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HELICOPTER CRASHWORTHINESS

- **Study I**
  A Review of UK Military and World Civil Helicopter Water Impacts over the period 1971-1992
- **Study II**
  An Analysis of the Response of Helicopter Structures to Water Impact

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General Foreword

The research reported in this paper was funded by the Safety Regulation Group of the UK Civil Aviation Authority, the UK Department of Transport, and the UK Off-Shore Operators Association. The work was instigated at Westland Helicopters Ltd (WHL) Stress Department in response to Recommendations 7 and 8 of the Report of the Helicopter Airworthiness Review Panel (HARP Report - CAP 491), and comprised the following two studies:

i. A Review of UK Military and World Civil Helicopter Water Impacts over the Period 1971 - 1992.
ii. An Analysis of the Response of Helicopter Structures to Water Impact.

This paper contains unabridged versions of the corresponding Westland Helicopters Ltd Stress Department Reports, SDR 146 and SDR 156 respectively

The principal conclusions of these studies included:

- The primary cause of loss of life from helicopter water impacts was drowning (occupant fatalities resulting from excessive crash forces or as a result of structural collapse during an impact were a secondary issue).
- Designing the airframe to remain afloat for sufficient time to enable evacuation following a water impact should be a major objective if occupant survival is to be improved.

In response to the findings of the research reported in this paper, and in response to Recommendation 14.2(g) of the Review of Helicopter Off-Shore Safety and Survival (RHOSS Report - CAP 641), further research to establish the feasibility, techniques and costs of improving the crashworthiness of helicopter emergency flotation systems is currently planned.

Safety Regulation Group

23 May 1996

Study I
A Review of UK Military and World Civil Helicopter Water Impacts over the period 1971-1992

Summary
This paper reviews accidents to UK Military and World Civil Helicopters over the period 1971 - 1992 that have involved impact with water. All occurrences of helicopter water impacts that have resulted in occupants receiving serious or fatal injuries and /or the aircraft sustaining substantial damage have been considered. These criteria meet the minimum requirement for a notifiable accident as defined by Civil and Military airworthiness authorities. Accidents not considered relevant to this study, for example, ground accidents and catastrophic non-survivable accidents, were excluded.

Analyses of accident data were carried out to determine the distribution of impact conditions, accident causes and primary occupant injury mechanisms. The effectiveness of helicopter flotation systems was also reviewed. Mechanical failures were found to be the primary cause of accidents for both military and civil helicopters. These accidents accounted for only a small percentage of occupant fatalities in military helicopter accident s but were the primary cause of fatalities in civil helicopter accidents. Human factor issues (pilot error and disorientation) were found to be the primary cause of occupant fatalities in military helicopter water impacts. In fatal accidents where the cause of death had been established, drowning was found to be the major cause of loss of life.

Helicopter water impacts were categorized into three impact types that accounted for over 70% of all occurrences for which impact conditions were known. Analysis of these impact types is to be undertaken at a later stage in this programmed to assess the response of helicopter structures to water impact and to evaluate the level of crashworthiness in current designs. From this work, areas where potential design improvements could be made to increase occupant safety will be identified.

1. INTRODUCTION

Numerous studies have been carried out over the last 30 years into helicopter crashworthiness and occupant crash survival. This effort has resulted **in** the development of imp roved crash survival design criteria and has led to a significant increase in the probability of occupants surviving aircraft crash impacts. The bulk of this effort ha s to date been directed at the study of helicopter impacts onto solid ground width little emphasis on impacts involving water or non rigid surfaces.

However, although ground impact s account for the majority of helicopter accidents, collision with water has been identified as a significant accident category for both military and civil helicopters from the CAA's World Helicopter Accident Summary (1), for example, 494 civil helicopter accidents are listed for the period 1959 – 1990 with over 24% involving water impact. Similarly, UK military helicopter accident data indicates that for the years 1971 - 1983 over *21%* of the 254 accidents involved collision with water (2, 3, 4).

Previous studies have been carried out in the UK into helicopter ditchings and water impact, although with post crash survival as the primary emphasis, techniques for assisting underwater escape, survival equipment and flotation systems for example, have been the focus o f attention. Little consideration has been given to improving the probability of occupants surviving the initial aircraft impact with the water surface.

The aim of this present study is to review helicopter accidents involving impact with water and to determine impact parameters and primary injury causing mechanisms as an initial step in developing improved crash survival design criteria.

Early investigations of helicopter water impacts suggest that structural damage and occupant injury mechanisms are significantly different from and frequently more severe than helicopter ground impacts of an equivalent velocity. The absence of an effective undercarriage to absorb crash energies in a vertical impact is a major factor in increasing the severity of water impacts. Furthermore, the generally poor hydrodynamic performance of current helicopter designs precludes extensive high speed forward motion in the water that, for a ground impact, may reduce the aircraft kinetic energy through sliding friction. From the data compiled during the preparation o f this paper, a study o f the response of helicopter structures to water impact is being undertaken.

The aim of this work is to identify structural weaknesses and to evaluate levels of crashworthiness in current designs. In addition, areas will be identified where potential design improvements can be made.

2. SOURCES OF DATA

The primary sources of military accident data for this study have been the detailed accident reports prepared by the Royal Navy Aircraft Accident Investigation Unit at HMS Daedalus and a previous review o f helicopter ditchings by Reader (5). Other reviews o f military helicopter ditchings, namely those of Vyrnwy - Jones in 1989 (2) and Baker and Harrington in 1988 (6) were also consulted during preparation of this paper. Information on helicopter ground impacts was obtained from three report s by Vyrnwy - Jones for Naval, RAF and Army helicopters (2, 3, 4).

