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TAIL ROTOR FAILURES – WHAT CAN BE DONE? AN ENGINEERING APPROACH

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Abstract

A study, co-funded by the Civil Aviation Authority (CAA) Safety Regulation Group and the UK Ministry of Defence (MOD) Defence Procurement Agency, has been conducted into tail rotor failures (TRFs) and their consequences. The motivation for the study was the overwhelming evidence gathered by the UK Tail Rotor Action Committee (TRAC) that TRFs were occurring at rates much greater than the airworthiness design standards require. This was true for both tail rotor (TR) drive and control systems, the former in particular, and applied to both civil and military types. The principal aims of the study were to analyse and quantify the nature and extent of the problem, and explore ways to reduce failure/accident rates and/or mitigate their effects in the future. In addition, existing training procedures and handling advice were examined and means of improvement suggested to prepare aircrew better for the effects of TRFs. Such failures are usually time critical events, requiring the pilot to take specific actions within a couple of seconds to avoid an uncontrollable, and hence catastrophic, situation developing. The study was not intended to address type-specific solutions, but rather to identify key airworthiness, technology and training aspects that may ultimately reduce the incidence and/or criticality of TRFs. It should be noted, however, that advice to aircrew on TRF management and recovery must be defined on a type-specific basis.

1 Introduction

1.1 Background

There are two major types of TRF:

1. A TR drive failure (TRDF) is a failure within the TR drive system with consequent (usually total) loss of TR thrust. Example causes are internal fatigue or external impact resulting in a broken drive shaft.
2. A TR control failure (TRCF) is a failure within the TR control system such that normal pilot control of TR thrust has been partially or totally lost. Example causes are internal wear or external impact resulting in a severed control cable. The resultant TR applied pitch, or power, could be free to fluctuate, or may be fixed anywhere between a high pitch (HP) or low pitch (LP) setting, including the current trim pitch (TP).

Both of these TRFs are time critical emergencies. The pilot has to identify and diagnose the TRF type and react with the correct control strategy within a few seconds (or less), to prevent the aircraft departing into an uncontrollable flight state. Even if the pilot recovers from the initial transients, yaw (pedal) control will have been lost and the ability to manoeuvre safely and carry out a safe landing will have been significantly degraded. The TR and its drive and control systems are clearly flight critical components and should be designed so that the probability of failure is ‘extremely remote’. The airworthiness design requirements for UK military and civil aircraft define ‘extremely remote’ as being a probability of less than 10^{-6} [1] and between 10^{-7} and 10^{-9} [2,3] per flight hour respectively.

Royal Air Force Handling Squadron had expressed concerns over the advice provided to UK military aircrew in the event of TRFs over many years and, as a result, the MOD/CAA/Industry TRAC was formed [4]. This group had the objective of reviewing UK military and civil accident and incident data (collectively described as occurrences) in detail and recommended actions that would reduce TRFs and mitigate against their causes and consequences, leading to a reduction in accidents and associated fatalities. The concept of technical and operational causes was developed:

- Technical causes are where component/system failures are the *causes* of occurrences. These can include those causes internal to the drive train/controls and external, which include aircraft parts (e.g. detached panels), striking the TR.
- Operational causes are where component/system failures are the *result* of occurrences. These can include the TR striking the ground, obstructions or Foreign Object Damage (excluding aircraft parts), and the apparent loss of yaw control previously known as Gazelle 'Fenestron stall'.

The review of occurrence data indicated that the TRF rate due to technical causes is significantly worse than even the military requirement. Another concern was the relatively high TRF accident rate due to operational causes. The operating environment is such that the risk of collision with obstacles is relatively high and the TR is particularly vulnerable to damage. Deficiencies in the aircrew advice were also highlighted and programmes leading to the development of type-specific advice were recommended. At the time of writing, the only such study that has been completed is that for the Lynx [5]; however, DERA and Industry plans have been presented to the UK MOD for reviewing and revising military aircrew advice for the Merlin, Puma and Sea King types.

In addition to initiating the TRF aircrew advice activities, TRAC also recommended the need for a review of airworthiness requirements for helicopter TR systems. The evidence that TRs were, generally speaking, not meeting the spirit of airworthiness requirements, was stark and compelling. TRAC judged that work was required to establish how the airworthiness requirements could be changed to reinforce the criticality of the TR system and what kind of technologies could be employed to mitigate against the effects of TRFs.

