REDUCING THE VULNERABILITY OF MILITARY HELICOPTERS TO COMBAT DAMAGE

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Abstract

Military helicopters are highly susceptible to attack by a wide spectrum of battlefield weapons, from small arms to man portable surface to air missiles. In addition, a wide range of "non-conventional" threats such as rocket propelled grenades; anti-armour guided weapons and main battle tank main armament are also significant.

Considerable effort has been devoted to reducing the susceptibility of combat helicopters to these threats. A review of combat data reveals, however, that many helicopters are still lost to these less conventional or low technology threats.

"Cheap kills" which result from engagements by these less conventional threats tend to occur despite the presence of sophisticated defensive aids suites and hardening techniques that are relied upon by helicopter designers today.

This paper presents a brief review of helicopter combat loss data covering the period from the Vietnam conflict to recent operations in Afghanistan. This is supported by key conclusions from a number of helicopter vulnerability assessments performed on behalf of the UK MOD.

The paper provides a description of the basic vulnerability reduction measures applicable to all combat aircraft, and describes practical applications of these measures to the design of military helicopters.

Definitions

Any item of military equipment, including the military helicopter, must be survivable - it should be able to withstand a man-made hostile environment [Ref.1]. The inverse of survivability, "probability of kill" (P_k), is a function of two properties, *susceptibility* and *vulnerability*. The survivability paradigm is illustrated at Figure 1.

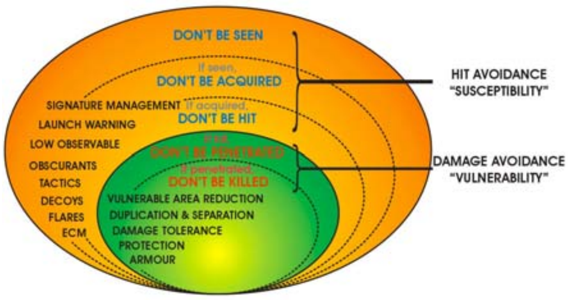

Figure 1: Survivability, a function of susceptibility and vulnerability

Susceptibility is the inability of the helicopter to avoid being hit by a threat weapon, measured as probability of hit, or P_h. Various steps may be taken to reduce it's susceptibility, including:

- the management and reduction of it's electromagnetic (RF & IR) and acoustic signatures;

- the use of active countermeasures such as jammers, decoys and flares;
- tactical flying to prevent detection by potential threats;
- suppression of enemy weapons.

Susceptibility reduction measures will contribute significantly to the survivability of the combat helicopter. However, it is inevitable that, at some point during operations the battlefield helicopter will find itself exposed to hostile fire. Many of the measures listed above are likely to be ineffectual against unsophisticated or novel weaponry, at which stage it is only effective vulnerability reduction measures that will allow the helicopter to avoid the "cheap kill".

Vulnerability is the inability of the helicopter to withstand the damage caused by a threat, once a hit has occurred. The term “hit” should be treated with a degree of caution. In the case of bullets and impact fuzed projectiles the term is used to denote a physical impact with the target. For proximity fuzed weapons a near miss is sufficient to trigger the warhead resulting in multiple (fragment) impacts with the target. Vulnerability is measured as probability of kill given a hit, or $P_{k/h}$.

The helicopter may initially withstand this damage by preventing the threat damage mechanisms from penetrating its external skin. While this particular criterion is more suited to armoured fighting vehicles, externally mounted armour is occasionally used in helicopters (a good example being the Mil. 8AMTSh. If penetration is unavoidable, various other measures may be taken to mitigate the damaging effects of the threat; these are discussed later in this paper.

Introduction

Helicopters have been used in war fighting since the latter stages of the Second World War, however it was not until the early 1960s in Vietnam that their full potential was recognised. Small numbers of UH-1 helicopters were used in Vietnam from 1962 onwards initially to transport small groups of soldiers and later as improvised gun ships.

The US Army formed their first helicopter Air Assault Division in early 1963, tasked with developing the necessary tactics to allow helicopters to deliver large numbers of troops to the battle. This allowed the basic tempo of war fighting to be increased dramatically as the troop commanders were no longer constrained by the topography of the battlefield. At the end of 1964 the US 11th Air Assault (Test) Division conducted a major exercise which proved the theory of modern helicopter warfare and presaged the incorporation of helicopters into the regular army [Ref. 2]. With the escalation of hostilities in 1965 the stage was now set for helicopters to play a major part in any future conflicts. At this time the helicopter fleet had little or no protection against hostile fire, initial vulnerability reduction features being limited to armoured panels around the crew seats.

Initially, tactics decreed that helicopters would fly at reasonably high altitude (above 3000 ft) in order to avoid the majority of machine gun fire coming from the ground. This was a reasonably successful tactic, although the helicopters were vulnerable when delivering their troops into landing zones, in these instances coming under almost constant small arms fire [Ref. 3]. With the advent of the 9M32/SA-7 missile the tactics were modified by flying at consistently low altitude in order to place the helicopters below the lower kinematic boundary of the missile’s engagement envelope. This was successful to an extent but forced the helicopters to fly where small arms fire was at its heaviest.

In 1965, the US Army recognised a need for a dedicated attack helicopter. At the time it was believed that producing a vehicle that was tolerant to a degree of damage from the significant threats of the day was a better way of ensuring survivability than relying upon high speed and agility. A solution to the requirement was developed rapidly using the basic dynamic system of the original UH-1 troop-carrying helicopter but with a new fuselage configuration featuring a tandem cockpit. This conceptual design developed into the AH-1 Huey Cobra and can be considered to be the forerunner of all current attack helicopters; many remain in service today.