For civil helicopter accident data, the CAA World Helicopter Accident Summary (1) was the primary source. Additional data was provided by the Department of Transport Air Accidents Investigation Branch accident reports. ICAO (International Civil Aviation Organization) accident reports and US National Transportation Safety

The accident reports and reviews referenced above contain significantly more information than has been possible to include in this present study. Considerable information is available, for example, on escape problems from ditched helicopters and other post crash survival issues. These references remain a valuable source of data for researchers requiring additional information. The aircraft accident data presented in this paper has been compiled from the best available information and while every effort has been made to ensure the reliability of this data, total accuracy cannot be guaranteed.

Lack of detailed information in accident reports on occupant injuries and structural crashworthiness issues was found to be a significant problem in the preparation of this report. The lack of estimates or calculations of aircraft impact velocities and attitudes, for example, prevented a statistical analysis of impact conditions from being undertaken. In civil helicopter water impacts, the cause of death was established in less than half of the total number of fatal accidents. Similar problems have been reported by Baker and Harrington (6), Hodges (7) and Reader (5) in their reviews of helicopter ditchings. Although it is recognized that for some accidents where the aircraft wreckage ha s no t been recovered, certain information is not available, it is felt that in many cases a detailed description of structural damage to the aircraft and estimates of impact conditions would greatly benefit future studies into helicopter crashworthiness. A detailed account of occupant injuries and their probable cause would also be a valuable addition to future accident reports.

In addition to the published reports listed above, valuable information was also provided by Lt Cdr Pau l Barton from HMS Daedalus, Robert Carter of the Air Accidents Investigation Branch and James Ferguson.. Their contributions are gratefully acknowledged.

3. DEFINITIONS AND TERMINOLOGY

Ditching - A forced landing onto water following a loss of power or control. This definition is in agreement with UK military terminology. It should he noted, however, that in civil aviation requirements, a ditching is defined as a controlled alighting on water. This definition is equivalent to the military precautionary alighting on water which considers the cont rolled alighting to be pre-meditated.

Crash Landing - A landing involving high impact velocities and a significant or total loss of control.

Water Impact - A landing on water that meets one of the above definitions. The term water impact, therefore, includes both ditchings and crash landings onto a water surface.

Survivable Crash - A crash in which the forces transmitted to the occupant s do not exceed the limits o f human tolerance and in which the structure surrounding the occupants remains sufficiently intact to permit survival.

Significant Survivable Crash - A crash determined to be survivable and in addition, meets one or more of the following minimum injury or damage criteria:

a) At least one occupant receiving serious injury.
b) The generation of impact forces likely to cause injury to occupants.
c) The aircraft structure sustaining substantial damage.

It should be noted that the term survivable means impact survivable. The presence of a post crash fire or loss of life as a result of drowning are not considered factors in determining whether or not an impact is survivable.

4. ACCIDENT CLASSIFICATIONS

All reported water impact occurrences over the period 1971- 1992 involving UK military and world civil helicopters of an AUW greater than 3500 kg were considered in the initial review of accident data.

Whilst every effort was made to include as many accidents as possible, this review is not claimed to be exhaustive due to the heavy reliance on previously published data. The minimum weight classification of 3500 kg ensures a minimum carrying capacity of 11 occupants, i.e. typically 2 crew and 9 passengers.

From an initial population sample of 130 civil and *74* military helicopter water impact occurrences, impacts of a minor nature, i.e. those no t meeting the minimum requirements to be classed as an accident, ground accidents and those considered to be non-survivable were excluded. Accidents for which limited or no information was available, were also excluded. These exclusions resulted in a final population sample of 98 civil and 61 military accidents. Of the 32 excluded civil accidents 16 were fatal (146 fatalities). Of the 13 military accidents excluded, 1 was fatal (4 fatalities).

In line with the accident data analysis procedures adopted in the Aircraft Crash Survival Design Guide (8) and other accident reviews (e .g . 9, 10), non-survivable accidents and those of a minor nature have been eliminated from the analyses carried out in this study. It has been argued that only significant survivable accidents are o f interest because it is the many fatalities and serious injuries occurring in these accidents that could be avoided by improved design. Hence, it is in this category of accident that the greatest benefits and improvements could be made.

Mens (11), however, argues that setting an initial bias on the analysis by eliminating certain occurrences , distorts the limits established for a given percentile accident. By excluding low severity accidents, for example, the 50th and 9 5th percentile potentially survivable crash velocities are artificially raised. A fundamental rule of any statistical analysis. Mens argues, is to examine a sample representative o f the entire population.

Without knowing the details of an accident, it is frequently difficult to determine whether an impact is significant, survivable o r minor. Certainly impact velocity is not a factor in determining how an accident should be categorized. A study carried out by Coltman et al (9) , for example, has shown that 35% o f significant survivable civil helicopter accidents in the US involved a vertical velocity below 5ft/sec. Normally this velocity would be well within the capability of most helicopters landing gears.

It is also difficult to se t limits on what accident should or should no t be included when a decision has to be based solely on the extent o f structural damage or occupant injury, Structural damage and injury may for example be due to factors other than impact forces. It has been observed in this present study that well controlled low velocity ditchings may still result in substantial structural damage and serious injury under adverse sea states. This difficulty in accurately determining what accidents should be included in an analysis may possibly account for the wide variations in the estimated values of the 95th percentile potentially survivable water impact for US Naval helicopters as defined in references 10 and 12. Vertical impact velocities for this crash severity vary from 28ft/s (10) to 50ft/s (12) with an even greater difference in the longitudinal impact velocities, i.e. 72ft/s (10), 124ft/s (12).

Lack of uniformity in the criteria by which accident severity is judged may also account for observed variances in accident data. Reference 9, for example specifies at least 1 injury of a minor or serious nature as one criteria for a significant survivable accident. Reference 12, however, specifies that at least 1 occupant receives major injury as the lower limit of a significant survivable accident.

