

I

Ministry of Defence

Modelling Operator Behaviour

An experimental approach to model operator behaviour on board fast RIBs

Author: M.R.A. Nieuwenhuis

Date: July 2005 Doc.nr: D 5050 / 463

Defence Materiel Organisation Directorate of Materiel Royal Netherlands Navy MARTECH / MMT

Thesis for: Delft University of Technology, Faculty of Mechanical Engineering and Marine Technology



I

1

ľ

try of D

Preface



With this thesis I finish my study in Marine Technology at the Delft University of Technology.

As a naval officer of the Royal Netherlands Navy I started this study just after graduation from the Naval Academy. After many years of serving onboard of several warships and specialisation as an Anti Submarine Warfare Officer, I was granted the opportunity to finish this study during my stationing in The Hague at the Directorate Materiel, department Naval Architecture.

The willingness of the Royal Netherlands Navy was of great value and during this last year I was exempted from my regular job to gain in-depth-knowledge about the thesis subject and to finish my study.

This thesis subject was quite an undeveloped territory, and this was exactly the reason I'd chosen it. In addition, this subject was not a regular sit-behind-the-desk study. It was really exciting to be literally involved during all the trials and to sail with the fast RIBs under pretty extreme conditions (at least extreme for me).

During this year, many people helped me to stay on the right track and I would like to thank all of them, especially Peter van Terwisga and Lex Keuning.

I also would like to thank the people involved during the trials. Without their support and (technical) improvisation talent, the trials probably would have failed completely.

Furthermore, I would like to thank the RNLBS, especially the skippers Jan van der Sar and Hugo van Duijvenbode with their crews. Their support during the trials was infinite. The majority of the crews of the RNLBS are volunteers and it is really remarkable they cancelled their free days to attend these trials. For those who would like to financially support the RNLBS, join the "redders-aan-de-wal". They deserve it!

Finally I have to thank Mark, my husband, who was really patient the last three years and supported me whenever possible.

Haarlem, July 29th, 2005

Michèle Nieuwenhuis



Abstract

Background

A few years ago, the Royal Netherlands Navy (RNIN) distinguished the requirement of high speed interceptors for the Netherlands Antilles & Aruba Coast Guard (NA&ACG). During the procurement process of the Coast Guard interceptors it became clear that comparison and evaluation of different commercial offers was extremely difficult. In non-linear motion prediction models, the motions of fast RIBs can be predicted with given wave conditions, but without the important influence of the operator. Eventually, such non-linear models give a pessimistic view of the craft, since such models neglect the beneficial actions of a good helmsman. Especially calculations of vertical accelerations of the ship will show unrealistic high values and just these vertical accelerations are of high interest during a design or procurement process.

Therefore, the section Hydromechanics of the Directorate Materiel department Naval Architecture and Marine Engineering of the Royal Netherlands Navy (RNIN) established a research program in cooperation with the Delft University of Technology section Hydromechanics (TUD), Maritime Research Institute Netherlands (MARIN), Royal Netherlands Lifeboat Society (RNLBS) and the Netherlands Organisation for Applied Scientific Research department Human Factors (TNO-HF). The main goal of this research program is to improve the quantitative comparison of alternative designs of fast RIBs, both during the design process and the procurement process. One of the requirements to attain this main goal, is an operator-behaviour-model to be implemented into non-linear models for motion prediction, for example in FASTSHIP, a non-linear motion prediction program, developed by the Ships Hydromechanics Laboratory of the Delft University of Technology.

Aim of this thesis

This thesis is part of the established research program as described above. To achieve the main goal of this research program, the aim of this thesis is to investigate and analysis operator behaviour and to develop a model for this operator behaviour.

The main aim of this thesis is to develop an operator behaviour model on board fast RIBs.

Implementation of an operator-behaviour-model into FASTSHIP is however beyond the scope of this thesis.

Research set-up

The behaviour of the operator tend to be intuitive and because of the intuitive actions and responses of the helmsman an experimental research approach is chosen.

The research set up of this thesis can be divided into three phases:

- Phase one: execution of the full scale trials and data collection. Trials have been
 executed with three different RIBs in conformity with the formulated trial protocol. The
 required data was recorded.
- Phase two: data incorporation and data analysis. The recorded data was incorporated and to gain insight into the operator behaviour, the data was analysed.
- Phase three: model development. Operator behaviour models for throttle application (throttle change) and the duration for this throttle application are developed and the cues, to which the operator has responded, are defined The operator models are developed using regression analysis.



Conclusions and recommendations

Based on the thesis research, the following conclusions can be made:

- Non-linear models for motion prediction give a pessimistic view of the fast RIB, since such models neglect the beneficial actions of a good helmsman.
- The recorded throttle data of the RIB 2000 (RNIN) showed only a few throttle applications by the operator. Therefore, the RIB 2000 data was not used during the rest of the research.
- The present state of techniques appeared to be insufficient to measure the wave height, wave form or wave pattern in front of the ship during the run. However, knowledge about the wave characteristics in front of the ship was important for the model development. In this thesis the heave height is used as wave height indicator.
- The contribution of steering control to the average speed is very small and therefore neglected in this investigation. Throttle control is dominant with respect to steering control.
- The main cue for the operator to use his throttle control is the wave slope. Although the operators indicated the wave height as a cue as well, the relation between the throttle application and wave height is weak. Generally the actual moment of throttle application happened to be in the wave trough.
- Both operators did not use their throttle for wave slopes smaller than respectively 2.9 degrees (RIB DR) and 3.3 degrees (RIB KH). Also the minimum wave height (heave height) the operators were responding to is 1.0 meter for both ships.
- The operator models for throttle change and throttle duration are valid for all sort of environmental, coastal, conditions in which the RIB can be operated safely and for wave heights larger than 1.0 meter. The operator models for throttle duration are only valid for wave slopes smaller than 7 degrees. In addition, the operator models for throttle change and throttle duration are only valid for the corresponding RIB.