The AH-1 incorporated a number of design features to provide a high degree of ballistic tolerance to the most widely encountered threat of the time (the .30cal/7.62mm bullet) [Ref. 4].

The remainder of this paper provides a brief overview of those weapons, which are considered to pose a particular threat to battlefield helicopters and a review of helicopter losses in combat from Vietnam to the present day. By reference to studies conducted in the UK on behalf of MOD it identifies those components of the modern combat helicopter that are most vulnerable and describes the techniques that can be employed to reduce their vulnerability.

Threats to Combat Helicopters

Since the Vietnam war era, the sophistication of anti-air weapons has increased dramatically and it has to be recognised that, in general, a helicopter will remain very vulnerable to a large range of these weapons. The probability of survival of a combat helicopter in an "all out" war situation relies heavily on the avoidance of those weapons by the use of sophisticated Defensive Aids Suites (DAS) rather than the inherent hardness of the helicopter to survive impact/engagements from them. However, with the increasing frequency of peace-keeping/operations-other-than-war (OOTW), the likelihood of encountering the high technology threats, which the majority of DAS are designed to counter, has diminished. This leads to the requirement to provide a reasonable level of protection against what are generally termed "low technology" threats. These typically consist of hand-held rifles (e.g. AK-47), heavy machine-guns (e.g. ZPU-2/4), small/medium calibre cannon (e.g. ZU23/2) and shoulder launched rocket propelled grenades (characterised by the RPG-7).

At the next level of sophistication are the shoulder launched MANPAD (MAN Portable Air Defence) SAM systems, these include the Russian SA-7/14/16/18 family of missiles, the US Stinger and French Mistral. Providing protection against these and larger systems is particularly difficult for a helicopter designer. The majority of MANPAD systems utilise IR seekers and consequently the best form of protection is to avoid being engaged. Combinations of IR Jammers, thermal flares and reduced IR signature from "hot spots" on the helicopter go a long way to reducing the risk from this class of weapon. Anti Tank Guided Weapons (ATGW) can also pose a viable threat although they are generally limited in kinematic performance and have poor performance against a maneuvering target.

For larger SAM systems the only viable form of protection is the use of a sophisticated DAS. This paper will concentrate on the lower level threats where designed in ballistic tolerance can contribute significantly to the overall survivability of the helicopter.

Combat data

Considerable evidence exists to provide an indication of the vulnerability of helicopters to combat damage. The following paragraphs provide a broad overview of helicopter losses since the Vietnam war.

Early US experience in Vietnam, 1966 to 1975

Between 1962 and 1973, the US military (principally the US Army) lost approximately 2600 helicopters to hostile action in Vietnam [Ref. 5]. The majority of these losses can be attributed to small/medium, calibre threats (7.62mm-23mm). On average, the US lost approximately one helicopter every two days to combat damage. Of course, it is not possible to infer the number of helicopters that *survived* combat damage, but the loss rate is still considerable.

It should be remembered that, despite the reliance placed on the helicopter during this conflict, combat helicopter design and tactics were still in their infancy, and these statistics undoubtedly reflect this. However the US rapidly became aware that certain parts of the helicopter were particularly vulnerable, detailed analyses being carried out as early as 1965. Practical efforts were made to provide protection to these components, initially through the use of strategically placed lightweight armour.

Soviet lessons learned in Afghanistan, 1979 to 1989

Several sources provide differing statistics for the loss of helicopters during this conflict [Ref. 6, 7 and 8]. A report by the US Directorate of Intelligence available on the internet assesses that between 1980 and 1985 some 640 Soviet helicopters were lost from all causes (although only around 300 of these have been confirmed by the intelligence community). A more recent report, also freely available, produced by the US Foreign Military Studies Office suggests that the total figure for the full ten years is 333 helicopters lost, but it is not clear whether this includes operational losses as well as combat kills.

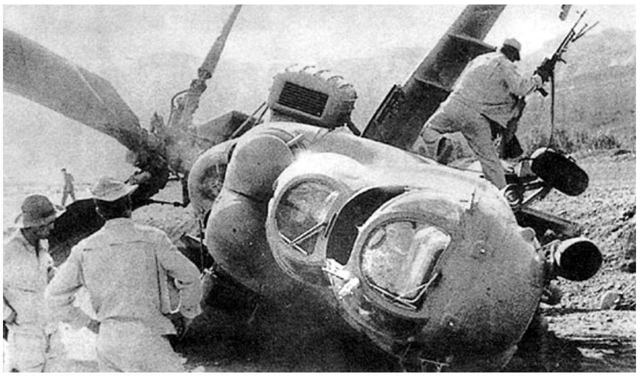

Figure 2: Mil.24 Hind, Afghanistan. Note the IR suppressor mounted on the exhaust

A third source suggests that between 600 and 800 helicopters were lost due to combat damage. Although many of these would be attributed to small arms fire up to 20mm calibre, a significant proportion of losses were caused by shoulder launched guided weapons including SA-7 and (particularly) Stinger. It is interesting to note that the first operational success of Stinger was in September 1986, with three Hind helicopters being destroyed in one operation, and that during 1987 Soviet helicopter losses were assessed at 1.2 to 1.4 per day.

It is also well documented that, once the SAM threat had been identified, changes in Soviet aviation tactics, and the introduction of vulnerability reduction measures (principally the incorporation of IR "hot brick" type jammers and IR suppressors on the engine exhausts) to the helicopters were instrumental in reducing losses.