Because the criteria for a survivable accident are difficult to apply, accidents are frequently assigned to this category if there is at least 1 survivor and at least 1 serious injury. However, occurrences have been reported of occupant s miraculously surviving accidents that, because of their severity, (mid air collisions, for ex ample) would normally be classed as non survivable. Considerable differences in how accidents are classified there for exist. Because accident data for this study has been compiled from more than one source, consistent accident data classification cannot be guaranteed. Differences in accident data classification can also make comparisons between individual accident reviews unreliable and hence such work should only be undertaken with caution.

A factor that is likely to distort any comparison between water impacts and ground impacts is the often trivial nature of the emergency that leads to an accident. A controlled ditching as a result o f a minor electrical problem for example, may result in severe damage or the total loss o f [h e helicopter. A similar problem affecting a helicopter opera ting over land would usually only result in a precautionary landing and would probably not feature as an accident statistic.

5. DATA ANALYSIS

5.1. Military Accident Data

Sixty one occurrences of UK military helicopter water impacts over the period 1971-1992 have been included in this analysis and are listed in Table 1. This table includes a description of the cause of the accident, the number and severity of injuries and brief notes o n the type and seventy of impact. These notes are intended to give an indication of the conditions prior to impact, for example, the degree of control. Information on impact severity has been taken primarily from Reference 5-A light impact is defined here as one in which the helicopter is under a controlled descent even though directional control may b e lost. For a heavy impact, the helicopter is assumed to have lost a substantial degree of control or has impacted the water in an adverse attitude. An out of control classification signifies a total loss of control and includes mid air collisions and free falls from altitude. The fourth category of impact , fly-ins, are primarily high forward speed, gradual rate of descent impacts with the aircraft approaching the water surface a t a shallow angle. These accidents are invariably the result of pilot error or disorientation.

The flotation and helicopter inversion data shown in Table 1 has again been taken from Reference 5. Immediate inversion indicates that the helicopter inverts before the occupants could escape and typically in less than 15 seconds. Delayed inversion indicates that evacuation was complete before inversion occurred; inversion times here are generally greater than 15 seconds. The term service able flotation refers to a successful deployment and prolonged inflation of the flotation gear. A partial inflation indicates that at least o ne of the flotation bags either failed to inflate or deflated shortly after deployment. The accidents listed in Table 1 have been categorized with respect to accident cause, impact type and severity.

5.1.1. Classification of Accidents with Respect to Accident Cause

An analysis of the cause of military helicopter water impacts is shown in Table 2. The most significant cause of accidents was determined to be mechanical failure with engines (3 1·1%), main rotor transmission (11·4%) and tail rotor (11·4%) being the most vulnerable components. Included under main rotor transmission failures are both mechanical and lubrication failures.

As shown in Table 3 the majority of accidents caused by mechanical failure resulted in low severity impacts and accounted for only 3 (6·5%) fatalities . In the majority of cases adequate warning of an impending impact would be given such that the air craft could be prepared and ditched under control. Table 4 shows that 23 o f the 61 impacts were controlled ditchings.

For example, of the 7 main rotor transmission failures, 6 resulted in successful controlled ditchings with no injuries. Of the 19 engine failures, 7 resulted in successful controlled ditchings with a further 9 resulting in a vertical descent onto water with a limited degree of control. Three engine failure accidents resulted in 4 serious injuries. A fourth accident, categorized as out of control, resulted in 3 fatalities. For naval helicopters, particularly those in an ASW role, a significant proportion of airborne time is spent in the hover. In this phase o f flight, engines and main rotor transmissions are highly loaded and hence the hove r is associated with a high incidence of failure o f these components. The 7 tail rotor failures resulted in 7 serious injuries but no fatalities.

Failure and mal functions in other aircraft systems accounted for 11 of the 61 accidents as shown in Table 2. Because these in-flight emergencies did not generally affect control of the aircraft, controlled ditchings were executed in the majority of cases. One accident, however, caused by a computer failure, resulted in 2 fatalities in a high speed fly-in accident.

The 3rd major category, pilot error and disorientation, accounted for 14 of the 61 accidents and resulted in 87% of the fatalities and nearly 50% o f the serious injuries. Five of the 14 accidents in the category of pilot error and disorientation were high forward speed fly-in accidents with the aircraft making a gradual descent into the water surface. Impacts were at a shallow angle with the water surface and extremely severe. All 5 accident s were fatal resulting in **11** fatalities. A further 3 accidents involved both vertical and forward velocity. The remaining 6 accidents were either controlled ditchings or out of control accidents.

In addition to the 14 accidents where pilot error or disorientation was clearly identified as a casual factor in the accident, 5 further accidents were considered to have had contributory causes from pilot error. Two of these accidents were fatal resulting in the loss of 5 lives. In 3 accidents, although mechanical failure was present, the pilot failed to follow required procedures to correct the situation. Failure to maintain rotor RPM in an attempted autorotative descent and shutting down the wrong engine following a single engine failure are two examples.

Comparing the distribution of accident causes established in this study with other accident reviews, shows a similar percentage of accidents resulting from mechanical failure. Brooks (13), for example has shown that 52% of Canadian Navy helicopter ditchings were the result o f mechanical failure in the period 1952 - 1990. Reade r (5) has reported that 50% o f Royal Navy helicopter ditchings over the period 1972-1988 were the result of failures to the power plant or transmission. Pilot error has been shown to be a major cause of military helicopter accidents in studies by SteelePerkins (15), Day (14) and Brooks (13) where between 23% and 46% of water impacts have been shown to be the result of pilot error. The maritime environment has been shown to be a significant factor in inducing disorientation among aircrew (16).

