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Research Article

Design of a Cost-effective Precision Guided Bomb

Abubakar Imam*, Salisu L

University Technology PETRONAS, Persiaran UTP, 32610 Seri Iskandar, Perak, Malaysia

ABSTRACT

The denial of developed nations to Technology Transfer (TT) to the developing countries and the refusal of some weapons-manufacturing countries to sell the required military platforms to developing countries faced with combatting insurgency and terrorism brought the importance of evolving HGC in defence production through reverse engineering. Thus, this study presents the design of a PGB through reverse engineering. The development of the PGB followed a four-part methodology, namely, establishing the design approach, selection of materials and design of a new energetic explosive material. The study employed a conceptual design approach involving an iterative design process requiring numerous design iterations to balance the system's various input/output requirements. The performance of the PGB was evaluated based on its suitability of attack strategy (blast frag etc.), delivery method, collateral damage and cost. The following described the engagement endgame of the PGB: if the warhead detonates in the vicinity of the target, it will damage the target. However, there was no certainty that the PGB would annihilate the target. Actual damage can only be ascertained in terms of Probability of Kill (Pk), which is a likelihood that the target will be incapacitated. Pk depends on the shock wave/fragments and the proximity of the warhead to the target.

Keywords: Technology transfer; Reverse engineering; Precision guided bomb; Warhead; Probability of kill.

INTRODUCTION

In the late 1970s, many developing countries sought a Code of Conduct to regulate Technology Transfer (TT) under the United Nations (UN) auspices to encourage TT [1]. However, it became difficult to regulate TT effectively given the incentives for owners not to transfer technology without an adequate return and the problem of monitoring compliance with any rules that might be imposed. This helps explain why TT is predominately mediated by national policies rather than by international disciplines. Consequently, developing countries have long employed both national policies and international agreements to stimulate TT. National policies range from economy-wide programmes such as education, funding of research and development, tax incentives for purchasing capital equipment and intellectual property rights (IPRs), and funding for the creation and acquisition of technology. Hence, TT can best be achieved through the extensive application of the reverse engineering method. Reverse engineering includes activities to determine how a product works or learn the ideas and technology initially used to develop the product. Thus, the AFN can effectively exploit the concept of reverse engineering to evolve Home-grown Capacity (HGC) in numerous technologies. One of such technologies is the Precision Guided Bombs (PGBs).

Statement of the problem

The denial of developed nations to transfer technology to the developing countries, coupled with the refusal of some weapons-manufacturing countries to sell the required military platforms to developing countries faced with combatting insurgency and terrorism, had brought to fore the importance of these countries to evolve HGC in defence production through reverse engineering.

Aim and objectives

This study aimed to present the design of a cost-effective remote control PGB through reverse engineering. The key objectives of the study include:

- To design a PGB capable of travelling at 420 m/s to hit a target advancing within an 18 m diameter circle over urban terrain.
- To select suitable materials for the PGB's components.
- To design a well suited energetic explosive material for the PGB.
- To test and evaluate the performance of the designed PGB.

Correspondence to: Abubakar Imam, University Technology PETRONAS, Persiaran UTP, 32610 Seri Iskandar, Perak, Malaysia, Tel: + 2348053946668; E-mail: asimam@nda.edu.ng

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METHODS AND MATERIALS

PGBs were first developed in the 1940s when the US Army guided glide bombs onto a target [2]. Before the precision guidance, bomb missions had an accuracy of 360 m, with about 16 per cent of munitions dropped, landing within 300 m around the intended target [3]. Several defence analysts posited that guidance systems hold huge potentials in enhancing weapon accuracy—however, technological challenges in developing guidance systems and enormous unit costs per munition used. Guidance systems during this era used television signals and required a chase hampered their usage. By the 1960s, PGBs gained prominence during the Vietnam War with the introduction of the laser-guided bomb. A study conducted in the 1970s found that more than 10,500 laser-guided bombs were used, with 5,107 weapons achieving a direct hit and another 4,000 performing a circular error probable of 25 feet [4]. PGBs have been utilized by the United States (US) in several military operations, including the Vietnam War, Operation Desert Storm, Afghanistan, Iraq, and Syria [5]. China and Russia [6-8] have developed sophisticated air defences and anti-ship missiles to compete with the US variants. PGBs can be employed in the ground, air, and naval operations. The fighting capabilities such as speed, target detection range, target identification, target tracking and engagement effectiveness of short-range GBs have greatly improved due to technological advancements. Typically, PGBs utilize radio signals ranging from the Global Positioning System (GPS), laser guidance, Inertial Navigation Systems (INS) and Infrared as guidance technologies to home to target. The homing guidance system provides continually improving quality of target information right up to the intercept point. The four main subsystems of PSBs are propulsion system, warhead, guidance system, radio transceiver and sensors. Commands deflect movable control surfaces from the guidance system to direct the munition in flight by placing it on the proper trajectory to intercept the target. Additionally, the PGB ould also be fitted with a radio receiver and control surfaces in the tail.

