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WORKLOAD OF THE STEERING WORK ON A HIGH-SPEED VESSEL

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The higher incidence of accidents occurring on board among the high-speed vessels has motivated this study focusing on the actual operating conditions contributing to the incidence. The working activities and workload of the officers and quartermasters were compared between the conventional and high-speed vessels of regular service ferry, by recording video-pictures and heart rate of the crews during actual navigations. An autopilot equipment was installed in the conventional vessel of over 6,000 tons, but not in the high-speed vessel of about 1,500 tons.

Either on the conventional or high-speed vessel, dominant activities of the officers were lookout and watching radar, which were conducted in standing on the conventional vessel and in sitting on the high-speed vessel. Major works of the quartermasters were lookout and radar watch in standing on the conventional vessel and steering operations with a joystick in sitting on the high-speed vessel. Despite these differences in postural conditions, the mean % heart rate increase in both crews was significantly higher on the high-speed than on the conventional vessel. In the quartermaster, the events requiring steering maneuvers on the high-speed vessel were associated with increase in heart rate.

The findings as a whole suggest occurrence of substantial mental strains in the crew on the high-speed vessel. These strains, certainly derived from caring for the safety in the absence of autopilot equipment, must have intensified the workload in the crew. In connection with the workload, the necessity for some fail-safe systems, including the autopilot facilities, and educational systems for techniques of steering high-speed vessels was discussed.

Key Words: high-speed vessel; conventional vessel; accident; steering work; heart rate

INTRODUCTION

Although trucking is currently the primary mode of freight transportation, it is facing obstacles such as labor shortages and problems with inappropriate traffic design and environmental degradation resulting from the congestion of roads, air pollution and noise. A modal shift away from trucking to railway or shipping should be encouraged. One of the impediments to shipping has been the speed of the vessel, which at present ranges from approximately 15 to 20 knots, much slower than that by other forms of transportation.

Recently, various types of high-speed vessels have been developed. Of the 1,365 passenger ves-

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sels operating in 1991, 32 were high-speed vessels, accounting for 2.3% of all passenger vessels (Ministry of Transport 1993). The incidence of accidents for the high-speed vessels was 3.8%, while it was 1.2% and 2.9% for the passenger vessels and ferryboats, respectively (Japan Marine Accident Inquiry Agency, 1996). Despite this higher rate of accidents occurring on high-speed vessels, studies dealing with the working behavior of the crew on high-speed vessels are limited in number. Inoue (1992) studied the relationship between the distance to obstacles (ship etc.) and the safety sense of officers on high-speed vessels. Furushou et al. (1995) reported that the extent of visual comprehension of steering workers on a high-speed vessel, a jet foil, was different in different navigation areas. Furushou et al. (1991) and Kai et al. (1992) studied the problems associated with a lookout of steering workers on high-speed vessels at night. However, the physiological load of the steering works on high-speed vessels and its possible role in the occurrence of accidents has not been clarified.

This study focuses on steering workers and their workload on the high-speed and conventional vessels, with a view to elucidating the steering operations contributing to their increased workload and their implications for the safety of the vessel.

METHODS

The effects of steering work on the crew and their workload were compared between high-speed and conventional vessels. The incidence of working activities and data of heart rate were collected during round trips between two ports, A and B. The distance between port A and port B was 113 km (Figure 1).

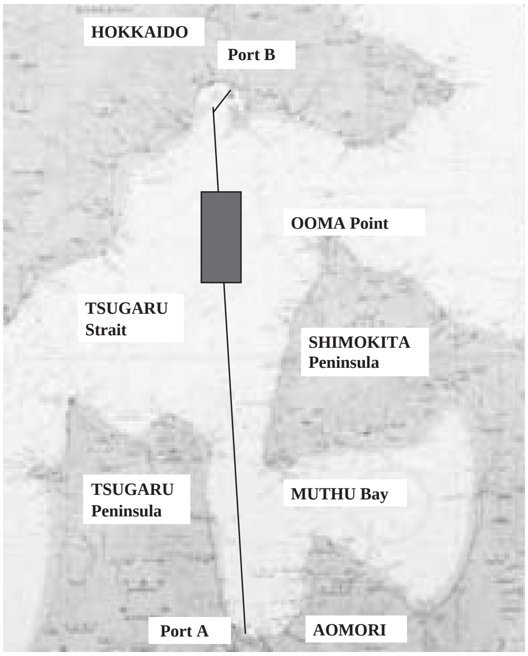

Fig. 1 Map of the Tsugaru Strait and Mutsu Bay area. Round trip ferry services are placed between port A and port B. A shaded square inserted indicates the area in which heart rate of the crew was compared between the conventional and high-speed vessels.

