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An investigation of ship steering gear direct and root causes

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Ship steering failures limit maneuverability and have led to very serious maritime accidents. However, many accident reports on steering failures do not identify direct or root causes. This prevents establishing trends or presenting concrete safety recommendations for the better training of seafarers, improved ship design principles, and maritime policy. This paper reviews accident investigation reports associated with vessel steering systems to assess the percentage of identifiable direct and root causes. Failure effects, modes, scope and type were extracted, in addition to component and subsystem. We discuss the implications and their relevance to major maritime stakeholders, and make recommendations to shipowners, the IMO, and the maritime industry at large.

Keywords: maritime risk assessment, accident investigation, loss of directional control, reliability analysis, root cause analysis.

1. Introduction

Identifying the causes and factors that lead to accidents is the principal objective of investigation. Proper identification of causes and causal factors is crucial to reduce the likelihood of accident recurrence and leads to better design, operational safety, targeted training of seafarers, and appropriate maritime policy - all of which contribute to enhanced maritime safety.

Hull and machinery failures annually comprise approximately 50% of all reported maritime casualties (Allianz Global Corporate & Specialty, 2024). The European Maritime Safety Authority (EMSA) splits these into three different types of losses: loss of propulsion, loss of electrical power, and loss of directional control (EMSA, 2023). Losses of directional control have led to serious maritime accidents, including the Amoco Cadiz oil spill in 1978. In this accident, the rudder jammed, and the ship was unable to maneuver. She eventually grounded on the shores of France and resulted in the worst maritime oil spill ever at the time of occurrence.

This study was motivated by a statement discovered in an accident investigation report by the German Federal Bureau of Maritime Casualty Investigation (BSU) (BSU, 2020). The report states that the causes of approximately 60% of recorded steering gear failures could not be determined. Therefore, this study analyzes ship accidents that initiated with a failure of the steering gear. We analyze accident investigation reports from global maritime flag states. The objective is twofold: 1) assess if the direct and root causes were identified and 2) propose recommendations to improve steering system reliability based on the findings. We survey previous studies on steering gears and make recommendations to various stakeholders in the maritime industry to confront the identified implications.

2. Equipment Details

The steering gear system is responsible for the ship's directional movement. The usual installation is composed of three parts: control equipment, power unit, and transmission. The first conveys a signal of desired rudder angle and activates the power and transmission units, the second provides the force when required and with immediate effect and the third is the provisions necessary to move the rudder (Molland, 2011).

As explained by Eyres and Bruce (2012), every ship must have a main and an auxiliary steering gear, unless the main steering gear already consists of two or more identical power units. This last case is mandatory for passenger ships, tankers of above 10.000 gross tonnage (GT) and all other types of ships above 70.000 GT. Control must be possible from the bridge and steering gear compartment, with possibility to control the auxiliary independently of the main.

Both power and transmission are handled by the electrohydraulic steering gear assembly, meaning that it is powered by a hydraulic pump driven by an electric motor. The hydraulic oil flow drives the hydraulic actuators or rams, which in turn moves the rudder. In addition to the pump, the hydraulic system contains at least one oil reservoir to ensure oil supply, an oil filter to hold any contaminants, a pilot directional valve to guide the oil flow and a safety valve to prevent damage in case of overloading. The electric motor will be powered by the main electrical switchboard, and in case of the auxiliary or emergency unit it will also be powered by the emergency switchboard.

There are two main types of steering gear assemblies in use today: ram-type and rotary vane. The former consists of two or four hydraulic rams/actuators connected by a link mechanism or a Rapson slide mechanism to the tiller that turns the rudder. The latter introduces pressure into compartments formed between a stator fixed to the ships structure and a roto attached to the rudder stock (Wartsila, 2015).

