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Analysis of Helicopter Maintenance Risk from Accident Data

Arjun H. Rao[1], Nicoletta Fala[2], and Karen Marais[3]
Purdue University, West Lafayette, IN, 47907

This paper identifies the most frequent unsafe maintenance actions (maintenance errors and violations) in helicopter accidents, and the helicopter systems that were affected by these actions. We use the National Transportation Safety Board (NTSB) accident database to analyze historical helicopter accident data between 1982 and 2013. We consider an accident to be maintenance-related if it had at least one maintenance-related cause, factor, or event. In 1982–2013, there were 590 (10.0% of the 5857 helicopter accidents between 1982 and 2013) accidents that were maintenance-related—498 were coded using the old system, while 92 maintenance-related accidents were recorded using the new system. In 1982–2008, incorrect *inspection* was reported in 22.9% of maintenance-related accidents; however, the subject codes do not provide additional information about the types of inspection. Accidents from 2008–2013 were coded using the new system. In this period, *preflight inspection* was blamed in 22.8%, and *scheduled/routine inspection* in 7.6% of maintenance-related accidents. Maintenance *Installation* was responsible (in part) for 20.2% of the maintenance-related accidents in 1982–2013. Incorrect *installation* during maintenance was more likely to appear in powerplant-related accidents than maintenance-related accidents overall. The helicopter *fuel system* (e.g., fuel injector, valves) and *turboshaft engine* parts (e.g., free turbine shaft, reduction gearbox) were frequently affected due to negligence during installation. *Failure to comply with Airworthiness Directives* (ADs) was reported 6.3% of the accidents where a structural part was affected—indicating violations of regulations.

Nomenclature

ASIAS	=	Aviation Safety Information Analysis and Sharing
FAA	=	Federal Aviation Administration
IHST	=	International Helicopter Safety Team
NTSB	=	National Transportation Safety Board
R-ASIAS	=	Rotorcraft ASIAS

I. Introduction

THE importance of maintenance to aviation safety has been repeatedly noted by regulators and aviation associations. For example, in a 2014 safety alert, the NTSB suggested that a lack of vigilance in performing maintenance tasks or in verifying that the work was done correctly can lead to accidents.[1] More recently, they advised pilots to perform advanced preflight inspection to detect improperly rigged flight control systems.[2] In 2011, the International Helicopter Safety Team (IHST) identified a strong maintenance program as one of the top-10 ways to prevent helicopter accidents.[3]

In previous work, we developed an approach to identifying high-risk sequences of occurrences in helicopter accidents.[4] Here, we build on this approach to show how the database can be used to gain a better understanding of the role of maintenance in helicopter accidents by analyzing maintenance-related helicopter accidents between 1982 and 2013. In particular, we attempt to address the following questions:

1. What are the top unsafe maintenance actions in helicopter accidents?
2. What helicopter systems or parts were affected most frequently by unsafe maintenance actions?

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[1] Graduate Research Assistant, School of Aeronautics and Astronautics, 701 W. Stadium Ave, Student Member.
[2] Graduate Research Assistant, School of Aeronautics and Astronautics, 701 W. Stadium Ave, Student Member.
[3] Associate Professor, School of Aeronautics and Astronautics, 701 W. Stadium Ave., Senior Member.

Section II of the paper describes previous research on rotorcraft safety, and the contribution of maintenance to rotorcraft risk. In Section III, we briefly describe the NTSB's accident database, and provide our approach to identifying maintenance-related accidents. We describe our approach and present the high-risk unsafe maintenance actions in helicopter accidents in Section IV. In Section V, we identify the helicopter parts/systems that were frequently affected by unsafe maintenance actions. Section VI concludes this paper and lays out future work.

II. Background

Aviation maintenance tasks are complex undertakings in which individuals perform varied tasks in an environment with time constraints, minimal feedback, and sometimes difficult ambient conditions.[5] Several researchers have carried out historical analyses of fixed-wing accidents in the General Aviation (GA) and commercial sectors (e.g., Refs. 6–9). Marais and Robichaud showed that in commercial aviation, maintenance-related accidents were more deadly than accidents in general, and that in a maintenance-related accident, the risk was dependent on the nature of the maintenance activity.[6] Goldman et al. showed that 7% of GA accidents between 1988 and 1997 could be attributed at least in part to a maintenance-related cause or factor.[7] Their findings revealed that the most common accident cause factors involved installation errors, general maintenance, and maintenance inspection. Tsagkas et al. identified specific factors that guided maintenance technicians towards alternative courses of action during maintenance activities.[8] Franza and Fanjoy conducted a statistical study on the probable causes for accidents involving Cirrus SR20 and Piper PA28-161 aircraft. They found that mechanical malfunction (not specified further) accounted for 20% of the probable causes for fatal accidents in the PA28-161 fleet.[9]

The human role in aircraft maintenance has received attention from multiple researchers (e.g., Refs 10–13). Fogarty and Saunders used the SHEL (software, hardware, environment, and liveware) model to classify 250 military aviation incidents in Australia between 1996 and 1998. They reported that *inadequate supervision* (40.4%) by supervisors and *incorrect procedures followed* (32.0%) by maintenance personnel were the most common maintenance errors.[13] Rashid et al. analyzed 58 helicopter accidents that (1) were exclusively maintenance related and reflected human factors issues, (2) occurred in 1995–2005, (3) involved maintenance crew with similar training, resources, and technical competence, (4) and represented currently used helicopters.[14] Unsurprisingly, they found that when parts failed due to unsafe maintenance actions, the failed parts were more likely to be those that required higher cognitive skills during assembly, installation, alignment, or adjustment.

Some studies have looked into the role of maintenance in helicopter accidents. Haaland et al. identified 59 tour-helicopter crashes in Hawaii between 1981 and 2008, and found that 34 (~58%) of the accidents were due to poor maintenance.[15] Baker et al. investigated 178 helicopter crashes related to the oil and gas operations in the Gulf of Mexico in 1983–2009.[16] Their analysis revealed that 10.3% of the accidents associated with mechanical malfunctions were due to maintenance errors. They found that critical rotorcraft systems such as main rotors and transmission systems were most often exposed to maintenance errors. Majumdar et al. analyzed causal factors for 237 helicopter accidents in the United Kingdom in 1986–2005, and 54 in New Zealand in 1996–2005.[17] They concluded that despite improvements in the reliability of rotorcraft engines, engine failure continued to be the main cause for maintenance-related accidents.

