VULNERABILITY REDUCTION TECHNIQUES FOR BATTLEFIELD HELICOPTERS

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This is an edited version of the article that was published in the Journal of Defence Science *Volume 10, Number 2, May 2005.*

ABSTRACT

Military helicopters are easy targets for weapons of many types. Though much effort has gone into making helicopters less vulnerable by hardening techniques and sophisticated defensive aids suites, many are still lost to less conventional or low technology threats. This article reviews helicopter combat-loss data from the Vietnam conflict to recent operations in the Persian Gulf. It describes basic vulnerability-reduction measures applicable to all combat aircraft, and practical applications of these measures to the design of military helicopters.

Definitions

Military equipment should be able to withstand the man-made hostile environment.[1] Survivability embraces two properties:

Susceptibility

The probability of being hit.

Vulnerability

The probability of being damaged given that a hit has occurred.

Susceptibility can be reduced by:

- Managing and reducing electromagnetic and acoustic signatures.
- Tactical flying to prevent detection, potentially cued by on - and/or off-board information on threat locations.
- Suppressing enemy weapons.
- Active countermeasures such as jammers, decoys and flares.

These measures will benefit combat helicopter survivability. However, as discussed below, the nature of operations will often bring the battlefield helicopter within range of hostile fire. Many of the measures are likely to be ineffectual against unsophisticated or novel weaponry; only effective vulnerability reduction measures will then prevent the helicopter from being killed. Vulnerability is the inability of the helicopter to withstand damage caused by a threat. For bullets and impact-fuzed projectiles the term ‘hit’ denotes a physical impact; for proximity-fuzed weapons, a near miss can trigger the warhead, resulting in many (fragment) impacts with the target. Vulnerability is measured as probability of kill given a hit, or $P_{k/h}$

Introduction

Helicopters have been used in wars since the later stages of WWII. However, not until the early 1960s in Vietnam was their full potential recognized when small numbers of UH-1 helicopters were used initially to transport 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 tempo of 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 that proved the theory of modern helicopter warfare and presaged the incorporation of helicopters into the regular army.[2] The escalation of hostilities in 1965 set the stage 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, vulnerability reduction features being limited to armoured panels around the crew's seats.

Initially, tactics decreed that helicopters would fly at reasonably high altitude (above 3,000 ft) to avoid most machine gun fire from the ground. This was reasonably successful, although the helicopters were vulnerable when delivering their troops into landing zones, then coming under continual small arms fire.[3] The 9M32/SA-7 missile caused the tactics to be modified to flying low, 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 recognized 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 prevalent threats was better than basing survivability on high speed and agility. A solution to the requirement was developed rapidly using the dynamic system of the original UH-1 troop-carrying helicopter but with a new fuselage configuration featuring a tandem cockpit. This concept developed into the AH-1 HUEY COBRA (FIG.1), the forerunner of all current attack helicopters; many remain in service today.

FIG.1 – AH-1 HUEY COBRA HELICOPTER (source: author)

The AH-1 incorporated design features to provide a high degree of ballistic tolerance to the main threat of the time (the 0.30 cal/7.62 mm bullet).[4] These early US operations illustrate several aspects of battlefield helicopter operations that remain valid today: the use in both attack and transport modes, and the need to fly low where hostile troops are potentially present.

The rest of this article outlines weapons that threaten battlefield helicopters and reviews losses in combat from Vietnam to the present day. Detailed vulnerability assessment codes enable design engineers to identify those components of the modern military helicopter that are most vulnerable to combat damage. The final section describes techniques that can be used to reduce the vulnerability of specific helicopter systems and components.

Threats to Combat Helicopters

The sophistication of anti-air weapons has increased dramatically since the 1960s; a helicopter is vulnerable to many of these weapons. The probability of survival in an all-out war situation relies heavily on avoiding such weapons, or on defeating them by Defensive Aids Suites (DAS), rather than depending on the inherent hardness of the helicopter to survive impact/engagements from them. However, the increasing frequency of peacekeeping operations reduces the likelihood of meeting high technology threats, which most DAS are designed to counter. This leads to the requirement for a reasonable level of protection against ‘low technology’ threats – typically:

- Hand-held rifles (e.g., AK-47).
- Heavy machine-guns (e.g. ZPU-2/4).
- Small/medium calibre cannon (e.g. ZU23/2).
- Shoulder-launched rocket propelled grenades (characterized by the RPG-7).