The control equipment can be separated in three distinct parts: remote control, feedback units and local control. The remote control is in the bridge and sends a command signal to the local control in the steering compartment to act upon the steering gear accordingly. The local control delivers a command input to the steering gear, which can be power on/off and directional control of hydraulic flow. The feedback unit picks up the actual rudder angle via a transmitting rod connected to a potentiometer, which sends the signal back to the bridge. If the vessel is fitted with a rudder angle Indicator, there will be an independent parallel connection sent to it from that same potentiometer.

The common remote-control modes are autopilot, follow-up (FU) and non-follow-up (NFU). The autopilot controls the rudders to keep the ship pointed to a predefined heading set in it, using a digital or analog signal to the local control switch unit in charge, indicating if the direction of movement is either port or starboard. In the FU mode the rudder command is given manually via a helm based on a desired rudder angle, the system compares such command to the actual angle provided by the feedback unit and the signal duration and intensity will vary according to the difference found. The NFU depends on active manual input and is usually used for emergency situations, as it has no connection to the feedback unit. In this mode, the command is given via a tiller to move the rudder either port or starboard, and the signal will be sent interrupt to maximum intensity to either side while the command is active.

3. Literature Review

3.1. *Relevant Maritime Regulations*

The IMO is the world's maritime organization body. The IMO defines in the Casualty Investigation Code (2008) that the general objective of accident investigation to be the prevention of future marine casualties and incidents. Causal factors, per the IMO, are defined as "actions, omissions, events or conditions" that lead to the casualty's occurrence or increase the casualty's severity. They additionally specify that "failures present in the whole chain of responsibility" should be identified. However, there are no specific instructions by the IMO regarding how to determine causal factors (IMO, 2008).

The International Safety Management (ISM) Code (IMO, 2018) determines in Chapter 9 that companies should include procedures for accident reporting, investigation and analysis, as well as for the implementation of measures to prevent recurrence. Chapter 10 establishes that companies must identify equipment and systems whose failure results in hazardous situations, and provide measures to promote their reliability.

Regulation 29 of Chapter II Part 1 of the International Convention for the Safety of Life at Sea (SOLAS) defines the minimum standards for the main steering gears systems, including several requirements to ensure system reliability and continuous operation (UN, 1974). In the event of a power failure to any one of the steering gear power units and/or electrical power supply to the control system, an audible and visual alarm shall be given on the navigation bridge. Audible and visual alarms shall also be given on the navigation bridge and in the machinery space in case of low-level of hydraulic fluid in each of its reservoirs. Regulation 30 goes further demanding audible and visual alarms in the machinery space's alarm system for overload of the steering gear's pump electric motors. In summary, it is mandatory to have alarms set for the following four failures: steering gear power unit power failure, steering

control system power failure, low steering gear hydraulic fluid level, and steering system electric phase failure/overload. These alarms are required to be recorded on the voyage data recorder (VDR) per the IMO's Code on Alerts and Indicators (IMO, 2010). In Regulation 26 of Chapter V of the publication, it sets the tests and drills to be performed regularly to the steering system, which allows for identification of anomalies and risks to operation before occurrence. Although covering both alarms and tests, there is no specific regulation defining requirements for steering gear maintenance.

3.2. *Risk Assessment Theory*

In risk assessment literature, there are several taxonomies for describing the causes and factors associated with accidents. A common taxonomy is defined by Rausand and Haugen (2020):

- *Direct causes*: the causes that lead immediately to accident effects (also called immediate or proximate causes, since they usually result from other lower-level causes)
- *Root causes*: the most basic cause of an accident, often pertaining to organizational factors
- *Risk-influencing factors* (RIFs) / *contributing factors*: the background factors that influence the causes and/or development of an accident

Causes are further divided into two categories:

- *deterministic causes*: events and conditions that, if present, always lead to the next event in the scenario
- *probabilistic causes*: events and conditions that, if present, increase the probability that the next event in the scenario will occur

An example of a deterministic cause is the failure of a necessary piece of equipment on another piece of equipment. For example, the failure of the cooling seawater pumps leading to the failure of the main engine. In this sequence, the first failure always leads to the next event. Examples of probabilistic causes are mariner fatigue or a lack of training. Their presence does not necessarily lead to the next event in the scenario, e.g. a collision, but it is more likely that an accident occurs if they are present.