5.1.2. Classification of Accidents with Respect to Impact Type

An analysis of military helicopter accident data with respect to impact type is shown in Table 4. Three impact categories were identified that accounted for over 70% of water impacts. Controlled ditchings can be seen to account for 37·7% o f water impacts. In a controlled ditching the aircraft is considered to be under full control such that the pilot is able to limit the rate o f vertical descent to an acceptable figure (e. g. 5 ft/s). Forward velocities are dependent on whether the helicopter is under power or autorotatating but are generally below 30kts. Aircraft attitudes are invariably level in roil and pitch except for autorotative descents where flare out prior to touchdown may result in a slight nose up pitch attitude. All controlled ditchings are classed as light with no serious injuries and are well within the structural capability of the airframe.

The vertical descent under limited control category accounted for 27·8% o f water impacts. There were no fatalities in accidents in this category although 11 serious injuries were reported. As the aircraft is considered to be under partial control, impact velocities were higher than for controlled ditching but generally still within the capability o f the airframe structure. Aircraft forward velocity is again generally low but impact attitudes may involve pitch and roll angles dependent on the degree of control. In addition, the aircraft may be yawing on contact with the water surface if yaw control has been los t. Of the 17 accidents in this category, 4 were classed as heavy. Three of these impacts were the result of tail rotor failures and accounted for 7 of the serious injuries.

Fly-In accidents accounted for 8 o f the 61 accidents producing 34 fatalities and 9 serious injuries. Twenty one fatalities and 8 serious injuries occurred in one accident. Five of these accidents were high forward speed, shallow angle impacts wit h the water surface and extremely severe. The remaining 3 accidents involved significantly lower forward impact velocities and occurred while the aircraft was either in the hover or shortly after take-off.

Of the remaining 13 accidents, 7 were uncontrolled impacts and 4 were insufficiently documented to allow classification.

5.1.3. Analysis of Occupant Injuries

Of the 61 military helicopter accidents recorded in the period 1971-1992, 13 (21·3%) were fatal resulting in 46 fatalities.

Thirty eight deaths (82·6% of the total) were the result of drowning. The remaining 8 fatalities resulted from impact injuries in which 2 were attributable to seat failure, 2 from blade strike and 3 from multiple injuries sustained in catastrophic out of control accidents.

Thirty four (73·9%) fatalities occurred in accidents that were categorized as either controlled ditching, vertical descent with limited control or fly-in accidents. The remaining 12 fatalities occurred in accidents where the aircraft was essentially out of control.

There were a total of 18 accidents that involved fatal or serious injuries. Seven of these accidents resulted in 20 serious injuries: 12 injuries where spinal compression fractures, 2 involved other bone fractures and 6 where unknown. The high incidence of spinal compression fractures reflects the high vertical impact forces associated with helicopter water impacts. This finding is broadly in agreement with the findings of Vyrnwy-Jones (2) where spinal injuries were found to account for 73·3% of all major injuries in UK Navy helicopter water impacts. These figures, however, are significantly higher than the spinal injury rate observed for army helicopter accidents. A summary of occupant injury data is shown in Table 5.

Drowning was shown to be the major cause of death in survivable US Navy helicopter water impacts in a stud y by Glancy(12) where 54·7% o f fatalities were due to drowning and a further 38·0% were lost at sea presumed drowned. Rice and Greear (17) reported that 84·1% of fatalities in ditched US Navy helicopters over the period 1969-1972 were identified as either drowned (39·6%) or lost at sea (4 4·4%). Forty percent of that recovered drowned o r lost at sea was last seen still in the air craft indicating that the inability to escape, either because of incapacitation or disorientation, is a major issue.

5.1.4. Analysis of Helicopter Flotation Systems

Of the 61 ditchings, 35 (57·3%) resulted in immediate inversion, 15 (24·5%) were delayed inversions and in a further 9 cases the aircraft did nor invert. Seven ditching involved helicopters without flotation systems fitted and all resulted in immediate inversion. The 16 occurrences where a flotation system was fitted but not used also resulted in immediate inversion. In the 28 cases where the flotation system was successfully deployed, there were 5 cases where the helicopter inverted immediately. Fourteen of the above 28 cases involved controlled ditching and it was from this population that the 5 cases of immediate inversion occurred.

The number of ditchings resulting in immediate inversion calculated above is broadly in agreement with a Boeing Vertol stud y (see Reference 24) into 200 US Navy Marine helicopter ditchings where it was revealed that more than 50% of aircraft inverted and/or san k in less than one minute. Vyrnwy-Jones (2), in a study of 53 Royal Navy helicopter ditchings between 1972 and 1984 calculate d that 47% of helicopters either sank or inverted immediately after water impact.

The reason for 16 occurrences of the flotation system nor being used is unclear. It is possible that in a number o f cases the pilot had considered that a water take -off was feasible and hence was reluctant to deploy flotation equipment. Evidence indicates that in at least one case the pilot had attempted to deploy flotation gear but without success. In the remaining cases, pilot disorientation or incapacitation was a likely explanation for the failure to deploy flotation gear. These examples provide strong evidence for the automatic deployment of flotation aids when a helicopter contacts a water surface. At least 2 methods of automatically deploying flotation systems, in addition to a manual activation capability have been recommended by Reader (5).

To be effective, [he flotation system must withstand the initial impact with the water surface and keep the helicopter upright and afloat for long enough to enable occupants to evacuate. The high incidence of immediate inversions (over 57%) reflects the poor performance of flotation systems fitted to helicopters over the period 1971- 1992. Evidence shows that in some instance s flotation bags were damaged by the initial water impact and in other cases were made ineffective because of the failure o f the structure to which they were attached. Failures of flotation systems as a result of wave action in the post impact phase have also been recorded.