The following recommendations can be made:

- In future trials it is recommended to switch operators. RIB KH's operator should execute the trials on board of the RIB DR and RIB DR's operator should execute the trials on board of RIB KH.
- To validate the operator models, more trials should be executed, with different RIBs, different operators and different environmental conditions. Trials on board of the RIBs for the NA&ACG could also be used for validation purposes.
- To extend the operator models, less experienced operators and the use of bucket control should be considered. Also different headings, different speeds and different propulsion types should be investigated.
- To evaluate the caution of the fixed throttle setting during the trials, the run schedule has to be extended. The run with the fixed throttle has to be repeated at the end of the run schedule.
- When, in the near future, FASTSHIP is adjusted for the surge motion, the comparison between the measured vertical accelerations and the calculated vertical accelerations (FASTSHIP) should be repeated and considered again.
- Because of the relative small correlation and determination coefficients, found for the relation between the throttle duration and the wave slope, further investigation about relations of throttle duration is recommended.
- To share the outcome of trials regarding operator behaviour it is recommended to build a data base with the outcome of the corresponding operator trials.
- To improve the quantitative comparison of alternative designs of fast RIBs, it is recommended to implement the operator models for throttle change and throttle duration in the motion-prediction program FASTSHIP.

Nomenclature

Quantities and variables

α	Wave slope (deg)
8	Wave slope (deg)
	vvave speed (m/s)
3	Bandwidth parameter (-)
g	Acceleration due to gravity (-9.81 m/s ²)
Н	Wave height (m)
H _{1/3}	Significant heave height (m)
λ	Wave length (m)
mo	Moment of heave spectrum (m ²)
m ₂	Moment of vertical speed spectrum ((m/s) ² /s ²)
m ₂	Moment of vertical acceleration spectrum $((m/s^2)^2/s^4)$
R	Correlation coefficient (-)
R ²	Determination coefficient (-)
Te	Encounter period (s)
U	Ships speed (m/s)
ω _e	Encounter frequency (rad/s)
ω	Wave frequency (rad/s)
Х	Independent or controlled variable
Y	Dependent variable

Abbreviations

Bf DR	Beaufort (wind force) BIB De Redder			
FFT	RIB De Redder Fast Fourier Transformation			
GPS	Global Positioning System			
kts	Knots			
KH	RIB Kapiteins Hazewinkel			
JFC	Johannes Frederik Class			
JONSWAP	Joint North Sea Wave Project			
MARIN	Maritime Research Institute Netherlands			
NA&ACG	Netherlands Antilles and Aruba Coast Guard			
nm	Nautical miles			
RIB	Rigid hull inflatable boat			
RNIN	Royal Netherlands Navy			
RNLBS	Royal Netherlands Life Boat Society			
SOG	Speed over ground			
TNO-HF	Netherlands organisation for Applied Scientific Research department Human Factors			
TUD	Delft University of Technology			
VC	Valentijn Class			

Ministry of Defence

MARTECH / MMT D 5050 / 463 Ministry of Defence

Ministry of Defence

Table of Contents

1

Preface	iii
Abstract	v
Nomenclature	. vii
Quantities and variables	vii
Abbreviations	vii
1 – Introduction	1
1.1 General	1
1.2 Aim of the thesis	1
1.3 Research approach and research set-up	2
1.3.1 Research approach	2
1.3.2 Scope of the research	2
1.4 Reader's guideline	3
2 – Trials	5
2.1 General	5
2.2 RIBs	5
2.3 Different control methods	5
2.4 Trial protocol	6
2.4.1 Run schedule	6
2.4.2 Operator's task	6
2.4.3 Questionnaire	7
2.5 Recorded data	7
2.6 Sub conclusions.	8
3 – Data Incorporation	9
3.1 General	9
3.2 Filtering of the data	9
3.3 Peak Statistics	. 11
3.4 Sub conclusions.	. 11
4 – Heave motion as wave height indicator	.13
4.1 General	. 13
4.2 Determination of the heave motion	. 13
4.3 Constraints of the heave motion as wave height indicator	. 13
4.4 Comparison wave height and heave motion in FASTSHIP	. 15
4.4.1 FASTSHIP	. 15
4.4.2 Difference between wave height and heave motion	. 15
4.5 Comparison wave height and heave motion with heave spectra	. 17
4.6 Sub conclusions.	. 19
5 – Results of data analysis	. 21
5.1 General.	. 21
5.2 Influence of the control methods	. 21
5.3 Operator's visual field	. 22
5.4 Influence of active throttle control at the vertical accelerations	. 23
5.4.1. Active throttle control	. 23
5.4.2. Acceptance level	. 21
5.4.3. Experienced accelerations by the operator	. 29
5.5 Moment of throttle control	. 31
5.5.1. I nrottle control as anticipative control.	. 31
5.5.2 I nrottle control with respect to the incoming wave	. 31
5.6 Comparison measured and calculated accelerations	. 33
	. 33
	. 33
5.7 Differences between the operators regarding throttle application	. 35
J.& SUD CONCIUSIONS	. 35

