Bundesstelle für Seeunfalluntersuchung
Federal Bureau of Maritime Casualty Investigation
Federal Higher Authority subordinated to the Federal Ministry
of Transport and Digital Infrastructure

Investigation Report 405/20

Less Serious Marine Casualty

Allision with a quay wall by the tanker NORTHSEA RATIONAL in Hamburg on 25 November 2020

25 November 2021

This investigation was conducted in conformity with the Law to improve safety of shipping by investigating marine casualties and other incidents (Maritime Safety Investigation Law – SUG). According to said Law, the sole objective of this investigation is to prevent future accidents. This investigation does not serve to ascertain fault, liability or claims (Article 9(2) SUG).

This report should not be used in court proceedings or proceedings of the Maritime Board. Reference is made to Article 34(4) SUG.

The German text shall prevail in the interpretation of this investigation report.

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1 SUMMARY

The NORTHSEA RATIONAL cast off from her berth in Hamburg to sail for the North Sea on the morning of 25 November 2020. The ship is a chemical and products tanker sailing under the flag of Malta. The master, the second officer at the helm and the advising port pilot were on the bridge. The Köhlbrand was passed first and then the ship swung into the River Elbe. When the NORTHSEA RATIONAL was close to the desired course, the pilot informed the ship's command that it was now possible to switch to autopilot. At this point, the ship was sailing at a speed of 10 kts. The northern bank was not far away on the river.

During the switching operation, the rudder suddenly moved to starboard quickly and unintentionally, reaching a rudder angle of 26.7° in the process. It then returned to the midships position after a brief period. The rudder deflection caused the ship to start turning to starboard. The bridge team's efforts to regain control of the helm failed and the NORTHSEA RATIONAL continued to turn toward the bank. The ship's command responded by setting the controllable pitch propeller (CPP) to full astern and issuing an order to let go the port anchor, thus reducing the speed of the allision with a quay wall on the northern side of the river.

The allision caused heavy damage to the NORTHSEA RATIONAL's forecastle, which made it necessary to call at a shipyard. The quay wall also suffered heavy damage. Nobody was injured and there was no damage to the environment due to the event.

The investigation report deals extensively with the technical investigations into the cause of the accident. It addresses the incorrect configuration of the steering gear control system, the resulting heavy load on electronic components and the sudden failure of a relay. Three expert reports were prepared in the course of these investigations, the findings of which also form part of this report.

The safety recommendation made in this report refers to the improvement of the steering gear control manufacturer's manual.

2 FACTUAL INFORMATION

2.1 Photograph of the ship

Figure 1: NORTHSEA RATIONAL[1]

2.2 Ship particulars

Name of ship:	NORTHSEA RATIONAL
Type of ship:	Chemical and products tanker
Flag:	Malta
Port of registry:	Valletta
IMO number:	9334296
Call sign:	9HA2180
Owner:	North Sea Chemicals AS
Commercial operator:	North Sea Tankers BV
Shipping company:	Miklagard S Gemi İşletmeciliği
Year built:	2006
Shipyard:	Celik Tekne Shipyard, Turkey
Classification society:	DNV
Length overall:	108.5 m
Breadth overall:	16.0 m
Draught (max.):	6.4 m
Gross tonnage:	3,991
Deadweight:	6,232 t
Engine rating:	2,720 kW
Main engine:	MAN B&W 8L27/38
(Service) Speed:	14 kts
Hull material:	Steel
Hull design:	Double hull
Minimum safe manning:	10

[1] Source: Hasenpusch Photo-Productions.

2.3 Voyage particulars

Port of departure:	Hamburg
Port of destination:	Malmö, Sweden
Type of voyage:	Merchant shipping/international
Cargo information:	Fatty acid methyl ester (biodiesel)
Crew:	14
Draught at time of accident:	D_f= 6.20 m, D_a= 6.50 m
Pilot on board:	Yes
Number of passengers:	0

2.4 Shore authority involvement and emergency response

Agencies involved:	Vessel Traffic Centre Hamburg[2], Waterway Police (WSP) Hamburg
Resources used:	Three tugs
Actions taken:	Tug assistance to assigned berth

2.5 Marine casualty information

Type of marine casualty:	Less serious marine casualty: Allision with a quay wall
Date, time:	25 November 2020, 1022[3]
Location:	River Elbe
Latitude/Longitude:	φ 53° 32.6'N, λ 009° 55.04'E
Voyage segment:	Fairway mode
Place on board:	Damage to fore section
Consequences:	Return to port, call at shipyard for repairs to forecastle after lightering of the ship; steering gear repair

[2] Name of the vessel traffic service (VTS) for the Hamburg area.
[3] Unless otherwise stated, all times shown in this report are local (UTC + 1 hour).

Extract from Navigational Chart 1662,
Federal Maritime and Hydrographic Agency (BSH)

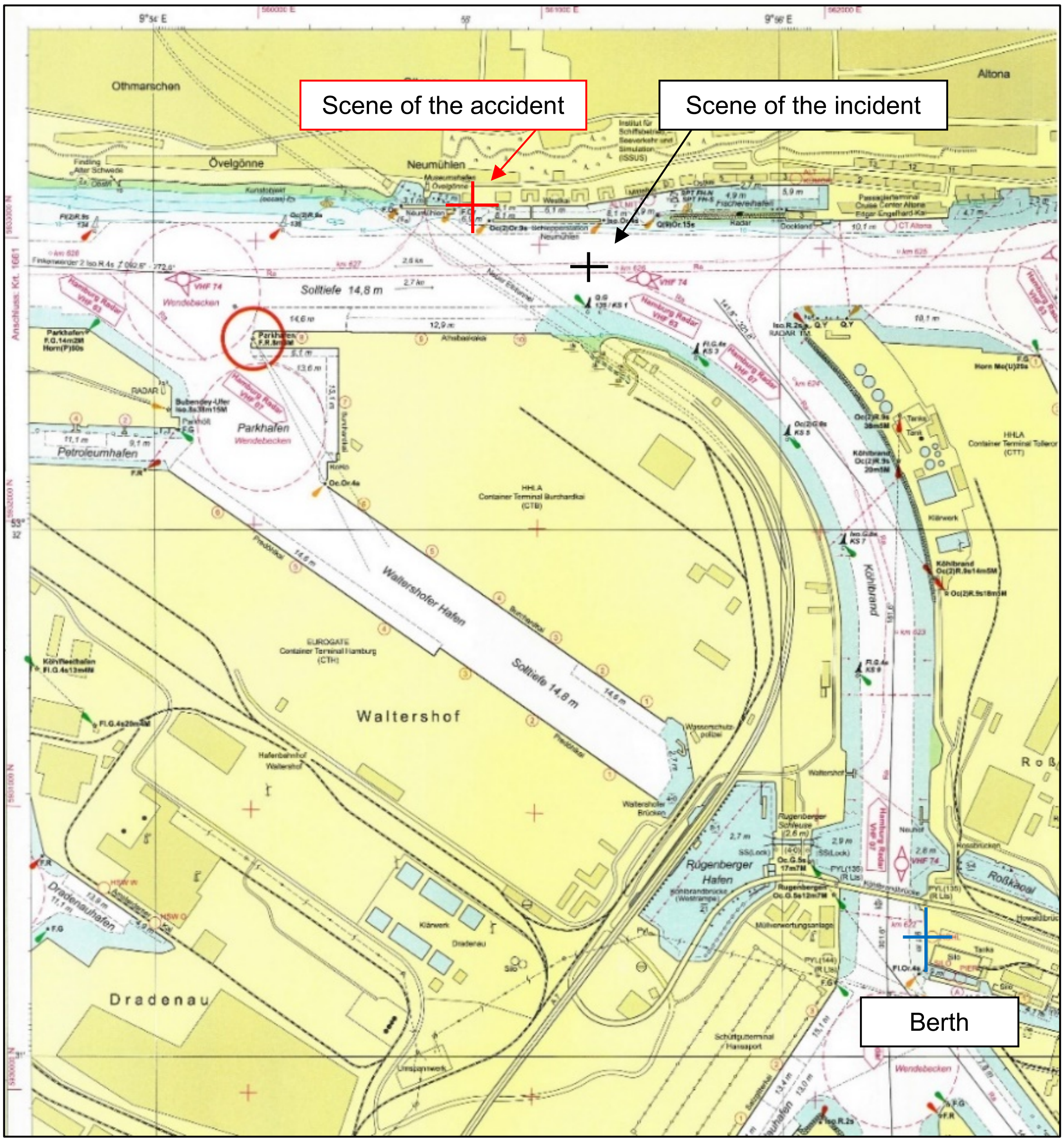

Figure 2: Navigational chart showing the berth, the scene of the incident and the scene of the accident

3 COURSE OF THE ACCIDENT AND INVESTIGATION

3.1 Course of the accident

The Maltese-flagged chemical and products tanker NORTHSEA RATIONAL was scheduled to depart for Malmö on the morning of 25 November 2020 with a cargo of biodiesel.[4] The ship had taken on this cargo in Hamburg at ADM Hamburg AG's berth at Köhlbrand.

The subsequent course of the accident is based on the account of the ship's master and other officers involved.

The ship was made ready for sea after loading was completed. The second officer prepared the bridge in accordance with the shipping company's specifications using a checklist. Preparations in the engine room for departure included an inspection of the steering gear. No malfunctions, leaks or other irregularities as compared to the normal condition were found.

The port pilot reached the ship at about 0940. All lines had been cast off by 1005 and the ship set sail in good visibility without tug assistance. According to the voyage data recorder (VDR), a north-west wind of 2–3 Bft prevailed at the time.

The pilot, the master and the second officer were on the bridge for the casting off manoeuvre and subsequently when the ship was in estuary mode. The latter acted as helmsman. He stood at the central console and operated the rudder manually. The pilot issued helm orders directly to the second officer. The master controlled the CPP's pitch from the central console in accordance with the pilot's recommendations.

The left-hand bend at Köhlbrand was passed without any complications and partly at reduced speed because diving works were taking place there. The speed was then increased again.

Köhlbrand was then left while maintaining the turn to port so as to steer the necessary course for navigating the river. At this point the tide was moving in the opposite direction. When a compass course of about 275°[5] had been reached, the pilot recommended switching to autopilot[6]. During the switchover to autopilot, the vessel suddenly began to turn to starboard. The turn was triggered by an independent and unintended rudder movement to starboard. The ship's speed was about 10 kts at this point. According to the master, the northern bank was about 150 m away.

[4] Specifically, fatty acid methyl ester (FAME).
[5] The chart course of the radar reference line in this area is 269°.
[6] Term used here and below for the automatic steering gear. Both terms mean an automatic course control system for a ship.

An attempt was immediately made to turn the ship to port using the hand steering but she continued to turn to starboard. It became apparent that there was a malfunction in the steering gear control system.

The master set the CPP's pitch to full astern to reduce the speed. It was clear to the master that there would be an allision with the northern bank. Accordingly, the tyfon was sounded to warn the surrounding area.

In addition, the port anchor was dropped (two shots of chain cable). This could be executed quickly because both anchors were prepared accordingly. This was dealt with by the chief mate and bosun, both of whom were still on the forecastle. Both measures reduced the impact speed. The deployment of the anchor caused a slight turn to port.

In his statement, the master concluded that the last exercise for the measures to be taken in the event of a steering gear fault had taken place five weeks earlier.

The impact with the quay wall was at an angle of about 60°. Therefore, most of the damage to the ship was on the starboard side of her bow.

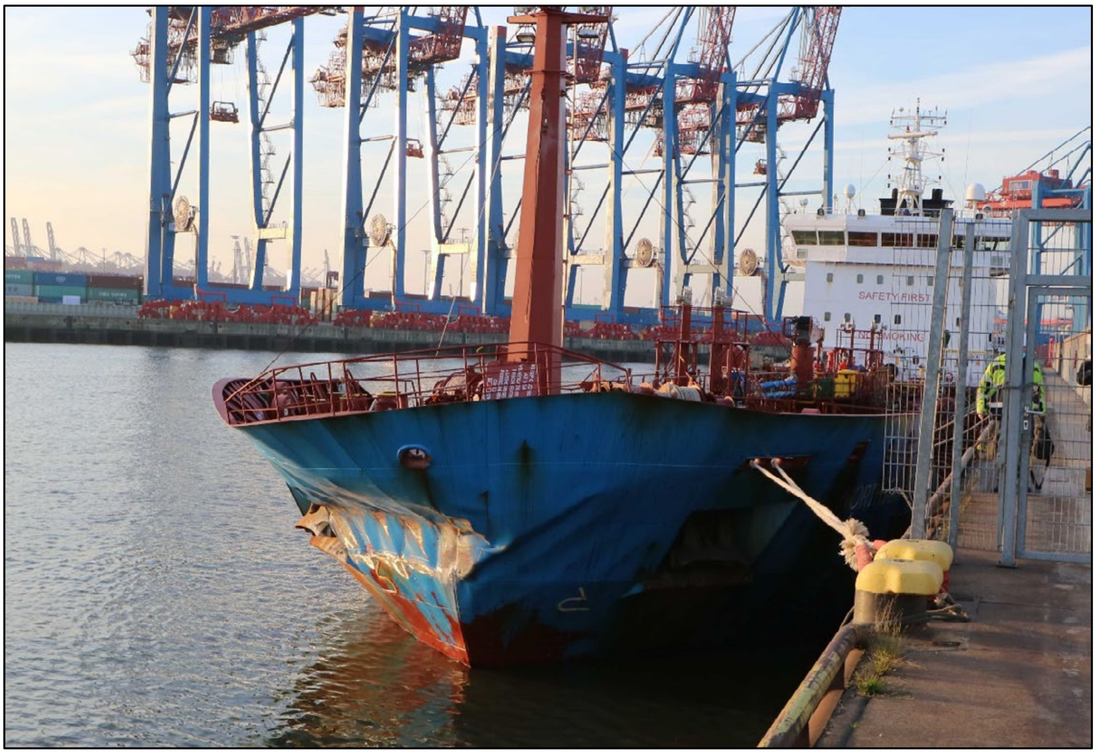

Figure 3: NORTHSEA RATIONAL – damage to the bow after the allision

An inspection of the compartments in the fore section and tanks carried out immediately after the allision revealed that there was no water ingress on the ship or contamination of the environment by escaping substances.