Because of inherent instability of current helicopter designs, e .g. high centre of gravity and narrow fuselage, there is a strong likelihood that the helicopter will invert even when successfully ditched in calm conditions. Main rotor blade strike with the water surface due to wave motion or excessive roll of the aircraft in the water and even application of the rotor brake can generate an overturning moment of sufficient magnitude to invert the helicopter. In sea states of 3 or greater, it has been reported that the majority of helicopters invert and/or sink regardless of how well controlled the ditching may have been (2).

5.1.5. Comparison between Military Helicopter Water Impacts and Land Based Impacts

From three reviews o f helicopter accidents (2, 3, 4) for [he 3 UK armed forces (RAF, RN, Army Air Corp), a study was made of the relative proportion of water impacts and accidents involving impact with the ground. Unfortunately no published reviews were available for UK military ground impacts in recent years, and as a result, the comparison was limited to data for the period 1971- 1982. It should be noted that the accident reviews contained in reference 2, 3, and 4 have employed different classification criteria in their data analyses to those adopted in this present study. Hence, comparison between these different reviews, even if they involve apparently similar populations, should be carried out with caution.

From the three accident reviews referenced above, a total of 231 accidents involving UK military helicopters were reported in the period 1971-1982. These accidents accounted for 95 fatalities. Of these 231 accidents, 169 were land impacts and 62 were water impacts. 15·4% of land impacts were determined to be fatal compared to 16·1% of water impacts.

The 169 land impacts involved 434 occupants; fifty eight occupants were fatally injured resulting in a survival rate of 86·6%. For water impacts there were 37 fatalities from a total of 253 occupants, producing a marginally lower survival rate of 85·3%. This difference in survival rates is not considered to be significant. The survival rates in Royal Navy *helicopter* accidents were calculated to be 85 2% for water impacts and 86·3% for land impacts (5); again the difference is not considered significant.

Brooks (13) has calculated a survival rate of 76% for Canadian Military helicopter ditchings over the period 1952- 1990. For US Navy/Marine Corps helicopter ditching in the years 1977- 1990, Barker (19) has shown a survival rate o f 83% in 115 survivable accidents. A study of us Army helicopter accidents over the period 1979 1985 (18) ha s demonstrated an occupant survival rate of 87·1% in 298 significant survivable accidents. In comparison, the 61 helicopter water impacts reviewed in this present study produced an occupant survival rate of 83·1%.

A comparison of land and water impacts has shown a significant difference in the distribution of major injuries. Whereas spinal compression fractures have been shown to be the most frequently identified serious injury to occupants in water impacts (see 5. 1.3), for land impacts, spinal injury accounted for only 16·5% of serious and fatal injuries in a study of us Army helicopter accidents (8) . A study of UK Army Air Corps land impacts ha s revealed that 18·0% of serious injuries are spinal in nature (4). Both these references have shown that head impacts arc the most significant cause o f serious injuries in army helicopter land impacts.

As discussed in 5.1.3, 73·3% of major injuries in RN helicopter ditchings were spinal injuries (2). It was also shown in the same study that if all RN accidents are considered (water, land and deck), then the percentage of spinal injuries falls to 50%. Day (14) also identified a reduced figure for spinal injuries of 34% for all RN helicopter accidents over the period 1960 - 1969.

A study o f US Navy helicopter ditchings by Coltman (10) concluded that the most serious crash hazard resulted from structural failure of crew and troop seats that allowed the body to strike adjacent structure. Of the total number o f major and fatal injuries, 27·4% were considered to be the result o f se at or restraint failure. Interestingly, only 10·5% of major/ fatal injuries were found to be the result of excessive decelerative force.

A study of US army helicopter accidents over the period 1979 - 1985 (18) has also revealed the most common cause of injuries to be secondary impacts caused by inadequate restraint or structural collapse. In survivable accidents, 60·1% of injuries were considered to be the result of the occupant striking, or being struck by aircraft structure. As for water impacts, occupants receiving excessive decelerative forces accounted for only a small percentage of injuries (12·3%). The most frequently identified deficiencies contributing to occupant injury were restraint systems (39·7%) and scats (23·4%).

Several studies have shown a high incidence o f injuries to lower and upper body extremities in army helicopter impacts. For example Shanahan (18) has shown that leg injuries account for 27·4% of the total number of injuries. Vyrnwy-Jones (4) has calculated a figure of 16·0% for similar injuries. Although these injuries are classified as severe for land impacts they are unlikely to be hazard o us to life, unless a post crash fire is also present. In water impacts, however, such injuries may incapacitate an occupant to the extent that he is unable to evacuate the aircraft. If the aircraft subsequently inverts o r sinks, then the outcome is variably fatal; the cause of death will be drowning wit h the original injury going unrecorded.

As discussed in 5.1. 1. Pilot error has been shown to be a major cause of aircraft water impacts (23·46%). Studies of UK and US army helicopter ground impacts, however, have shown that a considerably higher percentage of accidents are the result of pilot error Singlev and Sand (20) have shown that over the period 1968-1975, 71% of US army helicopter accidents were the result of flight crew errors. For UK Army Air Corps helicopter accidents, 75% were attributable to pilot error (4).

5.2. Civil Accident Data

Ninety eight notifiable water impacts to world civil helicopters over the period 1971 - 1992 have been included in this analysis and are listed in Table 6. This table includes a description of the cause o f the accident, the number and severity of injuries and a description o f the type of impact. The same categories of impact type as that used for the military data has been adopted here, these being controlled ditching, descent with limited control, fly-in and out of control. Where available, information on helicopter flotation system effectiveness is also presented. However, o f the 98 accidents, information on post impact flotation were only available in 56 cases. The terms used to describe helicopter flotation performance are as those defined for military helicopters in 5. 1. The accidents listed in Table 6 have been categorized with respect to accident cause and impact type.