Falkland islands 1982

Helicopter losses during the Falklands conflict were not high. Six Argentinean Puma were lost; one each as a result of small arms fire, surface to air missile and air to air missile. Two were shot down by a Sea Harrier using 30mm cannon.

The majority of UK helicopter losses were a direct result of operational accidents or the loss of the Atlantic Conveyor logistics ship. However, one Scout was destroyed in the air by a Pucara ground attack aircraft, one Gazelle was destroyed by a surface to air missile and two Gazelles were lost to small arms fire.

"Black Hawk Down!" Somalia 1992 to 1994

During Operation Restore Hope US forces in Somalia lost two Blackhawk helicopters [Ref. 9] during an air assault operation in Mogadishu. It is noteworthy that both losses were caused by rocket propelled grenades (RPG-7). A third helicopter was badly damaged in the same way during this operation, but managed to return to base. This is the first widely documented occasion where "non-conventional" weapons are known to have been used successfully against helicopters. The extremely short range (less than 500m) and poor kinematic performance of an RPG-7 effectively limit it as a threat to all but very close combat or urban warfare situations.

Chechnya

Between August 1999 and September 2001, 15 helicopters were recorded as having been damaged by ground fire, of which nine were losses. 40 fatalities occurred as a result, although some of these are attributable to the engagement itself rather than the subsequent crash. It is worth noting that all but two of the losses were caused by small arms fire, the remainder being attributed to RPG and shoulder launched SAM.

Although the Mil.8 Hip represents a significant proportion of these losses, it is also interesting to note that the more heavily armoured (and armed) Mil.24 Hind has also incurred considerable losses. No statistics have been compiled for subsequent years, but helicopter combat losses have continued in the theatre. Notable amongst these is the loss of a Mil.26 Halo transport helicopter, reportedly to a shoulder launched SAM, resulting in the death of approximately 120 passengers and crew.

Enduring Freedom, Afghanistan 2001 -

During Operation Anaconda (March 2002) [Ref. 10], an AH-64 Apache and an UH-60 Blackhawk were both hit by RPG and a further five Apache were reported to have been damaged by small arms fire. All aircraft are believed to have survived these encounters. Reports [Ref. 11] suggest, however, that one CH-47 Chinook was shot down with the loss of several crew and passengers and a second seriously damaged, in another operation in this theatre.

Operation Iraqi Freedom, 2003

It was reported [Ref. 12] that 31 out of 32 AH-64 Apache engaged in operations near Karbala sustained combat damage although only one failed to return. All of the helicopters were operational within 96 hours despite having at least 6 bullet holes in each. The damage was reported to have been as the result of gunfire (up to 30mm) and RPG impacts but none from radar guided SAMs.

This is, perhaps, a testament to the value of sound vulnerability reduction measures designed into Apache, rather than (as has occasionally been suggested) an indication of poor battlefield survivability.

Discussion The examples presented here are insufficient to draw detailed statistical conclusions. However, a number of important points may be inferred, the most significant of which may be that, despite improved survivability design and tactics since their early deployment in Vietnam, helicopter combat losses, although reduced, remain at a substantial level.

Against an opponent with a low level of weapon technology, losses remain inevitable. The lack of sophistication of the opponent merely serves to prompt the development of more effective methods of bringing weapons to bear, or more novel methods of attack, i.e. the "cheap kill". With the current state of world affairs it would perhaps be wise for the designer and operator of combat helicopters to consider potential threats which increase in novelty rather than in level of technology.

The nature of helicopter combat operations is such that significant loss of life is possible when a helicopter is successfully engaged. A cheap kill is no less likely to result in a significant high human and materiel loss than a high-tech kill.

As evidenced by the Falklands conflict losses, even a technologically advanced opponent will find the cheap kill a potent counter to the combat helicopter. However, high-tech countermeasures will have little or no effect on the cheap kill. This can only be countered by tactics (susceptibility reduction) and hardening the platform (vulnerability reduction).

In-theatre modifications to the helicopter may prove effective, but will often adversely affect its performance. The impact on performance may be reduced, and survivability will be increased, if these measures are driven by an analysis of the characteristics and capabilities of the threat, and implemented as a part of the aircraft design (or upgrade) process. The USSR implemented a number of vulnerability reduction design measures to the Su25 Frogfoot ground attack fighter as a direct result of experience during the war in Afghanistan. These measures reportedly reduced combat losses by a significant margin, admittedly in concert with tactical adaptations.

Vulnerability Assessment

Analysts have been assessing the vulnerability of combat vehicles since at least the early 1940s. Initially the assessments consisted of simple judgements of which parts were vulnerable to particular threats and estimates of vulnerable areas from a range of aspect angles. The probability of kill given a hit was simply obtained by dividing the estimated vulnerable area by the measured presented area from any given approach direction.

In the early to mid 1960s, the US started to develop vulnerability assessment tools such as VAREA (Vulnerable Area) and HART (Helicopter (vulnerable) Area and Repair Time) codes [Ref. 13]. These two codes evolved into the COVART model (Computation of Vulnerable Area and Repair Time) which became "operational" in the mid to late 1970s. The latest iteration of this code is still used extensively in the US for the assessment of fixed and rotary wing aircraft vulnerability.

In the UK a similar capability has been developed commencing in the late 1970s. The INTAVAL (Integrated Air target Vulnerability Assessment Library) suite of computer programmes has been used for the past 20 years in the assessment of air target vulnerability and anti-air weapon lethality. Separate modules exist to assess the effects of inert projectiles (fragments and bullets) and shells (both internally and externally bursting). A shot line approach is employed where individual fragments are passed through a geometric representation of the target and damage to individual systems assessed.