III. Identifying Maintenance-Related Accidents

In this section, we first provide a brief overview of the NTSB's accident database. Then, we describe how we identify maintenance-related accidents in the 1982–2008 (old coding system) and 2008–2013 (current coding system) periods.

The NTSB records accident information on their database, which includes fields related to aircraft type, geographic location of accidents, phases of flight, severity of injuries and damage, crew details, and type of maintenance. The NTSB uses occurrences to summarize the events leading up to the accident. They define an *occurrence as a distinct major event of relative significance that leads to an accident or incident*.[18] Figure 1 summarizes the NTSB accident recording system. Accident reports place each occurrence in a sequence (occurrence chain) leading up to the accident. In general, the final occurrence in a chain can be interpreted as the accident—that is, each preceding occurrence still leaves a possibility (though it may be remote), of escaping without injury or damage.

To record the findings (why the accident happened) for each accident, the NTSB uses subject codes and modifiers. The subject codes are designated as causes, factors, or events in accidents. It is usually impossible to assign precise importance levels to each of the findings in an accident. This difficulty is reflected in NTSB accident reports, which do not assign importance to multiple findings. Therefore, we consider an accident maintenance-related if it had at least one maintenance-related cause, factor, or event.

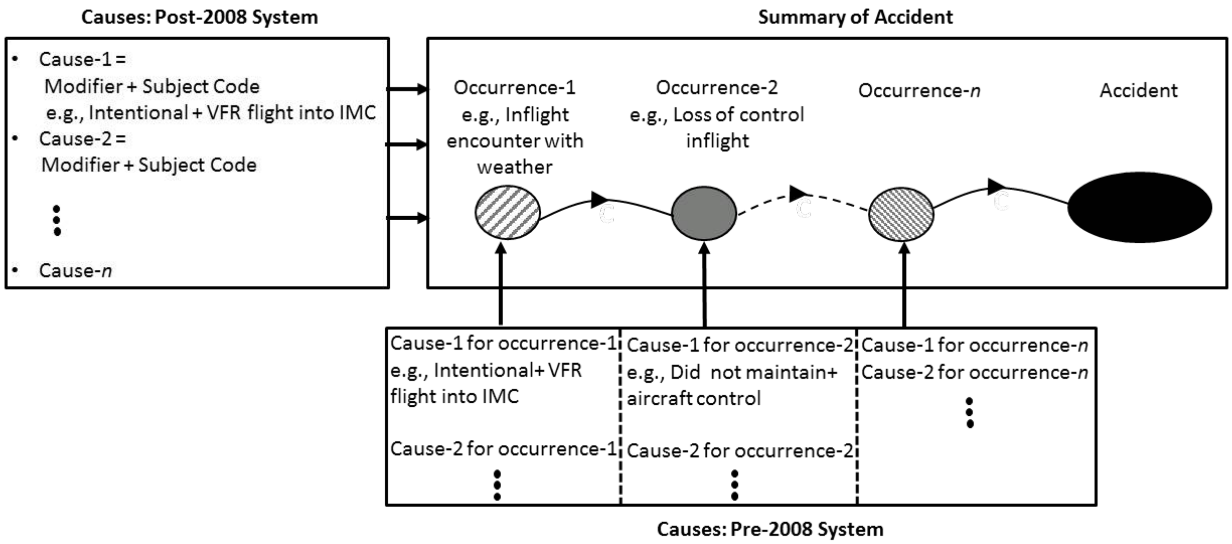

Figure 1: Summary of the NTSB accident recording system.

A. Old System (1982–2008)

Until 2008, the NTSB used five-digit *subject codes* to represent the key findings in accidents, as shown in Figure 1. Table 1 shows the NTSB's classification of the subject codes into four sections to describe the nature of the findings. NTSB-Sections IA and IB are used to list the primary events/findings that led to the accident. NTSB-Sections II and III are used to further define or explain the primary events or findings. With this system, all maintenance-related accidents were placed under Category IB, with 25 five-digit codes ranging contiguously from "*24100: Maintenance*" to "*24124: Top Overhaul*". A complete list of the maintenance-related subject codes is presented in the Appendix (see Table 5).

Table 1: NTSB Accident Classification 1982–2008[18]

Category	Examples
IA—Primary non-person related findings	
Aircraft Structure	Control surfaces, rudder, fuselage, landing gear
Aircraft System	Autopilot, hydraulic systems
Power plant	Bleed air system, compressor assembly, fuel system
Miscellaneous aircraft/equipment	Lights, coolant, fuel, lavatory
ATC/weather/airport facility/equipment	Approach aids, radar, meteorological services
Miscellaneous publication	Aircraft manuals, charts and other manuals
IB—Primary person-related findings	
Aircraft/equipment performance	Autopilot, communication equipment, navigation instruments
Operations/ATC/Maintenance	Missed approach, aircraft control, compensation for wind
II—Direct underlying events	Inadequate design, inadequate training, physiological conditions
III—Indirect underlying events	Inadequate surveillance of operation, insufficient standards

To illustrate the NTSB accident coding system, consider a maintenance-related accident from March 2007, when a Bell 206L-1 on an air-taxi mission lost engine power during cruise. The investigation findings blamed the accident on incorrect installation of the engine fuel line fitting by maintenance personnel (NTSB ID: DFW06FA083). Table 2 provides a breakdown of the corresponding subject codes and modifiers used to explain this accident in the database.

Table 2: Illustration of NTSB Accident Coding in 1982–2008

Numeric Code	NTSB Classification	Description
24111	Subject Code	Maintenance, Installation
3109	Modifier	Improper
4108	Personnel Modifier	Other maintenance personnel

B. New System (2008–Present)

In place of the subject codes, the NTSB introduced ten digit *findings* codes, which range from "*01000000XX: Aircraft handling/service*" to "*05000000 XX: Not determined*". The last two digits *XX* represent the modifier codes.