5.2.1. Classification of Accidents with Respect to Accident Cause

An analysis o f the cause of civil helicopter water impacts is shown in Table 7. The most significant cause of accidents was found to be mechanical failure with engines (19·3%) and main rotor transmission (17·3%) showing the highest incidence of failure. Failure or malfunction in aircraft systems other than power plant and transmission accounted for 14·2% of accidents. Accidents attributable to pilot error or disorientation accounted for 24·4% of the total number of accidents. An NTSB study (21) has shown that for US civil helicopters over the period 1977 - 1979, 39·5% of accidents were attributable to mechanical failure in the power plant and transmission. A similar figure of 41% for mechanical failures was calculated by Balfour (22) in a study of 27 UK civil and military helicopters between 1956 and 1975. These figures are in reasonable agreement with those determined in this present study.

From Table 7 it can be seen that the 55 accidents resulting from mechanical failure accounted for 60·3% of the total number of fatalities. Pilot error accounted for 30·1% of fatalities, a significantly smaller percentage than that shown for military accidents. In addition to the 24 accidents where the cause was determined to be pilot error or disorientation, there were a further 6 accidents where the pilot was considered likely to have been a casual factor. Of these 6 accidents, 3 were fatal accounting for 19 fatalities. These accidents, however, even if included in the pilot error category would not have significantly affected the percentages quoted above.

In the review of US civil rotorcraft accidents discussed in Reference 21, the pilot was cited as a cause o r related factor in more than 64% o f the total number of accidents. This study included both water and land impacts. This figure of 60% is significantly greater than the 30·1% determined for pilot error accidents in this study

5.2.2. Classification of Accidents with Respect to Impact Type

An analysis of civil helicopter water impacts with respect to type o f impact is shown in Table 8. Controlled ditchings accounted for 29·5% o f water impacts. The second largest impact type category was vertical descent with limited control that accounted for 25·5% o f the water impacts analyzed. The total number of accident in these two categories (55%) is broadly similar to that found for military helicopters (64%). However, whereas military helicopter controlled or limited control impacts did not result in any fatal accidents, Table 8 shows that for civil helicopters over 15% of fatalities were accounted for in these two categories.

Fly-ins and uncontrolled impacts accounted for 17·3% and 25·5% respectively of civil helicopter water impacts compared to 13·1% and 11·4% for UK military helicopter water impacts. Twenty three percent of fatalities occurred in fly-in accidents; uncontrolled impacts accounted for 58·5%. These proportions again are significantly different than the 73·9% and 26·0% of fatalities in fly-in and uncontrolled impacts for military helicopter accidents.

5.2.3. Analysis of Occupant Injuries

Of the 98 world civil helicopter water impacts over the period 1971 – 1992, 48 (48·9%) were fatal resulting in 338 fatalities. This fatality rate is over twice that for UK military helicopters. In accidents where the cause of death had been established (24out of 98), 56'7% of fatalities were the result of drowning. Of the 902 occupants involved in the 98 accidents, 338 lost their lives resulting in a survival rate o f 62·5%. This figure is significantly lower than the 83·1% survival rat e calculated for military helicopters.

Of the 98 water Impacts, 52 involved serious or fatal injuries; 22 of these accidents accounted for 46 serious injuries. In 17 of the 48 fatal accidents all occupants were killed A breakdown of the distribution of occupant injuries showed that of the 338 fatalities, 281 were passengers and 57 were crew. As shown in Table 8,276 fatalities (81·6%) occurred in accidents that were categorized as fly-in o r uncontrolled. Fifty one fatalities (15·0%), however, occurred in impact s classed as controlled or partially controlled. Insufficient information was available to enable a detailed analysis of injury mechanisms to be carried out. However, in 10 fatal accidents a total of 130 seat failures were recorded. In an accident to a 56 1 in July 1990 (see accident 11 in Table 6) in which 6 occupants out of 13 died, it was found that all occupied seats showed some form of impact damage. All of the passengers who died were shown to have occupied seats that collapsed on impact. Furthermore, 7 of the 10 fatal/serious injuries were due to flailing of the body that resulted in contact injuries.

5.2.4. Analysis of Helicopter Flotation Systems

Insufficient information was available to carry out a detailed analysis of civil helicopter flotation effectiveness. Of the 98 accidents included in t his analysis, however, limited information was available in 56 cases. In 37 water impacts the aircraft inverted o r sank before evacuation was completed. In the remaining 19 cases, the aircraft remained a float and upright for long enough to enable occupants 10 evacuate. In the 37 cases of immediate inversion, 26 were fatal accidents involving 181 fatalities. For the cases where a cause of death had been established (133 out of 18 1 fatalities), drowning was identified in 83 cases. In a review of North Sea helicopter ditchings by Ferguson and reported in Reference 24, 28 ditchings between 1969 and 1987 resulted in a survival rate of 62 %. Eleven (39·2 %) of the ditched helicopters were reported to have inverted o r sank immediately.

5.2.5. Comparison between Military Helicopter Water Impacts and Land Based Impacts

A comparison between land and water impacts for UK and world civil helicopters was not possible due to lack of published reviews or summaries on land impacts. Although raw data was available from the CM's World Helicopter Accident Summary and ICAO sources, analysis of this data was considered to be outside the scope of this present study. Findings from US studies, however, are considered relevant and worthy of inclusion.

In a study of US civil helicopter accidents over the period 1974 - 1989 (9) 9·7% of accidents where the impact scenario was known were determined to be water impacts. Survivable water impacts, however, accounted for 64·7% of fatalities. High vertical velocity land impacts accounted for only 5·8% of fatalities. For serious injuries, the high vertical velocity land impact category was shown to be the most severe with 45· 1% of all serious injuries. Excessive vertical forces cause d almost half of the injuries in this accident type. In comparison, water impacts accounted for 20·9%of the total number of serious injuries.