At the next level of sophistication are the shoulder-launched MANPAD (Man Portable Air Defence) SAM systems, which 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 and calls for sophisticated and potentially expensive solutions. Most MANPAD systems use IR seekers, and so the best form of protection is to avoid being engaged. Combinations of IR jammers, thermal flares and reduced IR signatures from hot-spots on the helicopter go far to reducing the risk from this class of weapon. Anti Tank Guided Weapons (ATGW) can also threaten although they are generally limited in kinematic performance and have poor performance against a manoeuvring target.

This article will concentrate on the lower level threats where designed-in ballistic tolerance can contribute significantly to the overall survivability of the helicopter.

Combat Data

Early US experience in Vietnam, 1966 to 1975

Between 1962 and 1973, the US military (principally the US Army) lost about 2,600 helicopters to hostile action in Vietnam,[5] most to small/medium calibre threats (7.62 mm – 23 mm). This represents about 10% of all incidents of US Army rotary-wing aircraft being hit by ground fire in the same period.[6] It is not possible to infer the number of helicopters that were involved in operations and did not sustain any combat damage although anecdotal evidence suggests that the loss rate was considerable. A large quantity of data was gathered by the US between 1962 and 1970 relating to:

- The types of helicopter that were hit by ground fire.
- The role they were engaged in at the time of the incident.

- The threat weapon and the damage sustained.

This large database has provided a valuable resource to the designers of helicopters since then, including all of the US Army types of recent years; in particular the:

- AH-56 CHEYENNE.
- UH-60 BLACKHAWK.
- AH-64 APACHE.
- RAH-66 COMANCHE.

It rapidly became apparent that certain parts of the helicopter were particularly vulnerable, and efforts were made to provide protection to those components, initially through the use of strategically placed lightweight armour (FIG.2).

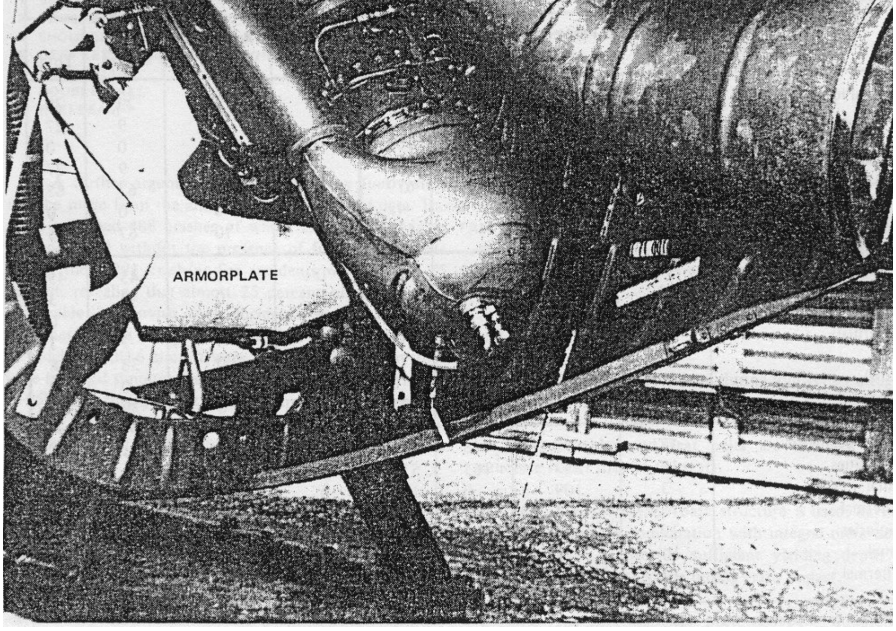

FIG.2 – ARMOUR FITTED TO ENGINE BAY OF OH-6 HELICOPTER (source: US Army)

Soviet operations in Afghanistan, 1979 to 1989

Several sources provide different statistics for the loss of helicopters. A US Directorate of Intelligence report[7] (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 second report,[8] also freely available, suggests that the total figure for the full ten years is 333 helicopters lost, but it is not clear whether this includes 'operational' losses (accidents) as well as combat kills. CORDESMAN[9] suggests that between 600 and 800 helicopters were lost from combat damage. Although many losses could be attributed to small-arms fire, a significant proportion were caused by shoulder-launched guided weapons including SA-7 and (particularly) STINGER. The first operational success of STINGER was in September 1986, with three HIND helicopters being destroyed in one operation. During 1987, Soviet helicopter losses were assessed at 1.2 to 1.4 per day.

