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An investigation into the deceleration mechanisms of a projectile travelling through a liquid and the influence of hydrodynamic-ram effect

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Abstract

If fragmentation or a projectile such as a bullet were to penetrate an aluminium fuel tank, kinetic energy is introduced to the fluid contained within that tank. In turn, kinetic energy is also imparted to the aluminium tank structure, causing structural damage. This research project focussed on designing and constructing a re-usable vessel for repeat firing of projectiles into a liquid and the investigation of the hydrodynamic ram effect. The vessel should enable the use of high-speed imaging to allow the measurement and analysis of deceleration of different projectiles at different velocities.

Introduction

The pressure transmission of impact into the fuel contained within the structure is a direct result of the low compressibility of a typical liquid found in a fuel tank, where a relatively small level of compression can cause high-pressure levels [1]. This process of energy transfer from a projectile travelling at high speed to a surrounding liquid contained in the tank, and in turn to the tank's walls, is often referred to as hydrodynamic ram (HRAM). It has three distinct phases: shock phase, drag phase, and cavity phase. Some would add a fourth exit phase to this list [2], others might disaggregate the cavity phase to cavity expansion and cavity collapse [3]. Older research literature may refer to phases differently, listing the phases as impact, fluid shock, fluid drag and exit [4]. HRAM can lead to catastrophic failure of the tank structure and result in further damage to other delicate aircraft components [5]. A simple summary of the phenomenon might be that hydrodynamic ram is the impact of fluid loads, particularly impulsive loads, on fuel tanks walls [6].
The research on this phenomena has grown from being predominantly a NASA [,] and military concern to being a broader aviation one. However, the exact nature of how hydrodynamic ram applies pressure to an enclosed fuel tank, and how this damages the structure of that tank, is not yet agreed. Recently a new way of looking at the issue has emerged, with the possibility of a fuel tank acting as a form of protective mitigation for other parts of the aircraft. Research is therefore being conducted into whether the aircraft fuel tank could act as a dampening system within the aircraft safety case, decelerating missile fragments from a detonation effectively enough to eliminate the sympathetic initiation of neighbouring missiles and an MCE occurring, even when an aircraft is stored with its full arsenal mounted.

Methodology

A key project objective was the production of a reusable tank which enable reproducible results. The initial design considerations posed several engineering problems. It needed to fit the dimensions necessitated by the gas-gun chambers employed and the indoor ballistic testing range. It also needed to have transparent sidings whilst maintaining structural integrity to allow for use of image capture utilising Phantom V1212 cameras. Finally, it needed to be strong enough to resist breaking both from the pressures created upon projectile entry, and from the residual impact on the back plate.

The final design utilised a steel frame, thicker steel end plates (to absorb any impacts from projectiles that may reach the back), polycarbonate sides, and a removable aluminium plate (target material, held in place with a retaining ring and seal) that could be changed after each shot. This plate needed to be easily replaced ensuring future capability, whereby different material types could be investigated as well as extending the data sets that can be acquired from a single design. Figure 1 presents the final tank design.



Figure 1: Final reusable tank design.

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High-speed Phantom cameras were used to produce video of the projectile's trajectory. Four different projectiles were used, as per Figure 2 (left hand side) below, to assess the effect of density, size, and orientation on the cavity effects and deceleration mechanism. The projectile selection was primarily made from the groups research into fragmentation design of modern missiles, enabling a fair comparison to current in-service munitions.