As discussed in 5.2. 1, Reference 21 established the pilot as a cause or related factor in over 64% of US civil helicopter accidents in the period 1977 - 1979 in which a probable cause was determined . This corresponds reasonably well with the figures for UK and US military land impact data. Reference 11 quotes a figure of 71·2% for US military helicopter pilot error accidents over the period 1968 - 1975; reference 4 quotes a figure of 75% for UK Army Air Corps helicopter pilot error accidents over the period 1971 - 1982.

In this water impact study, however, only 24-4% of civil and 23% of military helicopter accidents were attributable to pilot error. This difference may in part be explained by the high incidence of pilot error accidents in land based impacts where the aircraft hit obstacles such as trees and wires. Reference 21, for example, indicates that 17-8% of land based civil helicopter accidents involve collision with obstacles (wires, trees, poles). Over water night is generally free from such obstacles A paper by Bender(23) has shown that 27·2% of accidents involving MBH helicopters that were attributable to pilot error, were the dire ct result of collision with obstacles.

6. DISCUSSION

This study has reviewed water impacts over the period 1971-1990 Involving world civil and UK military helicopters. Analyses were restricted to accidents that resulted in substantial damage to the helicopter and/or the occupants receiving serious or fatal injuries. The 98 world civil accidents analyzed resulted in 338 fatalities and a survival rate of 62·5%. An analysis of 6 1 UK military helicopter water impacts revealed 46 fatalities and a significantly greater survival rate of 83·1%. Similar survival rates for US and Canadian military helicopter water impacts (83% and 76% respectively) have been demonstrated by Barker (19) and Brooks (13). Published data on civil helicopter survival rates was unfortunately only available for fatal accidents involving both water and land impacts. This study of CS civil helicopters carried out by the National Transportation Safety Board (21) revealed a survival rate of 27·6%. This compares with a figure of 33·5% for fatal water accidents in this present study.

The primary cause of helicopter water impacts was shown to be mechanical failure in engines, transmission and rotor systems. For world civil accidents 26·1% were the result of mechanical failure in these components; for UK military helicopters the figure was 55·7%. The second most common cause of accidents was determined to be pilot error for both civil water impacts (24-4%) and military water impacts (22-9%). These figures are significantly lower than the frequency calculated for pilot error accidents on land where figures of the order of 70% have been demonstrated (4. 20). Although the maritime environment is known for its potential to induce disorientation, it is believed that the high numbers of pilot error land impacts are, at least in part, the result of collision with obstacles and heavy landings.

Although only a small percentage o f military accidents were found to be the result of pilot error (2 2·9 %), these accidents accounted for 86·9% of fatalities, mechanical failures that accounted for 55·7% of accidents, resulted in only 6·5% of fatalities. A different distribution of fatality causes was observed in civil helicopter water impacts. Pilot error, that accounted for 24 -4% of accidents, resulted in 30· 1% of fatalities. Mechanical failure accidents (56·1%) produced 60 ·3% of the total number of fatalities in civil helicopter water impacts.

A possible explanation for this difference is that in military helicopters, where pilots are trained in simulated engine and tail rotor failures, for example, they are better able to respond to real emergencies. Table 4 and 8, for example, show that of the 61 military helicopter water impacts. 37·7% are controlled ditching, whereas for civil helicopters. 29 ·5% of the 98 water impacts were controlled ditchings. Furthermore, 25·5% o f civil helicopter water impacts were classed as out of control compared to only 11·496 for military helicopter accidents.

The cause of death in the majority of accidents analyzed where a cause had been identified was shown to be drowning. In military helicopter water impacts, 82·6% of fatalities were due to drowning; 56·7% of fatalities in civil helicopter water impacts were the result of drowning. It should be rioted for civil helicopter accidents, however, that the cause of death was identified in only 48% of the fatalities analyzed. It can be seen from these results that the high fatality rate associated with helicopter water impacts is not an indication of the severity of impact or the magnitude of impact forces but rather reflects the scale of post crash survival problems.

When a helicopter ditches in to water it frequently invert s and rapidly sinks. This study has shown that in approximately 60% o f military and civil helicopter water impacts, the aircraft inverts or sinks immediately or at least before occupant evacuation was completed. A consequence of this rapid inversion or sinking is that the majority of survivors in water impacts would have had to have made some form of underwater escape. It has been reported that even if the crew and passengers are uninjured, escape is frequently hindered in such cases by loss of vision, disorientation and panic if the occupants have not been trained in underwater escape (2) . Occupants whose evacuation is further hindered by debris and difficulty in releasing restraint harnesses, commonly perish (24)

Rice and Greear (17) have reported the inrush of water as the main problem in escaping from a submerged helicopter from interviews with survivors. This often coupled with disorientation and difficulties in reaching or opening escape hatches, was reported by 50% o f survivors of us navy helicopter ditchings. The high incidence of escape difficulties a rising from the inrush of water has been noted as a cause for concern in other studies (5. 6).

Injuries to occupants would present a further hindrance 10 evacuation from a submerged or inverted helicopter. Cont ac t between occupant and adjacent helicopter structure has been shown to be a major cause of injuries in both civil and military land impacts (4 , 9, 10, 18), These contact injuries are typically the result of scat failure , structural collapse o r inadequate restraint that allows excessive flailing of the body extremities.

The extent to which these injuries at a non-fatal level have contributed to the high incidence of drowning in water impacts is not known. What has been shown, however, is the high incidence of spinal injuries in military helicopter water impacts. This finding is in disagreement with a number of studies into military helicopter land impacts and is only substantiated by other UK water impact studies (5). The reason for the high frequency of spinal injury in water impact s may possibly be that the more incapacitating in juries (i.e. contact injuries) do no t appear in the injury statistics if subsequent loss of life is attributable to drowning.