1.2 Objectives

The present project flowed from the above recommendations, and the following primary objective was defined:

'To build on previous work to establish improved requirements, improve aircrew emergency advice and to make recommendations on emergency systems that might ultimately reduce the incidence and/or criticality of a tail rotor failure.'

The outline plan included a literature search, analysis of occurrence data, ground-based piloted simulation trials on the DERA Bedford Advanced Flight Simulator (AFS) to investigate both handling qualities aspects of TRFs and potential mitigating technologies, and an assessment of extant training simulators. The defined tasks were as follows:

1. To review and update the nature and extent of the TRF problem. This section of the research would: extend the review of occurrence data performed by TRAC to include available foreign civil and military data; update the UK civil and military data content; and characterise and summarise the complete occurrence experience. A search and review of all relevant literature was also to be performed and reported.
2. To review relevant technologies which could potentially be utilised either to reduce the incidence of TRFs or mitigate their effects. In particular, the relevance of the conclusions of the ground-based simulator trials and any other work identified by the literature survey to civil aircraft operation was to be established and reported.
3. To assess potential solutions for reducing the occurrence and/or mitigating the effects of TRFs. These included a larger fin, emergency deployable fin, air brake devices, TRDF annunciator, Spring Bias Unit (SBU), Health and Usage Monitoring Systems (HUMS), TR strike warning, power chop function and Back-up Control Systems. These measures were to be assessed with reference to the occurrence data, practicability, cost to implement (retrofit and new build), and benefits.

4. To review the existing airworthiness requirements material and make recommendations for additions and/or changes. The material relating to TR systems contained in the current military [1] and civil [2,3] certification requirements were to be reviewed in light of the findings of 1, 2 and 3 above. Recommendations for any additions and/or modifications were to be substantiated. This review was to include an examination of the handling qualities requirements associated with the three phases of a TRF (recovery, post-TRF flight and landing).
5. To review the existing emergency procedures and handling advice and make recommendations for change. This section of the project was to review the emergency procedures and handling advice relating to TRFs for all current UK military helicopter types and all civil aircraft types currently on the UK register, commenting on its usefulness. Means of establishing optimum handling advice and techniques for validating them were to be investigated and reported. It should be noted, however, that generation of new aircrew advice for individual types was not within the scope of this project.
6. To review military and civil practice regarding pilot training and make recommendations for simulation requirements to improve the effectiveness of training. The issues of fidelity and means of validation of the flight simulators utilised for pilot training were also to be reviewed and reported. Allowance was to be made for visiting and assessing two representative flight training simulators.

Task 1 was carried out by Stewart Hughes Limited (SHL, part of Smiths Industries) [6] and DERA. Task 2 was carried out by SHL and GKN Westland Helicopters Limited (GKNWHL) [6,7]. Task 3 was carried out by GKNWHL [7] and DERA who undertook a simulation trial using the DERA Bedford AFS [8,9]. Task 4 was carried out within DERA and included a second ground-based simulation trial [8,9]. Task 5 was conducted by GKNWHL [10], who also supported DERA in conducting Task 6. The simulation trials were conducted using a Lynx AH Mk 7 model, modified as appropriate to represent a variety of yaw stiffness and damping attributes, and to simulate the effects of mitigating technologies. The main rotor stiffness was also modified to investigate the response of a lower effective hinge offset main rotor, typical of civilian helicopters. Almost 50 hours of motion-based, pilot-in-the-loop simulation were utilised over the two simulation trials.

2 Summary of major findings

This was an extensive programme and has been reported on in [8] and [9]. The subsections which follow provide only a brief summary of each of the major activities.

2.1 The nature of TRFs

The management and control of a TRF can be assessed in three phases:

1. Transient: the failure transient and recovery to a safe flight condition.
2. Manoeuvre: manoeuvring in the failed condition.
3. Landing: the ability to perform a successful landing.