	/
	Ministry of Defence
6 – Model development	
6.1 General	
6.2 Determination of the ships speed	
6.3 Determination of the wave form	
6.3.1 Wave form indicators	
6.3.2 Determination of the wave slope for each incoming wave	
6.4 Building a parameter data base	
6.5 Regression analysis throttle change	
6.5.1 Procedure of regression analysis	
6.5.2 Examination of relations	
6.5.3 Multiple regression analysis	
6.6 Regression analysis throttle duration	51
6.7 Moments during the trials with zero throttle control	
6.8 Operator models for throttle change and throttle duration	
6.8.1 Operator model for throttle change	
6.8.2 Operator model for throttle duration	
6.9 General validity of the operator model for throttle change	62
6.10 Sub conclusions	62
7 – Conclusions and Recommendations	65
7.1 Conclusions	65
7.2 Recommendations	
References	69
Tables and Figures	71

l

1 – Introduction

1.1 General

In many countries of the world, high speed small ships, or high speed interceptors, are used for many different operations including military operations, commercial operations, general policing duties, pilotage, search and rescue operations, coast guard operations, offshore and leisure. The expression "interceptor" mainly refers to operations with a "detecting, localising and intercepting" role, such as for example counter drugs operations and search and rescue operations. Many of the high speed interceptors are so-called rigid inflatables (RIB).

A few years ago, the Royal Netherlands Navy (RNIN) distinguished the requirement of high speed interceptors for the Netherlands Antilles & Aruba Coast Guard (NA&ACG). During the procurement process of the Coast Guard interceptors it became clear that comparison and evaluation of different commercial offers was extremely difficult. In non-linear motion prediction models, the motions of fast RIBs can be predicted with given wave conditions, but without the important influence of the operator [1][2][3]. Eventually, such non-linear models give a pessimistic view of the craft, since such models neglect the beneficial actions of a good helmsman. Especially calculations of vertical accelerations of the ship will show unrealistic high values and just these vertical accelerations are of high interest during a design or procurement process.

Human factors are long time neglected in the design process. However with RIBs able to operate under extreme conditions and speeds beyond 50 knots, obviously, human factors cannot longer be neglected. These days, many conferences are held at which "human factors in the design process" play a leading role. Design and procurement decisions should be made based on the overall performance of the boat instead of the performance of the boat itself within given environmental conditions and excluding the human factor of the operator.

Therefore, the section Hydromechanics of the Directorate Materiel department Naval Architecture and Marine Engineering of the Royal Netherlands Navy (RNIN) established a research program in cooperation with the Delft University of Technology section Hydromechanics (TUD), Maritime Research Institute Netherlands (MARIN), Royal Netherlands Lifeboat Society (RNLBS) and the Netherlands Organisation for Applied Scientific Research department Human Factors (TNO-HF). The main goal of this research program is to improve the quantitative comparison of alternative designs of fast RIBs, both during the design process and the procurement process. One of the requirements to attain this main goal, is an operator-behaviour-model to be implemented into non-linear models for motion prediction, for example in FASTSHIP, a non-linear motion prediction program, developed by the Ships Hydromechanics Laboratory of the TUD.

1.2 Aim of the thesis

This thesis is part of the established research program as described above. To achieve the main goal of this research program, the aim of this thesis is to investigate and analysis operator behaviour and to develop a model for this operator behaviour.

The main aim of this thesis is to develop an operator behaviour model on board fast RIBs.

Implementation of an operator-behaviour-model into FASTSHIP is however beyond the scope of this thesis.

To attain the thesis aim, interviews with several operators are held and full scale trials have been executed with three different fast RIBs. During these trials, many data are recorded. Investigation and analysis of these recorded data eventually lead to the development of an operator-behaviour-model.

1.3 Research approach and research set-up

During several interviews with operators of fast RIBs, it appeared that is was very difficult for the operator to give full explanation of his particular actions and responses. Except from mentioning a few cues, like wave height and wave form, the operator wasn't able to define this wave height or wave form into concrete numbers. His behaviour tend to be intuitive. Because of the intuitive actions and responses of the helmsman an experimental research approach is chosen.

1.3.1 Research approach

It is always a real challenge to approach human behaviour from a mathematical point of view. To develop a clear understanding of the operator's intuitive responses, many different data are required. Therefore it was decided to execute full scale trials with experienced operators on three different RIBS of the RNLBS and RNIN. During these full scale trials, the required data were collected, and it was also possible to interview the operator "in action". This helped the operator to describe his actions and responses and these "in action" interviews formed one of the starting points for the data analysis. For the full scale trials a trial protocol is formulated, including trial set-up and the specification of the data to be recorded.

Based on the experimental research approach with full scale trials, the research set up of this thesis can be divided into three phases:

- Phase one: execution of the full scale trials and data collection.
- Phase two: data incorporation and data analysis
- Phase three: model development

1.3.2 Scope of the research

Every research has to deal with several restrictions. These restrictions are of high importance for the outcome data and the corresponding data analysis and results. For this research the following restrictions apply :

- The maximum average speed can be regarded as one of the performance parameters of the RIB. Therefore only the highest possible speed is considered.
- Since head-sea courses are most limiting to the RIB's performance, only head-sea courses are considered.
- To exclude misjudgements of the operator as much as possible, only the most experienced operators are involved in the full scale trials. Normally this would be the skipper of the RIB.
- Some operators manipulate their forward speed with the use of bucket control, however this type of control is beyond the scope of this paper because of the difficulty with data comparison. Therefore bucket control was not allowed.
- All RIBS were equipped with water jets, no other types of propulsion was considered.