The investigation was conducted on six days in 1998 (26 and 27 June and 1, 2, 5 and 6 July). The weather was cloudy on 27 June and on 1, 2, 5 and 6 July, with the wind velocity of 2-3, 5, 4, and 3-4m/sec, respectively. It was rainy on 26 June with an average wind velocity of 5m/sec.

The conventional vessel: departure from port A at 7:30 → arrival at port B at 11:10, departure from port B at 12:10 → arrival at port A at 15:50 on 26 June, and 2 and 6 July.

The high-speed vessel: departure from port A at 12:00 → arrival at port B at 14:00, departure from port B at 15:20 → arrival at port A at 17:20 on 27 June, and 1 and 5 July.

Vessel conditions

The vessels investigated in this study were regular service ferries for passengers and vehicles. The outline of vessel specifications is shown in Table 1. A comparison of vessel characteristics showed that the high-speed vessel was smaller in hull scale but faster in speed and had a shallower draft, a shorter stopping length, shorter stopping time, greater tactical diameter, and shorter turning time than the conventional vessel. The difference in the hull scale was also a factor affecting the required crew size; the size of the crew (8 people) on the high-speed vessel was much smaller than that on the conventional vessel (14 people). Thus, the conventional vessel plied for 24 hours, while the high-speed vessel plied for shorter day trips. The conventional vessel was installed with an autopilot equipment, while the high-speed vessel was not.

Table 1. The characteristics of two vessels studied.

	High-speed vessel	Coventional vessel
Gross tonnage	1,498 tons	6,358 tons
Number of crews	8	14
Bridge type	cocpit type	conventional
Number of passenger	423	600
Number of vehicles	106 cars	96 trucks, 20 cars
Length	90.0 m	125.0 m
Breadth	14.9 m	21.0 m
Depth	10.3 m	12.0 m
Speed	35 knots	20 knots
Output power	35360 PS	18200 PS
Fore draft	3.4 m	4.7 m
After draft	1.4 m	6.0 m
Trim	0.01m	1.28 m
Stopping time	38 sec	175 sec
Stopping length	470 m	1026 m
(Left turn)		
Degree	30	35
Turning time	54.3 sec	87.8 sec
Advance	418 m	338 m
Transfer	234 m	138 m
Tactical diameter	502 m	324 m
(Right turn)		
Degree	30	35
Turning time	56.7 sec	88.8 sec
Advance	437 m	343 m
Transfer	226 m	129 m
Tactical diameter	499 m	321 m

Floor arrangements of the bridge and working scenes of the crew are shown in Figures 2 to 5. In the conventional vessel, only one seat was placed independently from the steering wheel and 2 radars. In the high-speed vessel, 5 seats were set in front of a console, of which the central one was assigned for operating the steering joystick. Two radars were located at both sides of the console, but they could not be operated while seated. A chart table was located in the backspace in both vessels.

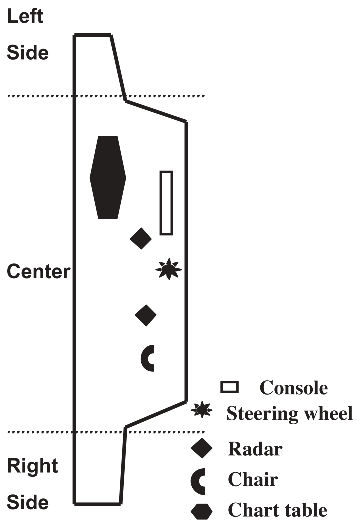

Fig. 2 Floor arrangements of the bridge in the conventional vessel.

Fig. 3 The crew working in the bridge of the conventional vessel.

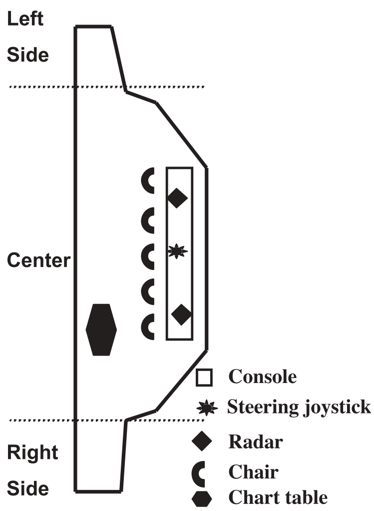

Fig. 4 Floor arrangements of the bridge in the high-speed vessel.