A typical target will consist of between 1500 and 2000 components which are either critical to maintaining flight or mission capability or provide shielding to those components. Figure 3 illustrates a section of a typical target description. Each component is modeled in terms of its physical dimensions, location within the target and its material composition. Component damage algorithms are assigned to each vulnerable component, which express the degradation to its functionality as a result of fragment mass and (typically) impact velocity. Failure logic (fault tree) analysis is used to calculate whole target vulnerability by summing the individual component vulnerabilities whilst taking account of the duplication and redundancy present within the system.

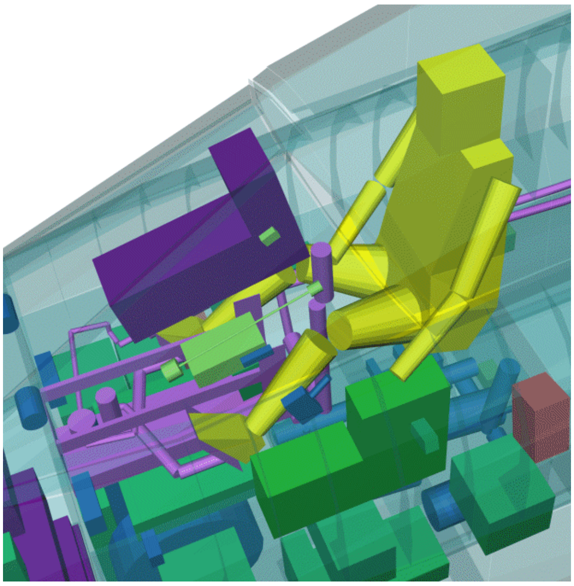

Figure 3: Detail from a typical INTAVAL target description of a combat aircraft

System and component Vulnerability

Detailed vulnerability analyses of battlefield helicopters will reveal the critical components and their contribution to overall helicopter vulnerability. The analysis may be performed in a variety of ways, ranging from a visual inspection of the helicopter or its design to a detailed assessment using vulnerability analysis software.

The analysis should consider the range of threats, be they small arms fire or surface to air guided weapons, each of which will be characterised by a particular damage mechanism. The analysis should also account for the required residual capability of the helicopter after receiving damage. Should the helicopter simply remain capable of maintaining controlled flight for sufficient time to reach a suitable landing position, or should it remain capable of performing a weapons delivery mission?

A detailed, software driven assessment may produce images similar to the one at figure 4. This provides a reasonable indication of the vulnerability of a large, generic assault helicopter to attack by various inert shot - small arms bullets or AP shell. It has been assumed that the helicopter need only remain controllable after being damaged.

In this particular case, the pilot represents a large proportion of the helicopter's vulnerable area - he is both relatively large in area and highly likely to be incapacitated if hit. It has been assumed here that the second crewman does not have the ability to take control of the aircraft in the event that the pilot is incapacitated. If the opposite were the case, then the pilot would not show as vulnerable in the figure (unless a single bullet could kill both, e.g. for an attack from ahead). However, if it were required that the helicopter should be able to deliver it's weapons after being damaged then both the pilot and second crewman would show as vulnerable.

A similar logic may be applied to the engines. Figure 4 assumes that both engines are required for controlled flight, although if only one surviving engine were sufficient then the overall helicopter vulnerability would be somewhat lower than shown. The drive shaft to the main rotor gearbox has been assumed to be too large or robust to be severed by a small arms projectile.

The hydraulic lines provide power to the main and tail rotor controls. Normally this system is duplicated, and it might be expected that this would render it invulnerable. However, in the case above it has been assumed that the duplicated lines are not separated and, consequently, a single shot could overcome the redundancy. Hydraulic fluid is a potential fire raiser, and this may also contribute to the overall vulnerability of the helicopter.

The controls transmit the pilot's commands to the rotor blades, and if severed, the helicopter will become uncontrollable. They show a medium to high level of vulnerability because it has been assumed that the projectile is only just

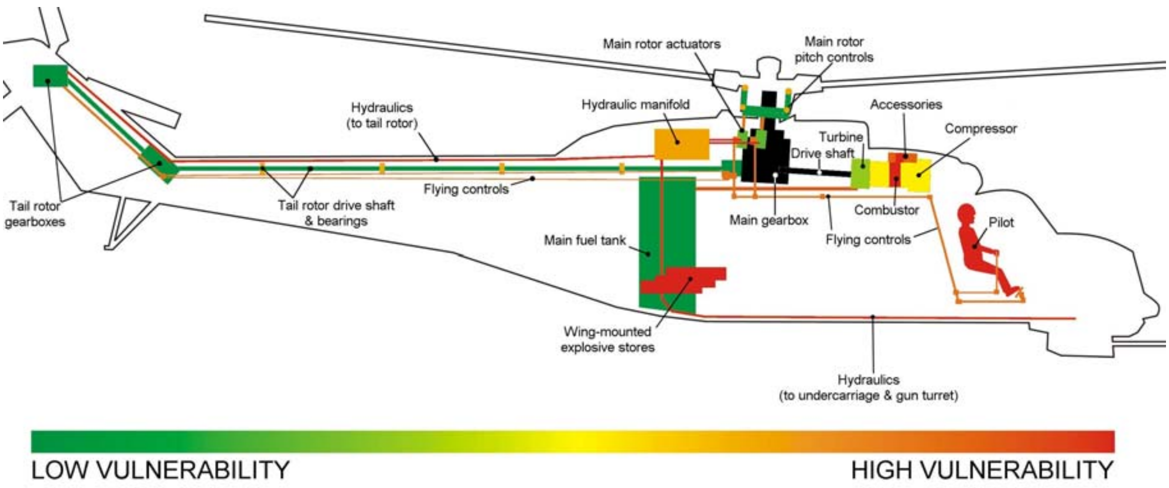

Figure 4: Assault Helicopter Component Vulnerability to Small Arms Fire

large enough to sever a rod, and that certain impacts may fail to achieve this. The helicopter's weapons are also assumed to be particularly vulnerable; if hit they are likely to detonate sympathetically, with potentially catastrophic consequences.