1.4 Reader's guideline

In chapter 2 the trials are described, like the used RIBs, the trial protocol and the run schedule executed during the trials. In chapter 3 the data incorporation process of the recorded data is described. In chapter 4 the feasibility to use the heave motion as a wave height indicator is discussed, based on calculated spectra of the heave motions and calculations of FASTSHIP runs. In chapter 5 the results of the data analysis are discussed and in finally in chapter 6 the development of the operator model is presented. This thesis will finish with conclusions and recommendations in chapter 7. In the text of this thesis, many cross references are made regarding appendices. These appendices are presented in a separate manual.



.

l

l

Ministry of Defe

2 – Trials



2.1 General

Because of the intuitive behaviour of the operator, an experimental approach is chosen and full scale trials are executed. In this chapter, these full scale trials are described. In paragraph 2.2 the used RIBs are presented and in paragraph 2.3 the different control types are discussed. In paragraph 2.4 the trial protocol is treated, including run schedule, operator's task and the presented questionnaire and in paragraph 2.5 the recorded data is described. This chapter ends with sub conclusions in paragraph 2.6.

2.2 RIBs

The full scale trials have been conducted with three different fast RIBs:

- RIB 2000 (RNIN)
- RIB "Kapiteins Hazewinkel" (KH) of the "Johannes Frederik Class" (JFC) (RNLBS),
- RIB "De Redder" (DR) of the "Valentijn Class" (VC) (RNLBS)

Fact sheets of these RIBs are included in Appendix A.

The trials with RIB 2000 of the RNIN are conducted off the coast of Den Helder, the trials with RIB KH are conducted off the coast of Hoek van Holland and the trials with RIB DR are conducted off the coast of Katwijk aan Zee. Table 1 illustrates the trial conditions.

	RIB 2000	RIB KH	RIB DR
Wind force	4 Bf	5 Bf	6 Bf
Wind direction	E	WNW	W
Significant wave height	1.0 m	2.0 m	2.25 m
Maximum wave height	1.5 m	3.1 m	3.6 m
Average wave period	4.0 s	5.0 s	5.0 s
Maximum wave period	7.0 s	10.0 s	9.0 s

Table 1: Environmental conditions during trials

Unfortunately, the environmental conditions during the trials with the RIB 2000 of the RNIN appeared to be not worse enough. A sufficient significant wave height was required to analyse the use of throttle control by the operator. The significant wave height during the trials with the RIB 2000 was not sufficient enough for throttle control by the operator. The highest possible speed was achieved by a maximum throttle position during the complete trial, with only a few changes in the throttle position. Therefore, the RIB 2000 data was not used during the rest of the research. The data analysis and model development are based on the trials with both RIBs of the RNLBS. In appendix F and G the data signals of these RNLBS RIBs are presented.

2.3 Different control methods

In preparation of the trials, during and after the trials, interviews and discussions were held with all operators. These operators were all highly experienced and all having a long time career as operator of a fast RIB. Especially the RIB operators of the RNLBS have experienced operations under very extreme conditions at sea when lifesaving was of highest priority.

For an operator it is very difficult to give full explanations of his actions and responses at sea. During the interviews with these highly experienced operators, two types of control to influence the ship motions were mentioned by the operators:

- throttle control.
- steering control.



In table 2 these two control types are specified:

Control type	Nature of control	Object of behaviour	Cue for operator
Throttle	Feed forward	Prevention of slams, injuries and (materiel) damage	Wave height, intuition
Steering	Feed forward	Finding optimal path through waves	Wave height, wave form (expressed by wave slope), wave pattern
	Feedback	Correction of heading	Yaw

Table 2: Different control types

The mentioned cues in table 2 are indicated by the operator himself. Operational sailing requires active behaviour of the operator, which often results in the application of both control types simultaneously.

2.4 Trial protocol

In this paragraph, the trial protocol is described. In sub paragraph 2.4.1 the run schedule is treated, in sub paragraph 2.4.2 the operator's task during the trials is explained and in sub paragraph 2.4.3 the questionnaire, presented after the trials, is described.

2.4.1 Run schedule

The control types and the indicated cues, mentioned in paragraph 2.3, form the basis for the run schedule. The aim of the run schedule was to investigate the influence of both control types separately, by excluding one of the control types. Every run took 20 minutes. The following run schedule was executed:

- Run 1: familiarisation run. During this run, the operator had to make himself familiar with the specific environmental conditions, like waves, wind, crew etc.
- Run 2: Fixed throttle control, free steering control. Just before the runs started, the
 operator had to set the throttle in the right position, so that the RIB will sail with
 maximum acceptable speed. The operator had to feel comfortable with the throttle
 position; during the run he was not allowed to change this throttle position. Steering
 control was not allowed during this run.
- Run 3: Fixed steering control and free throttle control. The operator had to use his steering wheel as little as possible. Only yaw corrections were allowed to maintain the head-sea-course.
- Run 4: Free throttle control and free steering control. Both control types were allowed.

The run scheme is part of the trial protocol. A summary of the trial protocol is included in appendix C.

2.4.2 Operator's task

During all runs the operator's task was to sail the ship with maximum possible speed, given the environmental conditions, on a head-sea-course. To realize such a maximum speed and to find the optimal path through the incoming waves, the operator was allowed to actively manipulate the steering and/or throttle control, depending on the run number. To eliminate the learning process, which will even apply to a highly experienced operator, a familiarisation run was executed in advance.