Shortly afterwards, the ship was able to separate from the quay using her own propulsion and by hauling in the anchor. A short while later, the NORTHSEA RATIONAL's crew made fast to one tug at the bow and one at the stern. These tugs helped the ship move to the assigned berth and a third tug escorted them. The ship was made fast at her new berth at 1115.

3.2 Investigation

3.2.1 NORTHSEA RATIONAL

The NORTHSEA RATIONAL has been operated by the current management since June 2020, i.e., the crew also changed at that time.

Her size is typical for ships of this type (length: 108 m). She has 13 cargo tanks with a capacity of about 6,455 m³. Her superstructure is located aft.

The ship is equipped with a Controllable Pitch Propeller and a Becker rudder.

3.2.2 VDR recording

BSU investigators backed up the data on the ship's VDR (JRC JCY-1700) on the afternoon of the day of the accident. This involved removing from the VDR the CompactFlash card used as a storage medium and copying its contents. The storage medium was then returned to the crew.

The recording on the memory card covered the period between 023003 and 153103 on 25 November 2020. The emergency backup was therefore carried out at the new berth where the ship had docked after the accident.

3.2.2.1 NMEA data

For the investigation, only data from the period relevant to the accident (100522 to 103007) were analysed. In particular, the stored NMEA data[7] for the steering gear control system and the autopilot for the time 1020 to 1022 for:

- Override[8]
- Selected steering mode
- Commanded rudder angle
- Commanded heading to steer and
- Vessels heading

were of interest.

[7] NMEA: National Marine Electronics Association. This organisation defines standards for communication between navigational devices on ships.

[8] A more detailed definition of the meanings can be found in DIN EN 61162-1 – Maritime navigation and radiocommunication equipment and systems – Digital interfaces – Part 1: Single talker and multiple listeners (IEC 61162-1:2016); specifically, subsection 8.3.55 HTC – Heading/track control command; HTD – Heading /track control data.

From the data it can be seen that the steering gear started to put the rudder to starboard at 102020. The steering gear control was set to manual control at this time. However, according to the helmsman's statement, the rudder was not placed to starboard by the helmsman. The maximum deflection to starboard was reached at 26.7° at 102026. The rudder then ran back again. The midship position was reached at 102036 with 00.5°.

The investigators noted that during the return of the rudder to the midship position from 102030 to 102042, the rudder control was switched from manual to autopilot. The commanded heading to steer during this time was 274.8°. Since the deviation of the ship's heading from the commanded course was small at 275.3°, the rudder angle given by the autopilot was reduced from 06.0° starboard at first to 00.7° starboard (at 102034). This was also followed by the actual rudder angle.

For a short period of 2 seconds, the autopilot then gave a rudder angle to starboard (102036, 8.2°), although the deviation from the given course was now approx. 3° to starboard. From 102038, the autopilot gave a rudder angle of 6.5° to port. The given rudder angle increased to 12.7° to port at 102040. This seems logical, as the deviation from the given course was +4.4° in the meantime. As already shown, the rudder was switched back to manual steering at 102042.

A second switch to autopilot occurred at 102052. The heading given at this time was 282.1°. The heading was 282.9°. At 102054, it was switched back to manual steering.

In the further course up to the pier approach, the steering gear remained on manual control. Switching to non-follow-up mode (override) (see section 3.2.6) was not recorded.

3.2.2.2 Playback of the data with the software

The replay (100522 to 103007) was carried out using the VDR manufacturer's software, which the BSU already has and is designed for this purpose.

The first usable radar image was recorded at 1012, as this is when this radar installation was first switched from standby to operating mode[9]. The ship had already passed the bridge at Köhlbrand.

It was not possible for the BSU to play back the movement data and associated radar image simultaneously with the manufacturer's playback software. Therefore, a

[9] According to the Performance Standards for Shipborne Voyage Data Recorders (VDRs) (subsection 5.4.7 of Resolution A.861(20)), which are applicable to the ship, only one radar installation must be recorded. The findings on the time at which the radar installation mentioned was switched on do not suggest that neither radar installation was switched on during the casting off manoeuvre.

separate presentation of the ship's movement data in conjunction with the audio recording of events on the bridge (Spreadsheet 1), on the one hand, and the radar images (Figures 6-10), on the other, are provided below.

The playback software presentation contained information on the ship's speed through water (STW) in digital and analogue form, the heading (HDG), the rudder position, the water depth beneath the keel, the position, the time and the wind (direction and speed).

The playback software presentation did not contain any information about the pitch selected for the CPP[10], the position of the telegraph, the response of the steering gear control system to steering commands and signal implementation (order and response), or the autopilot's status and settings.

Figure 4 gives an impression of how the playback software presents the data. The figure shows the point at which the rudder position to starboard was at its greatest (26.7°). The STW is 9.7 kts.

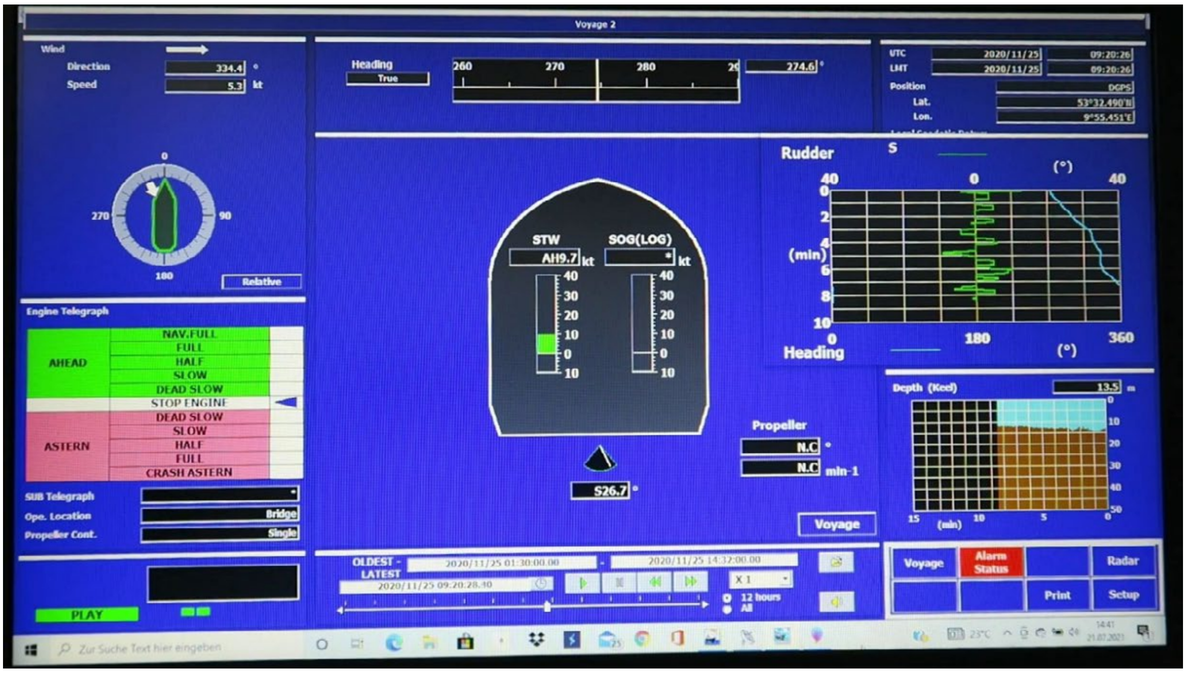

Figure 4: Still frame from the VDR playback at 102028

Time at which the rudder position to starboard was at its greatest after the malfunctioning of the steering gear control system.

Figure 5 is an extract from the playback software data presentation. It shows the different rudder positions and courses during the critical period, i.e., about three minutes before and two minutes after the malfunction. After the sharp deflection

[10] Subsection 5.4.11 of Resolution A.861(20).

to starboard, another smaller deflection to starboard (about 8°) followed by a deflection to port (about 4°) were recorded. The rudder then remained in a near-midship position.

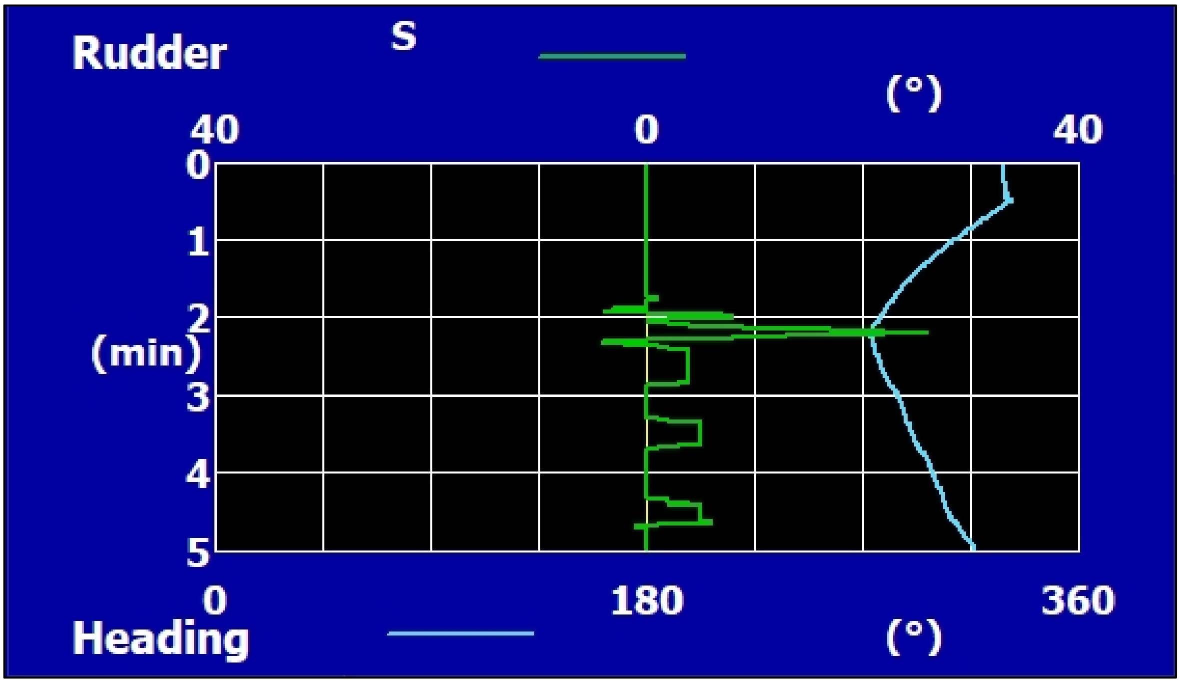

Figure 5: Rudder positions and courses about three minutes before and two minutes after the malfunction

3.2.2.3 Audio data

The following tabulation is a compilation of the ship's positions taken from the radar images and the VDR's audio and data recordings. The presentation begins with the arrival of the pilot on the NORTHSEA RATIONAL's bridge. The chronological sequence contains only the details that the BSU considers necessary for comprehension. The master's communication with the forecastle conducted in Turkish is not shown, for example. The sounding of the tyfon is also shown only once. The times in the spreadsheet are local time in Hamburg (UTC + 1).

No audible alarms could be heard on the bridge during the period shown. The investigators assess the quality of the audio recording as excellent.