The development of the PGB followed a four-part methodology, namely, establishing the design approach, selection of materials and design of a new energetic explosive material. A conceptual design approach was employed for the PGB design. The method involved an iterative design process requiring numerous design iterations to balance the system's various input/output requirements. The process comprised four phases, as detailed below.

Baseline selection

The AGM-114 Hellfire missile (Figure 1) was selected to serve as the baseline for the PGB to fast-track the design process.

Design process

An Excel Warhead Spread sheet (Enclosure 1) was used to make changes in the baseline missile aerodynamics, propulsion, weight and flight trajectory to reflect the new requirements of the new missile concept. The aerodynamics aspect of the conceptual design process involves finding alternatives configurations in the geometry of the missile. Output from the aerodynamics calculation would then be passed to the propulsion system for sizing. Propulsion sizing includes providing sufficient propellent of range and time-to-target requirements [9]. Following adequate iterations, the next step is evaluating the new PGB against the defined requirement/scenario; If it does not meet the requirement, the design is then changed and resized for the next iteration and evaluation.

Materials selection

This section described the criteria adopted in the selection of materials for the PGB components. The various components/subsystems of the PGB include the airframe, the radome, the nozzle, and the rocket motor insulation are:

Airframe

Airframe plays a vital role in the PGB's functionality, including enhancing flight performance, reducing weight, permitting higher flight Mach number, reducing cost and providing higher reliability. In operation, the PGB would be subjected to a high temperature for a short time and would experience tensile deformation. Hence, the critical selection property of the airframe will be yield strength [10]. Therefore, the composite material was recommended for the airframe system. The strength-to-weight capability of advanced composites is very high. The reinforcing elements in the composite provide the required stiffness and strength necessary to carry the primary structural loads. For most airframe applications, continuous graphite (carbon) fibres have been used as the reinforcing elements. The fibres provide structural stiffness and strength, which can save weight [11].

Radome

Considering the operating parameters of the PGB, silicon nitrate (Si_3N_4) ceramics was selected for Radome material. The physical and chemical properties of silicon nitride include high strength, thermal stability, lightweight, low thermal expansion, chemical stability, low dielectric constant, and high stiffness. It also possesses higher strength capable of withstanding higher velocities and temperatures and longer flight durations and can be stable at a temperature above 1600°C and have a low and steady thermal dielectric constant, low thermal expansion coefficient, high resistance to thermal shock, high stiffness and strength, high chemical stability, and high resistance against moisture [12].

Nozzle

In operation, the PGB would be exposed to high temperatures over 3000°C. This imparts a higher specific impulse to the nozzle system, resulting in higher temperatures and pressures that need to be contained. The fact that propellants produce very hostile, abrasive environments; existing materials for boost throat applications have been shown to erode at unacceptable rates, leading to a loss in performance due to throat widening. The critical requirement for nozzles is the retention of shape during flight. Hence the material requirements include a) materials for the nozzle housing with high tensile specific strength at temperatures; b) insulating materials with good insulation properties at high temperatures; c) insulating materials with good resistance to erosion at high temperatures; d) insulating materials compatible with the gas stream at the operating temperatures [10]. Therefore, selecting a suitable material for the