2.4.3 Questionnaire

To gain an insight into the behaviour of the helmsman, a questionnaire was presented after every run. The operator was questioned about his actions, reasons of his actions, the observed wave height and the maximum acceptable (vertical) accelerations. Answers to this questionnaire together with the impressions during the "in action" interviews form the basis in determining the steps in the analysis phase.

2.5 Recorded data

The development of a clear understanding of the operator's responses, requires many different data. Since one of the cues mentioned by the operator is the wave height, wave height data are of high priority. Measuring the wave height in front of the ship during the run, therefore appeared to be really essential. The first idea was to measure these wave heights with laser equipment, but these laser equipment was very hard to attach to the ships and the performance of the laser would reduce significantly because of water spray.

Unfortunately, the present state of techniques appeared to be insufficient to measure the wave height, wave form or wave pattern in front of the ship during the run. Because of the importance of knowledge about the wave height and wave form, another way of collecting the required wave characteristics had to be considered. Finally, the recorded vertical acceleration at the operator's position is used to calculate the heave motion. This heave motion is used as wave height indicator. The use of the heave motion as wave height indicator.

During the trials with both RIBs, wave data at the trial position were collected at the website of "Rijkswaterstaat" [4]. During the trials with the RIB DR, wave data were also measured with a wave measurement buoy.

Sensor	Number	Position	Data
Accelerometer	6	4 underneath	accelerations in x, y and z-direction
		the operator	(high sample rate) and z-direction (low
		chair	sample rate)
		afterdeck	acceleration in z-direction
		foredeck	acceleration in z-direction
Rate sensor	2	x and y axis	rate of roll and pitch (°/sec)
Touthwire sensor	2	lower deck	deflection of the steering wheel (% of
			maximum steering angle)
		lower deck	throttle position (% of maximum
			throttle)
GPS	1	antenna outside	position and SOG
Video camera	2	helmet with	what/where operator is looking at
		camera	
		fixed camera	behaviour operator (inside) or
		(inside or	incoming waves (outside)
		outside)	
Wave measurement	1	in	wave data
buoy		neighbourhood	
		of trials	

The recorded data are listed below in table 3.

 Table 3: Recorded data with corresponding sensor position

The definition of the axes is shown in figure 1. The location of the sensors (RIB KH) is shown in figure 2. An overview of the sensor parameters and sensor details is listed in appendix B.





Translations	Rotations	
x-direction: surge	x-axis: roll	
y-direction: sway	y-axis: pitch	
z-direction: heave	z-axis: yaw	

Figure 1: Definition of axes and degrees of freedom

Figure 2: Location of sensors (RIB KH)

2.6 Sub conclusions

Full scale trials were executed with three different fast RIBs. However, the significant wave height during the runs with the RIB 2000 appeared to be not enough for sufficient "throttle position changes" by the operator. Therefore, the RIB 2000 data was not used during the rest of the research. The data analysis and model development are based on the trials with both RIBs of the RNLBS.

3 – Data Incorporation

3.1 General

Many different data are recorded during the full scale trials. The data files (matlab-files) are provided by MARIN. The matlab-files are transformed into binary files (with corresponding units instead of volts) reckoned with calibration factors and offsets of the sensors. Especially the rough acceleration signals displayed a lot of noise, probably caused by the engines and water jets. During the data incorporation process, the data are filtered and examined statistically. An complete overview of the rough and filtered data signals is shown in appendix F and G. In paragraph 3.2 filtering of the rough data signals is discussed, in paragraph 3.3 the peak statistics of the data are presented and in paragraph 3.4 the sub conclusions of this chapter are discussed.

3.2 Filtering of the data

The measurements are executed with different sample rates. During the first trial with RIB KH the used sample rates were 500 Hz and 2000 Hz. During the second trial with RIB DR the used sample rates were 1000 Hz and 2000 Hz. Because of the high sample rates, many samples are generated. The amount of samples and the signal noises make it very hard to analyse the unprocessed data and therefore it was required to filter the data for better analysis opportunities. Unfortunately, any form of filtering will reduce the peaks for some sort amount. The aim during the filtering process here, was therefore to loose as less as possible signal peaks and don't loose any phase information.

In paragraph 3.1 it is mentioned that the noise probably is caused by the engines and the water jets, both high frequency signals. Two indications confirm this impression:

- The reduction of the signal bandwidth, when the power (throttle) decreases. It appeared, these high frequencies observed in the acceleration signal, are propulsion related. This bandwidth reduction is illustrated in figure 3.
- The frequency at which the accelerations occur is closely related to the encounter frequency (for theoretical background regarding encounter frequency, see appendix E). However, the observed frequencies in the rough acceleration signal are much higher than the experienced encounter frequency. Therefore, these high frequencies must be generated by another source than the ship motions. The only two sources which were able to generate such high frequencies are the engines and the water jets.

Using a Fast Fourier Transformation (FFT) the data signal was divided into several sine or cosine elements with corresponding frequencies and phases. Because the performed accelerations are ship motion related, and therefore encounter frequency related, only the lower frequencies of the unprocessed signal are interesting. Therefore a band filter had been applied to filter the data. The selected bandwidth of the band filter was 0-10 Hz (=0-62.83 radians). Only sine and cosine elements with frequencies within this particular bandwidth are taken into account. With this small bandwidth in the lower frequency domain, the noise generated by the water jets and engines is eliminated.