Other components although critical are nevertheless far less vulnerable. The main fuel tank is the largest single critical component in the helicopter, but a single bullet (or even a larger calibre inert shell) is unlikely to do sufficient damage to deny a supply of fuel to the engines within a short period after attack. If the helicopter were required to survive for longer than it took for the tank to leak dry, then that component would also show as highly vulnerable. Furthermore, if there was a high probability of the damage resulting in a fire, then the fuel tank would show as far more vulnerable.

Similarly, the gearboxes and driveshafts (main, tail rotor and intermediate) are highly critical, but are probably too robust to be significantly damaged by a small projectile, although a larger projectile would have a better chance of causing critical damage.

<u>Helicopter vulnerability</u>

Many vulnerability assessments have been performed on a wide range of battlefield helicopters, considering various threat weapons. Whilst these cannot be discussed in detail, it is possible to identify generic trends.

Three classes of helicopter are considered;

- Small utility helicopter (SUH), with a MTOW of around 5,000kg, (e.g. Lynx, UH-1);
- Large utility helicopter (LUH), with a MTOW of around 10,000kg to 15,000kg, (e.g. Mil.8, Merlin);
- Dedicated attack helicopter (AH), (e.g. Apache, A129, Mil.24). These are variable in size but are typified by designed-in survivability features.

Figure 5 provides a general indication of the level of vulnerability each class of helicopter will have for the various, less sophisticated, threats that were discussed earlier in this paper.

It can be seen that single hit $P_{k/h}$ ($SSP_{k/h}$) is unsurprisingly low for small arms and larger calibre AP rounds, although a $SSP_{k/h}$ of 5% translates to a much higher 20% if, for instance, five bullets hit the helicopter. Perhaps more surprising is the observation that there is little difference between $SSP_{k/h}$ for a highly survivable attack helicopter and that for the LUH. However, it should be remembered that these figures are based on the precondition of a threat hitting the helicopter. The probability that the AH will be hit (P_{hit}) is bound to be considerably lower than P_{hit} for the LUH, by virtue of both the size and stealthiness of the former.

Notwithstanding the accuracy of the $SSP_{k/h}$ figures given above it is clear that the probability of surviving a successful engagement by any explosive threat is likely to be low. However, there are means by which vulnerability may be reduced, and the $SSP_{k/h}$ for the AH is based on the assumption that some of these have been

	Probability of kill given a single random hit ($SSP_{k/h}$)		
	AH	**LUH**	**SUH**
Small arms (7.62mm - 14.5mm)	1%	>1%	5%
Inert cannon (20mm - 40mm)	2%	1%	10%
HE cannon (20mm - 40mm)	20%	40%	60%
Rocket Propelled Grenade	30%	60%	90%
Shoulder launched SAM	50%	80%	100%

Figure 5: Estimated Helicopter Vulnerability Data, note that the figures relating to RPG are based upon estimates of HE shell performance

implemented in the design of the helicopter. While 50% may appear to signify a high probability of loss, this should be contrasted with the $SSP_{k/h}$ for the SUH and LUH.

Principles of Vulnerability Reduction

There are four basic methods of reducing target vulnerability, these are:

- duplication of critical components or systems;
- reducing the presented area of critical systems by concentration or miniaturisation;
- internal (and external) armour or shielding;
- the use of damage tolerant component designs.

The last of these, damage tolerant component design, is simply the application of the previous three principles at component level, and will not be discussed further in this section.

Duplication

The duplication of components or systems is a common design feature in most helicopters generally employed as a safety measure against reliability failures, rather than specifically as a vulnerability reduction measure. The distinction is an important one. To provide a true reduction in vulnerability, a duplicated system must also include the separation of the two redundant sub-systems to ensure that a single threat has no opportunity to damage both. This requirement is often overlooked; indeed the co-location of two redundant components is often a specific designed feature, employed to ease maintenance.

It is clear that the “separation” of two duplex components is only effective from particular attack directions. This implies the need to understand the nature of the threat and consider very carefully its expected direction of attack. This understanding can subsequently be used to ensure adequate separation for likely attack scenarios.

It is also important to consider the nature of the threat; if the primary threat is a single warhead fragment or inert projectile then the level of duplication required to provide protection need only be limited. If the primary threat is considered to be from, for example, an internally detonating cannon shell, then to be truly effective, the two components must be more widely separated.

Vulnerable area reduction

This design goal is driven by the fact that $P_{k/h}$ is a function of the sum of presented areas of all critical components in the helicopter, and the miniaturisation of critical components will reduce their chance of being hit. However, miniaturisation generally carries with it a commensurate reduction in damage tolerance (robustness) that must also be considered.