We queried the database using derivatives of the word *maintain* and *inspect* to identify the findings codes and modifiers relating to our search. The final list of maintenance-related findings and modifiers is shown in the Appendix (see Tables 6 and 7).

For example, consider an accident involving a Hughes 369 in November 2012. During long-line operation[+] on a transmission tower in Childress, TX, the helicopter suffered engine failure, entered a spin, and crash-landed (NTSB ID: CEN13FA075). Post crash examination revealed that improper re-installation of the fuel system might have resulted in incorrect fuel gage readings, leading to fuel starvation. The findings code for this maintenance action is *0206203541*. Table 3 shows the breakdown of the findings code. To facilitate clarity, we will refer to findings codes as subject codes in the remainder of this paper.

Table 3: Illustration of NTSB Breakdown of Findings Code in 2008–Present

Findings Code	NTSB Classification	Description
0206203541	Category	Personnel issues
02***06***203541	Subcategory	Task performance
0206***20***3541	Section	Maintenance
020620***35***41	Subsection	Installation
02062035***41***	Modifier	Maintenance personnel

C. Characteristics of Dataset

Our dataset consists of NTSB reports on all maintenance-related rotorcraft accidents that took place in the United States from 1982 to 2013. We exclude military helicopter accidents from our analysis. Our analysis covers a total of 590 maintenance-related accidents (about 10.0% of the 5857 helicopter accidents between 1982 and 2013). 498 accidents took place from 1982 to 2008, and 92 from 2008 to 2013. The NTSB produces a report (usually available online in pdf format) for each accident, and also provides a coded summary in a searchable database format. This database allows large-scale statistical analysis of accidents that is currently infeasible using the accident investigation reports.

[+] Long-line operations, as the name suggests, involve the use of a long sling/cable for external load operations such as fire fighting, replacement of air conditioning systems on rooftops, installation of power poles, and business signs.

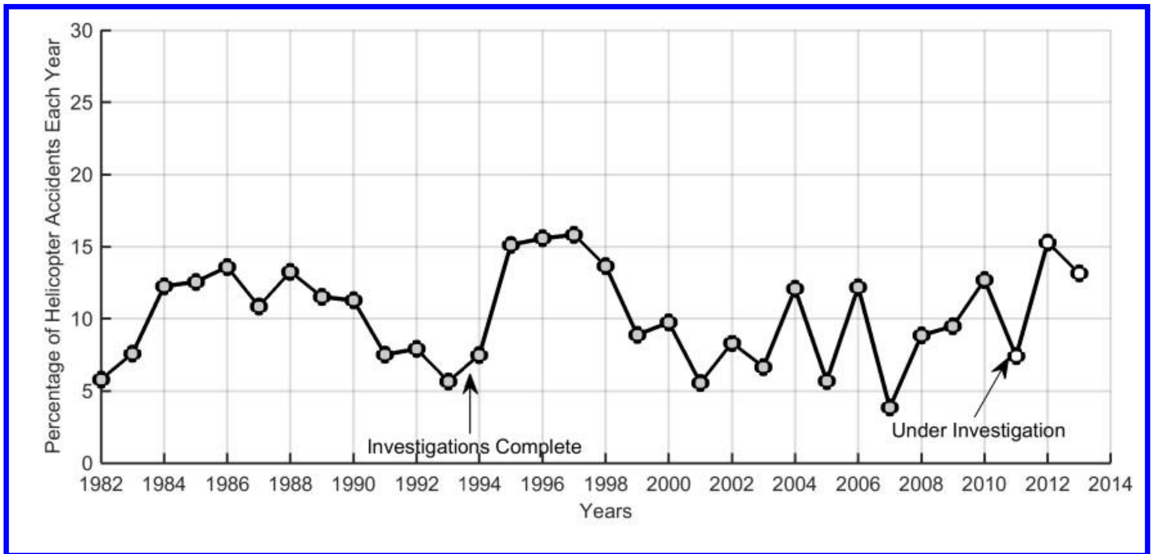

Figure 2: Proportion of maintenance-related accidents each year. On average, 10.2% of the accidents each year were maintenance-related.

There is no clear trend for maintenance-related accidents in 1982–2013, as shown in Figure 2. The proportion of maintenance-related accidents ranged from a minimum of 3.8% (in 2007) to a maximum of 15.8% (in 2012). Table 4 shows the number of accidents under investigation. Not surprisingly, the proportion of incomplete investigations is highest for 2014 (which might include some maintenance-related accidents). Therefore, we do not consider the accidents that occurred in 2014.

Table 4: Accident Year and Number Under Investigation

Year	Accidents still under investigation (% of total accidents that year)
2011	1 (0.7%)
2012	5(3.7%)
2013	5 (3.2%)
2014	48 (35.0%)

IV. Unsafe Maintenance Actions in Helicopter Accidents

Reason classified unsafe actions by humans into two principal categories: (1) *unintended* actions that include *slips, lapses,* and *mistakes*, and (2) *intended* actions such as violations (see Figure 3).[19] Errors represent the activities that fail to achieve the intended outcome (e.g., incorrect installation).[10] *Slips* are characterized by attention failures such as omissions (e.g., over-torquing a bolt), while *lapses* are generally due to *memory failures* (e.g., forgetting to replace a fuel cap). *Mistakes* are decision-making failures. Misinterpreting rules and reliance on past knowledge are common reasons for mistakes committed. *Violation* refers to the intentional flouting of rules and regulations (e.g., intentionally deviating from procedure). While some of these violations can be one-off (exceptional violation), routine violations tend to be habitual in nature.

Maintenance errors include poorly executed procedures, improper choices, misinterpretation of information, and inadvertent operation of switches and forgotten items in a checklist.[20] Maintenance violations include deviations or shortcuts from formal procedures prescribed in the regulations.