NASA specifies that root causes are often underlying organizational causes that are difficult to glean at the surface level. Proper identification of root causes therefore requires a more detailed evaluation method, commonly referred to as root cause analysis (RCA). The stopping point for root cause analysis is either when all organizational factors are identified, or data is exhausted for further analysis (NASA, 2020). The root cause analysis guide for the nuclear industry specifies that root causes are those that, "if corrected, would prevent recurrence". They are "the most fundamental aspect[s] that can be identified and corrected" (U.S. DOE, 1992).

There have been several studies attempting to better understand the factors and causes of maritime accidents. Most have used accident investigation reports as the principal data source. Puisa et al. (2018) reviewed accident investigation reports for passenger ships to determine the most common causal and systemic factors. Baalisampang et al. (2018) analyzed root causes of fire and explosion accidents for ships and preventative measures considering the identified root cause. To the authors' knowledge, there aren't any studies of this nature for technical equipment failures. Instead, technical equipment failure rates are commonly derived using commercially available failure databases like OREDA. These databases compile operational histories of failures to compute numerical failure rates.

3.3. *Steering Gear Reliability*

Academic research on steering gear analysis has been the focus of several studies, and the work can be generally grouped into two distinct categories. The first consists of practical analyses of system reliability or investigations of steering system behavior. The earliest is Aksu et al. (2006) who perform a reliability analysis of podded propulsion systems using FMEA, fault tree analysis and Markov chains. They use generic component data to assess reliability and compare the results to service data. Martins and Natacci (2008) develop a reliability model of a rotary vane steering gear system using FMEA and FTA in different operational conditions as the basis for reliability centered maintenance models. Besides the rudder equipment, the FTA includes failure of the electrical supply subsystem as a main event. Hidalgo et al. (2011) perform a similar analysis but limit the scope of the study to the failure of the main hydraulic system and the failure of the auxiliary hydraulic system. The study is restricted to the steering gear pumps, motors, filters, tanks, distributor and servo pilot valves, and hydraulic cylinders.

Two studies are very similar to accident investigation reports. Zhang and Li (2014) analyze a single observed failure of the research ship MV Tansuo Hao. The steering gear failed to turn to port. An extensive repair process struggled to locate the proximate cause until disassembling the solenoid reversing valve and discovering valve plate deformation. Extensive reuse of hydraulic oil may have led to impurities that caused the deformation. Ye (2018) analyzes a loss of rudder onboard an oil tanker. The proximate cause of the failure is the fatigue to the rudder stock lock nut. The study makes concrete recommendations to prevent future occurrences pertaining to the design phase, in-service inspections, and ship repair quality.

Goksu et al. (2023) develops a model for steering gear failures focusing on electrical and hydraulic component failures. Bayesian probabilities are developed from expert interviews. The results identify the primary proximate causes for both electrical and mechanical failures, but root causes at the organizational level are not addressed. Gurgen et al. (2023) propose a broader approach using fuzzy fault tree analysis to calculate the probability of loss of steering. The top-level events include the steering gear hydraulic power failure, rudder failure, and control failure. However, the FFTA relies on the deterministic approach, and does not investigate root causes. Both studies rely on expert judgement, limiting their reproducibility and objectivity.

4. Methodology

4.1. *Accident Investigation Report Data*

The data for the study was gathered from reports published by major Flag State Authorities of concluded accident investigation for merchant ships with GT of approximately 100 and above, without restrictions as for the publication date, and published in English. The reason for each of those conditions is the following:

- Ship Type: recreational and military vessels were excluded given differences in applicable regulations, manning, and equipment.
- Report Sources: the maritime authorities were chosen based on if websites allowed for an effective search on the matter and whose reports were concise and detailed.
- Report Condition: concluded reports are ensured to not have new findings or alterations which could impair the reliability of the datapoint.
- Ship size: ships above 100 GT are more likely to have standard types of steering gears, similar subsystems and components.
- Timeline: the amount of publicly available reports that indicate steering systems as the accident cause are few, therefore setting a timeframe would restrict the data availability.
- Language: English is the mainstream communication language worldwide, indirectly it can be inferred that readers of the study would be able to read and scrutinize any of the reports used.