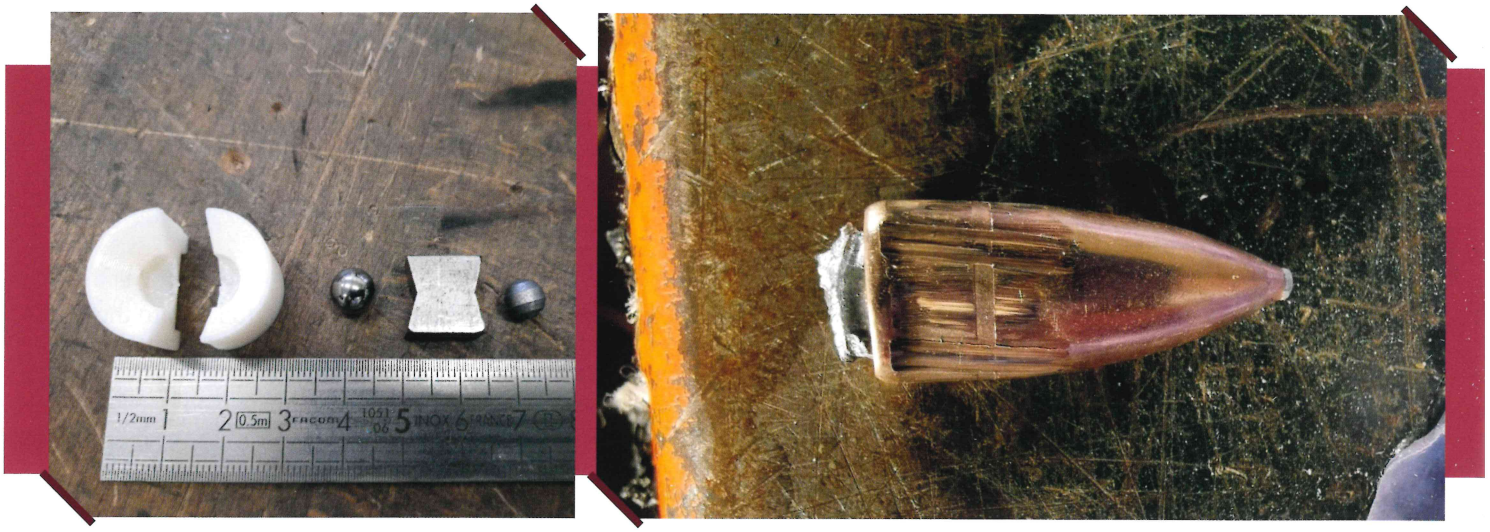


Figure 2: Left - Images of the three gas-gun projectiles, plastic sabot, and Right - rifle-range projectile (7.62 NATO steel cored ball round, post impact)

The three gas-gun projectiles were fired at five different velocities and velocity, deceleration, and video data was recorded for every shot for later analysis. Velocity was measured at three locations: at the guns muzzle, at the front of the tank, and at the rear of the tank. Firing pressures between 5-50bar in the 22mm calibre gas gun were used to achieve an appropriate muzzle velocity range of 100-500m/s. The rifle-range was able to achieve velocities approaching 800m/s, achieving much higher energies, allowing for visualisation of the HRAM (Figure 3) and shock phase (as per Figure 4).

Results

The results from the high-speed video of the fragment travelling through liquid shows that significant energy is imparted into the fluid as it is decelerated, eliciting a specific array of dynamic fluid behaviours. The critical fluid behaviour to be investigated and characterised is the hydrodynamic ram effect. This mechanism is often broken down into four distinct phases:

1. Shock phase
2. Drag phase
3. Cavitation formation phase
4. Cavity collapse phase

Figures 3 and 4 below are image frames taken from the high-speed footage highlighting the hydrodynamic ram stages as the projectile moves through the liquid.