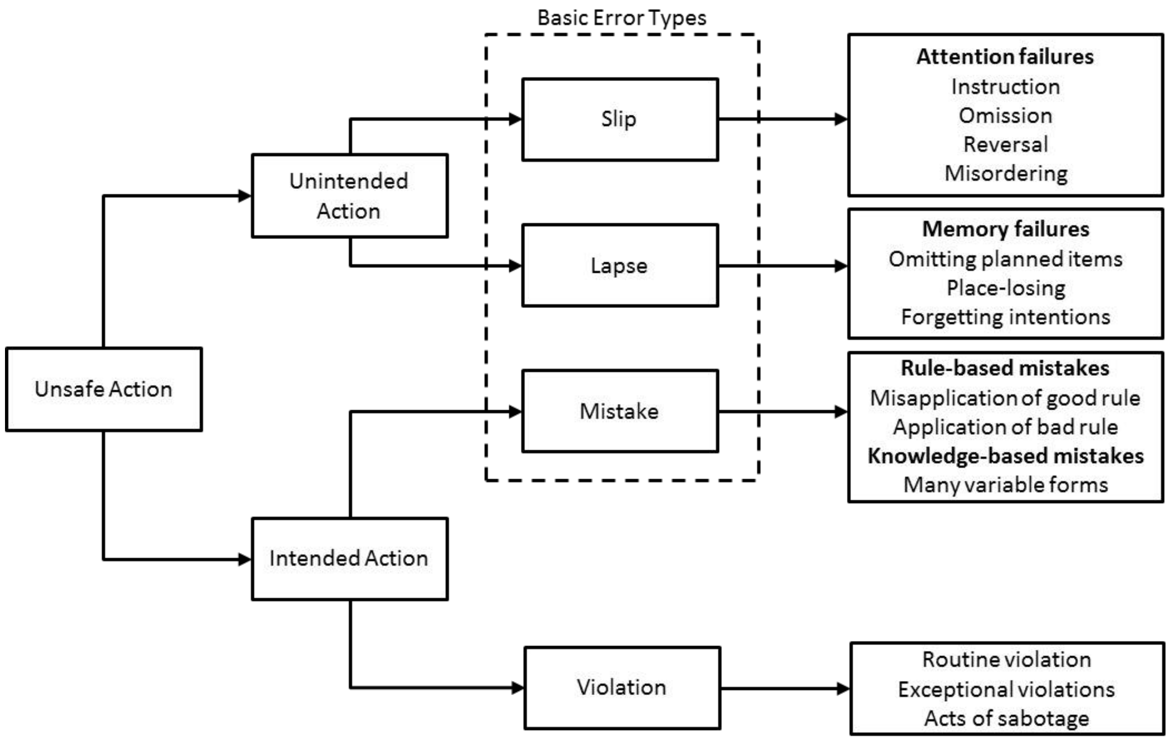

Figure 3: Categories of unsafe acts (adapted from Ref. 19).

As mentioned in Section III, we consider accidents that involved at least one maintenance-related cause, factor, or event as maintenance-related accidents. For the remainder of this paper, we refer to these maintenance-related causes, factors, or events in accidents as ,"*unsafe maintenance actions"*.

After identifying the maintenance-related accidents, we count all the times each particular maintenance-related subject code was involved in an accident. We define the node strength of each subject code *j* as the number of times that subject code was cited at least once in a maintenance-related accident, normalized by the total number of maintenance-related accidents:

$$P(Subject\ Code_j | Maint\ Rel\ Accident) = \frac{\sum_{i=1}^{n_{maint\ accidents}} TRUE(Subject\ Code_j \geq 1 | Maint\ Rel\ Accident_i)}{\#Maint\ Rel\ Accidents} \quad (1)$$

The total probability of all the subject codes in general does not sum to unity, because a given accident may involve more than one finding—in other words, any given accident may have (and usually will have) more than one subject code reported.

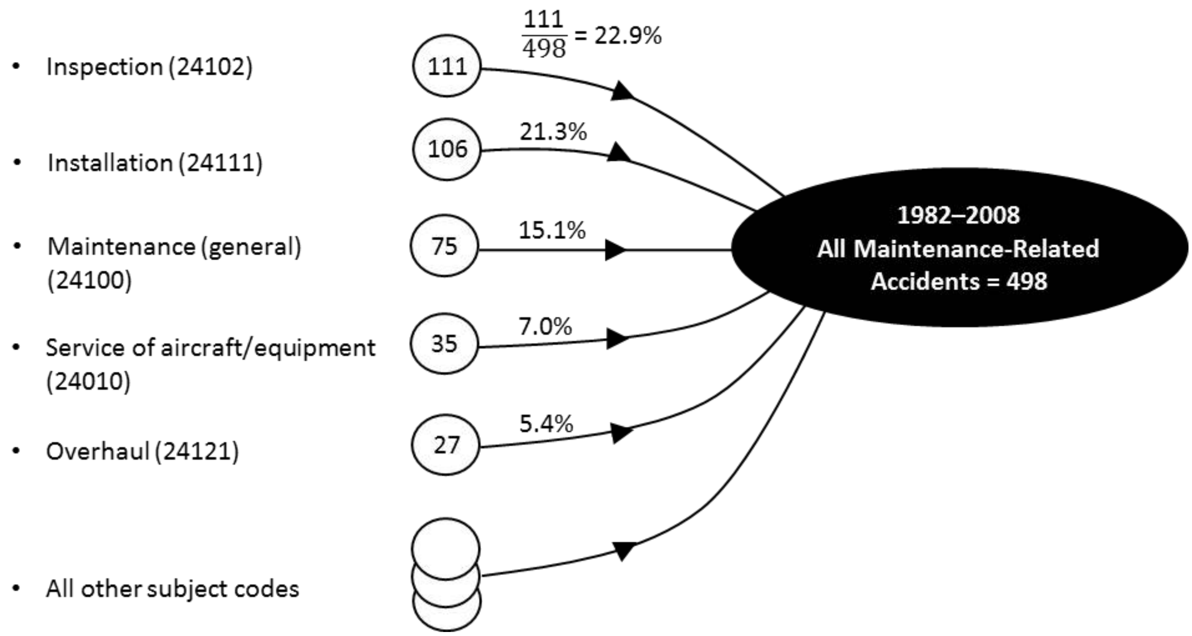

Figure 4: 67.1% of all maintenance-related accidents from 1982–2008 involved one or more of the top five subject codes. The percentages do not sum up to a 100% because each accident can have more than one subject code.