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

FIG.3 – MIL.24 HIND, ILLUSTRATING THE MEASURES TAKEN TO REDUCE SUSCEPTIBILITY TO IR GUIDED MISSILES. NOTE THE IR JAMMER IS NOT FITTED BUT THE MOUNTING PLATFORM FOR IT IS CLEARLY VISIBLE. (source: author)

Falkland Islands 1982

Helicopter losses during the Falklands conflict were not high. Five Argentinean PUMA were lost; one each from small arms fire, surface-to-air and air-to-air missile, while two were shot down by a SEA HARRIER using 30 mm cannon.

Most 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 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[10] during an air assault operation in Mogadishu. 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 500 m) 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[11] 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. 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, the more heavily armoured (and armed) Mil.24 HIND also incurred considerable losses. No statistics have been compiled for later years but helicopter combat losses have continued. Notable amongst these is the loss of a Mil.26 HALO transport helicopter, reportedly to a shoulder-launched SAM, resulting in the death of some 120 passengers and crew.

ENDURING FREEDOM, Afghanistan 2001

During Operation ANACONDA,[12] an AH-64 APACHE and a UH-60 BLACKHAWK were both hit by RPG and a further five APACHEs were reported to have been damaged by small arms fire. All aircraft are believed to have survived. Reports suggest, however, that one CH-47 CHINOOK was shot down with the loss of several crew and passengers, and a second was seriously damaged, in another operation in this theatre.[13]

Operation IRAQI FREEDOM, 2003

Data is being collected on the losses by coalition forces, including detailed analysis of combat damage and losses to helicopters. The US team of specialists (JCAT – Joint Combat Assessment Team) have the specific goal of capturing ‘perishable’ data relating to these incidents with a view to modifying tactics to mitigate the threat.[14] It is probably too early to draw conclusions and detailed assessments will almost certainly be classified. Three reports, all widely available, illustrate the types of weapons being used against allied helicopters.

In June 2003, a RAF CHINOOK was engaged by small arms fire from Iraqi soldiers. No significant damage was sustained by the helicopter but several occupants were wounded, three of them seriously.[15]

In late 2003, 31 of 32 US Army AH-64 APACHEs engaged in operations near Karbala sustained combat damage although only one failed to return.[16] 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 from gunfire (up to 30 mm) and RPG impacts but none from radar-guided SAMs. This is, perhaps, a testament to the value of sound vulnerability reduction measures designed into the APACHE, rather than (as has occasionally been suggested) an indication of poor battlefield survivability.

Six US transport helicopters were lost in Iraq between 23 October and 15 November 2003, most of them to enemy fire.[17] Most are said to have resulted from impacts or air bursts from RPG-7s. (FIG.4) shows typical fragment damage from a close-bursting RPG-7 warhead.

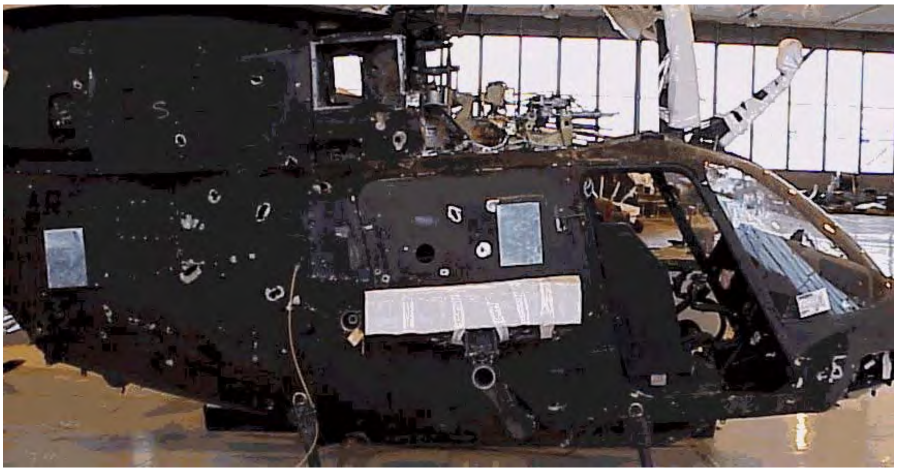

FIG.4 – COMBAT DAMAGED OH-58 HELICOPTER (source: unknown)

Discussion

The examples here are insufficient for drawing detailed statistical conclusions. However, important points may be inferred, the most significant of which is that, despite improved survivability design and tactics since Vietnam, helicopter combat losses, although fewer, remain at a substantial level.

As battlefield helicopters often operate at low altitude near to enemy troops, an opponent with a low level of weapon technology may still be able to inflict losses. A lack of advanced weapons may be compensated by the development of more effective methods of bringing available weapons to bear, or more novel methods of attack - the ‘cheap kill’.