Spreadsheet 1: Course of events based on the VDR recording

Time	Event	Heading (HDG) [°]	Speed Through Water (STW) [kts]
0930	The port pilot reaches the bridge.		
0933	During the exchange of information with the pilot, Gothenburg is named as the port of destination.		
0959	The bow thruster is running and casting off begins.		
1008	The port pilot reports by radio that they are passing the bridge at Köhlbrand.		
1012	Buoy KS 9 abeam on the port side.	001.5	9.2
1014	Buoy KS 7 abeam on the port side, mid-channel.	337	8.2
1016	Buoy KS 5 abeam on the port side (speed reduced due to diving works).	327	7.8
1018	Buoy KS 3 abeam on the port side.	300	8.8
102010	Port pilot: "Come to 275!". He informs the ship's command that it is now possible to switch to autopilot.	277	10.3
102020	The rudder position is 4.5° to port.	275.6	10.3
102028	The rudder moves to starboard, reaches a rudder position of 26.7° and then moves back immediately. The ship starts to turn to starboard.		9.7
102039	The port pilot apparently notices the starboard tack and recommends "Port ten."	278	9.7
102044	Port pilot: "No autopilot. We keep on hand steering!"		10.3
102046	Port pilot (directed at the second officer): "What are you doing?"	280	9.8
102048	Port pilot: "Port ten!" [The rudder is almost amidships.]	281	9.9
102102	The second officer indicates that the rudder is not responding.	287	10.4
102105	Port pilot: "Long horn! Long blast!"		
102107	Port pilot: "Port 20 the wheel!"	289	10.4
102117	Port pilot: "Long horn, long horn!"	294	10.3
102122	Long signals from the tyfon can be heard.		
102131	Master: "Let go anchor?" Port pilot: "Let go."	302	10.2
102135	Port pilot: "Full astern!"	305	10.3
102142	Port pilot: "Long horn, long horn!"	311	9.6
102150	Port pilot: "Long horn again!"	320	7.4
102210	Allision with quay wall.	330	7.0

3.2.2.4 Video data

The course of the voyage is shown below using selected radar images (Figures 6-10). Seconds are not shown on the clock in the radar image. The VDR stores four images per minute. Therefore, the image description contains the image number of the respective minute so as to have an approximate reference value. It is apparent that the radar was operated in the north-up relative motion off-centred display mode in the 0.75 nm range. The variable range marker (VRM1) was set to 0.155 nm.

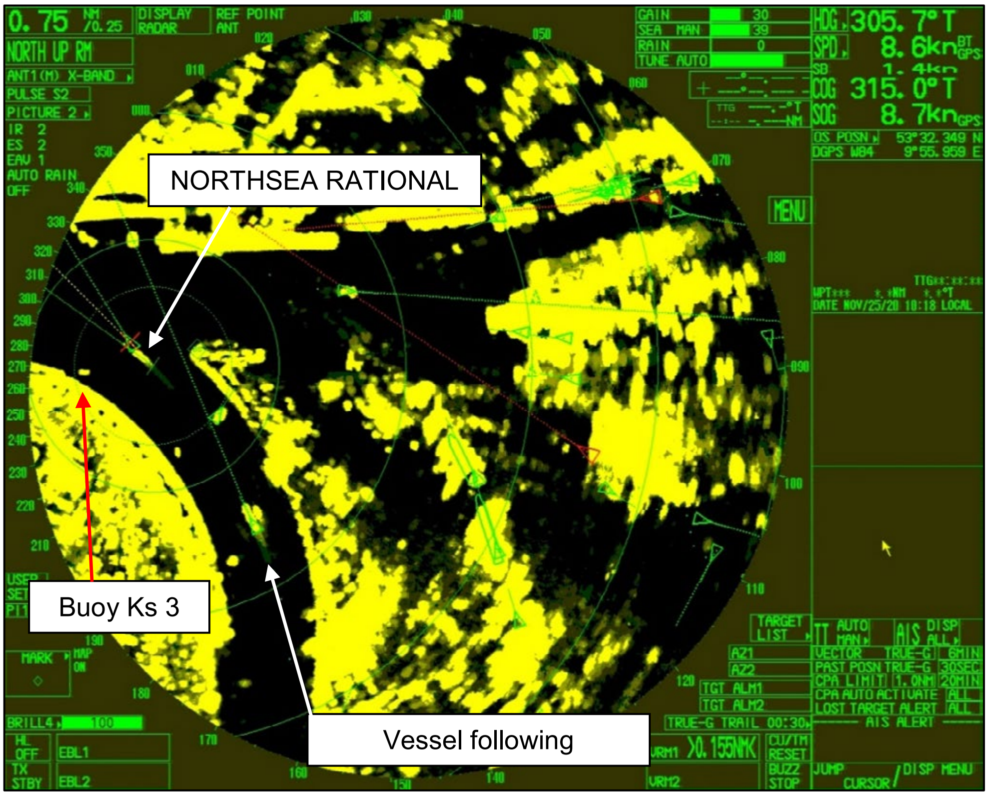

Figure 6: Radar image at 1018, first image[11]

[11] Source: Figures 6-10 are taken from the VDR recording.

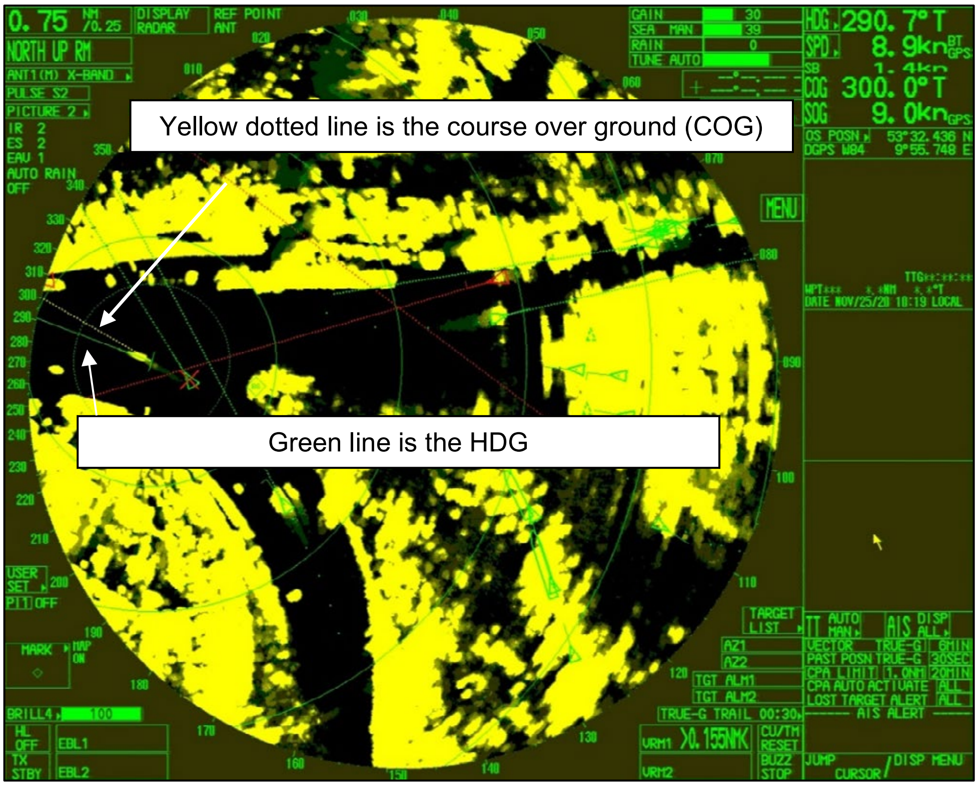

Figure 7: Radar image at 1019, first image

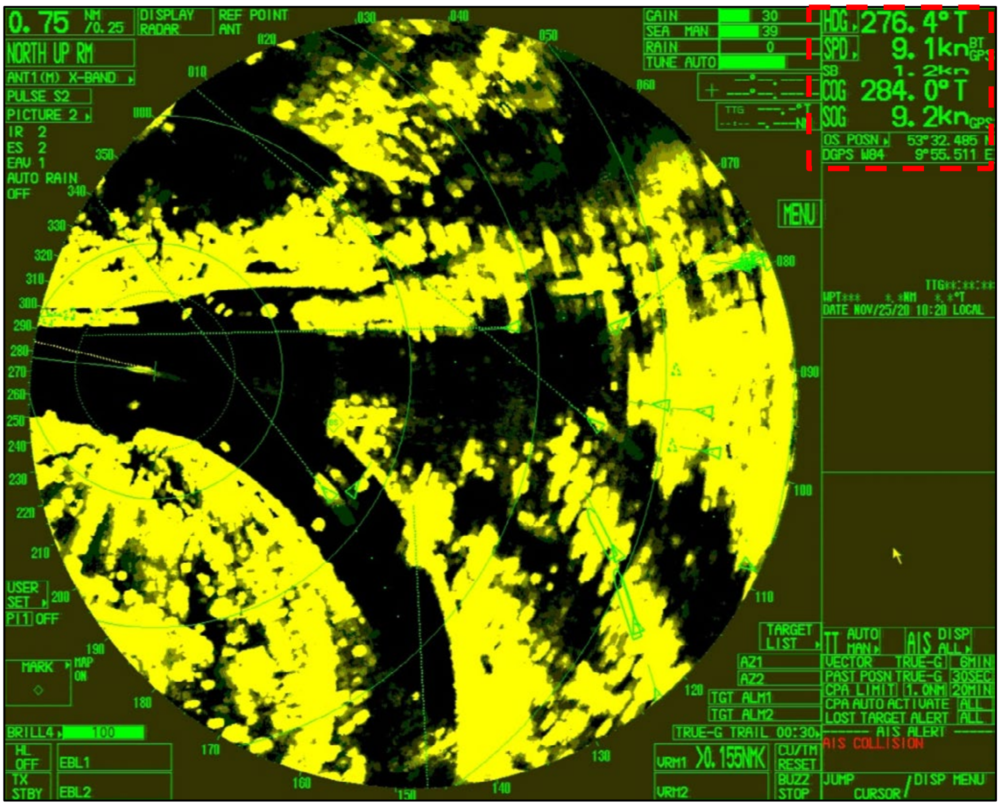

Figure 8: Radar image at 1020, first image

Radar image at about the time of the malfunction.