Between 1982 and 2008, the NTSB used 23 of the 25 subject codes associated with maintenance-related accidents. 67.1%, or 334 accidents involved one or more of the top five subject codes, as shown in Figure 4.

"*24102: Inspection"* was reported in 22.9% of the maintenance-related accidents. A majority of the accidents that involved inspection were modified by *inadequate*, and a further 11.6% blamed *improper* inspection. While it is evident that *inspection* is reported often, we cannot determine the time (e.g., preflight) at which these inspection actions were carried out using the pre-2008 subject codes.

Problems with *installation* were reported in 21.3% of maintenance-related accidents. While *maintenance personnel* committed a significant proportion (77.4%) of incorrect *installation*s*,* 7.5% of the accident reports suggested that the *manufacturer* was partly responsible. Consider for example a serious hard-landing accident that occurred in Tok, AK in August 1990 (NTSB ID: ANC90LA135). During an external load mission, the Aerospatiale SA-315B lost engine power while in hover, autorotated, and made a hard-landing. The resulting investigation found that the fuel was contaminated due to incorrect *installation* of the fuel filter by the maintenance personnel. The NTSB also blamed *inadequate design* by the *manufacturer*—leading to the improper installation. In few cases (e.g., NTSB ID: FTW91LA162) a relatively new helicopter part was affected due to incorrect installation during manufacture, while in other accidents that blamed the manufacturer included insufficient information provided in *service bulletins* or *manuals*.

While the *general maintenance* category (24100) is reported at least once in 15.1% of the accidents, it does not provide any information on the specific nature of the maintenance activity. Even the top modifiers such as *improper* and *inadequate* that supplement this code do not lend insight into the type of maintenance action. The ambiguous nature of this code suggests that it was most likely used to classify maintenance causes/factors/events that did not fall into any other category.[6, 7]

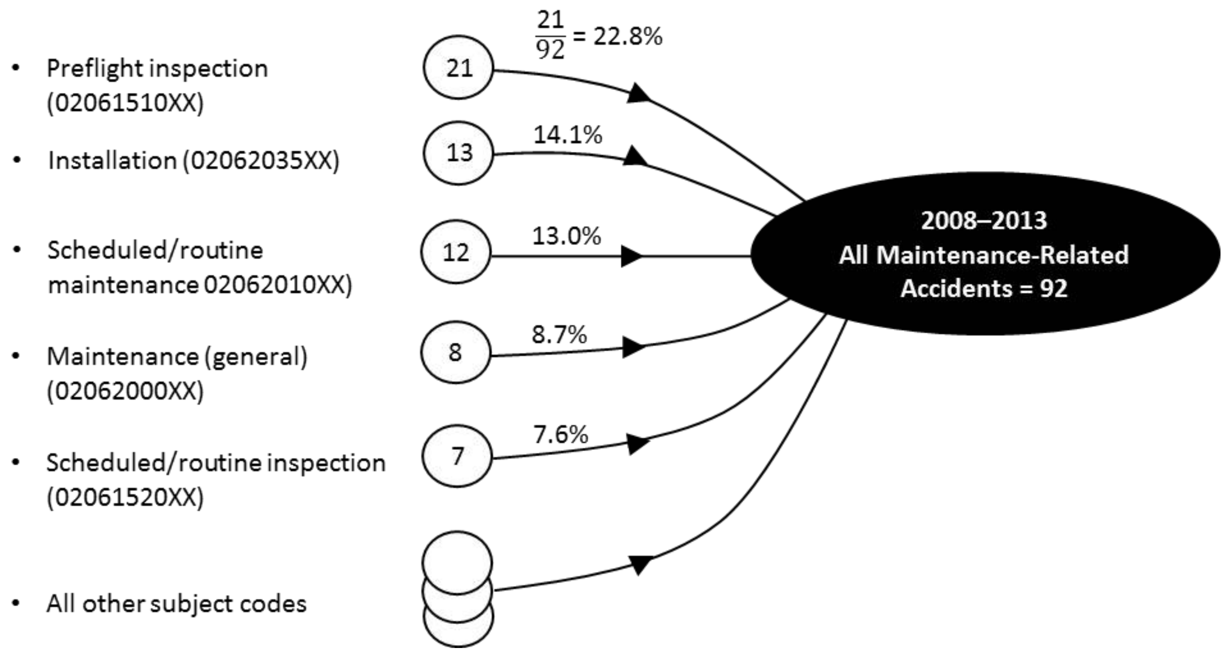

Figure 5: 61.1% of all maintenance-related accidents from 2008–2013 involved one or more of the top five subject codes. The percentages do not sum up to a 100% because each accident can have more than one subject code.

In 2008–2013, 61.1% of maintenance-related accidents involved one or more of the top five subject codes, as shown in Figure 5. While the proportion of accidents covered by the top five codes is smaller than for 1982–2008, the NTSB investigators used only 11 of the available 21 maintenance-related codes in the new system (see Appendix/Table 6). The use of fewer codes could possibly be due to fewer maintenance-related accidents in 2008–2013.

Unlike the frequent citing of *general inspection* (24102) in the pre-2008 accidents, in the 2008–2013 period investigators used the new coding system to more accurately represent the nature of inspection. They reported incorrect *preflight inspection* either by the *pilots* or helicopter *crew* as one of the findings in 22.8% of the maintenance-related accidents.

Unsafe *installation* actions continue to be a problem in 2008–2013, appearing at least once in 14.1% of maintenance-related accidents. Similar to *installation* accidents in 1982–2008, 93.2% of these accidents blamed faulty installation on maintenance personnel, while the remaining 6.8% were attributed to the pilots.