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 than a high-tech kill to result in a significant high human and materiel loss.

As evidenced by the Falkland Islands losses, even a technologically advanced opponent may find low technology threats a potent counter to the combat helicopter and difficult to defeat. However, these may be countered by a combination of tactics, aided by threat warning (susceptibility reduction) and hardening the platform (vulnerability reduction).

In-theatre modifications to a helicopter to reduce vulnerability may be effective but will often weaken performance. The impact on performance may be reduced, and survivability will be increased, if an analysis of the characteristics and capabilities of the threat drive these measures and is implemented as a part of the aircraft design (or upgrade) process. The USSR implemented vulnerability reduction design measures to the Su-25 FROGFOOT ground-attack fighter as a direct result of experience during the war in Afghanistan. These measures, along with tactical adaptations, reportedly reduced combat losses significantly.

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 of 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.[18] These 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 assessing fixed and rotary wing aircraft vulnerability.

In the UK, a similar capability has been developed, starting in the late 1970s. The INTAVAL (Integrated Air target Vulnerability Assessment Library) suite of computer programs 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 used where individual projectiles are passed through a geometric representation of the target, and damage to components and systems is assessed.

A typical target will consist of 1,500 to 2,000 components that are either critical to maintaining flight or mission capability, or shield those components. (FIG.5) shows a section of a typical target description. Each component is modelled in terms of its physical dimensions, location and 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 in the system.

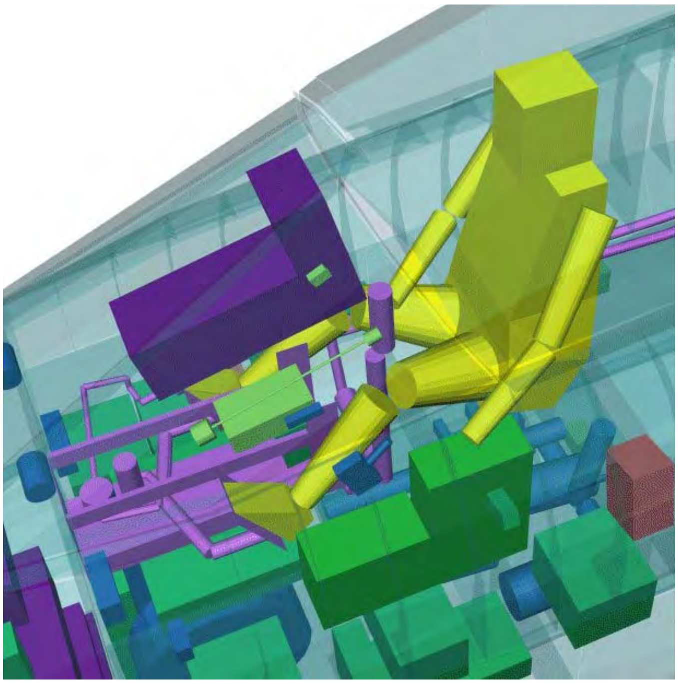

FIG.5 – DETAIL FROM A TYPICAL INTAVAL TARGET DESCRIPTION OF A COMBAT AIRCRAFT
(source: Dstl)

System and component vulnerability

Detailed analysis of the vulnerability of battlefield helicopters reveals the critical components and their contributions to overall helicopter vulnerability. The analysis may range from a careful visual inspection of the helicopter or its design to a detailed assessment using vulnerability analysis software. The analysis should consider the particular threat of interest, which will typically be characterized by a specific 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 long enough for it to reach a suitable landing position?

or

- Should it remain capable of a weapons delivery mission?

A detailed, software driven, assessment may produce images similar to the one at (FIG.6). This gives a reasonable indication of the vulnerability of a large, generic assault helicopter to attack by inert small arms bullets or Armour Piercing (AP) shells. It has been assumed in generating FIG.6 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 cannot take control of the aircraft if the pilot is incapacitated. If the opposite were true, 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 its weapons after being damaged, both the pilot and second crewman would show as vulnerable.

A similar logic may be applied to the engines. FIG.6 assumes that both engines are required for controlled flight although, if only one surviving engine were sufficient, 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 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 may detonate sympathetically, with potentially catastrophic consequences.

