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Aerodynamic characteristics of high performance rounds at Mach 1.8 to 4

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ABSTRACT

This paper presents a wind tunnel investigation of the aerodynamic performance of two high performance supersonic rounds: a standard 155 mm M549 projectile and a new optimum round that was redesigned from the standard round. The experiments were performed over a wide range of Mach numbers ($M = 1.8$, 2, 2.5, 3, 3.5, and 4) providing new data for the consideration that these rounds can be flown beyond the maximum nominal flight speed of Mach 2.5. The angle of attack was varied during the test over a range of angles ($-5°$ to $+5°$) in order to determine the pitching moment derivative. The results show that the redesigned body provides significantly lower drag and pitching moment derivative, which are both desirable to enhance the range of the round and its stability. In comparison of the experimental data with the simulation predictions, good agreement was observed for the drag, the normal force derivative and the pitching moment derivative. It was also found that increasing the Reynolds number only significantly affects the skin friction drag.

1. Introduction

The external aerodynamics of generic rounds, such as ogive shaped bodies, at supersonic speeds is of fundamental interest. Because of the simplicity and the streamlined nature of the shape, such bodies can be found in many flight objects, such as the fuselage of aircrafts, gun rounds, and rockets. This paper is part of a larger research effort to characterize the aerodynamic performance of generic round projectiles in supersonic flight and design them in order to achieve the best performance to support the requirements of various missions. In an earlier part of this work by Jiajan et al. [4], a standard 155 mm diameter M549 projectile was adopted as a generic spin-stabilized round as depicted in Fig. 1. The maximum speed of this round is about Mach 2.5. We then pose the following practical questions: what is the aerodynamic performance of this round beyond its intended maximum nominal speed of Mach 2.5? How would the body be redesigned to give optimized performance if the flight capability is to be extended to higher speeds, say Mach 4? To answer these questions, a theoretical investigation was carried out to characterize the aerodynamic performance and stability of the 155 mm round at the nominal as well as at higher Mach numbers. The body was then redesigned by varying the lengths and geometry of the three body segments – nose, cylindrical body, boattail – by coupling a semi-empirical drag prediction method with an optimization solver so that the aerodynamic drag of the body was minimized while its stability is maintained. Here, the key feature of the redesign process is that not only was drag examined in detail, stability – both static and dynamic – was also incorporated as performance requirements. It was shown in Jiajan et al. [4] that the optimized body provides up to 15% drag reduction while it remains both gyroscopically and dynamically stable over the extended range of flight Mach numbers ($M = 1.5$ to 4). This is achieved with a reduction in volume or payload of 4%.

Since the development of the redesigned 155 mm round was only supported by numerical simulation in Jiajan et al. [4], a wind tunnel experiment is the next logical step to further study experimentally the aerodynamic performance of the design as well as to confirm the effectiveness of the redesign procedure. The objective of the current paper is to present the experimental results of the aerodynamic performance of the baseline and the redesigned rounds over an extended range of Mach numbers from 1.8 to 4.

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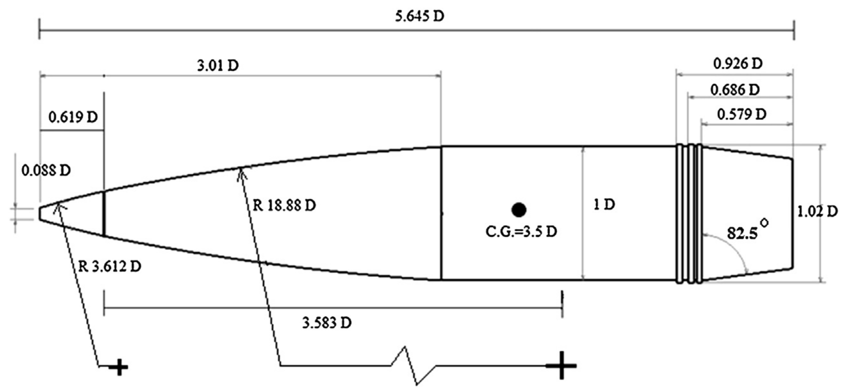

Fig. 1. The configuration of the standard 155 mm M549 round. Dimensions in body diameter ($D = 155$ mm).

Besides the need to verify the performance of the redesigned 155 mm round, there are two additional reasons that make testing of the standard and redesigned 155 mm rounds very useful. First, although experimental data of the standard M549 projectile can be readily found in the open literature (e.g., [6,8,13]), its performance at Mach numbers beyond the nominal flight conditions has not been tested, to the best of our knowledge. Therefore, experiments at higher Mach numbers will make a good contribution to the existing database of the 155 mm projectile. Second, the size of the round makes it an excellent candidate for wind tunnel experiments. The full-scale, or near-full-scale, body can be readily tested in large-size high quality flow wind tunnels without the added effects of scaling. Its dimensions also permit accurate force measurements to be conducted.