The following maritime authorities were consulted: European Marine Casualty Information Platform (EMCIP, Europe), Bundesstelle für Seeundfalluntersuchung (BSU, Germany), Marine Accident Investigation Branch (MAIB; UK), National Transportation Safety Board (NTSB; USA), Transportation Safety Board of Canada (TSBC; Canada), and Australian Transport Safety Bureau (ATSB; Australia). All the obtained reports were scrutinized using the set of criteria mentioned previously, leaving 34 total reports for analysis.

4.2. *Report Review*

The most relevant information from each report was collected and labelled accordingly per the following categories: report data, ship data, accident data and failure data. The key failure data extracted was the 1) failure effect, or the manifestation of the failure in the steering system (e.g., “sudden loss of steerage” or “unintended steerage”, and 2) failure mode, collected in form of a statement that summarizes the anomaly in the steering system that led to loss of directional control (e.g., “hydraulic pump pilot valve stuck”). The mode was then categorized by failure scope and failure type. The scope signalizes if the failure originated in a single component, multiple components or general. The failure type indicates the working group of the failed component (either mechanical, hydraulic, electric or generic, when it does not fit any of the previous categories).

Direct and root causes were extracted based on the failure mode and the conclusions by the Flag State. An example is an accident where the direct cause was poor wiring of electric components either during construction or after maintenance.

The direct cause was loose wiring, but the identified root cause is incorrect installation. Root causes were not always identified in the investigation report.

The component and subsystem were also identified. The subsystem names were taken from the IACS Unified Requirements M69 (International Association of Classification Societies, 2008) as such: rudder actuator, rudder stock with bearings & seal, rudder, power unit & control gear, local control systems and indicators, remote control systems & indicators, and communication equipment. "Overall Steering System" was used whenever there was no clear identification of the component.

5. Results

Of the 34 total accident investigation reports, there were 18 groundings, 10 collisions, 5 allisions, and 1 loss of directional control. Most accidents occur in restricted waterways or near ports. There were two large clusters of accidents in the St. Lawrence Seaway and the north German ship canals.

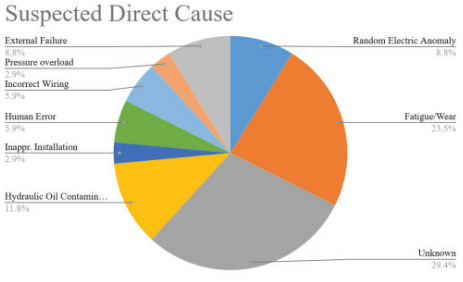

Figure 1. Direct cause overview

Figure 1 displays the overview of the direct causes. Approximately one third (29.4%) of the direct causes are undetermined or not specified in the report, i.e. there is no direct cause explicitly confirmed as result of the investigation of the report. Fatigue/wear (23.5%), hydraulic oil contamination (11.8%) and random electric anomalies (8.8%) are the most commonly identified direct causes. The number of unknown failures is less than the 60% of steering gear cases that are unresolved as claimed by BSU Report 32/19 (BSU, 2020). However, hydraulic oil contamination and random electric anomalies are often assumed, rather than determined. Taken together, they comprise 61% of all reports.

Figure 2 displays the overview of suspected root causes. Approximately half of all reports do not identify any root cause (47.1%). The most commonly identified root causes are inappropriate design (23.5%), with the second highest incidences being inappropriate installation and maintenance (each with 12%), meaning many causes of steering failures during operation originate during the project and manufacturing period, either the pre-delivery or refurbishment periods of the ship.