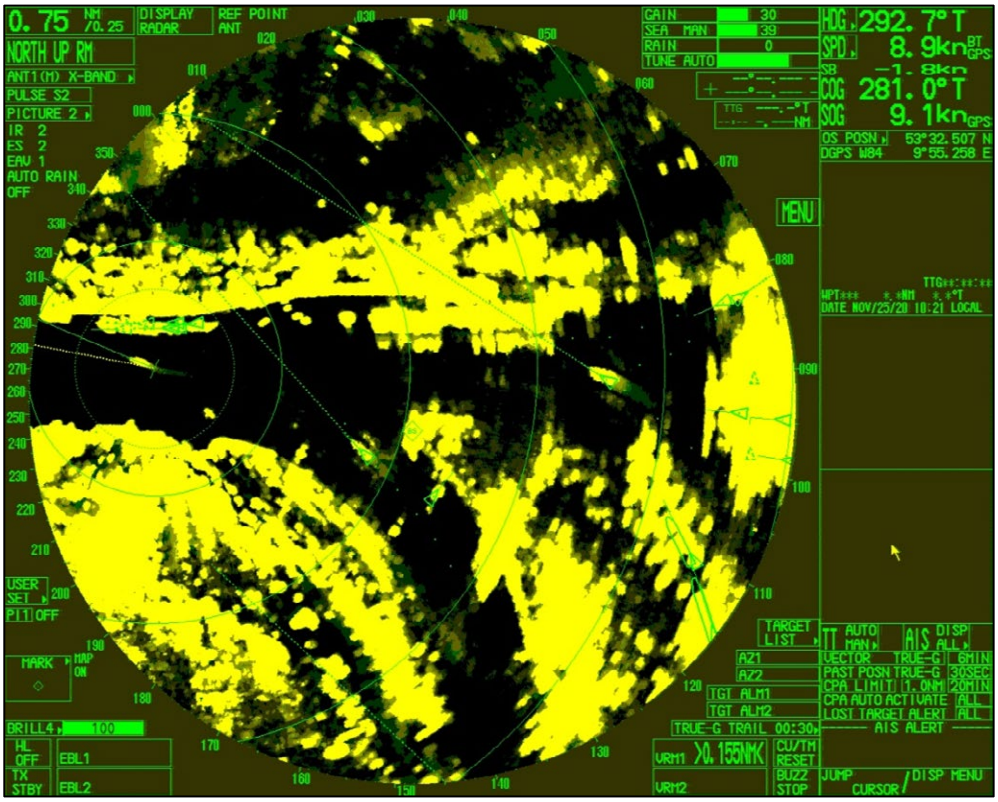

Figure 9: Radar image at 1021, first image

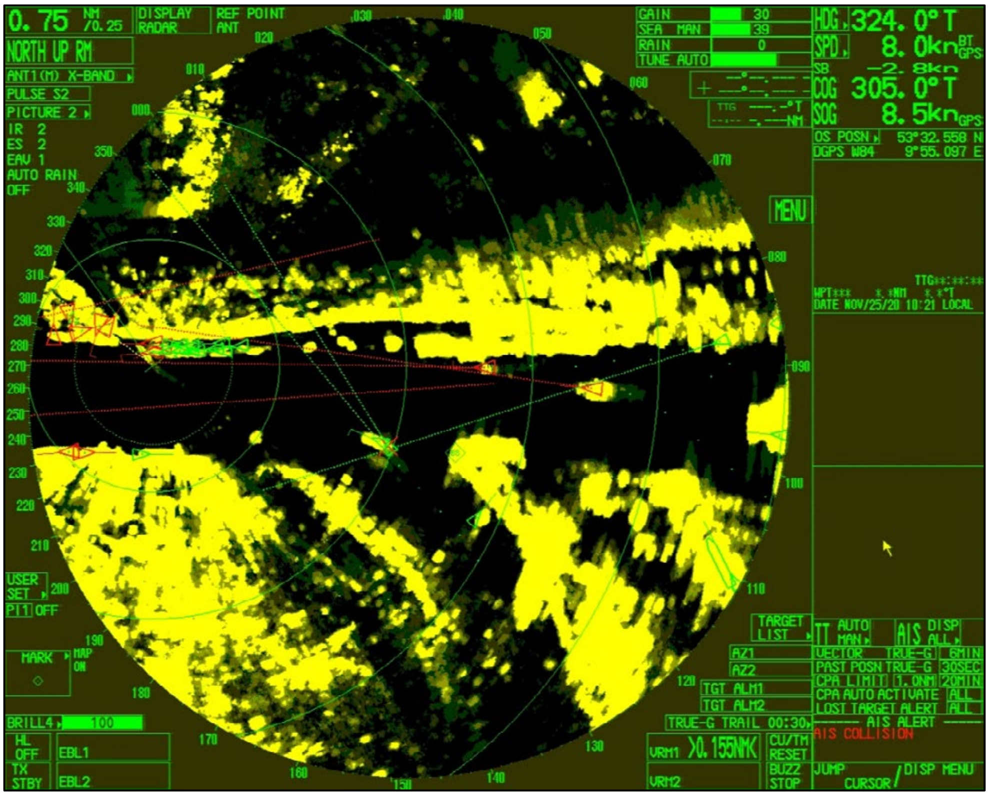

Figure 10: Radar image at 1021, fourth image

3.2.3 Crew

The NORTHSEA RATIONAL's 14 crew members were all Turkish nationals. Turkish was therefore the language used on board. Entries in the deck log book were made in English.

The master held an unrestricted certificate of competency (STCW II/2) in the management level. He began his career in 2004 and has served as a master since 2015. The master began his duties on board the NORTHSEA RATIONAL on 10 October 2020. It was his first contract on this ship. He had previously served on similar ships that were also built at the shipyard in Tuzla.

The second officer began his maritime training in 2016. He has served as second officer on various tankers since 2019. He began his duties on board the NORTHSEA RATIONAL in June 2020.

The time sheets submitted by the above crew members covered a period of four days prior to the accident and did not provide any evidence of fatigue among the bridge team.

3.2.4 Course of the investigation

WSP Hamburg notified the BSU about the incident at about 1200 on the day of the accident. Marine casualty investigators visited the ship for the first time a few hours later. During this visit, the master and the second officer were asked about the basic course of events. Extensive written statements were guaranteed by the legal counsel and later submitted. The investigators also secured the VDR recordings and other documents.

During the survey, the second officer demonstrated the operating steps when switching from hand steering to steering by autopilot and back. There were no malfunctions.

In its response to the draft, the shipping company pointed out that similar malfunctions had previously occurred again when the crew had tested the systems in the presence of the waterway police. A failure of the steering gear had also occurred during a follow-up inspection on 27 November 2020 in the presence of various experts.

During the interview, the master reported that a similar incident, i.e. a sudden unintended rudder deflection, had also occurred in June 2020. Since this took place in the open sea, there were no repercussions. During the service carried out subsequently in Immingham on 23 June 2020 by a specialist firm, minor damage to a contact of the sensor for the actual rudder angle (feedback unit) on the steering gear was identified and repaired. The ship's command submitted the associated service protocol to the BSU.

On 26 November 2020, Malta's investigating authority was informed about the accident and the preliminary investigation conducted by the BSU.

On 3 December 2020, the ship was visited again for further investigations on board. The investigators were accompanied by Prof. Dr.-Ing. Wirz from the Department of Marine Engineering at the Hamburg University of Technology in the capacity of technical expert. The BSU later instructed Wirz to prepare an expert report.

Since the investigation subsequently focused on a technical issue within the steering gear (or its control system), the expert commissioned by the BSU examined the steering gear and its components again on 8 December 2020. Two other experts acting on behalf of the insurer and the owner of the ship were also present at these and all other visits.

The experts examined parts of the steering gear again on 23 December 2020 after the ship had shifted to Bremerhaven for repairs to the hull in the meantime.

Following an assessment of all the findings obtained up to that point, the BSU's preliminary investigation was changed to a main investigation on 6 January 2021. The NORTHSEA RATIONAL shipping company's legal counsel was advised of this decision.

In the meantime, the autopilot had been sent to the manufacturer (Navitron Systems Ltd.) in the United Kingdom. The NT991G Mk2 autopilot was examined there by two employees on 8 January 2021. All interested parties took part via videoconference.

During the investigation on board, the rudder failure was linked to the malfunctioning of two relays in the steering gear control system. For a non-destructive electrical examination, Wirz submitted the secured relays to Prof. Dr.-Ing. Ackermann for a sub-assessment.

A further sub-assessment on the more detailed examination of the relays, in particular the contact surfaces, was then made by MQ Engineering GmbH.

3.2.5 The NORTHSEA RATIONAL's steering gear

The following description of the functioning of the steering gear forms part of the expert report prepared by Wirz[12]. Here and in the following, the parts taken from the expert opinion are shown in italics.

"The steering gear as a whole comprises a spade/high-lift rudder combination with a maximum rudder angle of 35° and rotary vane steering gear manufactured by Tenfjord, whose products are distributed and serviced by Rolls-Royce and therefore now also by Kongsberg[13].

Rotary vane steering gear is an extremely compact electro-hydraulic system with axisymmetric housing that contains the rudder stock bearing and the hydraulic actuator. The actuator consists of a hub pressed onto the rudder stock with two or three vanes, which is rotatably mounted in the housing. The housing has the same number of vanes (known as stoppers). Hydraulic working chambers are enclosed in the housing between the vanes and the stoppers, each hydraulically connected with the one opposite. When hydraulic oil is pumped into one of the connected chamber groups at a defined flow rate, the vanes deflect in a circumferential direction to take up the oil, which creates a turning motion. The volumes of the other chamber group then reduce and their oil filling is displaced. As soon as a load moment is applied to the rudder stock (through friction of the bearings or when in operation through a hydrodynamic moment of the rudder), positive pressure builds up in one chamber group and thus between the vanes and stoppers. Since the other chamber group is depressurised in the meantime, a directional driving pressure difference develops at the vanes, consequently a circumferential force due to the vane surface and a torque due to the radius to the axis of the rudder stock. To change the direction of rotation, the oil flow is simply not pumped into one chamber group but into the other. Accordingly, the chamber groups merely exchange roles (receiving and displacing element)."

[12] Prof. Dr.-Ing Friedrich Wirz: *Gutachten / Analysebericht zur Kollision von M/T Northsea Rational im Hamburger Hafen im November 2020* [expert/analysis report on the allision involving the MT NORTHSEA RATIONAL in the port of Hamburg in November 2020]. Referred to below as 'steering gear report'.

[13] In 2019, Kongsberg Maritime took over Rolls-Royce Commercial Marine's business activities in rudder and steering systems for ships and other areas.

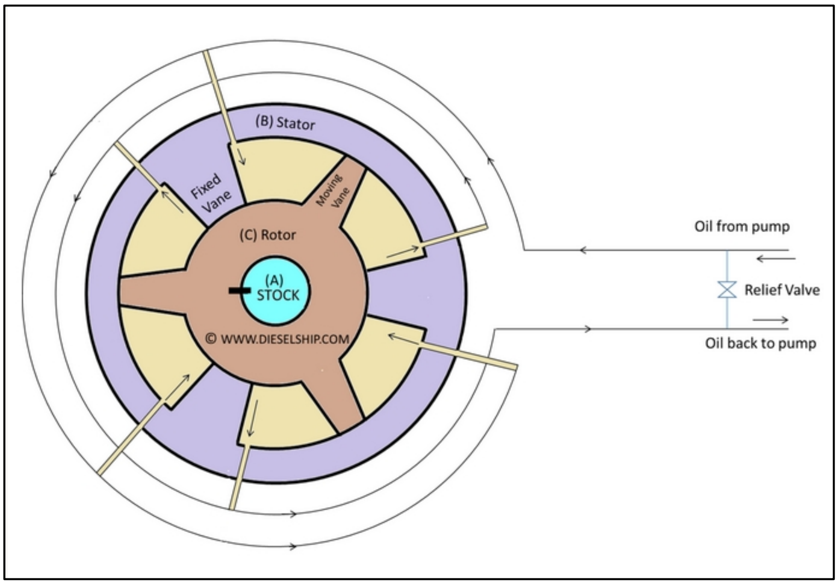

Figure 11: Simplified diagram of rotary vane steering gear[14]

The steering gear shown has three vanes. A steering gear with two vanes is installed on board the NORTHSEA RATIONAL.

"It is important to note that the rate and direction of turn of the steering gear is determined by the amount and polarity of the oil flow rate pumped into the driving and receiving chamber groups, respectively, and that secondly, there is a fixed correlation between the steering gear torque and the hydraulic pressure difference. In this case, the oil flow rate is determined by the hydraulic pumps and the rate of turn is a result. On the other hand, the torque is determined by the operating conditions at the rudder, so the pressure difference is a result. In other words, a pump does not 'make' pressure but rather delivers a flow rate. The resulting pressure or pressure difference is predetermined by the external load. Of importance here is that the pump has a sufficiently powerful drive and appropriate compressive strength and protection so as to be able to deliver against the resulting operating pressures. As a consequence of these relationships, the direction of delivery and pressure difference can also have reversed polarities, enabling the system to work in all four operating quadrants (two motoring and two generating quadrants). Generating operation can occur due to an overbalanced rudder[15], for example.

The maximum rudder angle is determined by the geometry of the steering gear. As soon as the vanes and stoppers are blocked on one side or the other, the mechanical end limit (usually 37°) is reached. To avoid frequent mechanical stress, electric limit switches are used to stop the pump drive at a rudder angle of 35° on each side."

[14] Source: https://dieselship.com/marine-technical-articles/marine-engineering-knowledge-general/rotary-vane-steering-gear. Retrieved on 14 July 2021.

[15] On a balanced rudder, the axis of rotation is not directly at the leading edge of the rudder blade but offset to aft a little and the hydrodynamic effects in front of and behind the axis contribute to stability of the rudder position. On an 'overbalanced' rudder, the turning axis is further aft and the hydrodynamic forces act in the direction of a hard-over rudder position. Rudder movements are therefore supported. On an 'underbalanced' rudder, the axis of rotation is further forward and the forces push it in the direction of a zero rudder position.

Figure 12: NORTHSEA RATIONAL's steering gear[16]

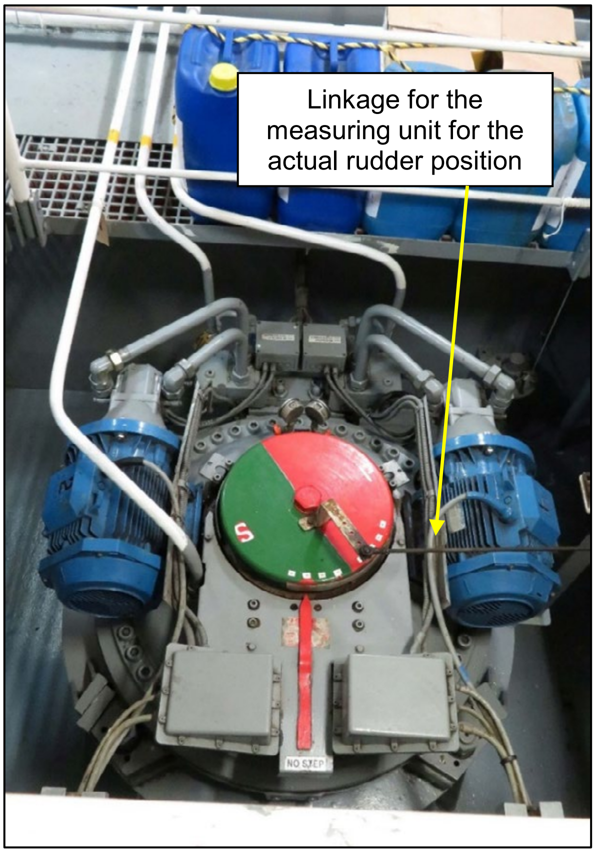

Figure 13: NORTHSEA RATIONAL's steering gear, top view

"In the present case, the hydraulic pump units are mounted in a compact manner on the steering gear's housing (see Figures 12 and 13). *In accordance with class design regulations, two identical pump units, hydraulically connected in parallel, are provided for reasons of redundancy. The hydraulic system is a closed, controlled circuit, i.e., the*

[16] Source: Figures 12 and 13: WSP Hamburg.

two connections to the chamber groups in the actuator are directly connected to the pumps. Flow and return are created solely by the direction of flow of the pumps and can change according to the required direction of rotation of the rudder. Each pump unit consists of a fixed displacement pump (fixed geometric displacement capacity), the delivered flow rate of which is proportional to the pump speed. The pump is driven by a three-phase asynchronous motor. To enable a variable flow rate from the pump, its rated speed and thus also that of the electric motor must be variable. Due to the design, this requires the use of a frequency converter to convert the constant frequency of the shipboard power supply of 50 Hz into a variable input frequency for the motor, which is then proportional to the motor speed. Each pump unit has its own control cabinet, which also contains the respective frequency converter.