The ability of the aircrew to fly the aircraft within defined safety and performance standards within the three phases will depend on a number of key aspects. These include aircraft configuration, the flight condition prior to failure (including speed and altitude), the pilot’s attentiveness, training and skill, the TRF type and cues, and the responsiveness of the aircraft.

Depending on the phase of flight and the TRF type, TRFs result in rapid pitch, roll and yaw excursions. Even if immediate and appropriate action is taken, pilot workload and disorientation can be very high. If such action is not taken, there is a serious risk of aircrew injury and airframe and collateral damage. In simulation trials, with a standard pilot intervention time (PIT) of 2 seconds, it was shown that TRDF at high speed results in a transient sideslip which is likely to be beyond the structural limits of the aircraft. Height loss can be as much as 600 feet depending on the collective control strategy used. There appears to be little that can be done to avoid the spin entry caused by a TRDF in the hover with the same PIT. Simulated recovery from HP TRCFs in both forward flight and in the hover was very difficult. A failure in the hover leads to a rapid build-up in yaw and the chances of recovery without significant damage are low, even in the low hover unless a landing is made positively and rapidly. LP TRCFs are similar in some respects to TRDFs, except that the TR continues to provide some yaw stiffness and damping in forward flight, and damping in the hover. TP TRCFs are very benign compared to the other TRF types.

2.2 The extent of TRFs

A database of 344 TRF occurrences was constructed for this study from UK, US, Canadian and New Zealand sources. The accident rates across the various UK and US fleets averaged between 9.2 and 15.8 per million flying hours (see Figure 1). The largest causes of TRF are either the TR striking or being struck by an object, which causes approximately one half of all TRF occurrences and fatalities, and failure of the TR drive system, which causes approximately one third of all TRF occurrences and fatalities (see Figure 2). TR drive shafts, gearboxes and couplings are chiefly responsible for the latter. The largest numbers of TRFs occur during transit (27%), followed by landing (23%). The UK MOD type most subject to failure is the Lynx (combined Service rate of 33.2 per million flying hours). Other types which also stand out as exceeding the airworthiness design requirements by a dangerous margin are the MOD Puma (24.0) and Sea King (22.8) and the US Navy and Marine Corps AH-1 (19.5) and SH-2 (19.3).

2.3 Airworthiness design requirements

The attitude excursions during the transient phase of a TRF are critical to the pilot being able to achieve a successful recovery and featured as the primary response characteristics of interest during the piloted simulation trials [8, 9]. In the US handling qualities requirements standard ADS-33D [11] the allowable response transients following system failures are described in terms of handling qualities defined as Levels 1,2 and 3 (in increasing order of handling qualities deficiencies). The attitude and acceleration transient response criteria, without failure warning and cueing devices, applicable to hover/low speed and near-Earth forward flight conditions are based on the aircraft displacement after 3 seconds without any pilot action. The aircraft would be displaced by about 30 feet (10 m) in all directions at the upper excursion limits. This military standard considers nap-of-the-Earth operations where tactical use is made of the ground for stealth, and such transient excursions are likely to result in a collision. It is suggested that such criteria are equally applicable to civil helicopter operations close to the ground. For up-and-away forward flight conditions, the requirements are based solely on staying within the Operational Flight Envelope (OFE).

Having recovered from the failure, the pilot’s next action will depend upon the type of failure and the initial flight condition. The critical response that determines the capability to manoeuvre with power on will be the yaw response to collective which are described in ADS-33D in terms of yaw rate to height rate response. In terms of manoeuvrability, the ability to turn on cyclic without losing control is characterised by the turn co-ordination criteria expressed in ADS-33D in terms of the ratio of sideslip to roll attitude following a control input designed to generate a step change in aircraft attitude.

A review of Joint Aviation Requirements JAR-27 [2] and JAR-29 [3] by DERA identified a regulatory gap relating to TR control system failures – current designs are neither pushed, by regulation, towards fail-safe solutions through redundancy (the preferred solution where practical), nor to higher ‘simplex’ integrity through detailed design assessment. A two-path solution has been proposed as practicable and appropriate:

1. A detailed failure modes and effects analysis should be carried out.
2. Any single failure, or combination of failures, not shown to be extremely improbable, should not prevent continued safe flight and landing.