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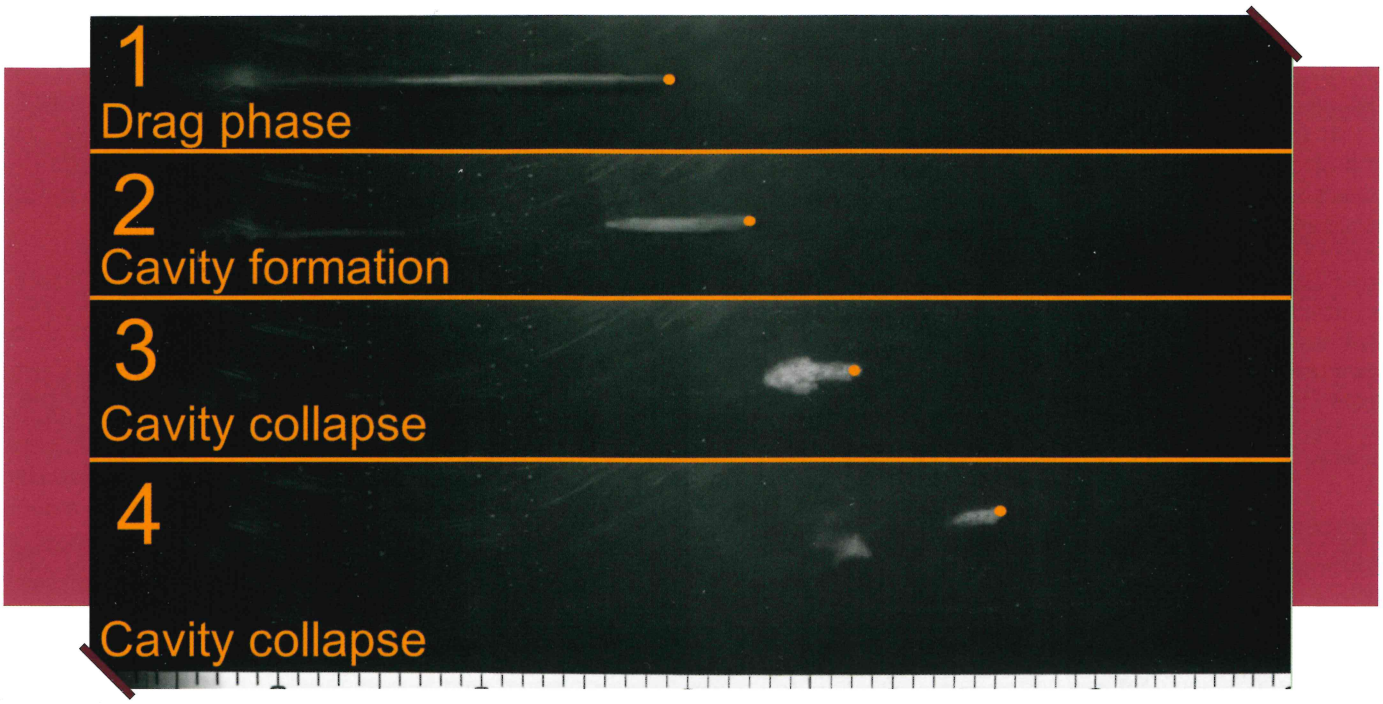


Figure 3: The cavitation and drag effects produced from an 8mm steel ball fired into the tank containing water at 250m/s.