With the application of the band filter with corresponding bandwidth, the maximum negative vertical accelerations after filtering appeared to be around 10 m/s². Because of the position of the accelerometer during the trials, in close vicinity of the centre of gravity, these accelerations are also the maximum negative vertical accelerations expected.

An example of the rough and filtered vertical accelerations is shown in figure 4.



Figure 3: Reduction of the signal bandwidth when throttle decreases



Figure 4: Rough and filtered vertical acceleration signal

Minister of De



The other requirement is the conservation of the phase information of the signal. During data analysis, the actual throttle moment will be compared with the corresponding moment of heave motion. Any phase shift in the signals will influence the data analysis outcome negatively.

Applying the band filter will not cause any loose of phase information. This is illustrated in figure 5. In this figure, the result of the double integration of the rough, unfiltered vertical acceleration, the "rough" heave motion, is compared with the result of the double integration of the filtered vertical acceleration, the "filtered" heave motion. The first diagram in figure 5 represents the rough vertical acceleration and the second diagram represents the filtered vertical acceleration. The third diagram represents the rough heave motion and the fourth diagram represents the filtered heave motion. As can be seen in the diagrams, both double integrations produce the same heave motion, with heave peaks performing at the same moment. The appearance of the peaks at the same moment indicates there is no phase shift after filtering the signal.

Unfortunately, as mentioned before, filtering will cause a reduction of the signal peaks. Also here, the band filter will reduce the absolute value of the acceleration peaks slightly. However, compared to acceleration measurements during other trials found in literature, the value of the acceleration peaks after filtering is still representative for the occurred accelerations [5][6].

3.3 Peak Statistics

Determination of the peak statistics gives a quick overview of the data details and is also an easy comparison tool, especially for data of different runs. The peak statistics of the data include: minimum of the data, maximum of the data, standard deviation of the data and mean of the data.

Remarkable are the differences between the maximum values of the vertical accelerations measured with the accelerometers at high sample rate and at low sample rate. Both accelerometers were positioned in the same position, below the operator's chair. It appeared the values of the maximum vertical accelerations measured at high sample rate are significantly higher than the vertical accelerations measured at low sample rate. This difference in maximum acceleration values is caused by different characteristics of the accelerometer used at low sample rate is limited to 20 m/s² and the accelerometer used at high sample rate is limited to 10 m/s². In appendix D, a table of the peak statistics is illustrated.

3.4 Sub conclusions

During the data incorporation process, the high frequencies in the acceleration signal appeared to be propulsion related and generated by the engines and water jets. Filtering of the rough data signals eliminated these high frequencies caused by the engines and water jets. Using a band filter did not cause any phase shift.



Figure 5: No phase shift after filtering the signal

Ministry of Defence

4 – Heave motion as wave height indicator

4.1 General

As mentioned in paragraph 2.5, it is not possible to directly measure the wave height of the incoming wave just before the ship. Since the operator indicated this wave height as one of the cues on which he bases his actions, wave height information becomes very essential. Therefore the heave motion is chosen as wave height indicator, assumed the error between the wave height and heave height is limited. The maximum acceptable error is arbitrarily chosen at 15 %. When the error is smaller than this limit of 15 %, it can be concluded the heave motion is usable as wave height indicator. In paragraph 4.2 the determination of the heave motion is discussed. Off course, some constraints occur using the vertical position as indication for the wave height. These constraints are discussed in paragraph 4.3. In paragraph 4.4 and 4.5, the feasibility of the heave motion as wave height indicator is demonstrated in two independent ways. In paragraph 4.6 the sub conclusions of this chapter are discussed.

The input used for the FASTSHIP calculations is illustrated in appendix L - FASTSHIP input.

4.2 Determination of the heave motion

To obtain the heave motion of the ship, the measured unfiltered vertical acceleration signal, with sample rate of 500 Hz, at the operator's position, is integrated twice. To avoid large numerical errors which will interfere the integration outcome, called numerical drift, only short time legs of the acceleration signal are integrated at once. Regrettably, integrating short time legs of the signal will result in meaningless absolute values of the integrated vertical position signal. However, the difference between the maximum and minimum vertical position, the distance between top and trough, is representative for the heave height. Therefore, the distance between the maximum and minimum value of the vertical position is used as wave height indicator. The double integration process is illustrated in figure 6.

4.3 Constraints of the heave motion as wave height indicator

Three important constraints occur using the vertical position as wave height indicator:

- The moment the ship will actually fly over the wave crest, the ship will experience some airtime. Therefore, the heave motion to indicate the wave height is only applicable for the first part of the wave, from wave trough to wave crest.
- Possible hydrodynamics effects of the RIB which could affect the heave motion, and therefore the wave height indication, are neglected. However, hydrodynamic effects will cause differences between the wave height and heave height. In paragraph 4.4 and 4.5 this hydrodynamic influence at the heave motion is determined, to show the error between the heave motion and wave height in terms of percentage. It appeared that this error between the wave height and corresponding heave motion remains within the defined limit of 15%.
- Contribution of the pitch angle to the vertical accelerations, caused by the body fixed axis system, is not taken into account.



Figure 6: Double integration process, from vertical acceleration to vertical position

4.4 Comparison wave height and heave motion in FASTSHIP

4.4.1 FASTSHIP

The behaviour of the RIB KH is calculated using the computer program FASTSHIP. In this calculation, the used wave input was the same as the wave conditions during the trials, like the average wave period and the significant wave height. FASTSHIP is developed at the Ships Hydromechanics Laboratory of the TUD. FASTSHIP is a non-linear strip theory based program for the calculation of hydrodynamic loads, motions, and derivatives of planing ships in irregular head waves. The non linear characteristics of a planing craft in head waves do not allow the linear frequency domain approach, thus the equations of motion had to be solved in the time domain [7].

