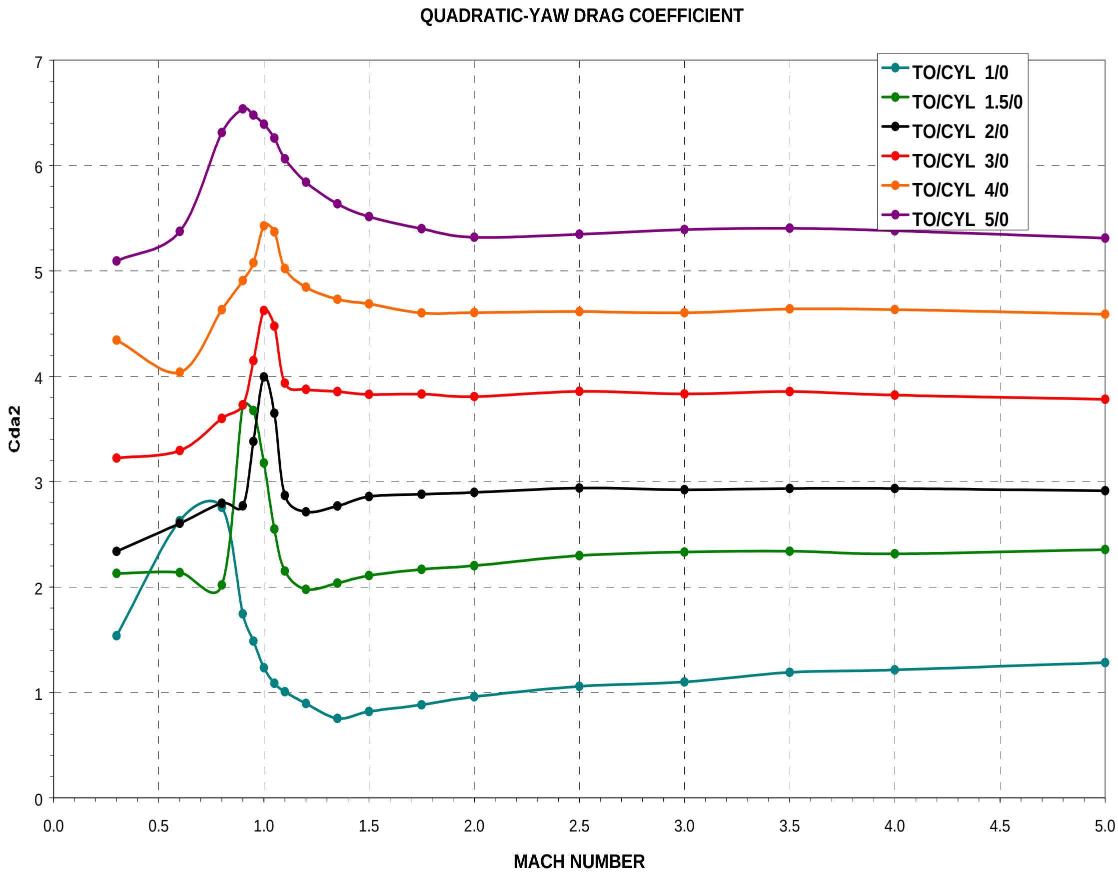

Figure 2. Quadratic-yaw drag coefficient as a function of Mach number for tangent ogives with zero afterbody lengths. The lower curves are for the shorter ogives, while the upper curves are for the more slender ogives.

VisualCFD certainly is capable of doing that for axisymmetric projectiles with not-too-extreme geometries and failed to find solutions for the flow field around projectiles with steep boattails or very slender ogives at hypersonic Mach numbers.

Given these limitations, quadratic-yaw drag coefficients were determined for fixed projectile configurations with singly varying geometric parameters at selected Mach numbers. To illustrate this, the effect of varying forebody length at fixed Mach numbers was determined in this study and is shown for isolated tangent ogives in Fig. 2. The effects of ogive shape and length, meplat, afterbody length, boattail length and angle on the quadratic yaw-drag coefficient were also studied and are reported elsewhere [10].

CONCLUSIONS

Although originally developed for other applications, CFD codes can be used "to fill aerodynamic data matrices" which improve the accuracy of predicted aerodynamic coefficients at selected Mach numbers in aeroprediction codes. Together with data from ballistic range tests, they allow rapid determination of aerodynamic coefficients and trajectory information in a matter of seconds. This was illustrated for the quadratic-yaw drag coefficient.

DEDICATION

This paper is dedicated to the memory of Major-General George Ruhlen, United States Army. George started his career as an artillery man and saw combat in that capacity, before moving to higher goals. Most of all, he was a very good friend to the family with a tremendous sense of humour. He was a gentleman in the true sense of the word and is missed by us all.

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