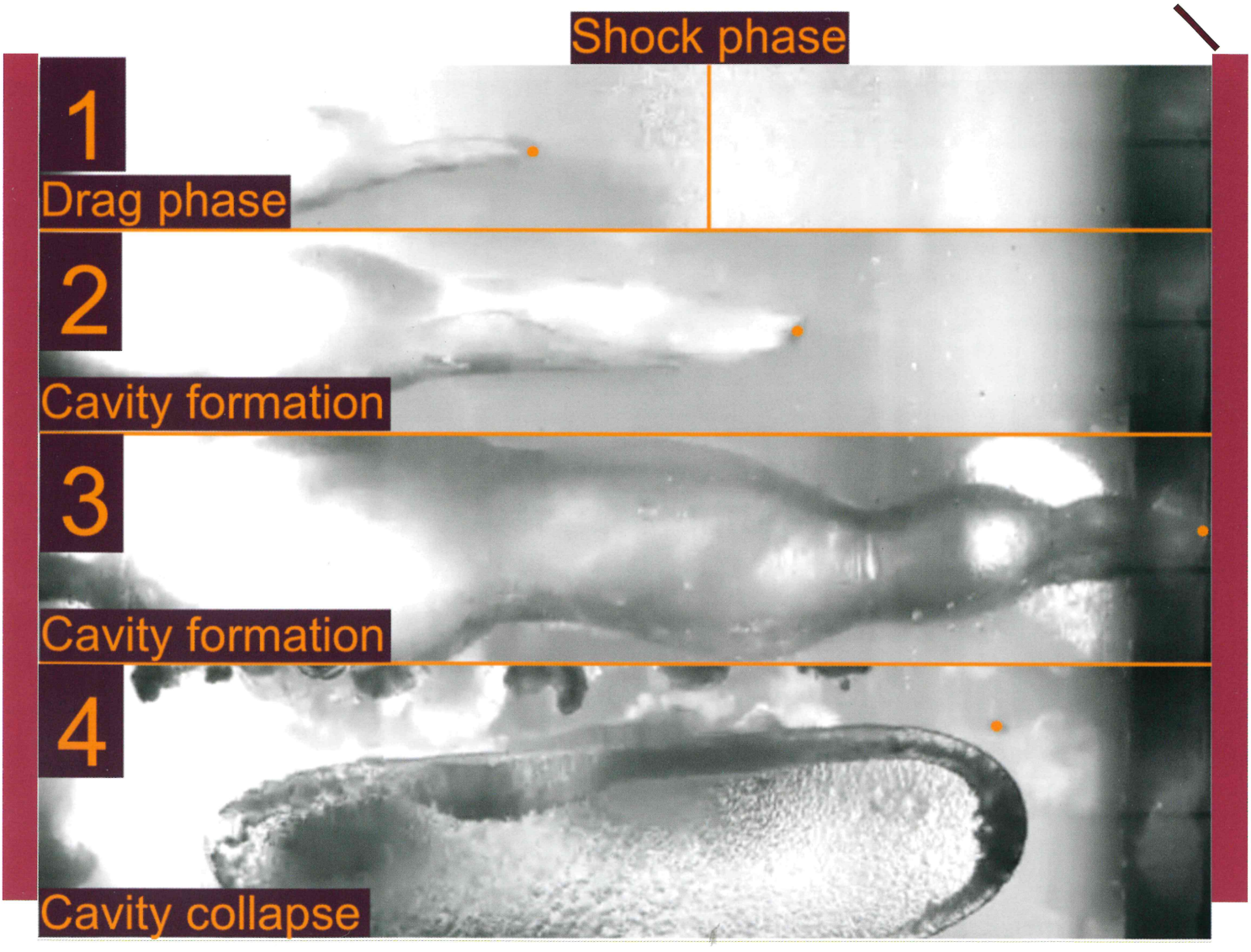


Figure 4: The cavitation and drag effects produced from a 7.62x39mm steel ball fired into the tank containing water at ~770m/s.

Conclusions

The experimental set-up was effective for observing the previously discussed stages of the hydrodynamic-ram effect (Figures 3 + 4). This achieves the project objective of being able to reproducibly observe deceleration and cavitation across a range of projectiles and velocities, laying the groundwork for further experimentation and modelling. Kinetic Energy Density (KED) calculations indicate that the rear-plate of the tank will survive impact from a tungsten sphere impacting the front-plate at 1500 m/s, suggesting reusability for further testing at higher velocities.

Linear slowdown was not experienced within the drag equation. This is likely due to the hydrodynamic effect causing the cavitation and drag forces to change throughout the projectile's path. This dynamic slow-down means that the drag coefficient is not easily calculated, and more advanced equations to predict projectile slow-down are required.

Hydrodynamic-ram effect in all 4 stages was only observed in the use of the high-velocity 7.62x39mm projectiles. For the lower KED projectiles, only the later stages were observed. In order to also trigger the shock phase, higher-velocity impacts are required. Maximum cavity size was seen to increase directly proportional to KED for each projectile. Accounting for velocity, the tungsten sphere data showed a much smaller cavitation increase per KED increase, compared to the steel sphere and steel bowtie, suggesting that material density may play a more significant role than shape.

Acknowledgments

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