Fig. 5 The crew working in the bridge of the high-speed vessel.

Steering conditions

The watch rotation on the conventional vessel comprised one officer and one quartermaster. The officer did lookout and the quartermaster kept steering the wheel in principle. However, they were often both looking out because the steering wheel operations required far less work when the autopilot equipment was in use. Except for the set-up at the time of departure from the port, little trim adjustment was required until arrival.

The watch rotation on the high-speed vessel comprised one officer and two quartermasters. One of the quartermasters was always operating the joystick (steering wheel) since there was no autopilot equipment on the ship. It was often necessary to adjust trim by another quartermaster because the effect of wind was amplified by the shallow draft. The quartermasters rotated their duties every 30 minutes.

During the navigation, the crossing conditions included the presence of other vessels. The number of vessels encountered during a trip ranged from 8 to 10, most of which were the regular service ferries that repeated navigation along the same course line. Few fishing boats were observed during the investigations although this area was a good squid-fishing field.

Activity analysis

On each of the 6 round trips, we recorded the working activities of the crew at a position about 5-8 m away with a video-camera generating time signals at 1 second intervals (Handycam TR-66: SONY Co.). The subjects were officers and quartermasters at work in the round trips. The videotape was analyzed at 1 second intervals and the incidence of a given activity and working position, respectively, was calculated as percentage of the duration of the activity or position against the total recording time.

Heart rate analysis

Heart rate of the crew was measured with a portable heart rate recorder (TM-2425: A/D Co.). Instantaneous heart rate measured based on the R-R interval and accumulated in the recorder was fed to the personal computer, and the mean heart rate was calculated for a given interval. Subjects were an officer aged 32 and a quartermaster aged 40 on the conventional vessel, and an officer aged 35 and a quartermaster aged 30 on the high-speed vessel, respectively.

The physiological load may differ among individuals with the same heart rate because the maximum heart rate or resting heart rate of an individual varies with age and other conditions. Taking these situations into account, individual heart rate was converted into a relative heart rate increase by considering the maximum and resting heart rate levels in each subject. According to the formula by Isozaki et al. (1996), the % heart rate increase was calculated as follows;

$$\% \text{ heart rate increase} = 100\,(HR_{ex} - HR_{rest}) / (HR_{max} - HR_{rest}),$$

where HR_{ex} is the mean heart rate actually measured in activities, HR_{rest} is the mean heart rate at rest, and HR_{max} is the maximum heart rate. The heart rate at rest was measured while the subject was seated, with the eyes closed, before each work shift began. Because it was difficult to measure the maximum heart rate, we used the expected maximum value corresponding to the subject's age proposed by Aunola et al. (1979), i.e. subtracting the subject's age from 220. The health condition of the subject indicated there had not been a heart-related illness.

RESULTS

Working activities

The incidence of working activities averaged for the 3 round trips on each type of the vessels are shown in Table 2. In the case of officers, working activities in the bridge on the conventional vessel

Table 2. Working activities of crews on board the high-speed and conventional vessels.

	High-speed vessel			Conventional vessel	
Activities	Officer (%)	Quarter-master 1 (%)	Quarter-master 2 (%)	Officer (%)	Quarter-master (%)
Lookout	43.2	23.8	5.4	55.8	32.4
Lookout by binocular	15.3	6.8	2.1	2.1	3.6
Watching meter	0.1	0.2	0.0	1.0	2.6
Watching radar	12.6	2.2	0.4	8.5	6.4
Steering operation	0.0	27.2	32.5	0.0	2.0
Conversation	0.7	0.3	0.4	0.1	0.3
Telephone	1.2	0.4	0.2	0.4	0.9
Recording	5.7	0.4	0.4	3.0	5.6
Walking	0.1	0.5	0.6	0.1	1.4
Wait for next process	0.4	1.4	2.2	0.3	4.6
Others	1.3	11.4	7.3	1.8	7.7
Out of bridge	19.5	25.4	48.5	26.9	32.5

mainly consisted of lookout without binocular, which accounted for more than 50%, followed by watching the radar amounting to around 9% and lookout with binocular 2%. Watching the radar increased on June 26 because it was a misty day with difficulties in watching forward with the eyes.