One restriction of FASTSHIP is the use of a fixed speed during the calculations. In the near future, the surge motion will be also taken into account in the program and calculations with variable speed should then be possible.

4.4.2 Difference between wave height and heave motion

The chosen speeds for the FASTSHIP runs are 21.6 knots and 15.6 knots. The speed of 21.6 knots was the average speed of run number 4. The speed of 15.6 knots was the minimum measured speed during this particular run. FASTSHIP produces a table including the wave heights with corresponding heave heights. Based on the constraints mentioned in paragraph 4.3 only the first part of the wave and heave motion is considered. So, the wave height is determined from wave trough to wave crest and the corresponding heave height is also determined from heave trough to heave crest. The second part of the wave and heave motion is not used, because of the possibility of airtime of the ship. During airtime, the size of the heave motion and the wave motion are no longer related.

Considering only the small heave heights (heave motion from trough to crest < 1.0 meter) of the FASTSHIP outcome, a large error between the wave height and corresponding heave height of 86 % appeared. This error exceeds the defined limit of 15 %. Heave motions smaller than 1.0 metres are therefore unusable as wave height indicator. The limit of 1.0 meter arises from the interference limit of the operator: 1.0 meter is the minimum heave height where the operator has used his throttle control.

Neglecting the heave motions smaller than 1.0 meter and only considering heave motions larger than 1.0 meters the observed errors between wave height and heave height are illustrated in table 4. The errors are determined using equation 4.1:

Waveheight - heaveheight * 100%

heaveheight

(4.1)

Speed (kts)	Error (%)	Standard deviation (%)
21.6	5.8	18.0
15.6	-6.6	18.9

Table 4: Errors between wave height and heave height from FASTSHIP calculations

Remarkable is the negative error of the FASTSHIP run with speed of 15.6 knots. During this run, the heave heights are generally higher than the corresponding wave heights, as opposed to the run with speed of 21.6 knots. This event is clearly demonstrated in figure 8. Both the calculated errors shown in table 4 are within the defined limit of 15 %. In figure 7 and 8 details of the run with corresponding speed are illustrated.



Figure 7: Comparison of wave heights and heave heights (speed 21.6 knots)



Figure 8: Comparison of wave heights and heave heights (speed 15.6 knots)

Ministry of Defe

4.5 Comparison wave height and heave motion with heave spectra

A second way of comparison the wave height and the heave motion is determining a heave spectra of the signal. Based on the outcome presented in paragraph 4.4, it is expected that the significant heave height will correspond to the significant wave height measured during the trials. In figure 9 and 10, the spectra of the vertical accelerations, the vertical speeds and the heave motions of run number 4 of the RIB KH and RIB DR are shown. With the moments of these spectra, the significant heave height is determined using equation 4.2:

$$H_{1/3} = 4.0 * \sqrt{m_0} * \sqrt{1 - \frac{\varepsilon^2}{2}}$$
 (m) (4.2)

 $\boldsymbol{\epsilon}$ is called the bandwidth parameter:

$$\varepsilon = \sqrt{1 - \frac{m_2^2}{m_0 * m_4}} \tag{4.3}$$

 m_0 is the moment of the heave spectrum (in m^2), m_2 is the moment of the vertical speed spectrum (in $(m/s)^2/s^2$) and m_4 is the moment of the vertical acceleration spectrum (in $(m/s^2)^2/s^4$).

In table 5 the calculated moments, calculated significant heave heights, corresponding measured significant wave heights and the calculated error between the significant heave heights and significant wave heights are shown.

	Moments	Significant heave (m)	Significant wave (m)	error (%)
KH	m ₀ =0.3225	1.97	2.0	1.5
	m ₂ =1.4485			
	m ₄ =13.4966			
DR	m ₀ =0.3719	2.17	2.25	3.7
	m ₂ =2.0228			
	m ₄ =19.0915			

Table 5: Error between wave height and heave height based on heave spectrum

Also the calculated errors shown in table 5, based on the spectra of the signal, remain within the defined limit of 15 %.

Finally, the calculated error in terms of percentage between the wave height and heave height appeared to be small. As well as during the FASTSHIP calculations as during the spectra and moments calculations, the error is within the defined, acceptable limit. Therefore, it can be concluded that the heave motions larger than 1.0 meters and determined from trough to crest can be used as indication for the wave height.



Figure 9: Spectra of run number 4 (RIB KH)



Figure 10: Spectra of run number 4 (RIB DR)

Ministry of Defe

4.6 Sub conclusions

The main conclusion of this chapter is the confirmation of the feasibility of the heave height as wave height indicator. This confirmation is demonstrated in two independent ways, by FASTSHIP calculations for RIB KH and by the determination of the heave spectra for both ships. However, only the first part of the heave motion is usable as wave height indicator, because of the possibility of airtime. Airtime will result in a heave motion which is no longer related to the wave height.

Heave motions smaller than 1.0 meter are not usable as wave height indicator because of the large error between these small heave heights and the corresponding wave heights.

Other constraints which occur using the heave height as wave height indicator are the neglected hydrodynamic effects of the ship and the neglected contribution of the pitch angle to the vertical accelerations.

The minimum heave height to which both operators applied their throttle control was 1.0 meter.