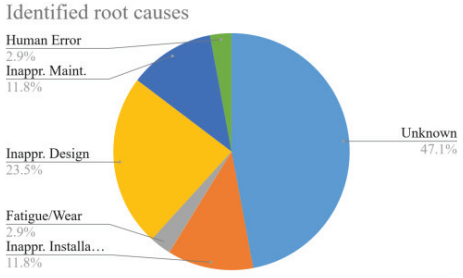

Figure 2. Root cause overview

Regarding subsystems, most failures fall into one of three groups (see Figure 3): remote control systems & indicators (38%), local control systems and indicators (24%) and power unit & control gear (21%). These results are also aligned with BSU's claim that "steering gear failures were predominantly due to technical issues regarding other ship's systems". This is in alignment with the finding by EMSA's STEERSAFE (2021) that the control system is among the commonly observed failures leading to reduced or loss of steering. According to Marine Insight (2008), remote control systems rank among the most common problems found in a ship's steering gear system. It is also relevant that SOLAS Chapter V Regulation 26 includes the operation of remote-control systems as the one of mandatory tests to be performed before departure, which indirectly sets its importance within the steering arrangement. Most failure types were electric (41%) and are all respectively distributed within those three subsystems mentioned above. Electric failures had been the identifiable root cause of two USCG's publications: Maritime Safety Report 16-16 and Findings of Concern 003-22 (USCG, 2016, 2022). Generic failures (29%) had the second largest volume of appearances,

meaning there was not enough information to determine the specific type.

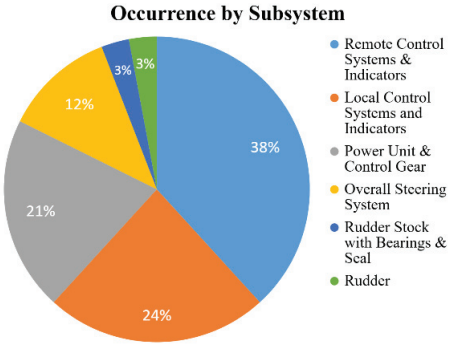

Figure 3. Overview of subsystem occurrence

The components most responsible as direct causes were command relays and remote-control mode switches, each being mentioned in five reports. Those are followed by local control switches, pilot directional hydraulic valves, potentiometers and solenoid valves, each appearing in two reports each. In sum, those account for 64% of the identifiable causes. These components have been mentioned as sources of failures in other studies such as: Martins and Natacci (2008) have a few of them included in the Failure Tree Analysis such as solenoid valve, pilot directional valve and hydraulic hose however, no specific value is indicated regarding findings for each individual component. Hidalgo et al. (2011) identified pilot directional valves as the components of second highest relevance to criticality within the steering gear installation. Zhang and Li (2014) found the pilot directional valve to be at the origin of a steering failure and Han et al. (2020) found that the pilot directional valve was the source of a chronic issue of steering gear stuck failure, with root causes being wear and hydraulic oil contamination. The pilot directional valve has also appeared as a source of accident in the USCG Marine Safety Alert 16-16 (USCG, 2016), and the solenoid failure was used as a case study in the AMSA Maritime Safety Awareness Bulletin 9 (AMSA, 2019). In contrast, none of the components found in the present study appear in the fault tree analysis by Gürgen et al (2023).

6. Discussion

This study was motivated by a comment that many steering gear failures observed by the BSU were not connected to an explicit root cause. This paper has demonstrated that the BSU's claim is substantiated when including reports from other maritime accident databases. We have also reviewed the limitations in the maritime regulations and academic research pertaining to steering gears.

The inability to correctly identify root causes for equipment failures significantly inhibits the ability for 1) ship owners and operators to implement changes to enhance system reliability, 2) maritime authorities to make pertinent safety recommendations. For identifiable sources of failure, addressing root causes is an effective strategy. However, the data is currently extremely limited for discerning patterns of individual component failures or conducting more sophisticated analysis.