2.4 Technologies for preventing TRFs

Monitoring functions provided by current HUMS were assumed to be:

- TR drive shaft vibration
- TR drive shaft hanger bearing vibration
- Intermediate and TR gearbox vibration
- TR vibration
- Airframe vibration

Functions requiring HUMS development were as follows:

- Cockpit indication for vibration monitoring functions
- Gearbox and bearing temperature monitoring
- On-demand vibration checks
- Continuous rotor vibration monitoring
- TR rotational speed monitoring
- TR control input/output monitoring
- TR control mapping against flight parameters
- TR drive torque monitoring
- Gearbox oil level sensing

Based on a detailed analysis of 31 example occurrence reports, coupled with estimated HUMS detection effectiveness, conservative estimates are that 18% of all TRFs, and 49% of TRFs caused by failure of the TR drive system could have been prevented by current HUMS. This is achieved primarily through monitoring of the TR drive system using current HUMS technology as an aid to maintenance. In addition, a development of the existing HUMS technology would have prevented or mitigated a further 5% of all TRFs, and 15% of TRFs caused by failure of the TR drive system. However, the use of HUMS technology will not bring the occurrence rate to an acceptable level; 78% of TRFs are unlikely to be prevented by HUMS and are caused predominantly through the TR striking, or being struck by an object. Other means are required to help avoid hazards, make the TR system less susceptible to damage and maximise the chances of a pilot successfully dealing with a failure that occurs in flight. Another technology proposed is a scanning laser tip strike warning system that would draw the pilot’s attention to the actual position of an obstacle. This may help avoid occurrences if the pilot can react appropriately. In the occurrence scenarios involving training or aggressive manoeuvring the pilot may already be workload limited. The effectiveness of this technology in helicopters is so far unproven, but might have prevented a further 8% of all TRF occurrences.

2.5 Technologies for mitigating TRFs

TRCF problems can be addressed by improved design of the control circuit, in particular, the incorporation of a fail-safe pitch (such as provided on operation of some types of SBU or Negative Force Gradient (NFG) spring). Activation of such a system in the event of a control rod disconnection between the pedals and the servo or between the servo and the TR (e.g. failure of control cables or hydraulic systems depending on the individual system type), can result in relatively benign TP TRCF conditions. A well designed warning device, which directed the pilot rapidly to the failure recovery, could be effective at reducing the PIT. An attitude command/attitude hold control system response type, particularly when associated with large (i.e. 20% or more) attitude hold authority, will significantly reduce the failure transients when compared to rate command systems. The use of controllable main rotor (MR) speed, together with appropriate collective control inputs provides a very effective means of changing MR torque and reducing yaw rates during TRCFs in the hover.

The piloted simulation trials showed that additional fin area can be used to off-load the TR in forward flight, however, considerable area is required to contain the initial yaw motion resulting from a TRDF. Additional fin area can also dramatically reduce the sideways flight capability. Assuming it is fixed (i.e. no rudder), such a fin could be a disadvantage in TRCF cases that have resulted in high TR thrust conditions since the increased fin lift will exacerbate the situation. A drag parachute has the ability to be retrofitted, requires a relatively small area to produce significant yaw stiffness and does not affect low speed performance. The deployment of the drag parachute helps to constrain heading and the drag component results in a reduced speed for the given power level. It should be noted, however, that deployable devices such as this may not suppress the initial transients depending on the deployment time. A twin TR system could offer many benefits, however, it should be associated with a twin drive shaft system and duplex controls for the maximum benefit to be realised.

From a detailed analysis of 29 example occurrence reports, it is considered that the various mitigating technologies would have produced a beneficial effect in 90% of all the cases and in 88% of the cases caused by failure of the TR drive system. If the retrofit devices alone are considered (i.e. precluding twin TR and duplex TR drive) these proportions would still be 79% of all cases and 69% of cases caused by failure of the TR drive system. In many cases more than one technology would have been beneficial. The technologies providing benefit in most cases were the drag parachute, inflatable fin and twin TR with duplex TR drive. The ducted fan and variable camber fin solutions also featured to a lesser extent and, for the TRCF cases, the SBU-type devices were largely beneficial. Most of the other technologies were not judged to be beneficial in the limited cases studied.