The hydraulic parallel connection of the pump units creates an important steering gear characteristic, i.e. the flow rates of the two pumps accumulate but the maximum pressure difference remains the same. This means that each pump can be operated separately or they can both be operated together, with the effect that the rate of turn of the steering gear is doubled by adding the second pump. On the other hand, the maximum torque can be achieved with one pump alone or both pumps together.

The turning motion is generated by delivering an oil flow rate into one chamber group and simultaneously displacing an equal oil flow rate from the other chamber group[17]."

3.2.6 Steering gear control

"'Steering gear control' refers to the production of control signals for the steering gear.
[…]

As described above, the rate of turn and direction of the steering gear depends on the amount and polarity of the oil flow rate. The amount and polarity of the oil flow rate depend on the direction of rotation and rated speed of the pump unit(s). In turn, these depend on electrical input variables (voltage, current, frequency, as well as the polarities of these variables) at the electric motor. Accordingly, the task of the control system is to transmit the electrical operating values to the electric motors so that they drive the pumps at the rated speed and direction of rotation required.

There are two ways of controlling a rudder from the perspective of the navigator. Either he wants to set the rudder to a desired angle within the range available (35°port...0...35°starboard) [A] or he only wants to move the rudder further to port or starboard, regardless of its current position [B]. There is a discrepancy between these two perspectives, i.e. for the steering gear only the functions 'do nothing', 'turn to port' and 'turn to starboard' (at any rate of turn) exist. With regard to the signals to the electric motors, this means that there is no difference between the two types.

[17] Steering gear report.

Accordingly, the navigational mode as per [B] can be passed on to the steering gear directly. This is known as non-follow-up mode (NFU). Only a dual binary signal is needed for this, which is generated either via a joystick with three positions (port, 0, starboard) or via two push-buttons (one pressed: port, the other pressed: starboard, none pressed: 0). In the push-button version, the steering gear can only be operated in binary or digital mode. This means that an analogue gradation of the rated speed with the help of the frequency converters is not possible, but rather only the states standstill and full speed in one or the other direction of rotation.

The navigational mode of operation according to [A] requires the intermediate step of a position control. It is referred to as follow-up mode (FU)[18]. A rotary wheel or button (or a classic steering wheel), a so-called 'FU tiller', is used as an operating element, the angular position of which corresponds to a selected rudder angle on the basis of a scale. Sensors for detecting the actual rudder angle are installed on the steering gear. These are simple potentiometers that generate an output voltage proportional to the angle. In the actual steering gear control unit (an electronic unit installed in a control cabinet on the bridge), the actual rudder angle according to the potentiometer and the selected rudder angle according to the FU tiller are compared with each other. If both values are the same, the control signal is 0 (i.e. nothing). If the values deviate from one another, a control signal in the appropriate direction emerges from the control deviation. The steering gear then moves in the required direction until the selected rudder angle is reached.

For small control deviations (difference between selected and actual values), the frequency converter could come into play, i.e., if only small position adjustments are required, then a reduced pump speed is sufficient to deliver the small amount of oil into the steering gear within an appropriate period. A so-called 'peak overshoot', i.e. exceeding the selected position, can also be avoided in this manner. Such an overshoot can cause the control system to correct in the reverse direction. If a peak overshoot then occurs in the other direction, an oscillation around the selected position can be produced. This is discussed in greater detail below.

The steering gear control unit discussed thus far only includes the manual mode of operation, where the rudder can be steered or the position regulated in either NFU or FU mode. Moreover, almost every ship has an autopilot. This has the task of putting the ship on a predetermined heading or keeping her within an envelope. Of course, the rudder angle is used as a control variable for this. In that respect, the autopilot is

[18] Expert's Note: *"In practical terms there is no sharp distinction between the concepts of control and steering in steering gear systems. Strictly speaking, steering is the influencing of a variable without checking the actual state, while control influences the variable and the actual state."*

another higher-level control. In this case, a comparison of the selected and actual course is carried out. The output is then the selected rudder angle, which the steering gear control unit is responsible for setting and maintaining. In this respect, a data link exists between the autopilot (in this case Navitron) and the steering gear control unit (part of the overall steering gear package and thus Kongsberg). This link may be regarded as a FU or NFU specification. This aspect will also play an important role subsequently. The choice between manual and autopilot mode of operation is made on the autopilot by means of a selector switch. If it is necessary to switch from manual operation to autopilot, the autopilot is first switched on and then control is assigned to the autopilot by pressing a button on the control unit. When switching back to manual operation, the autopilot is switched off. Switching the control between autopilot and manual operation will also play a role subsequently[19]."

3.2.7 Operation of the steering gear on the bridge

Operation of the steering gear control system was possible from three positions on the NORTHSEA RATIONAL's bridge (in the central console and in each of the closed wings).

The full range of functions was provided by the rudder position control system in the central console, the bridge console. The autopilot control unit was also in the central console. Figure 14 provides an overview of this.

Instructions were provided next to the controls. On one hand, they described how to switch from hand steering to steering by autopilot and back. On the other hand, the process for switching to emergency steering, i.e. NFU mode, was shown.

[19] Steering gear report.

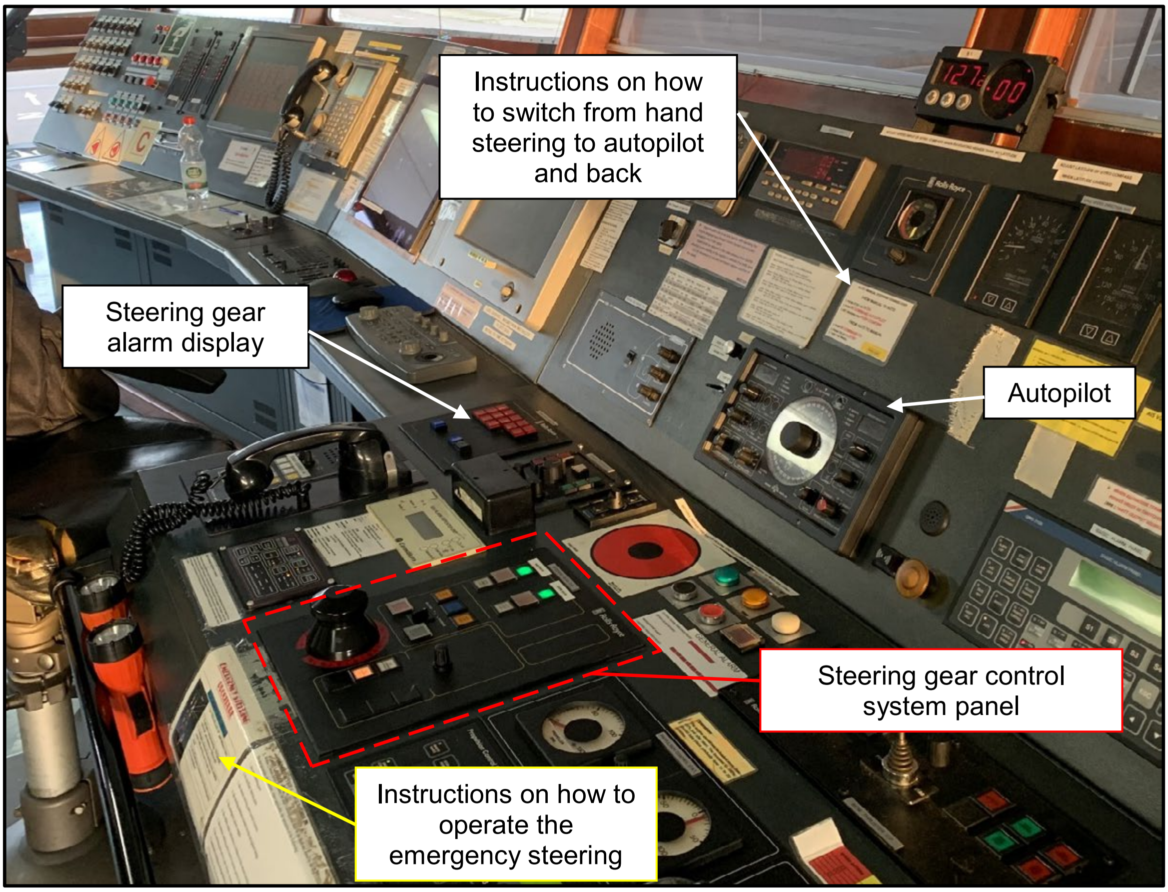

Figure 14: Steering gear control system panel in the central console

Figure 15: Autopilot control panel

Figure 15 shows the autopilot control panel in detail. The knob for switching on, off or to standby is located at the bottom right.

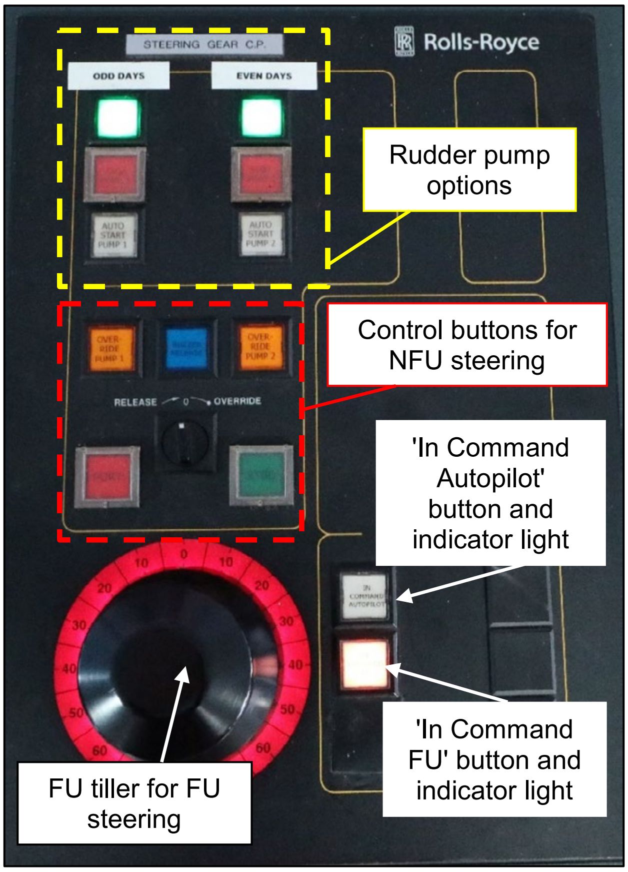

Figure 16: Steering gear control system panel

To switch from hand steering to autopilot, the autopilot must first be put into operation, which is done by switching to the 'Standby' position. After successful completion of the self-testing process, the autopilot can be switched to 'ON' (Figure 15). The 'In Command Autopilot' button in the steering gear control panel (Figure 16) must then be pressed. The continuous illumination of the integrated lamp indicates that the function has transferred successfully. A flashing lamp indicates an error.

In the case described, the course set when the autopilot is started up is the heading that the autopilot follows as the selected course. Alterations to the selected course are set and only confirmed on the autopilot.

To switch back to hand steering, the 'In Command FU' button must be pressed. Continuous illumination of the integrated lamp indicates completion of the transfer here, too. The autopilot can then be switched to standby. Tests carried out on the ship's bridge on the day of the accident revealed that the reverse procedure delivers the same result. In both cases, the rudder could then be moved with the FU tiller.

The instructions for the switching procedure found on the central console in the bridge (see Figure 17) corresponded to the procedure described above.

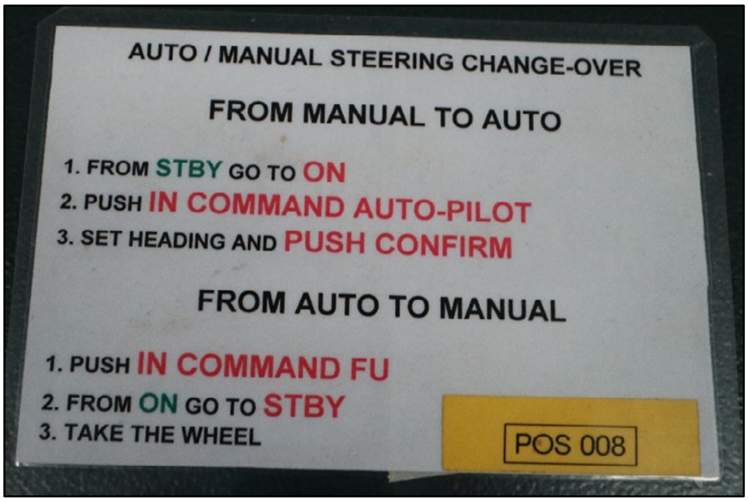

Figure 17: Instructions for the switching procedure

It was only possible to switch from FU to NFU steering and back on the rudder position control panel in the central console (marked with a red dashed line (---) in Figure 16). FU steering constitutes normal operation. NFU steering is the emergency steering. When NFU steering is switched to, the normal signal path is bypassed. For example, this means that pressing the push-button for starboard directly activates the hydraulic circuit for moving the rudder to starboard. This is also known as the override function.