20.0% of the maintenance-related accidents between 2008 and 2013 reported *scheduled routine/maintenance* or *scheduled inspection*. These cases generally involved helicopters that had recently undergone periodic checks such as annual maintenance or 100-hour inspections. *Maintenance personnel's* failure to detect flaws in helicopter systems was responsible for almost all (95.7%) accidents in these categories. In the next section, we will present the types of aircraft systems/parts that were most susceptible to missed detection during scheduled maintenance/inspection.

V. Helicopter Systems/Parts Affected by Unsafe Maintenance Actions

This section highlights the helicopter systems that were frequently affected by unsafe maintenance actions. Section A presents results for accidents coded using the old system (1982–2008), while Section B lays out post-2008 results.

A. 1982–2008

In 1982–2008, all *non-person related* accident findings were placed in NTSB Section IA of the coding manual, as shown in Table 1. These *non-person related* accident findings generally pointed out the aircraft parts that were affected by faulty maintenance—for example, *aircraft structure,* or *powerplant* problems that were precipitated by unsafe maintenance actions.

Not surprisingly, 93.0% of the 498 maintenance-related accidents between 1982 and 2008 involved problems with the *aircraft structure* or *powerplant.* The remaining 7.0% of maintenance-related accidents included trouble with the *electrical* system, incorrect hydraulic *fluid* or lubricating oil levels. Therefore, we focus on the maintenance actions that resulted in *aircraft structure*-related accidents and *powerplant*-related accidents.

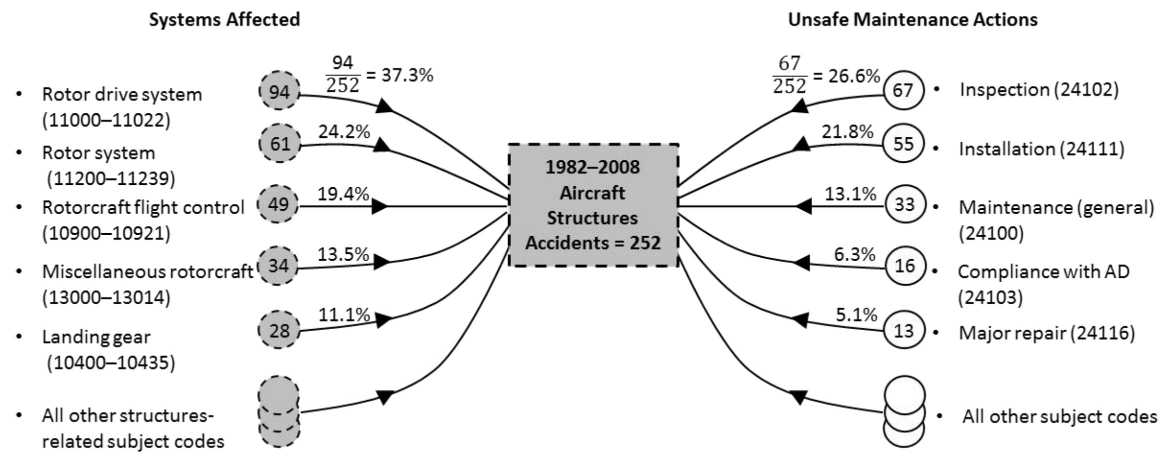

Figure 6: 66.7% of maintenance-related *aircraft structures* accidents involved one or more of the top five unsafe maintenance actions, which affected one or more of the top five systems.

Between 1982 and 2008, 66.7% of the maintenance-related *aircraft structures* accidents involved one or more of the top five maintenance subject codes, as shown in Figure 6. Structures-related accidents and maintenance-related accidents overall (see Figure 2) share three of the top five maintenance subject codes: *inspection, installation,* and general *maintenance.* Incorrect *inspection* during maintenance was more likely in helicopter accidents that were structures-related (26.6%), compared to maintenance-related accidents overall (22.9%), which is not surprising since structural integrity is primarily ensured through inspection. Incorrect *inspection* was the most likely reason when one of the top five structures-related systems failed in an accident.

Maintenance personnel's failure to *comply with airworthiness directives (ADs)* was reported at least once in 6.3% of the structures-related accidents. These accidents generally involved the operation of a rotorcraft while not in compliance with FAA-issued ADs.* In 1982–2008, all maintenance-related accidents that blamed a failure to adhere to directives affected either (or both) the helicopter's *rotor system* (e.g., rotor blade, rotor hub) or *rotor drive system* (e.g., gearbox, drive belt).

"*24116: Major repair"* was reported at least once in 5.1%, or 13 maintenance-related accidents between 1982 and 2008. 61.5% of the accidents that accidents that involved *major repair* affected the helicopter landing gear. Improper/low shock absorber strut pressure was a common problem involving helicopter landing gears.

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* Airworthiness Directives (ADs) are legally enforceable regulations issued by the FAA in accordance with 14 CFR part 39 to correct an unsafe condition in a product. Part 39 defines a product as an aircraft, engine, propeller, or appliance.[21]

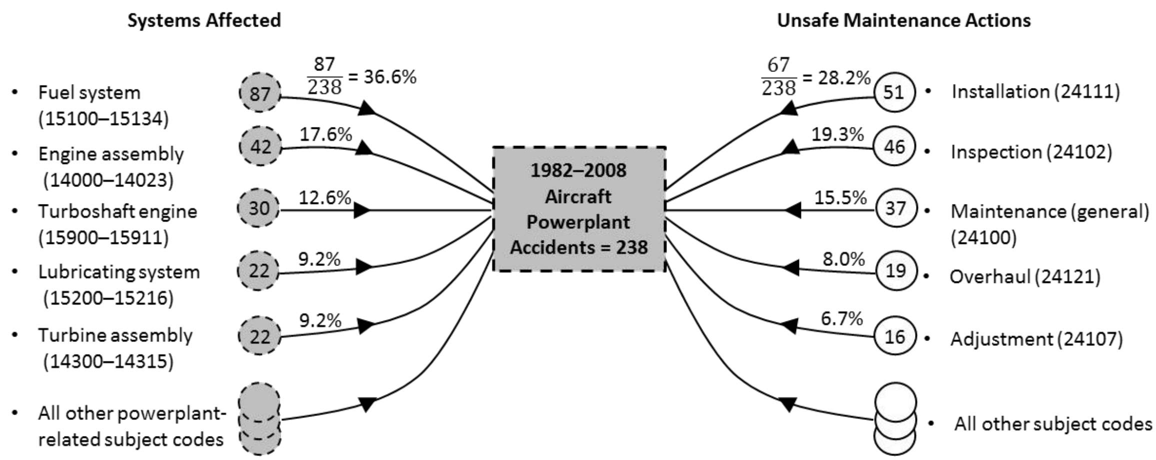

Figure 7: 68.4% of the maintenance-related *powerplant* accidents involved one or more of the top five unsafe maintenance actions, which resulted in one or more of the top five systems being affected.