2.6 Emergency procedures and advice to aircrew

Ensuring that the advice given to aircrew is safe requires that a validation process be undertaken. The validation process has to be undertaken against a set of defined criteria, which should be stated with the advice given. During the previous Lynx validation exercise [5] the following criteria were developed and are considered to be generally applicable:

Type 1: Validation provided by a full in-flight demonstration of the recovery technique.

Type 2: Validation provided for the recovery technique using the best available engineering calculations coupled with piloted simulation.

Type 3: Validation provided for the recovery technique based on the best engineering calculations only.

Ideally, all advice and recovery techniques should aim to achieve Type 1 validation. However, from a practical standpoint, TRDFs can only be demonstrated by piloted simulation and therefore the associated recovery techniques can, at best, only achieve Type 2 validation. On this basis, the Lynx TRF advice was validated to Type 1 for TRCFs and Type 2 for TRDFs. Of the 36 types whose advice were analysed (see Table 1), only the Lynx provides *validated* advice for both TRDFs and TRCFs. The standard of advice varies not only between manufacturers but also between marks of aircraft. The majority described the major symptoms associated with TRDFs, however, as can be seen from Table 2, only 14% considered the loss of components at the tail pylon and identified the possible consequences of a major change in the aircraft centre of gravity. Only 17% discussed a defined TR pitch condition in the event of a control circuit failure. Advice on the appropriateness of using a power and speed combination during recovery from a TRDF was offered by only 53%. Control circuit failure was not considered at all by one third of the types. The variation in the standard of advice would suggest that there is considerable room for improving the level of advice currently given in the Aircrew Manuals (AMs).

2.7 Training

Nine training simulator facilities responded to a questionnaire aimed at assessing the level of TRF simulation training provided to aircrews and instructors. More than half of the facilities were commissioned in the 1980s, and two thirds employ simulators equipped with six degree of freedom motion systems. Two thirds reported some degree of flight data validation over the OFE, but only the three Lynx simulators are likely to have benefited from any form of TRF validation. All of the respondents provide some form of TRF diagnosis and recovery instruction, although this is not a formal part of the teaching course in at least one case. Both TRDFs and TRCFs are covered in some form by most, but it is unclear how realistically they are modelled. In some cases it was stated that the rate of recovery from simulated TRFs is improved dramatically by the training provided, but it remains unclear how successful these recovery techniques would be in the actual aircraft. The highest confidence is thought to lie with the Lynx simulators due to the techniques having been validated through DERA/GKNWHL flight test and ground-based simulation studies.

There is evidence that some flying training schools discuss TRFs and demonstrate TRCFs in flight to a limited extent.

Criteria for validation of training simulators were formulated by the US Federal Aviation Administration in 1994 and are in the process of being formulated in a similar fashion by the Joint Aviation Authorities Committee [12]. There are four standards ranging from Level A to Level D (the highest). The first rotary wing facilities to be certified to Level C and Level D (of which there is currently only one) were commissioned in 1998.

The investment that the UK MOD is providing over the next few years will result in half of all European military motion-based helicopter training simulators being situated in the UK [13]. Recommendations have been made to the UK MOD for further study into how the civil simulator requirements may be tailored to the military environment.

3 Recommendations

The recommendations of the project are numerous and detailed within [8] and [9]. The major recommendations are as follows:

- It is recommended that the JARs be amended to provide a two-path solution to closing the regulatory gap in respect of TR control systems:
    1. A detailed failure modes and effects analysis should be carried out (e.g. as specifically required in the UK MOD DEF STAN 00-970).
    2. Any single failure, or combination of failures, not shown to be extremely improbable, should not prevent continued safe flight and landing (e.g. JAR-25 paragraph 671 and JAR-29 paragraph 1309).
- It is recommended that the ADS-33D failure transient limits, collective to yaw requirements and sideslip excursion limitations are used as a means of quantification in the failure modes and effects analysis, as part of the two-path solution.
- Manufacturers should be required to analyse the effect of TRFs and, where these effects are significant, provide at least Type 2 validated aircrew advice. Where such advice is not provided, it is recommended that advisory operational restrictions be provided (similar to the H-V diagram for engine failures) on types particularly susceptible to TRCFs. Such restrictions could also be realised through the inclusion of a reference to flight control/handling characteristics following TRFs in Sub-Part B of JAR-27 and JAR-29.
- The fitting of appropriately designed HUMS, focussed on monitoring TR drive system failure is strongly recommended. Action should be taken to further define the HUMS required for specific types or categories of helicopter. This should take into account the specific failure types, the handling qualities of the aircraft post-failure and economic factors.
- TRCF problems should be addressed by improved design of the control circuit, in particular, the incorporation of a fail-safe pitch. The fail-safe pitch should function in the event of a control rod disconnection between the pedals and the servo or between the servo and the TR. Further type-specific studies should be carried out to determine the mechanisms and settings required, and to investigate the transient behaviour on TRCF and activation of the device.
- MR speed control (increase and decrease from trim) should be provided to the aircrew to assist in recovery from TRCFs in the hover.
- Deployable devices, such as an inflatable fin and drag parachute, should be investigated for retrofit on existing types and incorporated in the design of future types to provide additional yaw stiffness in the event of TRF.
- The advice given for TRFs has to be type-specific because the appropriate recovery techniques in the event of a TRF will be dependent upon the fuselage aerodynamic characteristics and anti-torque system in use. Ideally, all TRF advice should be validated to a minimum of Type 2, and Type 1 should be sought for TRCFs. The potential outcome of failing to provide appropriate advice is catastrophic and successful recovery from only one occurrence could effectively repay the cost of a TRF advice validation programme. It is strongly recommended, therefore, that type-specific piloted simulation and (where possible) flight test programmes are put in place to achieve this.
- The minimum training simulator certification level appropriate for TRF training should be Level C as defined in US Federal Aviation Administration Advisory Circular AC 120-63. Inherent in this is the recommendation that all training simulators are built with available motion in all six degrees of freedom (surge, sway, heave, roll, pitch and yaw), and that the field of view be as representative as possible, particularly with respect to the provision of ground speed visual cues.
- Where TRF flight test data or Type 1 or Type 2 validated TRF advice cannot be provided, subjective assessment of training simulators should be carried out against the experience of those who have suffered TRFs. Where not undertaken already, such experience should be shared within the piloting community, perhaps collated by the civil authorities or pilots

associations and made readily available to the training organisations.

- Although full realism cannot be provided in most cases, it is recommended that all flying schools at least demonstrate the effects of extreme TR pitch jams to aid diagnosis, and that techniques are explored by the students where safe to do so.

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- UK Air Accident Investigation Branch
- US National Transportation Safety Board
- Transportation Safety Board of Canada
- New Zealand Civil Aviation Authority
- US Navy and Marine Corps Safety Centers
- US Coast Guard Headquarters

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6 Tables

Make	Type	TRCF			TRDF		
		Disconnect	Low power	High power	Hover	Climb	Forward flight
Agusta	A109C				●		●
Eurocopter	SA3130				●		●
	SA315				●		●
	SA341G				●	●	●
	AS332L	●	●	●			●
	AS1350B2		●		●		●
	AS355N		●		●	●	●
	AS365N2				●	●	●
	EC120B				●		●
	EC135T1		●	●	●		●
	BO105		●	●	●		●
	BK117		●	●	●		●
Bell	206B	●					●
	206L		●	●	●		●
	212	●	●	●	●	●	●
	214ST	●	●	●	●	●	●
	222		●	●	●		●
	412EP	●	●	●	●	●	●
	47G						●
Enstrom	280C	●	●	●	●		●
	480		●	●	●		●
Hiller	UH12E						●
Kaman	SH2D		●	●	●	●	●
MD Helicopters	500D						●
	520N		●	●	●		●
	MD600		●	●	●		●
	MD900		●	●	●		●
Robinson	R22				●		●
	R44				●		●
Sikorsky	S61N	●			●		●
	S76C	●	●	●	●		●
	SH60B	●	●	●	●		●
Schweizer	269C (300C)						●
Westland	Lynx Mk 7	●	●	●	●		●
	Sea King		●	●	●		●
	W30		●	●	●		●
Coverage (%)		28	61	56	83	19	100