Only a small rotary wheel for the FU steering and a display for the rudder position were installed (Figure 18) at the respective control positions in the closed wings.

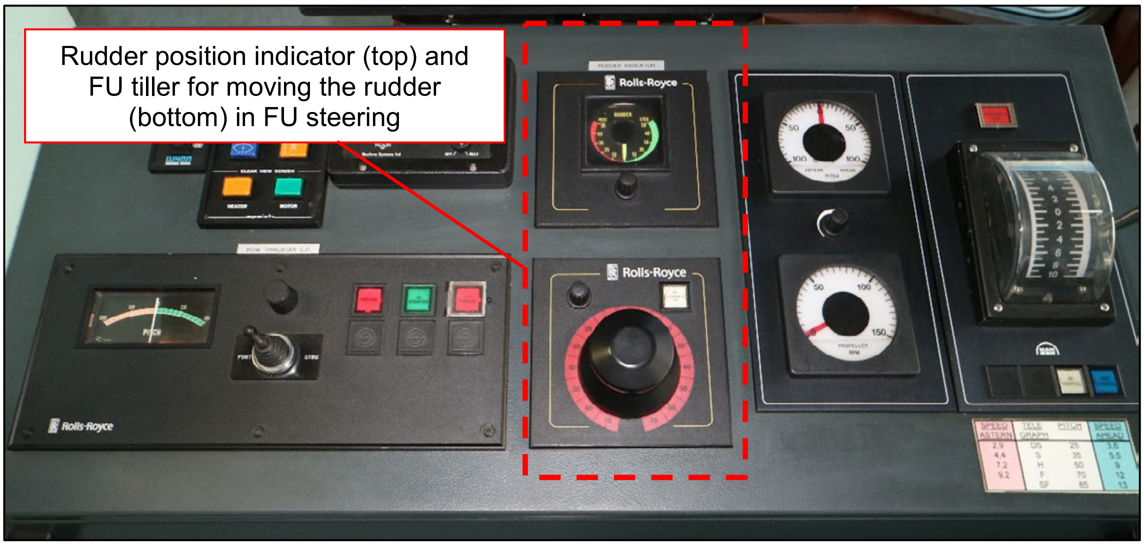

Figure 18: Control position in the starboard wing

3.2.8 Examination of the steering gear

"The steering gear could be operated after clearance by the master. In the steering gear compartment, one NFU steering control, which is operated via two push-buttons (port, starboard), is provided on each of the two control cabinets for this purpose. Prior to that, a selector switch on both control cabinets (off, local control, remote control from the bridge) is used to switch to local control. When starboard is pressed on switch cabinet No.1 (located on the port side), for example, pump unit No.1 (PU1 – installed on the steering gear on the port side) moves from standstill with a speed ramp[20] of about one second to the rated speed and the steering gear turns to starboard. When the button is released, the rated speed returns to zero also within about one second and the system stops. In the direction of port the behaviour is similar, as is the use of the control cabinet on the starboard side and pump unit No.2 (PU2). It should be noted that the frequency converters have no function other than controlling the ramps to reduce the starting currents. However, as explained above, this is not intended in NFU mode. As expected, the system stops automatically if the buttons are held down to the limit positions of the steering gear. Also as expected, if the NFU buttons on both control cabinets are pressed at the same time and in the same direction, both pump units run and the steering gear's rate of turn is doubled.

One characteristic soon became apparent: PU2 was at times much too slow in repeated NFU single operation compared to the steady rated speed of PU1. This was also evident in simultaneous operation, e.g. when PU1 and PU2 were switched simultaneously but in opposite directions. Instead of a standstill, a slow creep occurred in the direction in which PU1 was pumping. It was not possible to ascertain the cause of this malfunction on site. However, the crew apparently investigated the phenomenon between the first and second visit on board. The crew advised the author that a single relay in the control cabinet was found to be defective and exchanged for an identical relay that had been installed in the same control cabinet. The latter was in a supposedly unimportant function and therefore reportedly dispensable. Since then, both pump units have been running identically and without any issues. Since it was not possible to establish a link between the course of the accident and the above anomaly, this aspect was not investigated further after consultation with the client.

Furthermore, checks to ensure the hydraulic system did not have any faults were made in the steering gear compartment. One hypothesis of the author was that the rotary vane system might have an unusually high creep rate. Due to the actual principle, a crawl rate in rotary vane systems is inevitable. Since the seal between the linearly sliding surfaces (e.g., vanes in the housing or stop on the hub) can never be technically tight, unlike rod or shaft seals, there is always leakage from the high- to the low-pressure side when a pressure difference is applied. In the case of balanced rudders,

[20] 'Speed ramp' refers to the chronological sequence of a speed change, i.e. a value for the speed acceleration. The ramp begins when the speed change starts and ends when it is completed (see Wikipedia, 8 September 2021 [in German]).

this leads to the rudder 'creeping' back to the zero position when in the deflected state (rudder angle not equal to 0°) due to the restoring hydrodynamic moment. Depending on the degree of tightness, this happens slower or faster. In FU mode this creeping motion would be constantly corrected by the position control. However, in NFU mode the rudder will creep to the zero position if this behaviour is not known or not noticed. In the case of overbalanced rudders, this behaviour can actually reverse because then the hydrodynamic moment is directed toward large rudder angles and the rudder may move to the limit position unnoticed in NFU mode. The author's assumption that the accident could have been caused by the rudder moving to its limit position at an increased creep rate could be refuted. On the one hand, the rudder should have a strong restoring moment characteristic (as a flap rudder). Accordingly, even if there is an increased creep rate in the steering gear, it would not cause the rudder to move to its limit position but rather only to return to the zero position. On the other hand, the rate of leakage in the steering gear was checked on site by moving the system to the limit on both sides and measuring the leakage oil flow via an open return line. This was surprisingly low for a rotary vane system and would have made it completely impossible for internal leakage to cause such a rapid and unintentional rudder alteration. In the course of that, it was also possible to measure the starting pressures, which constitute a measure of the system and the rudder stock bearing's internal friction. Based on the author's experience, these values were also low and therefore harmless. It can therefore be stated that the steering gear is without defects in terms of its hydromechanics.

Another operating test consisted of verifying the FU function of the steering gear control unit on the bridge. Communication between the bridge and the steering gear compartment was possible via shipboard telephone. On the bridge, a pump unit was activated and the FU tiller used to set a rudder angle. In the steering gear compartment, local operation was selected via the selector switch on the other control cabinet and an attempt was made to move the rudder with the NFU buttons. However, it became apparent that the position and thus control deviations briefly achieved by this were immediately compensated for by the steering gear control unit. Finally, checks were carried out in the steering gear compartment to ensure the rudder angle sensors (as described above) were operable. This involved loosening and moving by hand the linkage between the rudder stock and the potentiometers (one for the display, one for the FU steering – each integrated in a grey housing; one for the autopilot – in its own black housing). These movements were correctly transferred to the rudder position indicator and the FU steering on the bridge; the feedback to the autopilot could not be clearly reproduced 'in the dry'. However, a continuity check of all signal lines between sensors and bridge was carried out by a specialised firm and completed without any findings. In that respect, malfunctioning potentiometers can also be ruled out as the cause of the accident[21]."

3.2.9 Steering gear control unit and autopilot

"After any hydraulic, electrical or mechanical malfunction on the steering gear and its local control cabinets could be ruled out, attention turned to the interaction between steering gear control unit and autopilot.

[21] Ibid.

To begin with, it should be noted that a rudder angle can be correctly selected with the tiller and then held stable in the steering gear control unit's FU mode. The rated speed of the pump unit(s) is reduced when approaching the position selected and stopped when it is reached.

However, as soon as control is transferred to the autopilot, strange behaviour is exhibited in several respects:

a) *if a selected rudder position is set to the autopilot mode of operation (regardless of whether the selected angle is zero or the amidships position or another angle), the steering gear will apply that angle at the full rated speed of the pump unit(s). Once the angle is reached and exceeded (because pump units are still delivering the full oil flow), the pump units are reversed and deliver in the opposite direction. A new peak overshoot develops and the process reverses. The process continues in this manner with a cycle duration of about four seconds. The selected (mean) angle is thus reached, but the pump units operate at the selected position permanently and move the rudder backwards and forwards by a few degrees of deviation. Such behaviour is undesirable in all respects. Firstly, the 'paddling' of the rudder leads to increased resistance of the rudder in the water. This is associated with an increased power requirement of the ship's propulsion and increased fuel consumption. Secondly, the movement backwards and forwards causes a continuously alternating operation of all electrical and hydraulic components, which should actually remain in standby mode after reaching the selected position. Since starting and braking both constitute an increased electrical, hydraulic and mechanical load on all components, greatly increased wear and a reduction in the service life of the components affected must be expected given the extremely high number of switching operations;*

b) *the value of the selected angle that the steering gear aims for in the autopilot mode of operation depends on the current position of the steering gear control's FU tiller when the transfer to autopilot takes place. An example follows for illustration:*

    - *the FU tiller is set to 0° (rudder amidships), the course of the ship at the pier is 127°. A course of 165° is preselected on the autopilot. A deviating course therefore exists when the transfer to autopilot takes place, requiring a course alteration to starboard. Consequently, the autopilot moves the rudder +25° to starboard (+ and – are used below for movements to starboard and to port, respectively). It remains in this position but exhibits the oscillation described under a). Given the deviating course of +38° (= 165°-127°), it is reasonable to assume that a large initial rudder deflection of +25° is appropriate. Of course, this remains at the pier because the course does not alter and the control deviation thus remains constant;*

- *the FU tiller and thus the rudder are at -15° (port), the course is still 127° and a course of 165° is preselected on the autopilot. When the transfer to autopilot takes place, the rudder then only moves to +10° (starboard) instead of +25° as in the previous case;*

- *the FU tiller and thus the rudder are at +10° (starboard), the course is still 127° and the same course of 165° is preselected on the autopilot. When the transfer to the autopilot takes place, the rudder then moves to +35° (starboard) and remains there oscillating;*

- *the rudder angle that the autopilot aims for is obviously not an absolute rudder angle (e.g. +25°) but rather an angular difference to the current initial rudder angle. From the author's point of view, this behaviour of the autopilot is nonsensical both in a navigational and in a technical sense because if the transfer to the autopilot takes place from a previous rudder angle not equal to zero, then the autopilot interprets the current actual angle not equal to zero as a zero angle;*

c) *control is returned from autopilot to the steering gear control unit (and thus to the manual mode of operation) by switching off the autopilot, as already described. If the rudder is amidships and the FU tiller is at 0°, this works perfectly and we can immediately control the rudder via the tiller. However, if the rudder is amidships and the tiller is at a different angle, nothing happens, i.e. the rudder remains in its current position. Only one flashing light indicates that transfer from the autopilot to the steering gear control unit has failed. However, if the tiller is then set to 0° within a limited time, it locks in place, as it were, and then takes charge of steering the rudder. The same behaviour is also exhibited when the current rudder angle is not equal to zero before the transfer but the tiller is set to 0°. In this case, too, control can only be achieved by first putting the tiller on the actual rudder angle at that moment.*

   This characteristic is mentioned in the operating instructions for both the autopilot[22] [...] *and the steering gear control unit*[23] [...]*, notably that the autopilot only transfers control when the tiller is at the actual rudder angle. Since the author is not from the maritime community, he cannot give an assessment of the meaningfulness or safety objective of this function. However, it is reasonable to assume that the transfer from autopilot to the manual mode of operation may not occur at all or at least not quickly enough in stressful situations and/or if knowledge of this function is lacking.*

Finally, it should be noted that there are two buttons for the emergency steering on the bridge console directly above the FU tiller. These are binary (or NFU) buttons. As was shown during the investigation on board, operation of the steering gear using these

[22] Here in connection with the FU steering of the manufacturer of the autopilot.

[23] Rolls-Royce Instruction Manual, 1. Control Systems – Steering Mode FU: "If the in command push button is activated, the system require [sic] that the order signal is equal to the position of the steering gear before the actual steering mode will be activated. If not, the in command light will start flashing to indicate that the operator must change the order signal. The order must be changed inside a period of 6-7 sec."

buttons was possible at any time and from any initial situation (autopilot or steering gear control unit mode of operation)[24]."