On the high-speed vessel, activities of the officer in the bridge mainly comprised lookout without binoculars accounting for ca. 40%, followed by lookout with binocular amounting to around 15%, and watching the radar ca.13%. On the high-speed vessel, the incidences in officers for lookout through binoculars and watching the radar were higher than on the conventional vessel.

In the case of quartermasters, activities in the bridge on the conventional vessel mainly comprised lookout without binocular, which accounted for ca. 30%, with watching the radar about 6% and wheel operation corresponding to 2%. By contrast, their works on the high-speed vessel was considerably different; for each of the two quartermasters, joystick operation accounted for ca. 27% and 32%, lookout without binocular 24% and 5%, lookout with binocular 7% and 2%, respectively. Watching the radar was infrequent. On the high-speed vessel, the joystick operations thus occupied a major part of works of the quartermaster in the bridge.

Working positions

The incidence of working positions averaged for the 3 round trips on each type of the vessels are shown in Table 3. The officer took working positions in the bridge on both vessels most frequently at the center of the bridge. On the conventional vessel, lookout in the center and right side of the bridge, accounting for more than 50% in total, was exclusively done in standing, and looking at the radar also in standing accounted for ca.10%. In the case of the high-speed vessel, by contrast, lookout by officer in sitting accounted for 43%, lookout while standing to see the distance with the binoculars 24%, and looking at the radar in standing ca.13%. The position of the officer shifted frequently from sitting to standing to watch the radar because it was not possible to operate the radar while sitting.

The quartermaster also took the working position most frequently at the center of the bridge on both vessels. On the conventional vessel, lookout and operating the radar by the quartermaster while standing accounted for 37% and 5%, respectively. On the high-speed vessel, by contrast, joystick operation in sitting amounted to 40 to 50%. One of the quartermasters additionally took standing position for lookout in 10%.

Table 3. The working positions of crews on board the high-speed vessel and the conventional vessels.

	High-speed vessel			Conventional vessel	
Positions	Officer (%)	Quarter-master 1 (%)	Quarter-master 2 (%)	Officer (%)	Quarter-master (%)
Left side	0.0	0.2	0.1	0.2	0.5
Center (standing)	24.2	10.3	0.0	45.4	36.7
Center (sitting)	42.9	53.2	42.4	0.0	0.0
Center (radar)	12.6	2.2	0.4	10.5	5.1
Chart table	0.1	0.6	0.3	3.0	5.6
Right side	0.0	3.5	3.5	13.3	13.5
Others	0.7	4.6	4.8	0.7	6.1
Out of bridge	19.5	25.4	48.5	26.9	32.5

Heart rate increase

Figures 6 and 7 illustrate examples of the temporal change in % heart rate increase of an officer during navigation with conventional vessel and high-speed vessel, respectively, from port A to port B. On the conventional vessel, the increment attains to around 10 %, though with considerable fluctuations, in the first half of the trip, and reduces to around 5% in the second half. By contrast, in the case of the high-speed vessel, the increment fluctuates between 5 % and 15 % in the first half of the trip, and increases gradually to reach 25 % in the second half. The Tsugaru Strait area, where the vessel operation was difficult due to ocean current, is situated in the second half of the trip.

To evaluate the difference in cardiovascular responses in the crew between the vessels, mean % heart rate increase was calculated for the period when the vessels passed the Tsugaru Strait area, and was compared between the vessels. Although the subject crew was different between the two vessels, the % heart rate increase should have provided numerical values standardized across the subjects.

The results are shown in Table 4. For the officer and quartermaster inclusive, the heart rate increase was significantly higher on the high-speed than on the conventional vessel ($p<0.01$ for the officer and $p<0.05$ for the quartermaster).

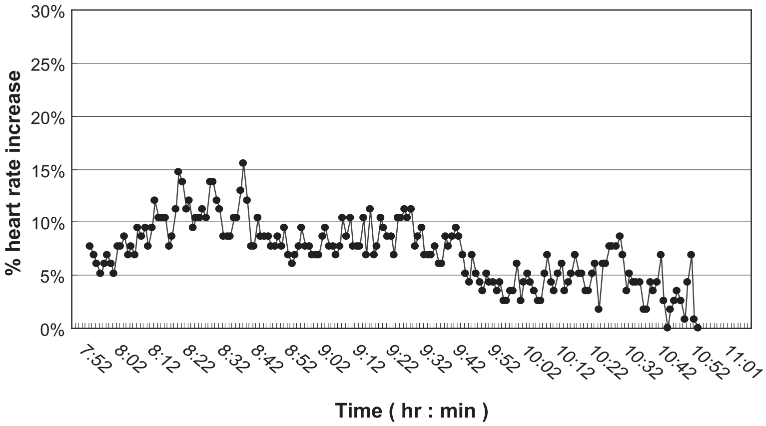

Fig. 6 The % heart rate increase of an officer on the conventional vessel navigating from port A to port B.