Table 1; Content of Aircrew Manual TRF advice

Make	Type	A	B	C	D	E	F	G	H	I	J	K	L	M
Agusta	A109C				●			●	●	●	●			
Eurocopter	SA3130	●					●	●	●	●				
	SA315	●			●	●	●	●	●	●				
	SA341G				●		●	●	●	●	●			
	AS332L	●					●		●	●		●		●
	AS1350B2				●				●	●	●			●
	AS355N	●			●				●	●	●			●
	AS365N2	●			●		●							●
	EC120B	●			●		●		●		●			
	EC135T1	●			●			●	●				●	●
	BO105	●	●		●		●	●	●				●	●
	BK117	●	●				●	●	●	●	●		●	●
Bell	206B				●			●	●		●			
	206L	●			●	●		●	●	●	●			●
	212	●		●		●		●	●	●	●			●
	214ST	●		●	●	●	●	●	●	●	●		●	●
	222	●			●	●		●	●		●			●
	412EP	●		●	●	●		●	●	●	●		●	●
	47G	●							●					
Enstrom	280C	●					●		●	●		●		●
	480	●		●	●	●	●	●	●	●	●			●
Hiller	UH12E						●		●	●				
Kaman	SH2D	●	●	●	●	●	●	●	●	●			●	●
MD Helicopters	500D				●		●	●	●					●
	520N				●			●			●		●	●
	MD600				●	●		●	●				●	●
	MD900				●			●	●				●	●
Robinson	R22	●					●	●	●					
	R44	●							●	●	●			
Sikorsky	S61N	●	●				●	●			●	●		●
	S76C		●		●		●	●	●	●		●		●
	SH60B	●			●		●	●	●	●		●		●
Schweizer	269C (300C)								●					
Westland	Lynx Mk 7	●	●		●	●	●	●	●	●	●	●	●	●
	Sea King	●	●		●	●			●	●	●		●	●
	W30	●	●		●		●	●	●	●	●		●	●
Application (%)		69	22	14	69	31	56	69	92	61	53	17	33	69

Key to column headings:

A. Prompt action required to stop rotation about yaw axis.
B. Increase in vibration gives a warning of impending failure.
C. The aircraft pitch attitude could change following loss of tail components.
D. Speed increase/decrease to improve/reduce fin efficiency.
E. Use of MR speed to aid control.
F. Use of cyclic to control flight path and reduce sideslip.
G. Use of collective to control heading.
H. Autorotation required.
I. Engine off condition specified.
J. Possible power and speed combination in forward flight/no power and speed combination.
K. Fail-safe pitch available.
L. Benefits in wind direction for landings.
M. Run-on landing required.