Furthermore, a notable aspect is the discrepancy between the observed failure effects and the focus of existing studies, which predominantly center on the physical equipment itself. The results of this study show that the control systems are often where the proximate cause of the failure manifests. FMEA has been applied to control systems, and should continue to be so (Ahvenjärvi, 2001). However, as control systems become increasingly advanced, particularly with the advent of autonomous ships and power management optimization, the need to address the reliability of digital systems and components becomes paramount. Assessing the reliability of these systems may require the incorporation of other systems-based risk approaches like the Systems-Theoretic Process Analysis (STPA).

As maritime technology evolves towards greater automation and connectivity, system resilience against cyberattacks becomes a critical aspect of maritime safety. Future steering gear systems must incorporate cybersecurity measures to mitigate these risks. Failure analysis frameworks will also evolve to assess vulnerabilities to such attacks. Addressing these dual challenges requires close collaboration between maritime stakeholders.

6.1. *Recommendations*

1. Ships should have a dedicated, detailed, and independent performance monitoring system for the steering gear.
2. Ship owners and operators should implement standardized internal failure reporting systems that capture detailed diagnostic information for every incident, regardless of severity. These reporting systems should go further than identifying direct causes, and mandate reporting failure circumstances, root cause hypotheses, and corrective actions for actionable datasets at the company level. Additionally, implementing such procedures equips shipowners to enhance collaboration with maritime authorities. This aligns with Chapter 9 of the ISM Code (2018), which emphasizes preventive action to increase system reliability.
3. Shipowners should conduct regular diagnostic audits of the steering gear. These audits would ensure potential issues are detected early and provide a basis for improvements to maintenance systems.
4. The IMO should promote an industry-wide shared database of equipment failures to promote collaborative safety improvements. This database should aggregate direct causes, root cause hypotheses, and corrective actions. A shared resource of this nature allows better identification of trends and recurring issues, the development of standardized preventive measures and steering gear maintenance policies, and foster collaboration among maritime stakeholders to address system vulnerabilities.
5. The IMO should amend the casualty investigation code to include definitions of direct cause and root cause to enable better determination of the events leading to casualties and incidents. Furthermore, the IMO should promote reporting of minor incidents to reduce the bias of the GISIS database.
6. Since there is not enough data to determine failure patterns of each component or further sophisticated statistical calculation, a set of minimum steering gear maintenance requirements by the IMO could be set up, similar to the ones for firefighting equipment and lifesaving appliances. This would be a valuable preventive measure to help shipowners and operators to improve the safety and reliability of their vessels.

6.2. *Further Work*

This study has not attempted to determine probabilistic causes such as ship type, inspection history, type of equipment, etc. During the course of the analysis, several failure trends were observed including failing to report previous failures, developing workarounds for poorly functioning equipment, bad record keeping onboard, and limited crew resources. The effect and widespread presence of such factors should be analyzed in a follow up study. Additionally, using methodologies such as loss causation models or event tree analysis would allow for identification and mapping of discrete events that occur in sequence, offering a structured way to understand the pathways to steering gear failure. Additionally, causal factor charting would be a valuable approach to developing accident sequences and better ship safety management programs.

7. Conclusion

There is a critical need to better understand steering gear failures and their root causes to enhance maritime safety and operational reliability. Based on an extensive review of steering gear reliability studies and accident investigation reports from the leading maritime flag states, this paper provides recommendations that emphasize the importance of failure reporting, diagnostics, and preventive measures at the company level. The establishment of a shared industry failure database would foster collaboration and allow for better identification of trends and systemic issues affecting ship components. As maritime technology advances towards greater automation and digitalization, the challenges posed by digital system reliability and cybersecurity threats must be addressed. Future research should aim to further expand the database of steering gear failures, refine accident models, and establish best practices.

Data Availability

An overview of the reviewed accident reports and the data can be found at the following URL: https://github.com/spenceradugan/ESREL2025.

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