68.4% of the maintenance-related *powerplant* accidents involved one or more of the top five maintenance subject codes, as shown in Figure 7. Three of the top five maintenance subject codes are common to maintenance-related accidents overall—similar to structures-related accidents. Incorrect *installation* during maintenance was more likely to appear in powerplant-related accidents (28.2%) than maintenance-related accidents overall (21.8%). Negligence during *installation* was the most likely reason when the helicopter *fuel system* (e.g., fuel injector, valves) or *turboshaft engine* parts (e.g., free turbine shaft, reduction gearbox) failed in maintenance-related accidents.

The NTSB reported problems with reciprocating engines using the *engine assembly* subject codes. Reciprocating engines suffered most frequently from incorrect *inspection,* unlike their turboshaft counterparts, which suffered more from incorrect *installation*. 19.0% of maintenance-related accidents involved reciprocating engine trouble following a complete engine *overhaul*—the second most common maintenance action associated with reciprocating engines. The repeated occurrence of "*24119: Service bulletin/letter"* in 14.3% of accidents involving *engine assembly* highlights the helicopter operator's/maintenance personnel's failure/inability to act on the suggestions provided by the manufacturer.

B. 2008–2013

In 2008–2013, 90% of the 92 maintenance-related accidents were distributed among aircraft structures, systems, powerplant, propeller/rotor system, and fluids/miscellaneous hardware. Aircraft powerplant and propeller/rotor system were the two most affected helicopter parts.

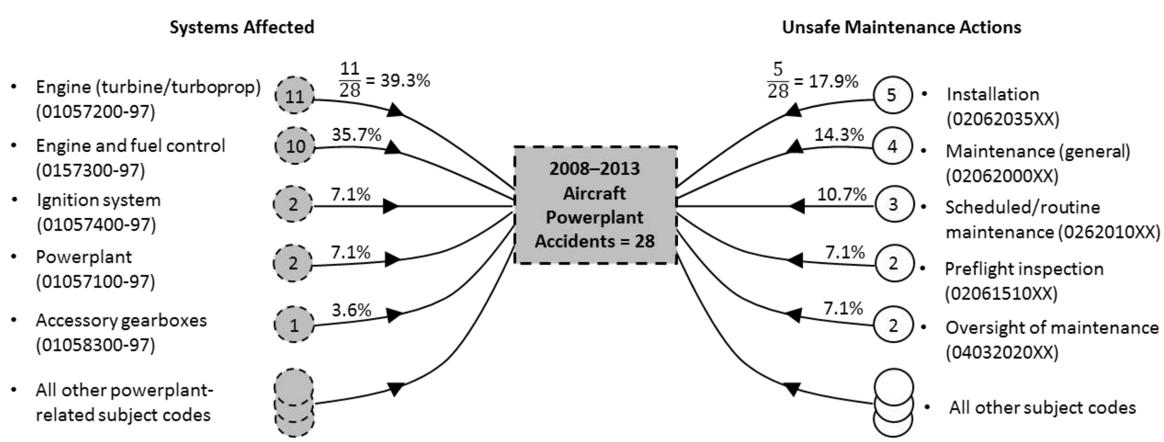

Figure 8: 60.7% of maintenance-related *powerplant* accidents involved one or more of the top five unsafe maintenance actions, which resulted in one or more of the top five systems being affected.

In 2008–2013, 60.7% of the maintenance-related *powerplant* accidents involved one or more of the top five maintenance subject codes, as shown in Figure 8. Four of the top five maintenance subject codes are common to maintenance-related accidents overall. Similar to powerplant accidents pre-2008, incorrect *installation* actions continue to be a problem. Incorrect *installation* during maintenance was more likely to appear in powerplant-related accidents (17.9%) than maintenance-related accidents overall (13.3%).

The *engine and fuel control* system is vital to the normal functioning of rotorcraft powerplant. This system includes fuel sensors, governors, carburetor, and control system electronics. Similar to pre-2008 accidents, issues with the *fuel control system* continue to be a problem. In 2008–2013, 35.7% of the powerplant-related accidents reported problems with the *fuel control system*. Specifically, maintenance actions frequently resulted in improper functioning of *fuel controlling* units and *turbine governors.* Also, all the accidents that involved the *engine and fuel control* system were reported under the *general maintenance* category, suggesting that the investigators might not have known the specifics of the maintenance action that resulted in fuel systems malfunctioning.

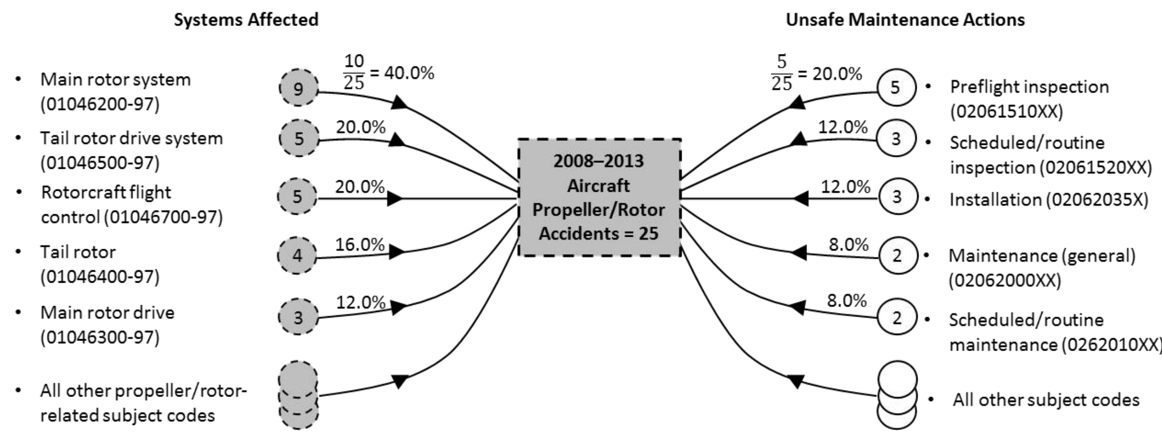

Figure 9: 48.0% of maintenance-related *propeller/rotor* accidents involved one or more of the top five unsafe maintenance actions, which resulted in one or more of the top five systems being affected.