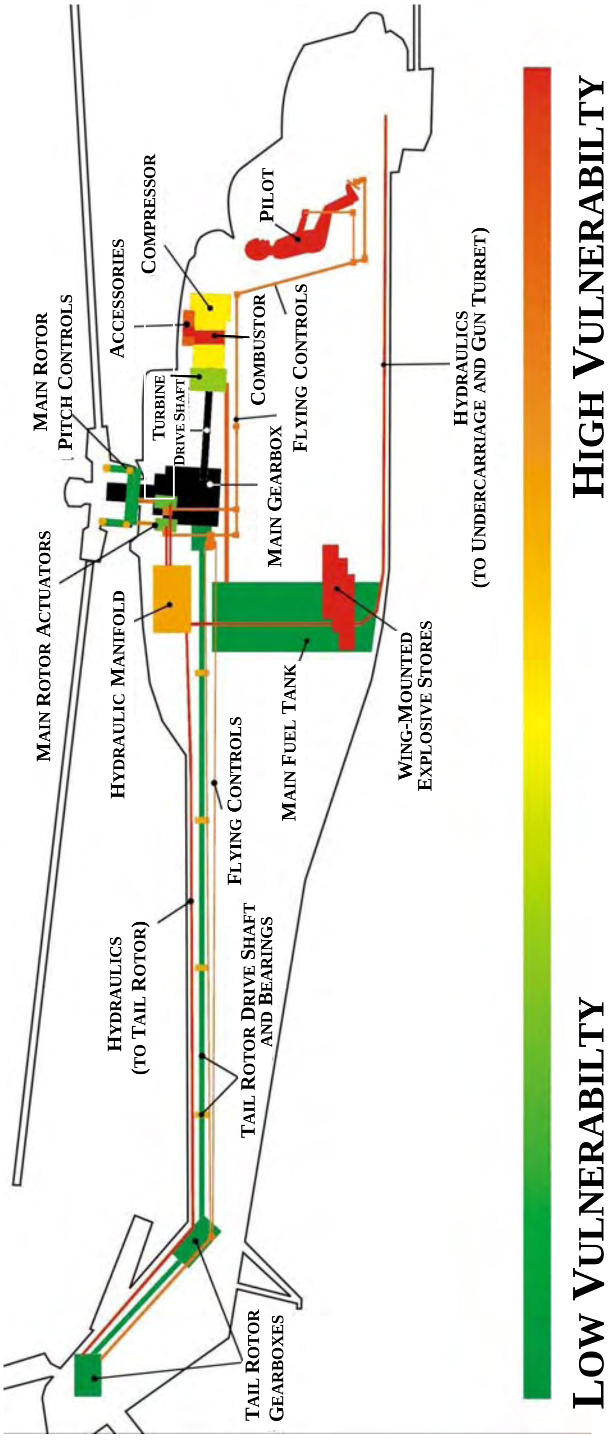

FIG.6 – ASSAULT HELICOPTER COMPONENT VULNERABILITY TO SMALL ARMS FIRE (source: QINETIQ)

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, that component would also show as highly vulnerable. Furthermore, if there were a high probability of the damage resulting in a fire, the fuel tank would show as being 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.

Helicopter vulnerability

Many vulnerability assessments have been made 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 5,000 kg (e.g. LYNX, UH-1).
- Large Utility Helicopter (LUH), with a MTOW of around 10,000 kg to 15,000 kg (e.g. Mil.8, MERLIN).
- Dedicated Attack Helicopter (AH) (e.g. APACHE, A129 and Mil.24). These differ in size but are typified by designed-in survivability features.

Table 1 indicates the level of vulnerability each class of helicopter will have for the various, less sophisticated, threats that were discussed earlier.

TABLE 1 – *Estimated helicopter vulnerability data.*
Note that the figures relating to RPG are based on estimates of HE shell performance.

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

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, 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 lower susceptibility 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 ways of reducing vulnerability and the $SSP_{k/h}$ for the AH is based on the assumption that some of these have been implemented in the helicopter's design. While 50% is a high probability of loss, it should be contrasted with the $SSP_{k/h}$ for the SUH and LUH.

Principles of Vulnerability Reduction

Four methods of reducing target vulnerability are:

- Duplication of critical components or systems.
- Reducing the presented area of critical systems by concentration or miniaturization.
- Internal (and external) armour or shielding.
- The use of damage-tolerant component designs.

The last of these 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 common in most helicopter designs, normally as a safety measure against reliability failures rather than specifically for reducing vulnerability. The distinction is important: to provide a true reduction in vulnerability, a duplicated system must also separate the two sub-systems so that a single threat cannot damage both. This requirement is often overlooked; indeed, the two components are often co-located to ease maintenance. Separating two duplex components is most effective for particular attack directions. This implies the need to understand the nature of the threat and consider very carefully its expected direction of attack to ensure adequate separation for likely attack scenarios.