Alternatively, the concentration or grouping of critical components will also reduce their cumulative presented area and hence the $P_{k/h}$ of the helicopter. At first sight, this would appear to contradict the requirement for separation discussed above. However, while separation is a method applicable to duplicated critical components, grouping is applicable to singularly vulnerable or non-duplicated components, such as the cyclic and collective pitch and yaw control rods. The loss of any one of these three control axes might be expected to result in the loss of the helicopter, so separating them would confer no survivability benefits. However, by grouping them together, a reduction in vulnerable area may be achieved.

Again, it can be seen that this reduction is only effective from one particular attack direction - from all other directions no benefit has been achieved. Once more, the designer must be advised by an understanding of the threat against which he is attempting to counter.

Shielding

The use of armour, either parasitic or integral, implies considerable weight, cost and performance penalties and should be treated as a last resort, at which stage it should be used sparingly. A detailed vulnerability analysis of the helicopter will allow the designer to position the armour to its best effect.

One potential method for reducing mass of armour is to increase the line of sight thickness by inclining the armour, as per the glacis plate on an armoured fighting vehicle. This is a relatively simple prospect for an AFV designer who will have a good idea as to the likely direction of the threat. For an aircraft designer, this may present more of a problem.

An alternative to parasitic armour is, at the design stage, to make use of robust, non-critical components to provide shielding.

Vulnerability reduction measures for helicopters

The previous section describes the basic principles of vulnerability reduction, applicable to any military vehicle. These principles may be applied specifically to the components and systems within a battlefield helicopter, and a variety of such applications are discussed below.

Analysis of data gathered from Vietnam [Ref. 10] allows the most frequent causes of loss to be identified, these are listed in figure 6 in the general order of frequency of occurrence.

It is not the intention of this paper to provide a comprehensive description of all possible measures, rather a selection of potential methods. Their application will depend very much on the specific design and role of a particular combat helicopter, and also on the expected threats against which the helicopter must be hardened. In general those causes of loss identified in figure 6 have been concentrated upon.

Crashes	Forced Landing	Mission Abort
Engine F/Controls Crew Fuel	Fuel Lubrication Engine Mech. Controls Main Rotor	Crew Precautionary Fuel Main Rotor Hydraulics

Figure 6: Causes of helicopter losses/mission aborts in Vietnam conflict

Powerplant

The design of small gas turbine engines with high inherent ballistic tolerance is beyond the scope of this paper. However a few design rules to minimise engine vulnerability are presented below. The positioning of engines can have a significant effect on the overall survivability of the helicopter however. Most purpose-designed combat helicopters of recent years incorporate widely spaced twin engines in their design (for example Ka.50 Hokum, Rooivalk, YAH-63, AH-64, Tiger, etc). The separation of the engines provides a degree of protection to one engine should the other one catastrophically break up. Some designs also incorporate armoured firewalls between the engines to provide additional protection, the A-129 being a notable example. The introduction of armoured panels within the engine bay of the (fixed wing) Su-25 Frogfoot as a result of combat experience in Afghanistan reportedly led to a significant reduction in combat losses due to small/medium calibre impacts.

In terms of the engines themselves, location of (vulnerable) accessories on the top or inside faces of the engines will provide a degree of protection to those components. Centrifugal compressors are generally more robust than axial ones, etc. If all else fails the designer can simply armour the engine bay in its entirety, this being the case for the Mil. 24 Hind.

Control system

The impracticality of totally duplicating mechanical control runs makes it necessary to increase the ballistic tolerance of the flying control signaling system. To some extent the control runs in the cockpit will receive a degree of shielding from armour placed around the cockpit. This is particularly noticeable in cases like the AH-64 Apache (shown in figure 7) where there are several armour panels mounted away from the immediate vicinity of the crewmembers. The survivability of the control rods can be improved significantly by increasing their diameter such that they retain a minimum level of stiffness despite ballistic damage. A rod diameter of 40mm is considered as a minimum diameter to provide tolerance to a tumbled 12.7mm bullet. Sufficient clearance needs to be allowed between the control rods and adjacent structure such that petalled sections, due to ballistic damage, of the rod do not foul the structure.

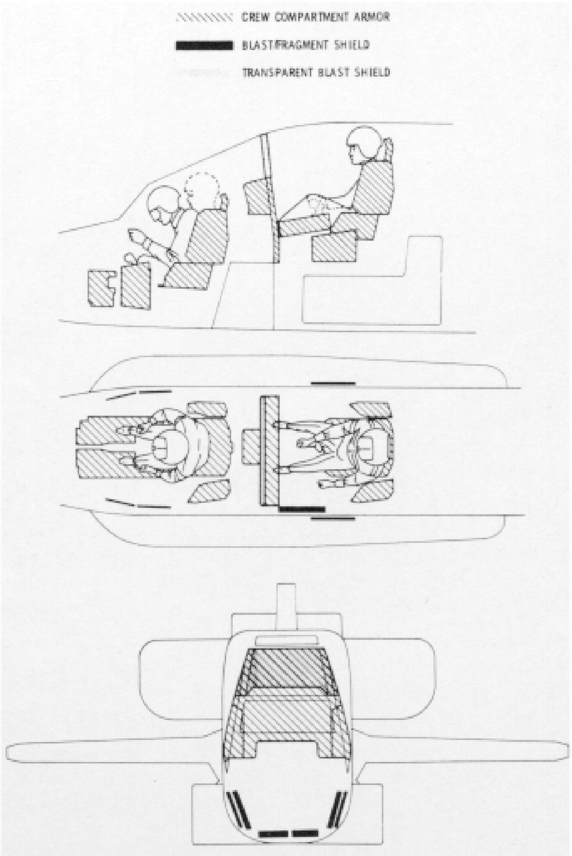

Figure 7: Armour protection in and around the cockpit of AH-64 Apache

The use of Carbon Fibre Reinforced Plastic control rods has been introduced in some helicopters over the past 10 years. These rods offer benefits in terms of increased stiffness, allowing rods, which are longer than their metallic counterparts and are also lighter. In terms of tolerance to damage they do avoid the problems of petalled damage described above and exhibit reasonable levels of tolerance to small threats, however they are prone to delamination causing considerable reduction in buckling stiffness and they can be seriously effected by fire damage. This can also be true of aluminium rods and generally controls routing through the engine/transmission bays should be manufactured from either steel or titanium.