In 2008–2013, 48.0% of the maintenance-related *propeller/rotor* accidents involved one or more of the top five maintenance subject codes, as shown in Figure 9. Inadequate *preflight inspection* was responsible in part for 20.0% of the accidents that involved the *propeller/rotor* system. Consider for example a June 2010 accident involving a Garlick OH-58A+ during an agricultural aerial application mission (NTSB ID: ERA10LA379). The pilot increased the RPM to 100% during idle flight and began to increase collective when the *main rotor* separated violently from the helicopter. The investigation report suggested that correct *preflight inspection* would have detected a fatigue crack in the inertial screw hole of the main rotor.

In the aforementioned accident, in addition to the *preflight inspection*, the investigation revealed that the maintenance personnel had failed to detect the crack during a recent *scheduled/routine inspection*. Between 2008 and 2013, deviation from procedure during *scheduled/routine inspection* was more likely to appear in *propeller/rotor* systems-related accidents (12.0%), compared to maintenance-related accidents overall (7.6%).

The *tail rotor drive system* includes the drive shaft, gearboxes, and the wiring for the drive system. Like with the main rotor system, this system was mostly affected by unsafe actions taken during *scheduled inspection/maintenance* or when the helicopter underwent *repairs.* Typically, rotorcraft consist of hydraulic actuators to overcome high control forces.[22] Generally, a hydraulic system includes a hydraulic fluid pump, and actuators, also known as *servos.* 60.0% of maintenance-related accidents involving *tail rotor drive systems* reported problems with the helicopter's servo system, making it difficult for the pilot to maintain control during flight.

VI. Conclusions

We began this paper by posing two questions about helicopter maintenance:

1. What are the top unsafe maintenance actions in helicopter accidents?
2. What helicopter systems or parts were affected most frequently by unsafe maintenance actions?

To answer these questions, we analyzed 590 maintenance-related helicopter accidents between 1982 and 2013. We used a frequentist approach to identify *unsafe maintenance actions* (maintenance errors and violations) that had the highest likelihood of resulting in a maintenance-related accident. While some of our findings echo those of other researchers in that the helicopter powerplant continues to be plagued by maintenance-related problems, it also raises some new questions. For instance, why is *preflight inspection* the most frequently reported occurrence despite clear instructions provided to pilots, and regulations that mandate a thorough preflight check? Another question pertains to the use of "catchall" occurrences such as the *general maintenance* category—why and when are these "general" categories used? As we showed in the example of the engine fuel system, all unsafe maintenance actions related to this system were reported under the general category. More in-depth research on the aforementioned, and similar such questions might help us better understand the contribution of maintenance to helicopter accident risk. In future research, we will supplement our current work by analyzing incident reports relating to helicopter maintenance. The incident analysis will possibly help identify precursors to these maintenance-related accidents, and how we can detect and avoid these unsafe actions.

Appendix

Table 5: List of NTSB Maintenance Subject Codes and Description (1982–2008)[22]

Code	Description
24100	Maintenance
24101	Service of Aircraft/Equipment
24102	Inspection
24103	Compliance With Airworthiness Directives (AD)
24104	Annual Inspection
24105	100-Hour Inspection
24106	AAIP/Progressive Program
24107	Adjustment
24108	Alignment
24109	Balancing
24110	Calibration
24111	Installation
24112	Lubrication
24113	Modification
24114	Pressurizing
24115	Replacement
24116	Major Repair
24117	Major Alteration
24118	Recordkeeping
24119	Service Bulletin/Letter
24120	Design Change
24121	Overhaul
24122	Overhaul, Major (Engine)
24123	Rebuild/Remanufacture
24124	Top Overhaul

Table 6: List of NTSB Maintenance-Related Subject Codes and Description (2008–2013)[23]

Code	Description
01010500XX	Maintenance/inspections-(general)
01010510XX	Maintenance/inspections-Time limits

Code	Description
01010520XX	Maintenance/inspections-Scheduled maintenance checks
01010530XX	Maintenance/inspections-Return to service
01010550XX	Maintenance/inspections-Unscheduled maintenance checks
02061500XX	Inspection-(general)
02061510XX	Inspection-Preflight inspection
02061515XX	Inspection-Post maintenance inspection
02061520XX	Inspection-Scheduled/routine inspection
02062000XX	Maintenance-(general)
02062010XX	Maintenance-Scheduled/routine maintenance
02062015XX	Maintenance-Repair
02062020XX	Maintenance-Replacement
02062025XX	Maintenance-Fabrication
02062030XX	Maintenance-Modification/alteration
02062035XX	Maintenance-Installation
02062040XX	Maintenance-Unauthorized maintenance /repair
02062515XX	Record-keeping-Aircraft/maintenance logs
04023025XX	Scheduling-Maintenance scheduling
04032020XX	Oversight-Oversight of maintenance
04033025XX	Documentation/record keeping-Maintenance records

Table 7: List of NTSB Maintenance-Related Modifiers and Descriptions (2008–2013)[23]

Code	Description
13	Incorrect service/maintenance
14	Not service/maintained
15	Inadequate inspection
16	Not inspected
18	Related maintenance information
41	Maintenance personnel
65	Maintenance provider

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