Regarding the need to match the position of the FU tiller and the actual rudder angle, Kongsberg Maritime stated in its comments on the draft that this was intended. In this way, a possible accidental adjustment of the tillers at one of the control consoles in the wings would not lead to an unintended deflection of the rudder when switching back to manual steering. This, it said, was to increase the bridge crew's awareness of the overall situation. Kongsberg Maritime also stated that, if the client wished, it was technically possible to switch over when the positions of the tillers and the actual rudder angle differed. This would be the standard today. In principle, the classification societies do not have any requirements for this. It is no longer possible to make any statements today about the agreements made in this regard between the shipyard and/or the client at the time and the manufacturer of the steering gear control system at the time.

3.2.10 Electrical connection between autopilot and steering gear control unit

"As already mentioned, a connection exists between the autopilot and the steering gear control unit, which transmits the commands of the autopilot to the steering gear control unit. This connection transmits signals in one direction only (from autopilot to steering gear control unit); feedback is not given via this channel. The autopilot receives the necessary feedback on the actual rudder angle directly via a dedicated sensor/potentiometer on the steering gear.

The electrical connection between the two modules is located in the bridge console. As far as could be understood, it is a deliverable of the shipyard, which interprets the circuit diagrams and deliverables of autopilot and steering gear control unit and then executes the connection accordingly. Interestingly, the signal is transmitted via two relays, notably a port and a starboard relay. This seems to have been a precautionary measure by the shipyard, as there is no indication of this in the circuit diagrams of the autopilot and the steering gear control unit. This means that the electrical circuits of the autopilot and steering gear control unit are separated from one another electrically (referred to as a 'zero potential contact'). Such a zero potential contact signal transmission is a quite common method of protecting different electrical systems from one another, e.g. in the event of voltage peaks. This is due to the way a relay works. A control current on the primary side can only cause an opening or closing of the secondary circuit on the secondary side. The actual principle prevents any voltage or current peaks from passing through on either side. However, this goes hand in hand with the fact that the actual principle means that a relay is only suitable for digital signal transmission (on/off) but not for analogue (stepless). In the present case, the relays (as electrical switches) are arranged so that each can be controlled by the autopilot's primary circuit and thus either switches the respective secondary circuit off (at control voltage 0) or on (at control voltage x). Three switching states are thus produced in the steering gear control unit's two secondary circuits, i.e. both relays off (both secondary circuits open, meaning that the signal voltage on the steering gear control unit is 0 V); one relay switched (one secondary circuit closed, meaning that the signal voltage on the steering gear control unit is +10 V); the other relay switched (the other secondary

[24] Steering gear report.

circuit closed, meaning that the signal voltage on the steering gear control unit is -10 V).

Based on the behaviour of the steering gear in the autopilot mode of operation described above and on the circuit diagrams of the autopilot and steering gear control unit, it is evident that

- *the autopilot emits a control signal which is meant as a final, binary NFU signal because it acts as a FU steering control due to the feedback on the actual angle;*

- *the steering gear control unit interprets the input signal as a FU signal, which makes sense because it is a FU control unit and converts a FU signal into a digital or binary signal for the pump units;*

- *the relays can only transmit a digital signal and thus a signal that is not at all suitable for FU steering, however.*

The fact is that with a FU signal, the input voltage at the steering gear control unit in the analogue (i.e. stepless) range between -10...+10 V is proportional to a rudder angle (-35°...+35°). However, a digital signal as in the present case, and this is also what the autopilot means, can only satisfy the FU logic ('continue proceeding to port (-10 V) or to starboard (+10 V)). If (as in the present case) this digital signal is transmitted to the steering gear control unit, the latter interprets the 0 V signal as 'move the rudder to the zero position', the -10 V signal as 'move the rudder to hard to port' and the +10 V signal as 'move the rudder to hard to starboard'. From the perspective of the steering gear control unit, a signal voltage of +/-10 V would therefore have to be programmed for each selected rudder angle not equal to 0° or +/-35°. However, neither the selected output of the autopilot nor the signal transmission via relays is capable of this. The following situation arises: the autopilot aims to move the rudder to +17.5°, for example. To achieve this, it switches the starboard relay, which therefore produces a signal voltage of +10 V in the steering gear control unit's secondary circuit. The steering gear control unit understands that a hard-over rudder position of +35° is required and moves the rudder to starboard at the maximum rated speed of the pump unit(s). For the steering gear control unit to be able to interpret the command correctly, the signal voltage would have to be +5 V. Therefore, as soon as the rudder angle of +17.5° and thus the selected position from the perspective of the autopilot is reached, the autopilot switches off the steering signal to keep the position. The 0 V signal voltage is then produced at the steering gear control unit. The steering gear control unit understands that the rudder should be moved to the midship position again and switches the pump(s) to the opposite direction at full rated speed. The autopilot then identifies another control deviation (insufficient angle) and switches the starboard relay again, i.e. the steering gear control unit aims to move the rudder to the hard-over to starboard rudder position again, and so on. Accordingly, there are two steering controls, each of which is acting as a FU steering control with a NFU output signal. Since all this is reinforced by the fact that the steering gear control unit assumes the greatest possible control deviation due to the full deflection signal (+/-10 V), the pump units each run up to full rated speed. Due to the rotational inertia during the reversal, this results in correspondingly high peak overshoots or large amplitudes of the paddle movement around the selected position."

As part of the comments on the draft, Kongsberg Maritime also addressed the discrepancy between construction plans and actual steering gear control. The manufacturer pointed out that steering gears are usually installed on board at an early stage. Due to the long period of construction, it is no longer possible to give details today. In principle, however, the work was carried out by the company's own or authorised technicians at that time. The fact that a different manufacturer was chosen for the autopilot leads Kongsberg Maritime to conclude that the autopilot was only installed on board after the installation of the Rolls-Royce components had been completed. It is likely that the relays in question were then used.

3.2.11 Relays as zero potential contacts between autopilot and steering gear control unit

"Inter alia, it is perfectly clear that in this context the two relays are exposed to excessively high switching frequency. As long as the autopilot is in operation, the relays are switched on and off with cycle times in the single-digit second range. The autopilot is presumably in continuous operation during sea voyages with manual operation usually only being used when manoeuvring. A rough estimate aims to illustrate this: a cycle time of four seconds (two seconds switched on, two seconds switched off) results in 15 switching operations per minute and 900 switching operations per hour. This is equal to almost 4 mn switching operations in one year at half the average operating time. According to Finder[25] (the manufacturer), the mechanical service life is 20...50 mn switching cycles and the electrical service life 200,000 switching cycles. The electrical service life would therefore be reached after only a few months and the mechanical service life after 5...12 years. Since nothing is known about the age of the relays, in the worst case they could still be the original parts from when the ship was first built and thus have been in operation since 2006.

Since the two relays exhibited black deposits inside the transparent plastic housing when inspected and the service engineer described at least the starboard relay as defective after removing it and a continuity measurement (he was unable to be more precise at a later date), a decision to secure the two relays and examine them more closely was taken. To that end, expert in electrical components Prof. Dr.-Ing. Günter Ackermann (Emeritus at the Hamburg University of Technology and former head of the Institute of Electrical Power Systems and Automation) was requested to examine the relays. He was unable to identify a malfunctioning of the relays or their plug base with his extensive measuring equipment, however[26].

Since Professor Ackermann is not familiar with material examinations and the non-destructive functional analysis of the relays did not deliver any findings, the materials testing laboratory MQ Engineering in Rostock was commissioned with the further examination of the components. The examination steps and findings are set out in a

[25] *Finder relay datasheet* (Note: Not reproduced in the report).
[26] Ackermann, G.: Findings of the Inspection of the Relay of the Rudder controller M/T Northsea Rational, 29.01.2021 [sic]. See section 9.1 of the Annex.

detailed report[27], which states that the visible deposits are mechanical wear material that covers the operating contacts. The port relay exhibited furrows and scratch marks on the operating contacts and housing, which can be traced back to mechanical cleaning with previous opening of the relay. The starboard relay exhibited fatigue on the operating contacts, i.e. indications of high mechanical stress on the contact surfaces from which pieces had broken off due to material fatigue. No indication of electrical discharges or other electrical stresses was found. However, silver sulphide layers were found on the operating contacts of the port relay, which are known to be caused by prolonged exposure to sulphurous atmospheres (such as sea air) and can increase contact resistance.

The last section of the report is reproduced verbatim. Start of quote: "The wear products present in both relays and the silver sulphide layers that were additionally found on the port-side relay are therefore to be considered potential causes of a malfunction that occurred at least temporarily. The fact that the external contacts of the port-side relay were mechanically cleaned implies that there had been problems with this relay at least once before and that these were evidently related to the contact surfaces." End of quote.[28]

3.2.12 Further steps of the examination

"Messrs Diedrichs had already replaced the autopilot unit with an identical one before the author's involvement. The examinations on board already discussed were therefore carried out with the replacement unit. The original unit was sent to the manufacturer (Navitron) in the UK and examined there on 8 January 2021. Due to the coronavirus pandemic, the parties involved took part in the examination (conducted by two employees of Navitron according to a standardised and previously accessible test procedure) via videoconference. To begin with, the sealed package was opened in front of a running camera. No irregularities were found during the examination. However, the ensuing discussion revealed three interesting aspects:

- *the fact described above that the autopilot sets only angular differences that are based on the rudder angle applied when the transfer takes place instead of the absolute rudder angle was unknown to the experts from Navitron and could not be explained;*

- *to eliminate the 'paddling' of the rudder, the installation of an additional unit between the autopilot and steering gear control unit, notably an analogue steering interface (ASI), was proposed, and*

[27] Oelschner, H. (MQ Engineering GmbH): *Inspektionsbericht Nr. 52 027 -1, Untersuchung an zwei potentiell schadhaften Relais / Schiffsobjekt „Northsea Rational“* [inspection report 52 027 -1, examination of two potentially defective relays/ship: NORTHSEA RATIONAL, 15 April 2021]. See section 9.2 of the Annex.
[28] Steering gear report.

– *the sensor signal of the 'black housing', which is fed into the autopilot, would then reportedly only serve to indicate the rudder position on the autopilot and thus reportedly not affect the control system[29]."*

[29] Ibid.

4 ANALYSIS

4.1 Technical recordings

The actions of the people on the bridge could only be assessed using the audio recordings from the VDR and the NMEA data. Other technical recordings such as the operation of switches on the steering gear control system or selected rudder positions while the steering gear control was on manual control, were not available. The technical standards for VDRs require the recording of such data only for the autopilots[30].

Not a single audible alarm can be heard in the audio recording from the VDR during the relevant switching period. In this respect, it remains unclear to what extent a malfunction or a failure to transfer from one control to the other was actually indicated.

4.2 Actions of the ship's command

The NORTHSEA RATIONAL was approximately on the radar reference line when the rudder failed. The distance to the northern bank was about 240 m. The distance to the pontoons in front of it, where tugs were moored, was approx. 180 m. Only one minute and 44 seconds elapsed between the problem occurring (102026) and the allision with the quay (102210). Since the pilot initially assumed that an operating error of the second officer had led to the hard-over rudder position to starboard and thus to the ship turning, he recommended counter rudder (102039) and switching back to hand steering (102048). It became clear only shortly afterwards that this was not an option because the steering gear control system did not respond to the manual input of a rudder position. This reduced the time available to the ship's command to a maximum of 80 seconds before hitting the quay wall. By then, the master and pilot attempted to reduce the ship's speed by performing a full astern manoeuvre and dropping the port anchor. In addition, the pilot issued an instruction to sound the tyfon vigorously to warn the surrounding area. This was appropriate, as in the indefinable direction of travel there were several tugs at the Neue Schlepperbrücke bridge and other vessels behind the jetty at Neumühlen.

The measures taken and the turning motion of the ship resulted in a speed reduction of about 3 kts.

4.3 Emergency steering

The investigators assume that the ship's bridge team did not attempt to regain control of the steering gear control system by transferring to emergency steering (NFU steering). However, the investigators do not believe that a transfer would have enabled the ship to sail round all the collision hazards. This is due to the time required to put the rudder to port, the poor flow at the rudder at the presumably maintained rate of speed (full astern) and the negative effect of the tidal current on the turning circle.

[30] A.861(20) 5.4.10 – Performance standards for Shipborne Voyage Data Recorders (VDRs).

Accordingly, the NORTHSEA RATIONAL would possibly have had an allision with the jetty at Neumühlen or collided with one of the vessels moored there.

4.4 Signal connection between autopilot and steering gear control unit

"The signal connection between the autopilot and steering gear control unit is executed unfavourably and leads to excessive switching frequency of the two relays that are intended to establish the zero potential contact. It can be assumed that at least the port-side relay has already exhibited irregularities in the past, as it was manually "cleaned". It is no longer possible to establish which irregularity made the cleaning necessary because Technical Management has only recently taken over the ship and does not know every detail of the history; [this also applies] *to the present crew. However, it is reasonable to assume that this was a malfunction due to the high switching frequency. It is also reasonable to assume that sooner or later the relay on the starboard side had to exhibit irregularities, too, due to the same mechanism of wear. An irregularity or malfunction in such a relay may occur in two ways, i.e. either the relay does not close despite control current or the relay does not open despite interruption of the control current or only opens with a delay, i.e. it sticks.*

The first case can be excluded with a high degree of certainty. If the starboard relay or neither relay had closed, there would not have been a deflection of the rudder when the autopilot was activated but rather the rudder would have remained in its initial position (amidships).