Although the tubular section of the rods makes up a large percentage of the total area of the flying control system, the tolerance of the end fittings and flying control levers can also be increased with a corresponding reduction in vulnerability. During the design of the UH-60 Blackhawk, Sikorsky developed a tri-pivot concept for rod end attachments which replaced the single bolted joint at the rod/bellcrank interface with no less than three. Any single pivot could be damaged without loss of function resulting [Ref. 14].

An alternative route to reducing the vulnerability of the bellcrank is shown in figure 8. In this concept the usual “L” shaped lever has been replaced by a triangular component incorporating a redundant loadpath. The bellcrank has sufficient stiffness to survive loss of one arm whilst still transmitting the (generally low) control forces. The inset in figure 8 illustrates a damaged component having been impacted by a 12.7mm AP projectile.

Figure 8: Damage Tolerant Flying Control Lever (Bellcrank) with Redundant Loadpath, (inset view of damaged section)

In certain older helicopter designs, control of the tail rotor pitch is accomplished by pairs of cables rather than rods, the Mil. 24 Hind falls into this category. Whilst the reduced diameter of the cables makes them less likely to be hit, an impact will almost always result in loss of yaw control. The replacement of these cable systems with a series of conventional flying control rods is likely to reduce vulnerability significantly.

In future it is likely that more use will be made of Fly By Wire (FBW) or Fly By Light signaling systems. These have the added advantage of allowing multiplexed control routes to be introduced although it is important to ensure that sufficient separation between routes is maintained. A study conducted in the UK suggests that in many cases a proximity bursting HE round is likely to result in a kill due to defeating multiple control lanes.

Crew

The effect of armoured crew seats on helicopter vulnerability is debatable. Under certain circumstances, a single shot incapacitation of both crew is possible, and crew armour will prevent this. However, from the majority of attack directions a single inert projectile is incapable of incapacitating both crewmen. Consequently, the use of individual armour could be seen as a waste of valuable armour mass budget.

Of course, crew armour is much more than simply "protecting the system" and it is acknowledged that the lives of two trained pilots may be more important than the survival of the helicopter. However, a limitation of armoured crew seats is that they provide protection only to the crew, and a significant volume of critical control components remain outside the envelope protected by the seat armour. A more efficient design would protect not only the crew, but also these exposed control components.

Explosive projectiles (HE shell) have a greater probability of incapacitating both pilot and copilot, and individual protection is more reasonable. However, a similar level of protection could be achieved by introducing an armoured barrier between the two crewmen. Figure 8 illustrates the armour protection fitted to AH-64, including a blast screen between cockpits providing protection from internally detonating 23mm HE shell [Ref. 15].

Fuel system

The fuel system represents possibly a larger presented area than any other system in the helicopter and, as such, will contribute significantly to vulnerability. The fuel system presents a twofold hazard; the helicopter depends on an uninterrupted supply of fuel in order to maintain flight. Secondly, the fuel presents a significant fire risk to other systems in the event that it is released into the airframe.

Fuel supply protection The use of self-sealing fuel tank and fuel pipe liners will prevent fuel loss resulting from damage caused by small arms AP projectiles. As a minimum, this should be applied to the engine feed tank and the pipe(s) connecting it to the engines. It may only be necessary to protect the lower part of the tank walls in this way in order to provide a “get home capability”. (Figure 9).

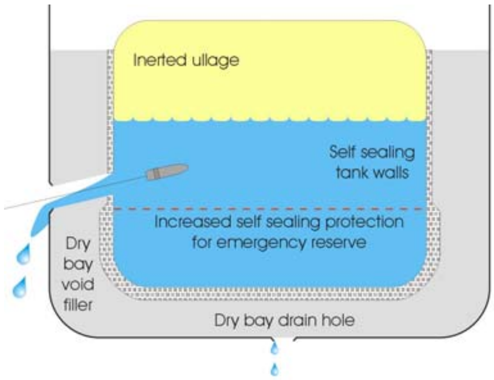

Figure 9: Damage Tolerant Fuel System

If the helicopter is equipped with several fuel tanks, a cross-feed mechanism will allow any one tank to provide a supply in the event of damage to another tank. However, it should be recognised that, in this case, the cross-feed valve will represent a region of high vulnerability whereby the entire fuel system can be cut off by a single projectile impact.

Fire/explosion prevention measures Foam filling in dry bays adjacent to the fuel tanks will prevent the accumulation of large quantities of spilt fuel, as will dry bay drain holes or vents. Bulkheads or baffles in the dry bays will also prevent leaked fuel migrating towards components that might ignite the escaped fuel. Hot metal and electrical components should be removed from bays likely to accumulate escaped fuel or fuel vapour, and the ullage in the tank itself should be inerted to prevent explosion of fuel/air mixture in the tank.