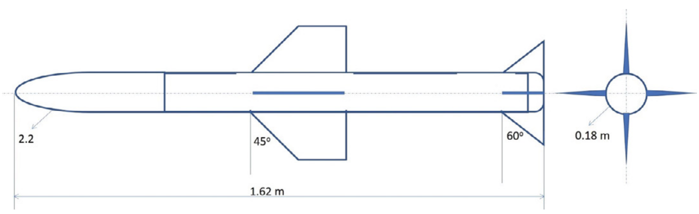

Figure 1: AGM-114 physical structure.

nozzle of the PGB requires a family material that possesses structural integrity, thermal protection, and low- or near-zero ablation rates above 3000°C. Thus, ultra-high temperature ceramics (UHTC) such as tantalum carbide (TaC) and hafnium carbide (HfC) were selected for the nozzle. These materials have the highest melting points known, 3950°C and 3928°C, respectively. Compared to refractory metal candidates such as Rhenium (W) and Tungsten (W), these carbides offer significant weight savings. Densities for TaC and HfC are 12.2 g/cc and 14.3 g/cc, respectively.

Rocket motor

Conceptually, a solid rocket motor is consisting of a tube, closed at each end, with apertures for the igniter and nozzle. The motor case must be strong enough to withstand the high internal pressures created during the motor burn. The primary selection criteria were high strength and stiffness, low susceptibility to high-temperature degradation effects, high volumetric efficiency, lightweight and easy attachment to airframe or launcher, and low cost. Other possible considerations include ease of manufacturing, handling, thermal conductivity, storage and operating environment. Several materials are used for the construction of motor cases. The leading candidates are steels (conventional quench & temper steel or nickel precipitation-hardened maraging steel), strip steel/laminates and composites (glass or carbon fibre). Aluminium and titanium alloys are also possible but unlikely. Steels usually give the best overall combination of high performance and low cost. The ratio of maximum allowable stress to material density is often used as a figure of merit (specific strength). However, the effect of thermal degradation must also be taken into account. Table 1 depicts the candidate materials with their property.

An empirical formula often used for calculating the design pressure in the design of medium size motors is:

$$p_D = (1.16\,p_c + 8)\,bar \quad (1)$$

The effects of stress concentrations of openings (for the igniter, nozzle, thrust termination ports) in the motor case and of any joints or flanges must be taken into account. All loading cases must be considered. For the cylindrical part of the motor case, thin-walled cylinder stress analysis gives:

For the hoop stress:

$$p_D = (1.16\,p_c + 8)\,bar \quad (1)$$

For the longitudinal stress:

$$\sigma_l = \frac{p_D D}{4t_c} \quad (3)$$

Where, t_c is the cylinder wall thickness.

There are several possible methods of constructing motor cases. The cases for small motors may be machined from solid, extruded, drawn, or machined from a tube. The cases for large motors may be fabricated by welding or assembled from segments and bolted or pinned together.

Explosives design

The PGB would require energetic explosive material to function effectively. Energetic materials include propellants, explosives, and pyrotechnics are chemical compounds or mixtures that store significant quantities of energy. Propellants and pyrotechnics release their energy through relatively slow deflagration processes, thereby taking several seconds to achieve complete combustion. At the same time, explosives release their energy on the microsecond timescale.

Explosive design process

Several energetic materials can be categorized as oxidizers, fuels, binders, catalysts, and technological additives, depending on the ratio of the molecule's constituent elements (i.e., carbon, hydrogen, nitrogen, and oxygen atoms). Additionally, energetic materials can play the role of oxidizer or fuel or function as monopropellants at a balanced oxygen content for a stoichiometry balance. It is important to note that all components of energetic composite materials are essential, and each must perform well in its role. Altering component's number and proportions in the composition will result in energetic materials with different explosive properties. Traditionally, forming a new energetic material requires selecting an energetic base material that possesses the necessary set of desired properties and systematically varying its composition to meet the desired requirement in the new material. The design of new energetic material is time-consuming and requires trade-offs between cost in energy content, safety, and cost. Therefore, a scientific experimental technique (Design of Experiment (DOE) was employed to simplify the process. Before using the DOE technique, a simple empirical method was developed to help indicate how each molecular constituent affected an explosive's performance. The method is to help guide the synthesis effort by providing insight as to what components were beneficial to high performance and which ones were not. Additionally, the empirical method will focus on the following properties density, heat of formation, atomic composition, and sensitivity to shock or impact. The material designed ($C_aH_bN_cO_d$) was a dynamic variant of Composition B compound containing a mixture of 65% RDX, 35% TNT and 10% wax.