The nature of the threat is also important because, if it is a single warhead fragment or inert projectile, the level of duplication required to provide protection need only be limited but, if from for example an internally detonating cannon shell, components must be more widely separated to be truly effective.

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; miniaturization of critical components will reduce their chance of being hit. However, miniaturization 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 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, 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 he is attempting to counter.

Shielding

The use of armour, either parasitic or integral, implies considerable weight, cost and performance penalties and is a last resort to be used sparingly. A detailed vulnerability analysis will enable the designer to position the armour most effectively.

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 relatively easy for an AFV designer who will have a good idea as to the likely direction of the threat. It is more difficult for an aircraft designer as the threat direction is generally unknown and, once an engagement starts, the crew will take evasive action, leading to an effectively random approach direction.

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 general principles described above may be applied specifically to the components and systems in a battlefield helicopter, and some are discussed here.

Analysis of data from Vietnam[18] shows the most frequent causes of loss to be identified (Table 2).

TABLE.2 – *Causes of helicopter losses/mission aborts in the Vietnam conflict*

CRASHES	FORCED LANDING	MISSION ABORT
Engine. Flying controls. Crew. Fuel.	Fuel. Lubrication. Engine.	Crew. Precautionary. Fuel.

Here, only a selection of potential methods are given, concentrating on causes of loss shown in Table 2. 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 hardening is required.

Powerplant

The design of small gas turbine engines with high inherent ballistic tolerance is beyond the scope of this article. However, a few design rules to reduce engine vulnerability will be described. The positioning of engines can have a significant effect on the overall survivability. Most purpose-designed combat helicopters of recent years have widely spaced twin engines (for example, Ka.50 HOKUM, ROOIVALK, YAH-63, AH-64 and TIGER). This separation provides some 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. Introducing armoured panels in 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 from small/medium calibre impacts.

Locating (vulnerable) accessories on the tops or inside faces of the engines will provide some protection to those components. Centrifugal compressors are also generally more robust than axial ones. If all else fails, the designer can simply armour the engine bay in its entirety, as in the Mil. 24 HIND.

Control system

The impracticality of duplicating entire mechanical control runs makes it necessary to increase the ballistic tolerance of the flying control signalling system. The control runs in the cockpit will receive some shielding from armour placed around the cockpit. This is particularly so in cases like the AH-64 Apache (Fig.7) where there are several armour panels mounted away from the immediate vicinity of the crew. The survivability of the control rods can be improved significantly by increasing their diameter so that they retain a minimum level of stiffness despite ballistic damage. A rod diameter of 40 mm is considered necessary to provide tolerance to either a tumbled 7.62 mm bullet or an un-tumbled 12.7 mm bullet. Sufficient clearance must be allowed between the control rods and adjacent structure so that sections of the rod petalled by ballistic damage do not foul the structure.