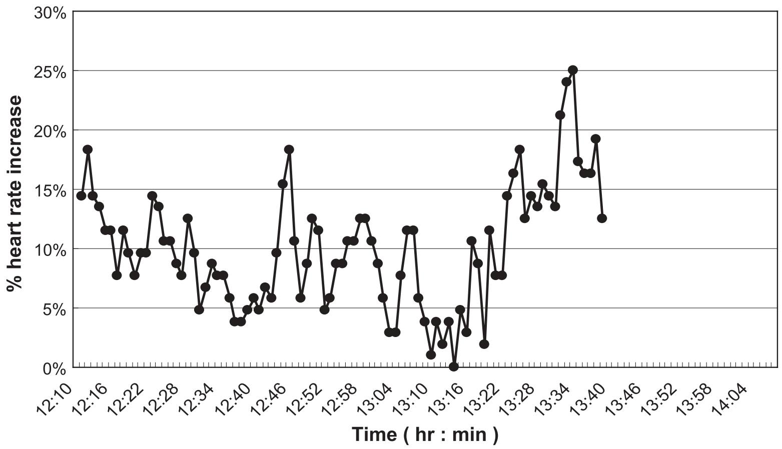

Fig. 7 The % heart rate increase of an officer on the high-speed vessel navigating from port A to port B.

Table 4. The *t*-test results for compared of % heart rates increased of the high-speed vessel and conventional vessel.

	Officer		Quartermaster	
	High-speed	Conventional	High-speed	Conventional
Number of observation	286	286	148	148
Mean	8.9	7.8	7.5	6.5
SD	3.8	4.4	5.0	3.1
Degree of freedom	285		147	
Significance	$p < 0.01$		$p < 0.05$	

The steering maneuvers on the high-speed vessel

The wheel operation of the conventional vessel installed with autopilot equipment was done only once every 20-30 minutes. As the high-speed vessel did not have the autopilot equipment, the wind influence in shallow water was notable, requiring the quartermasters to undertake counter-steering maneuvers. Accordingly, the frequency of quartermaster's steering maneuvers per minute on the high-speed vessel was analyzed.

As shown in Figure 8, the number of steering maneuvers differed between the different navigations as well as to the quartermaster on duty. Table 5 summarizes the results for 3 navigations. It is suggested that the number of steering depends on the experience and technique as well as the area the vessel passes, i.e. Tsugaru Strait vs. Mutsu Bay. The quartermaster steered often to avoid drifting objects while navigating because the hull rolled greatly when the high-speed vessel's water jet weakened due to the floating dust. Figure 9 illustrates the change of heart rate caused by the steering maneuvers on the high-speed vessel under various conditions. Heart rate fluctuates between 85/min and 95/min at each event requiring steering maneuvers.

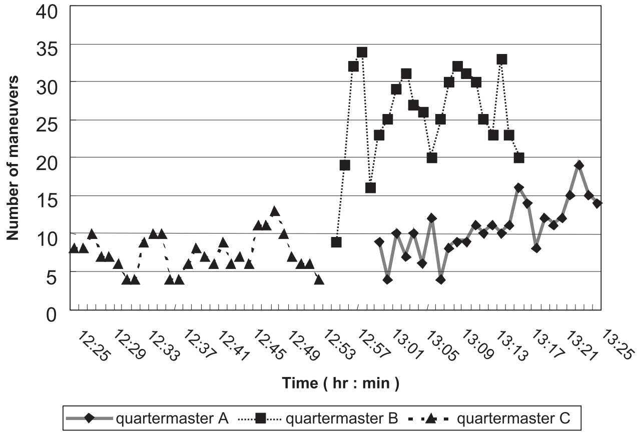

Fig. 8 The number of joystick operations per minute in three quartermasters on the high-speed vessel navigating on different days.

Table 5. The number of steering maneuvers of the quartermaster on the high-speed vessel.