Property of the new material

In it cast form, the composition of the new material features a density of 1.95 and a detonation velocity of about 10,668 m/s. The proposed material's detonation properties and explosive parameters such as density, gurney velocity, oxygen balance and decomposition products were predicted using ANSYS Autodyne software [11]. It was envisaged that the predicted detonation parameters of the newly designed material would exhibit higher VOD and detonation pressure compared to TNT ($C_7H_5N_5O_8$) and RDX ($C_3H_6N_6O_6$) (Figure 2).

The density of the proposed material was calculated using the volume additivity technique [13]. The VoD, detonation pressure and heat of detonation can be computed using EXPLO-5 [14]. The

Table 1: Motor case materials.

Serial	Item	Performance	Remarks
1	Steel	202 ×103	-
2	Maraging steel	215 × 103	-
3	Strip steel/Laminate	224 × 103	-
4	Glass fibre composite	588 × 103	-
5	Carbon fibre composite	1245 ×103	-
6	Titanium alloy	218 × 103	-
7	Aluminium alloy	174 × 103	-

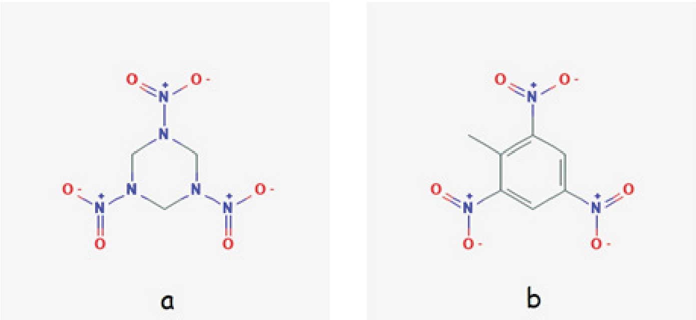

Figure 2: Molecular Structure. a) RDX and b) TNT.

explosive power, gurney velocity, explosion heat, and power index were calculated using the PGB Excel Spreadsheet (Enclosure 1). The method proposed by Zeman S and Jungova M [15] was employed to predict the electric spark sensitivity of the new material. More so, the peak overpressure and blast impulse of the newly designed material was computed using SPEE software [16]. The material's VOD and ballistic performance parameters were obtained using the methods proposed by Keshavarz MH and Zamani A [17].

Explosive train of the new material

To ensure safe handling of the explosive materials, they are separated into primary, intermediate, and secondary categories. The primary explosive detonates quickly, called sensitive explosives; medium materials require slightly more energy to explode and finally, the secondary (insensitive) explosives require relatively more energy to discharge. Thus, this arrangement of explosives is called the explosive train. In this case, the proposed RDX/TNT material will serve as the secondary explosive for the weapon system. However, their low sensitivity is usually used in conjunction with other susceptible explosive materials that initiate the detonation. The energy from its detonation would be used to set off the secondary explosive.

Storage of the PGB

The new explosive material of PGB contains nitro-glycerine reduces the possibility of exudation of nitroglycerine. To avoid problems arising out of changes in physical properties, it must not be stored in an environment, any part of which is liable to remain below 5°C for a continuous period exceeding one month. More so, deterioration of the proposed material in terms of physical properties or performance and a reduction of the shelf life will occur more rapidly with increasing temperature. It is recommended that wherever practicable, the temperature in a storage environment should not be allowed to exceed 30°C to avoid problems associated with autoignition. Additionally, high humidity conditions will produce deterioration in the physical and ballistic properties of the proposed material. Nearly all pyrotechnics deteriorate in conditions of high humidity to the detriment of their performance. Therefore, it must be ensured that adequate protection against high humidity.

Cost analysis

Table 2 depicts the relative importance of the PGB's subsystems overall cost. The IR-seeker subsystem appears to carry the highest cost (about 30 per cent) of the total PGB's cost.

RESULTS AND DISCUSSION

Performance evaluation

The performance of the developed PGB was evaluated using the Excel Spreadsheet (Enclosure 1). The evaluation was based on the PGB's suitability of attack strategy (blast frag etc), delivery method, collateral damage and cost. Table 3 depicts some critical parameters of the PGB.