Table 2; Detail of Aircrew Manual TRF advice

7 Figures

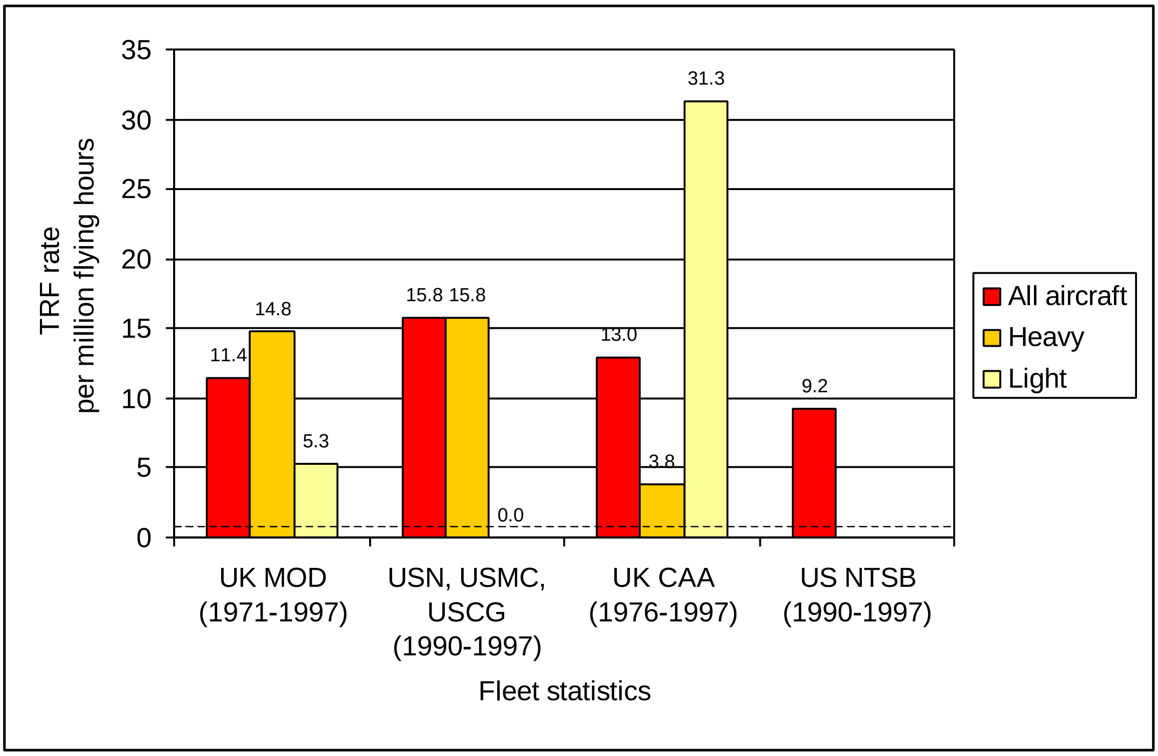

Figure 1; TRF accident rates for UK and US fleets

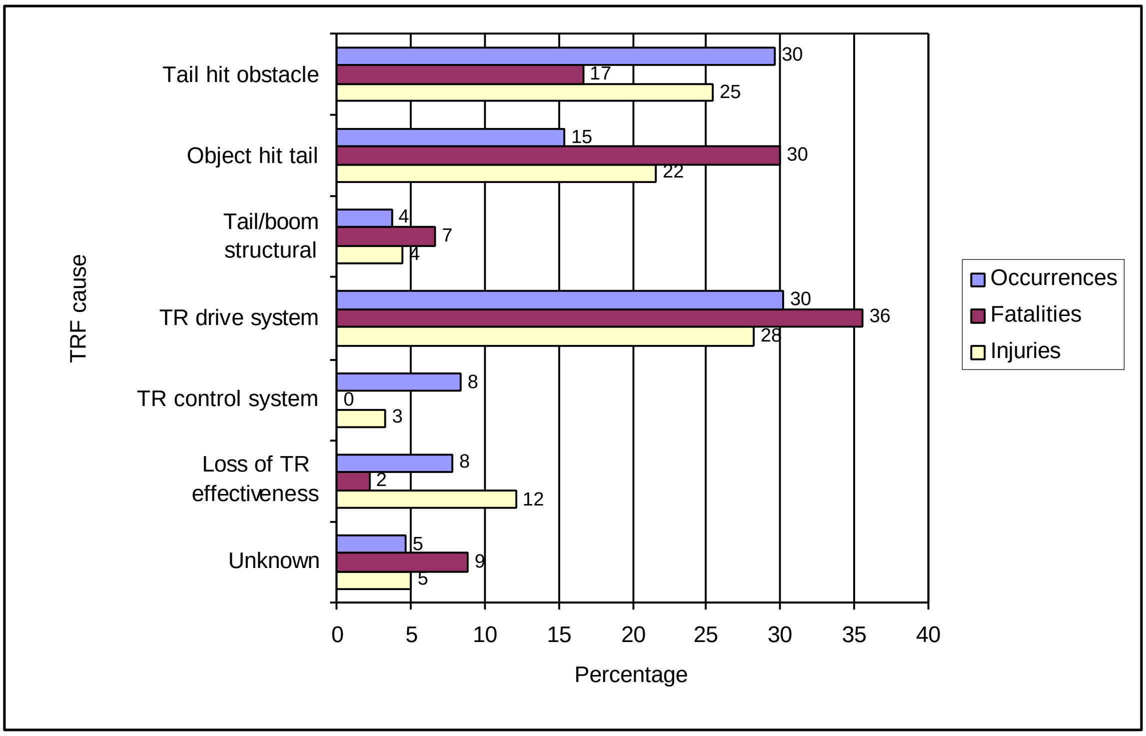

Figure 2; Distribution of TRF causes (all aircraft)