	Years of experience	Area	Steering maneuvers	
			Mean	SD
Quartermaster A	5	TSUGARU Strait	10.7	3.5
Quartermaster B	2	TSUGARU Strait	25.6	6.1
Quartermaster C	6	MUTSU Bay	7.4	2.4

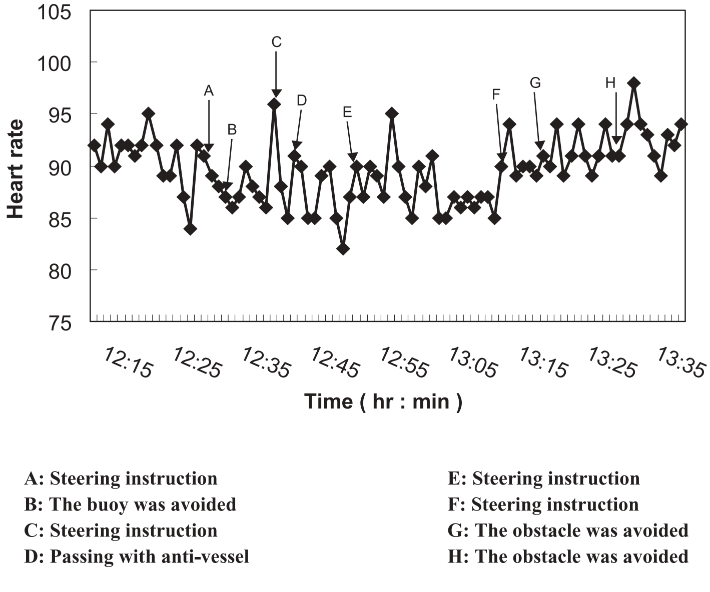

Fig. 9 The heart rate changes of a quartermaster on the high-speed vessel. Alphabets and arrows show events requiring steering maneuvers.

DISCUSSION

In the present study, we compared the workload characteristics of steering a high-speed vessel with those of steering a conventional vessel. Either on the conventional or on the high-speed vessel, dominant activities of officers in the bridge were lookout and watching radar. While the officers on the conventional vessel conducted these works exclusively in standing, they carried out these works on the high-speed vessel in sitting with occasional changes in posture into standing.

Despite these differences in postural conditions, the mean % heart rate increase of the officer was significantly higher on the high-speed than on the conventional vessel. Such an observation suggests that working of the officer on the high-speed vessel is associated with substantial mental strains, in addition to physical strains due to postural changes. As the navigation speed on the high-speed vessel increased, the officer had to pay additional attentions to the front.

By contrast, predominant works of the quartermasters in the bridge were specific to the vessel; lookout and radar watch in standing on the conventional vessel and joystick operation in sitting on the high-speed vessel. The mean % heart rate increase was significantly higher also on the high-speed than on the conventional vessel. Since the joystick operation appears to need the least muscular efforts, and the cardiovascular load is more favorable in sitting than in standing, the higher heart rate increase on the high-speed vessel suggests occurrence of mental strains owing to difficulties in steering a vessel navigating with high speed.

A particular attention was given in our study to the frequent steering operations required in the case of the high-speed vessel. The number of steering maneuvers differed among the investigations done. This was a result of different navigation conditions and the quartermasters on duty. In the event that a quartermaster steered through windy and serious tidal conditions, the skills and experience of the quartermaster affected his ability to steer the course, i.e. the skilled and experienced quartermaster maneuvered less frequently than the inexperienced one. Since the events requiring steering maneuvers were associated with increase in heart rate, it was confirmed that the joystick operations cause mental strains in the crew.

The development of mental strains in the crew on the high-speed vessel as shown in the above considerations suggests prevalence of mental activities to avoid the accidents. Such a situation may cause the workload of the crew on the high-speed vessel to become substantial. Despite this possibly increased workload of the crew, accidents occurring on high-speed vessels are still relatively high (Japan Marine Accident Inquiry Agency, 1996). This fact suggests the limitations in the prevention of accidents exclusively through improvements in human factors, and alternatively indicates the necessity for some fail-safe system such as autopilot facilities.

In actuality, however, our research clarified that such fail-safe system was lacking on the high-speed vessel and that supplementary works using the worker's skills and teamwork was crucial for successful navigation. In current technical education, there is no practice training for steering a high-speed vessel. At present, due primarily to a decrease in the number of crews, it is difficult to expect much from training on the job. The necessity has been suggested from this research to introduce safety education including training programs for learning what kinds of skills and teamwork are needed with a high-speed vessel.

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