Although an aeroballistic facility is naturally the first choice for testing a spinning body, e.g., the aeroballistic test of the standard 155 mm by Kline et al. [6], testing in a conventional wind tunnel is a common alternative due to its wider availability and diagnostic capabilities, such as the ease to employ force measurements. The drawback of a wind tunnel test is that the model must be held by a sting, which may alter the flow field significantly, and it is difficult to instrument the model so that it can spin. Nevertheless, several wind tunnel experiments [3,5,10,12,14–16] were performed to investigate various spin-stabilized round bodies in the past. A brief review of these works is given below.

One of the first wind tunnel experiments of the standard 155 mm projectile (1/3 scale) was performed by Platou and Neilson [14] in which a series of non-conical boattails was tested under both non-spinning and spinning conditions. These non-conical boattails were modified from the standard 155 mm round [6,8] to improve aerodynamic performance. Two supersonic Mach numbers (1.75 and 2.25) were tested. A spinning test was also performed to investigate the Magnus effect. The experimental results consist of measurements of pitching moment and Magnus moment derivative. Sivan and Jermey [15] also tested a 1/3 scale of the standard 155 mm round but at lower Mach numbers (0.7–1.8) for Reynolds numbers ranging from 1×10^6 to 4×10^6, angle-of-attack from 0° to 20°, and spin-rate from 0 to 400 rev/s. The test results indicated that the spinning motion has small effects on static aerodynamic coefficients, while a significant effect on the side force and yawing moment was observed. In addition, base pressure measurements were performed to obtain base drag. Good agreement was observed between the results of the aeroballistic test [6] and wind tunnel test data.

More recently, Viswanath [16] studied the use of multi-step afterbodies to reduce the drag of generic rounds in a small trisonic wind tunnel at Mach 0.7 to 2. Ibrahim and Filippone [3] tested the use of slot cavities on the conical boattail for drag reduction on a Secant-Ogive-Cylinder-Boattail (SOCBT) projectile. The tests were performed in a wind tunnel at Mach numbers of 1.36, 1.65, and 1.83 at zero angle-of-attack.

Kayser et al. [5] tested a spinning Secant-Ogive-Cylinder (SOC) at a relatively high Mach number of 3. Force measurements using a balance and surface pressure measurements were performed at different angles of attack. The results of Magnus effect and pressure distributions along the body were published. More spinning experiments in wind tunnels have been performed in recent years for force and moment measurements to study Magnus effects. Oh et al. [12] tested a 155 mm spin-stabilized projectile at transonic Mach numbers ranging from 0.85 to 1.05 and the angle-of-attack was from 0° to 8°. Measurements were carried out to characterize the dynamic Magnus effects and to estimate the spin-damping coefficients. Milinović et al. [10] studied a 40 mm diameter spin-stabilized projectile and measured the aerodynamic coefficients and derivatives to analyze the gyroscopic and dynamic stabilities for Mach numbers ranging from 0.2 to 3.0 and angle-of-attack from −10 to 10°.

The key difference between the current work and the past works reviewed above is that in the current study, both the standard 155 mm round and its redesigned version are tested at the nominal and higher Mach numbers (Mach 1.8 to 4). The results not only provide new data for the standard 155 mm round at flight speeds up to Mach 4, the new data also open up the possibility that the 155 mm bodies can be operated at higher than nominal flight speeds. It is expected that the redesigned round will be able to deliver superior aerodynamic performance, which means the flight range can also be improved. The experiments will further confirm the accuracy and effectiveness of the optimization procedure proposed by Jiajan et al. [4].

A computational simulation of the flow around the test articles is also included in this paper in order to facilitate the analysis of the experimental data and to accurately determine the aerodynamic performance of the tested bodies at the actual wind tunnel conditions. The experimental results of these rounds are compared with the numerical results based on both actual testing and free-flight conditions and the conclusion will be drawn.

2. Experimental setup

2.1. Facility and instrumentation

The experiments were carried out in the Singapore Wind Tunnel Facility (SWIFT) [7] as shown in Fig. 2. The SWIFT is an extensively refurbished trisonic blowdown wind tunnel capable of testing articles ranging from Mach 0.3 to 4.0 in a 1.2 m × 1.2 m square test section. The test-section Mach number and Reynolds number can be controlled based on the available total pressure which is ranging from 1.7 to 17.5 bars. The total pressure is controlled by a pressure control valve. The total pressure p_0 in the test