Engagement endgame

From the information in Enclosure 1, the following described the engagement endgame of the designed PGB. If the warhead detonates in the vicinity of the target, it is expected that the target will be damaged. However, there is no certainty that the target will be destroyed completely. The actual damage can only ascertain in terms of Probability of Kill (Pk). Pk is likelihood that the target will be incapacitated. For this application, Pk depends on the shock wave/fragments and the proximity of the warhead to the target. Table 4 depicts the likely levels of damage the target may experience.

To find the distance to which the target with soft body armour might be destroyed from 97.035 kg RDX/TNT explosive. The scaling factor = $w^{(1/3)} = [97.035]^{(1/3)} = 4.59$. With an over-pressure experienced at 18.5 m, the effect will be felt at = $R = 18.5\ m \times 4.59 = 85\ m$.

Damage Criteria for Fragmentation Warheads

The fragments kinetic energy determines the level of damage from a warhead on a target. Based on typical ballistics numbers, around 4000 J is sufficient to penetrate the target's light body armour. Therefore, to find the Pk from the missile against the target at 18.5 m from the detonation having 35,185 number fragments at about 4000 J each, neglecting drag. The closest value Pk|hit given in Table 3 is 0.9 at 4000 J.

So, the $N_{hit} = (1(97.035))/(4 \times \pi \times [18.5]^2) = 0.42$

Table 2: Cost analysis of the PGB's subsystems.

Serial	Item	Cost (% of Total Cost)	Remarks
1	Fuselage	20	-
2	Guidance subsystem	10	-
3	Propulsion subsystem	10	-
4	IR-seeker	30	-
5	Flight control subsystem	10	-
6	Dome	5	-
7	Test and evaluation	15	-

Table 3: PGB performance evaluation.

Serial	Item	Performance	Remarks
1	Fragment velocity	2,582 m/s	-
2	Taylor angle	9.4	-
3	Lethal impact	713 m/s	-
4	Over pressure experience at	18.5 m	-
5	Number of fragments	35,185	-
6	Density at lethal range	10.6 m^2	-
7	TNT equivalence	1.13	-

Table 4: Levels of damage and probability of kill.

Serial	Damage Level	Description	Pk	Remarks
1	Light	Minor damage, some functions lost, but still capable of operation.	0.1	-
2	Moderate	Extensive damage, many functions lost. Operation still possible but at reduced effectiveness	0.5	-
3	Heavy	Unable to operate	0.9	-

Therefore, Pk = 0.42 × 0.9 = 0.38. This implies that at 18.5 m, a person might have a 38%.

Production and deployment

When fully satisfied with the performance of the proposed guided missile system after test and evaluation, the missile is deployed for the desired mission.

CONCLUSION

The denial of developed nations to transfer technology to the developing countries and the refusal of some weapons-manufacturing countries to sell the required military platforms to developing countries faced with combatting insurgency and terrorism brought the importance of evolving HGC in defence production through reverse engineering. Thus, this paper presented the design of a PGB through reverse engineering. The defined Four objectives were defined to achieve the study's aim, including designing a PGB capable of travelling at 420 m/s to hit a target advancing within an 18 m diameter circle over urban terrain and selecting suitable materials for the PGB's components. Other objectives were designing a well suited energetic explosive material for the PGB and finally testing and evaluating the performance of the designed PGB. The development of the PGB followed a four-part methodology, namely, establishing the design approach, selection of materials and design of a new energetic explosive material. The study employed a conceptual design approach involving an iterative design process requiring numerous design iterations to balance the system's various input/output requirements. Performance evaluation of the PGB was conducted based on its suitability of attack strategy (blast frag etc), delivery method, collateral damage and cost using an Excel Spreadsheet (Enclosure 1). From the information in Enclosure 1, the following described the engagement endgame of the designed PGB. If the warhead detonates in the vicinity of the target, it will damage the target. However, there was no certainty that the PGB would annihilate the target. The actual damage can only be ascertained in terms of Probability of Kill (Pk), which is likelihood that the target will be incapacitated. For this application, Pk depends on the shock wave/fragments and the proximity of the warhead to the target. Table 4 depicts the likely levels of damage the target may experience.

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