The fact that the majority of fatalities occurring in water impacts is due not to impact forces but are the result of drowning, indicates the need for improved flotation. Not only would improved helicopter flotation provide increased time for occupants to evacuate, it would also offer occupants trapped in the fuselage a greater probability of being rescue d . To be effective, flotation equipment must keep the helicopter afloat and upright for long enough to enable occupants to evacuate . It must also be designed to withstand the impact forces generated on contact with a water surface. Failures to deploy the full flotation system, o r subsequent deflation following a successful deployment as a result of impact damage, are major causes of helicopter inversion. From the observation that over 50% of helicopter water impacts resulted in rapid inversion or sinking (se e also References 5, 2-i), the current standards of flotation system in both civil and military helicopters are considered inadequate, The practice of designing flotation systems for precautionary a lightings onto water or well executed cont rolled ditchings in relatively calm sea states, does not reflect the severity o f the large number o f water impacts in which the lives of the occupants are at risk.

Improved flotation can only be an effective survival measure if the aircraft fuselage with stands the initial impact with water and occupants remain within the aircraft. Fuselage break up o n impact wit h a water surface and occupants ejected from the aircraft (often still strapped in their seats) has been shown to result in a significant number of fatalities due to drowning in survivable accidents in both this and other studies (2, 24, 25). The nature of impact forces resulting from impact with a water surface is significantly different from and frequently more severe than land impact s of an equivalent velocity. Water impact forces are generated, for example, from pressure loads rather than mass inertia as in land impacts. Detachment or displacements of large mass items such as engines and main rotor transmission which occur under excessive inertia forces are seldom recorded in helicopter water impacts. If the structural failures observed in Water impacts are to be prevented, or at least made less hazardous, a better understanding of the response of structures to water impact is required. A requirement for designers to consider water impact as a crash case is also needed if change s to current design practices is to be realized.

From the result s of this study improved flotation is considered to be the primary factor in increasing occupant survival in helicopter water impacts (se e also references 5, 12). The second area where improvement s could benefit occupant survival is in the design of seats and restrains. Improved occupant restraint e.g. the provision of upper torso restraints for passengers) could reduce contact injuries by reducing the flail envelope for arms, legs and head (10, 18). Improved restraint would also, it has been argued, stabilize the occupant in his seat and minimize buffeting and disorientation against an in rush of water and during aircraft inversion (24). Restraining an occupant in an upright position in his seat during impacts involving significant vertical forces, would also reduce the probability of spinal injuries.

Improved occupant restraint can only be of benefit in survival terms if the seat structure itself does not allow the hazardous displacement of an occupant. Failures of the seat structure or seat to floor attachments have been shown to be a major contributory factor to occupant injuries in survivable US civil and navy helicopter accidents (9, 10). Following a civil S61 accident in 1983 in which 20 occupants lost their lives (see accident number 51 in Table 6) , scat failures were identified as a significant hazard to occupant survival. The Air Accidents Investigation Branch Accident Report (26) recommended that requirements concerning the strength of helicopter passenger seats be reviewed.

As noted earlier, the lack of detailed accounts in accident report s of structural crashworthiness issues, occupant injuries and their probable causes has imposed significant limitations on the scope of this paper. The almost total lack of calculated or estimated impact parameters such as velocity and attitude, has, for example, prevented a statistical analysis of impact conditions from being carried out. One objective of this analysis was to have been the definition of the level of crashworthiness in current helicopter designs in terms of potentially survivable impact velocities. This has not been possible for the above reasons. It is considered that more detailed accident reporting for both civil and military helicopter accidents would greatly benefit future studies in the area of helicopter crashworthiness and occupant crash survival.

7. CONCLUSIONS

i. Over 50% of UK military and 56% o f world civil helicopter water impacts resulted from mechanical failure to engines, rotor system and transmissions. For world civil helicopter water impacts, 60.3% of fatalities resulted from these accidents.

ii. Pilot error and spatial disorientation was found to be the second most significant cause of water impacts for both UK military (22.9%) and world civil helicopters (24.4%) . This class of accident accounted for 86.9% of fatalities in UK military helicopter water impacts.

iii. The majority of fatalities in both world civil (56.7%) and UK military helicopter water impacts (82.6%) were attributable to drowning where a cause of death had been identified. Although drowning was recorded as a cause of death in these instances, factors behind why these occupants drowned were invariably not investigated. Incapacitation due to injury and inability to escape through disorientation entrapment and jammed/obstructed exits has been cited in some cases as probable causes of drowning in helicopter water impacts.

iv. Compression fractures of the spine were found to be the most frequent nonfatal serious injury to occupants in UK military helicopter water impacts. Seat failures were identified as a significant hazard to occupant survival in both civil and military helicopter accidents. Improved occupant restraint and seat design to prevent occupants from experiencing injurious deceleration levels an d also to prevent incapacitating contact injuries is considered to be a significant factor in increasing occupant survival.

v. In helicopter water impacts, where information on flotation system effectiveness was available, over 50% of occurrences resulted in the helicopter inverting or sinking before evacuation o f occupants was completed. A significant number of accidents, therefore, involved underwater escape. Previous studies have shown that an inrush o f water, contributing to disorientation and difficulties in reaching and opening escape hatches, is the major hazard facing survivors in inverted or submerged helicopters.

vi. Improved flotation is considered to be the most significant factor in increasing occupant survival in helicopter water impacts. This could be achieved by improving the robustness and reliability of current systems (flotation bags and inflation mechanisms) and ensuring that such systems are better able to withstand representative water impact conditions.

vii. It is recommended that UK civil and military helicopter accident reporting procedures be revised to include an analysis of impact parameters and a more detailed account of structural crashworthiness Issues. Fur the r useful data could be gained from the inclusion of a detailed description of occupant injuries and their probable cause, this information would greatly assist future studies into helicopter crashworthiness and occupant crash survival.

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