On the other hand, the second case is considered to be highly likely. After the relays had passed through an extended period of inactivity when the ship was laid up, they were switched again for the first time directly after activation of the autopilot. An initial steering command from the autopilot to the steering gear control unit to move the rudder varying degrees to starboard switched the starboard relay. However, if this relay did not re-open when the selected position was reached despite removal of the switching current, then the rudder would be moved further to starboard until it did open. This is supported by the rudder angle curve, which according to the VDR recordings initially exhibits a wide deflection to about +27° (starboard), a subsequent reset to 0°, then two small deflections to starboard and port (each less than 10°), until the rudder finally remains in the zero position. Although the rate of turn of the rudder angle is high, this is understandable if we assume operation with both pump units, which is usual in confined areas. The yaw motion of the ship to starboard initiated by the strong rudder deflection could not be stopped to begin with, in particular as it was not possible to return to hand steering. That this did not succeed is related to the autopilot's discussed characteristic of transferring to hand steering only when the rudder angle selected on the tiller is the same as the actual rudder angle at that moment. In this frantic situation we may assume that the tiller was set to hard to port to counteract the yaw motion[31]. However, since the actual rudder angle was on the starboard side or in the neutral position, the transfer could not succeed. Having said that, the emergency control buttons positioned directly above the FU tiller would have made it possible to move the

[31] Note: This refers to the ship's turning motion to starboard.

rudder manually. It was not possible to clarify why this option was not made use of. When the ship's main propulsion was set to full astern – which is implemented quite quickly in a system with a CPP in constant speed mode – as a result of her continuous turn to starboard, the situation was aggravated by the fact that the flow at the rudder was now no longer in the normal direction (figuratively speaking, the propeller draws the water away from the rudder) and consequently could no longer achieve any steering effect. […]

The assumption that the relays had reached the end of their service life is further supported by the identical relay in PU2's switch cabinet. This relay was located in a position in the system through which steering commands of the steering gear control unit pass and is therefore exposed to the same high switching frequency as the relays on the bridge. Its malfunction was obvious, in particular as the crew remedied the issue by replacing the relay with a less stressed used component. However, the author is not aware of the location of the defective relay, so it is not available for verifying examinations.

Consequently, the irregularities a) and c) set out in [subsection 3.2.9] *are considered relevant to the course of the accident.*

The irregularity according to b) seems irrelevant but nevertheless noteworthy. It seems as if the autopilot interprets the actual rudder angle when the transfer takes place as a zero value and determines its changes on the basis of this notional zero position by polarity-based addition of the selected angle changes. It was no longer possible for the author to determine whether this behaviour could be stopped by installing the ASI[32]."

4.5 Findings

Wirz arrives at the following conclusion in his report:

"In the opinion of the author, the most likely course of the accident can be explained as follows: the signal connection between autopilot and steering gear control unit was executed in such a way that, inter alia, there was an excessive switching frequency of the zero potential contacts (relays) throughout the autopilot operation. On the day of the accident, the starboard relay failed and temporarily 'stuck' at the very moment that the first transfer of control to the autopilot took place. As a result, the rudder moved to a large starboard-side angle, putting the ship into a yaw motion to starboard in the process. This movement could no longer be stopped because the return to hand steering would have required a special operating method, which was not possible at that moment. […]

Accordingly, the cause of the accident was the execution of the signal connection between autopilot and steering gear control unit; however, the ultimate trigger was the temporary malfunctioning of the starboard relay, which is due to earlier excessive switching frequency with corresponding wear.

[32] Ibid.

Remedial action may include a number of measures:

- *replace relays exposed to a high switching frequency with new components at regular intervals. However, this measure would only address the final consequence of the unfortunate structure of the system and would not eliminate the cause;*
- *a direct connection between the autopilot and steering gear control unit would avoid the (apparently temperamental) relays, thus preventing their failure. However, this would not remedy the unfortunate structure and unfavourable mode of operation (paddling of the rudder);*
- *instead, the most sensible measure recommended is the appropriate execution of the signal connection and the type of signal implemented between autopilot and steering gear control unit (FU as opposed to NFU or analogue as opposed to digital). This is the only way to avoid paddling of the rudder and thus excessive switching frequency of the (then no longer needed) relays and all components of the steering gear, and instead enable a more common, conservative and efficient rudder operation[33]."*

[33] Steering gear report.

5 CONCLUSIONS

5.1 Cause of the accident

From the perspective of the investigators, the NORTHSEA RATIONAL accident constitutes an incident in which the chain of events led to an allision with the pier. The cause was the described wear on a relay, which led to its failure. Accordingly, this short-term failure was the direct cause of the accident. The failure occurred when the transfer to autopilot took place. The BSU's expert and its investigators are of the opinion that this failure led to a strong deflection of the rudder to starboard. This rudder deflection caused the ship to start turning. The expert believes that the immediate return of the rudder is an indication that the relay's operability was restored at this point.

The failure of the relay was not caused by an operating error of the crew. Rather, it was a random event and could not be influenced.

5.2 Influencing factors

5.2.1 Steering gear control system

When the ship was built, relays that were originally not envisaged in the circuit diagram had been installed in the steering gear control system. The investigators assume that this installation was carried out by the shipyard. The outcome of this was that a control signal capable of applying a value between -10 V and +10 V was turned into a binary signal. At the same time, this caused the steering gear to work at full power with every steering command, resulting in continuous overshooting and countersteering (paddling). On the one hand, this led to a heavy load on the components of the steering gear. On the other hand, this resulted in extremely high switching frequency within the electrical components. As shown, the relays were particularly affected by this[34].

The investigators believe that the NORTHSEA RATIONAL's crew was not aware of the existing problem until the investigations and examinations carried out in response to the accident. This applies even though a comparable event had occurred previously. However, since a fault was identified during the requested service, the crew members understandably thought they were safe.

The investigators also believe that it was unreasonable to expect the crew and the shipping company, which had only been in charge of the ship for six months, to examine all the ship's systems for potential vulnerabilities, especially as the steering gear did not appear to show any irregularities during normal operation. The 'paddling' described in subsection 3.2.9 would probably have been observed during an extended examination of the steering gear's behaviour in the engine room, but there was no immediate reason for this, as already described. The investigators believe that responsibility lies more with the classification society that monitored the ship's

[34] See also the expert report referred to in 9.2 and subsection 3.2.11 of this report.

construction. The deviation in the configuration of the steering gear control system could or should have been noticed at that point.

The investigators found no evidence to suggest that the crew on board at the time of the accident had made the manipulations on or attempts to clean the relay contacts, as identified during the assessment.

5.2.2 Switching from autopilot to FU steering

The second officer's attempt to switch back to hand steering during the return of the rudder failed at first because of the difference between the position of the FU tiller and the actual rudder position at that time. This was only achieved at 102030 when the actual rudder position (+09.0°) was close to the position of the FU-tiller (+06.0°).

The investigators assume that the II NO then switched back to manual steering at 102042, as the harbour pilot had recommended a rudder angle of 10° to port at 102039 in order to counter the ship's incipient turn to starboard.

The investigators assume that the rudder – the FU tiller – was then set to the rudder position recommended by the pilot (port 10). This again resulted in a discrepancy between the position of the FU tiller (now 10° to port) and the actual position of the rudder (almost amidships). Again, the transfer did not succeed because of the discrepancy that once more existed.

Switching is only possible if the current rudder position, i.e. a rudder position of 10° starboard, and the position of the FU tiller are as close to each other as possible or if the tiller is at least moved in the direction of the current rudder position. Ideally, the tiller should therefore also be at 10° starboard. In any event, it was not possible to effectively regain control of the FU steering before the allision happened.

During the investigation, the investigators gained the impression from the above that the bridge team was probably not fully aware of the need to match the tiller and rudder position when switching from autopilot to FU steering.

That the instructions on the central console for the procedure for switching from autopilot to FU steering and vice versa do not address the problem described can serve as evidence of this. In this respect, the crew can be credited with the fact that switching with a strong deviation between the current rudder position and the position of the tiller is rather unusual in the opinion of the investigators. The sharp deviation on the day of the accident only resulted from the brief failure of the relay and the resulting strong rudder deflection; it was not influenced or triggered by the helmsman. However, if the bridge team had been aware of the problems described above, it would have been able to actively intervene and retrieve the steering.

The BSU therefore sees an issue with training here. Efforts should be made by the shipping company to train the crews in all aspects of the steering gear control system.

In its statement on the draft, the shipping company considered that it was not a "normal" switching situation. No one would have to expect such a strange and unintended behaviour of the rudder. Therefore, matching the tiller and the actual rudder angle in such a scenario is far from intuitive.

The investigators did not address the question of whether the allision or another collision could have been prevented if the switch from autopilot to FU steering had been successfully transferred immediately. The BSU would have found the answer too speculative.

5.2.3 Manuals

During the analysis of the manuals of the manufacturer of the autopilot and the steering gear control system, the investigators noted that the description of the steering gear or the switching process to the FU steering is not presented in the manual as particularly relevant to safety. However, the NORTHSEA RATIONAL case shows that a potential risk prevails in this respect. With that in mind, the BSU believes there is a need for emphasis in the steering gear control manual.

6 ACTIONS TAKEN

On being questioned, the service firm commissioned by the shipping company advised that the ASI had been installed on board the NORTHSEA RATIONAL. At the same time, the relays were also removed. In addition, the linkage and the measuring unit for the actual rudder position were also removed, as this function is now covered by the autopilot. The steering gear control system thus now offers the full range of functionality.

The legal counsel of the shipping company informed on 8 October 2021 that the same technical conversion was carried out on the sister ship NORTHSEA LOGIC on 6 October 2021.

Prior to the conversion, the autopilot was no longer used on the NORTHSEA LOGIC during sailing in estuary mode.

As part of the comments on the draft, the shipping company informed that, after the incident, the managers of MV NORTHSEA RATIONAL have carried out video trainings with the command of all vessels under their management addressing these critical switching operations. Further, they have revised the navigation manuals of all vessels. The navigation manuals now expressly exclude the use of the autopilot in narrow channels or rivers even if requested or recommended by the pilot. Further, the manuals now require that every change from automatic to manual steering and vice versa needs to be supervised by a responsible officer.

Managers have as well revised the familiarisation forms, which expressly include the emergency change over procedure for the steering. An on-board training procedure on “Change over procedures between FU and emergency steering” has been implemented.

In addition, posters visualising the emergency steering procedure are being displayed in the wheelhouses.
The BSU notes that the measures implemented by the management of the NORTHSEA RATIONAL make safety recommendations to the shipping company or the ship's command obsolete. The report was amended to this effect.

7 SAFETY RECOMMENDATION

The following safety recommendation do not constitute a presumption of blame or liability.

Manufacturer of the steering gear control system

The Federal Bureau of Maritime Casualty Investigation recommends that the manufacturer of the steering gear control system, Kongsberg Maritime, adapt the current steering gear control system manuals so that safety-critical conditions during switching operations are better highlighted in the text.

8 SOURCES

- Investigations of the WSP
- Witness testimony
- Expert reports
  - Prof. Dr.-Ing. F. Wirz: *Gutachten / Analysebericht zur Kollision von M/T Northsea Rational im Hamburger Hafen im November 2020* [expert/analysis report on the allision involving the MT NORTHSEA RATIONAL in the port of Hamburg in November 2020]
  - Prof. Dr.-Ing. G. Ackerman: Findings of the Inspection of the Relay of the Rudder Controller M/T Northsea Rational [sic]
  - H. Oelschner: *Untersuchungen an zwei potentiell schadhaften Relais / Schiffsobjekt „Northsea Rational“* [examination of two potentially defective relays/ship: NORTHSEA RATIONAL]
- Navigational chart 1662, BSH
- Ship files and recordings from the ship's VDR
- Manual for the NT991G MK2 autopilot and manual for the NT990ASI analogue steering interface from Navitron (the manufacturer)
- Manual for the steering gear control system from Rolls-Royce (the manufacturer)

9 ANNEXES

9.1 Verification of the electrical functionality of the steering gear control system's relays

Prof. Dr.-Ing. Wirz requested a sub-assessment from Prof. Dr.-Ing. G. Ackermann for the determination of the electrical functionality. The ensuing expert report (Findings of the Inspection of the Relay of the Rudder Controller M/T Northsea Rational [sic]) is available on the BSU's website for this case.

9.2 Examination of the contact surfaces of the steering gear control system's relays

For a more detailed investigation of the steering gear control system's relays, in particular the contact surfaces, Prof. Dr.-Ing. Wirz requested another sub-assessment from MQ Engineering GmbH. The expert report prepared by Mr Oelschner (*Untersuchungen an zwei potentiell schadhaften Relais / Schiffsobjekt „Northsea Rational“* [examination of two potentially defective relays/ship: NORTHSEA RATIONAL]) can also be viewed on the BSU's website for this case.