Inerting of the tank was originally achieved by filling the tanks with a low-density reticulated foam. This method had the benefits of being simple and quick/easy to accomplish, however the filling of fuel tanks with foam led to significant longer term maintenance problems together with a not inconsiderable weight penalty. In future there is likely to be more reliance on systems which introduce an inert gas into the ullage space, these can use either bottled gas sources or an "On Board Inert Gas Generating System" (OBIGGS).

A tank mounted fuel pump will continue to pump fuel in the event of a fuel pipe rupture, unless it is switched off, leading to the escape of large quantities of fuel into the airframe. This may be prevented by using engine-mounted pumps, which suck fuel from the tanks. If the fuel line is damaged the flow of fuel will be halted. Although beneficial to reducing helicopter losses the use of suction fuel tanks may be limited in hot and high conditions due to fuel vapourisation effects.

Lubrication

The majority of current helicopters have a degree of run dry capability in all gearboxes, in general a minimum of 20 minutes running without oil is required.

For the YAH-64 grease lubricated gearboxes were specified for the first time. This provided the ability to sustain ballistic damage with virtually no loss of either lubricant or performance. A (known) impact on a gearbox would not necessarily result in a mission abort.

Drive train

The tail drive shafts associated with most conventional helicopters, the Boeing NOTAR designs being a notable exception, are particularly prone to ballistic damage. The majority of "older" designs generally have small diameter drive shafts, which although unlikely to be susceptible to damage from fully aligned small calibre bullets and fragments could suffer complete severance following an impact from a tumbled round. To reduce the susceptibility of the drive shaft to this and larger threats manufacturers have tended to introduce very large diameter shafts, the requirement to tolerate a fully tumbled impact from a 12.7mm round dictates a diameter of at least 115mm [Ref. 16]. The ballistic tolerance of these components to impacts from inert rounds up to 23mm is high.

In addition to reducing the vulnerability of the shafts themselves the various couplings and bearings are also hardened to provide a high degree of tolerance. The majority of western designed helicopters use a "Thomas" coupling to join drive shafts, in general these employ a number of redundant fixings such that the loss of 2 bolted joints (out of 6) can be tolerated.

The loss of drive to the tail rotor does not automatically result in the loss of the helicopter providing there is sufficient forward speed to maintain directional stability. An often seen serious consequence of the severance of a tail drive shaft is the loss of all control signaling and hydraulic power to the tail rotor gear box and in many circumstances structural failure of the tailcone. The use of anti-flail bearings to prevent large movement of the tail drive shaft significantly reduces the likelihood of major failures occurring.

Main Rotor

Considerable effort has been expended by helicopter designers over the past 30 years or more on the development of ballistically tolerant main rotor blades. In itself this is probably not a major challenge, however, a very high performance blade similar to the Westland BERP 3 (British Experimental Rotor Programme) design but with high levels of tolerance to large calibre threats is somewhat more difficult to achieve.

Tests have been conducted in the UK to quantify the performance of the BERP blades fitted to the Lynx helicopter fleet, it is not possible to reveal the results of those tests here but it is sufficient to say that, against small arms projectiles, the blades performed well.

For large calibre projectiles, the most effective method of providing a high degree of tolerance is to utilise a large cross sectional area spar (or spars) and use a ductile material. For this reason older designs of metallic blade are generally more tolerant than composite ones. Figure 10 shows a section of (metallic) blade from a Sea King helicopter that was impacted (in flight) by a 20mm round. The outcome of this engagement was a slightly higher than normal level of vibration.

Figure 10: Damaged Main Rotor Blade

Hydraulic systems

The duplication of hydraulic systems is commonplace in helicopter design, with most modern helicopters having at least two separate systems. However, this is generally done to improve the overall reliability of the hydraulic supply rather than to increase the level of tolerance to battle damage.

In order to maximise survivability where duplex systems exist it is important to ensure that wherever practical hydraulic lines follow different routes from reservoirs/pumps to the control actuators making maximum use of robust structure and systems as shielding.

Over recent years considerable effort has been expended in the development of non-flammable hydraulic fluids to reduce the risk of fire given an impact on part of the system. Although these fluids are less susceptible to fire than earlier ones they do still pose a significant fire risk.

Conclusions

Early use of helicopters on the battlefield inevitably resulted in a high attrition rate. The early tactics to counter this were to fly high enough to be effectively out of small arms range, UK studies indicate that this is generally around 3000 ft.

With the advent of large numbers of shoulder launched missiles in the late 1960s revised tactics were developed, these resulted in helicopters flying at low level and inevitably being impacted by large numbers of small arms projectiles. To counter the effects of this damage a high degree of ballistic tolerance was incorporated into the design requirements.

As a result of this experience a new “breed” of battlefield helicopters were developed commencing with the US AAH (AH-64 Apache) and UTTAS (UH-60 Blackhawk) helicopters, both of which exhibit low levels of vulnerability.

This paper has provided a brief overview of helicopter operations in conflicts over the past 40 years and has outlined some of the methods that can be incorporated into the design to enhance ballistic tolerance and hence platform survivability.

It is important in this age of sophisticated Defensive Aids Suites that future helicopters at least maintain the currently attainable levels of ballistic tolerance. Military operations in support of peace keeping or enforcement involve helicopters coming into contact with significant numbers of low technology threats which cannot easily be countered by electronic means.

The only sure counter to single or multiple impacts from typical threats widely utilised by terrorist/freedom fighter organisations is to either avoid being hit through tactical flying or to provide the helicopter with a high degree of tolerance to their effects.

It is essential that efforts to incorporate ballistic tolerant design in future helicopters is done early in the design stage. The difficulties in retrofitting such features are generally too great to warrant going back and changing an already frozen design.

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