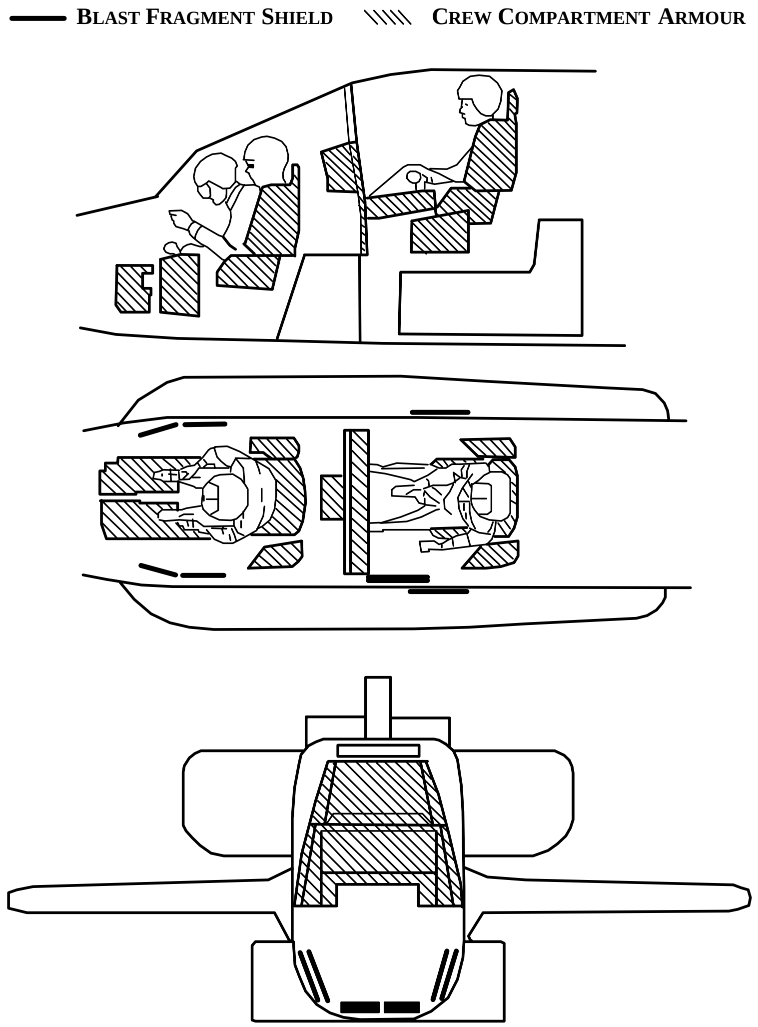

Fig.7 – Armour protection in and around the cockpit of AH-64 Apache
(source: Midland Counties Publications)

Carbon fibre reinforced plastic control rods have been introduced in some helicopters over the past ten years. These are stiffer, allowing rods to be used that are longer and also lighter than their metallic counterparts. They avoid the problems of petalled damage and show reasonable levels of tolerance to small threats. However, they are prone to delamination, causing considerable reduction in buckling stiffness, and they can be seriously affected by fire damage. This can also be true of aluminium rods, and controls routed through the engine/transmission bays should normally be made 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 fewer than three. Any single pivot could be damaged without loss of function resulting.[19]

Another route to reducing the vulnerability of the bell-crank is shown in (FIG.8). Here, the usual 'L' shaped lever has been replaced by a triangular component incorporating a redundant load-path. The bell-crank has sufficient stiffness to survive loss of one arm whilst still transmitting the (generally low) control forces. The inset in FIG.8 shows a component damaged by a 12.7 mm AP projectile.

In certain older helicopter designs (eg, Mil. 24 HIND), the tail rotor pitch is controlled by pairs of cables rather than by rods. Whilst the smaller diameter of the cables makes them less likely to be hit, an impact will almost always result in loss of yaw control. Replacing these cable systems with a series of conventional flying control rods is likely to reduce vulnerability significantly.

It is likely that more use will be made of Fly-By-Wire (FBW) or fly-by-light signalling systems. These have the added advantage of facilitating multiplexed control routes although it is important to ensure that routes are sufficiently separated. A UK study suggests that in many cases a proximity bursting weapon (e.g. HE projectile, RPG) will be able to kill a FBW-equipped helicopter owing to its fragmentation defeating separated control lanes. Routing the individual cables through areas providing shielding will give a high degree of protection against this type of threat.

FIG.8 – DAMAGE-TOLERANT FLYING CONTROL LEVER (BELL-CRANK) WITH REDUNDANT LOAD-PATH, BEFORE AND AFTER DAMAGE FROM 12.7 MM AP BULLET (source: author)

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 most attack directions, a single inert projectile is incapable of incapacitating both crewmen, so providing 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, armoured crew seats provide protection only to the crew, and many 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 shells) 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. FIG.7 shows the armour protection fitted to AH-64, including a blast screen between cockpits providing protection from an internally detonating 23 mm HE shell.[20]

Fuel system

The fuel system has a larger presented area than any other system in the helicopter and, as such, will contribute significantly to vulnerability. It presents a twofold hazard:

1. The helicopter depends on an uninterrupted supply of fuel to maintain flight.
2. The fuel is a significant fire risk if 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 technique 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 to provide a get-home capability (FIG.9).

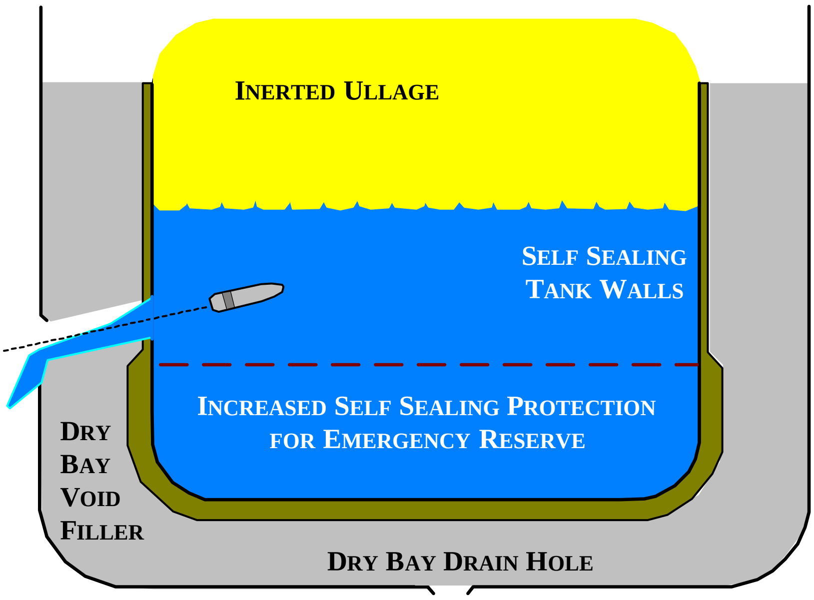

FIG.9 – DAMAGE TOLERANT FUEL SYSTEM (source: QinetiQ)

If the helicopter is equipped with several fuel tanks, a cross-feed mechanism will sustain supply if not all are damaged. However, the cross-feed valve will then be a region of high vulnerability whereby the entire fuel system can be cut off by a single projectile.

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 made inert to prevent explosion of any fuel/air mixture in the tank. This was originally achieved by filling the tanks with a low-density reticulated foam, a method that was simple and quick. However, the method led to significant longer-term maintenance problems and a weight penalty. In future, introducing an inert gas into the ullage space is likely to be used, the source being either bottled gas or an 'On Board Inert Gas Generating System' (OBIGGS).

A tank-mounted fuel pump will continue to pump if a fuel pipe ruptures 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 will be halted. Although beneficial to reducing helicopter losses, the use of suction fuel pumps mounted on the engine may be limited in hot and high conditions owing to fuel vaporization effects.

Lubrication

Most current helicopters have a degree of run-dry capability in all gearboxes. A minimum of 20 minutes running without oil is normally required.

For the YAH-64, grease-lubricated gearboxes were specified for the first time, an innovation that was adopted in the production AH-64. This enabled ballistic damage to be sustained with virtually no loss of either lubricant or performance. A (known) impact on a gearbox would not necessarily result in a mission abort.

Main rotor

Helicopter designers have expended considerable effort over the past 30 years or more on developing 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. The blades performed well against small arms projectiles.

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

FIG.10 – DAMAGED MAIN ROTOR BLADE (SOURCE: AUTHOR)

Drive train

With the notable exception of the 'No Tail Rotor' (NOTAR) designs (used in the MD Helicopters MD500/MD600), the tail drive shafts of most conventional helicopters are particularly prone to ballistic damage. Most 'older' designs have small diameter drive shafts; although unlikely to be susceptible to damage from fully aligned small calibre bullets and fragments, they could be severed by an impact from a tumbled round or larger calibre threat. To reduce this susceptibility, manufacturers have introduced very large diameter shafts – the requirement to tolerate a fully tumbled impact from a 12.7 mm round dictates a diameter of at least 115 mm.[21] These (large diameter) components have high ballistic tolerance to impacts from non-tumbled inert rounds up to 23 mm. 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. To join drive shafts, most western-designed helicopters use a 'Thomas' coupling with redundant fixings so that the loss of two bolted joints (out of six) 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 signalling and hydraulic power to the tail rotor gear box, and structural failure of the tail-cone. The use of anti-flail bearings to prevent large movement of the tail drive shaft significantly reduces the likelihood of major failures occurring.

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 overall reliability rather than to increase the level of tolerance to battle damage.

To increase survivability where duplex systems are used, it is important to ensure that wherever practicable 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 on developing non-flammable hydraulic fluids to reduce the risk of fire. Although these fluids are less susceptible to fire than earlier ones, they do still pose a significant fire risk.

Conclusions

This article 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 aid suites that future helicopters at least maintain the currently attainable levels of ballistic tolerance. Military operations in support of peacekeeping or enforcement involve helicopters coming into contact with significant numbers of low technology threats that cannot easily be countered by electronic means.

The only sure counter to single or multiple impacts from typical threats widely used by terrorists is to use tactical flying aided by threat warning to avoid being hit and to provide the helicopter with a high degree of tolerance when hits occur.

It is essential that efforts are made early in the design stage to incorporate ballistic-tolerant features. The difficulties in retrofitting such features are generally too great to be practicable.

Acknowledgement

This article is a revised version of those presented at the 29th European Rotorcraft Forum in Friedrichshafen in September 2003[22] and at the 2nd European Survivability Workshop in Noordwijkerhout in March 2004.

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