5 – Results of data analysis

5.1 General

The interviews with operators, their comments during the trials and answers after the trials have shown some area's of interest for the analysis process. Two possible cues, which are indicated by all of the operators, are the wave height and wave form. These indicated cues form the basis for the data analysis process. The main purpose of the analysis process is to analyse the behaviour of the operators, their actions and responses, and to describe the similarities and differences in the behaviour of both operators.

In paragraph 5.2 the influence of the control methods at the average speed is discussed and in paragraph 5.3 the operator's visual field is illustrated. The influence of active throttle control at the vertical accelerations is discussed in paragraph 5.4 and paragraph 5.5 describes the actual moments of throttle control. In paragraph 5.6 the comparison between the measured and calculated vertical accelerations is presented and paragraph 5.7 describes the differences between the operators. This chapter ends with the sub conclusions described in paragraph 5.8.

5.2 Influence of the control methods

The average speed can be indicated as a performance parameter of the ship. Considering the two control methods, the average speed gives an indication of the contribution of throttle control and steering control to the ultimate performance of the RIB.

The average speeds of the corresponding runs are illustrated in table 6. In this table, run 1 is not taken into account because this is the familiarisation run to eliminate the learning process of the operator.

RIB	Run number	Average speed (kts)	Distance (nm)	Standard deviation(kts)
KH	2	18.1	6.0	0.8
	3	20.9	7.0	2.3
	4	21.6	7.2	2.2
DR	2	14.7	4.7	1.0
	3	16.4	5.2	1.7
	4	17.2	5.5	2.1

Table 6: Differences in average speed

The difference between the average speed of run number 4 and the average speed of run number 2 illustrates the influence of the throttle control. The steering control was considered to be free during both these runs. The throttle control was the only variable with those runs: fixed during run number 2 and free during run number 4.

The difference between the average speed of run number 3 and the average speed of run number 4 illustrates the influence of the steering control. The throttle control was considered to be free during both these runs. The steering control was the only variable with those runs: fixed during run number 3 and free during run number 4.

Based on the average speed of the corresponding runs, the influence of both steering control and throttle control to the average speed can be determined:

For RIB KH:

- Influence of throttle control: $Influence = \frac{(21.6 - 18.1)}{18.1} * 100\% = 19.3\%$
- Influence of steering control:

$$Influence = \frac{(21.6 - 20.9)}{21.6} * 100\% = 3.2\%$$
(5.2)

For the DR:

• Influence of throttle control:

$$Influence = \frac{(17.2 - 14.7)}{14.7} * 100\% = 17.0\%$$

Influence of steering control:

$$Influence = \frac{(17.2 - 16.4)}{17.2} * 100\% = 4.7\%$$
(5.4)

Obviously, interference of the helmsman has a positive effect to the ultimate average speed. The contribution of the throttle control to the average speed is much higher than the contribution of the steering control. It can be said that throttle control is dominant with respect to steering control. Because of this small contribution of steering control to the average speed, steering control is neglected and the only focus during data analysis and model development will be throttle control.

From data analysis it appears that an increase of the average speed also results in an slightly increase of throttle control frequency during the run. This is true for RIB KH as well for RIB DR. So, the throttle control frequency during run number 4 is slightly higher than the throttle frequency during run number 3. The run with the highest average speed also covered a larger distance. Consequently, a larger covered distance results in an increase of the amount of incoming waves. More incoming waves also means a higher throttle frequency. Therefore, the increase in throttle frequency at higher average speeds is explicable and to be expected.

5.3 Operator's visual field

To gain insight into the operator's responses, knowledge about the operator's visual field is required. Where is the operator actually looking at and responding to? To satisfy this requirement of knowledge about his visual field, a helmet with fixed camera for the operator has been used. This camera registered all the movements of the operator's head.

However, the crew of RIB DR used an internal communication system, integrated in their helmets which they must wear for safety reasons. When the operator should have used the helmet with the fixed camera, he would not be involved in any internal communication. This was not acceptable and to use the helmet with the fixed camera was therefore not an option for the operator. Unfortunately, it was not possible to attach the camera to his own helmet with integrated communication system. Finally, during the trials with RIB DR the helmet with fixed camera was not used.

(5.1)

(5.3)

The crew of the RIB KH used another communication system and here it was possible to use the helmet with camera as shown in figure 11.



Figure 11: Helmet with fixed camera

During the trials and data analysis, it appears that the operator rarely looked at his instruments. And even when he looked at his instruments, it was rather just a quick scan than an actual guide for the operator. His focus was just outside, ahead of the ship and to the sides. The visual sector of interest for the operator is 180 degrees in total, 90 degrees off the ship's course at both sides. This finding confirms the initial statement of the operator about the indicated cues for his behaviour. At this point in the data analysis, it is still not completely clear to what cues he reacts, but the instruments, like speed and heading, are definitely no cues for the operator. The cues for the operator are located outside of the ship. Even when the operator of RIB DR did not use

the helmet with camera, it was obvious during the trials, that he also rarely looked at his instruments and mainly was focussing outside the ship. This confirms the conclusion about the cues located outside the ship.

5.4 Influence of active throttle control at the vertical accelerations

The vertical accelerations mentioned in this paragraph are the vertical accelerations measured by the accelerometer at the operator's position.

In general, vertical accelerations are generated by combination of the wave height, the wave slope and the speed of the ship relative to the incoming waves. When the relative speed of the ship is too high for a certain combination of wave height and wave slope, the ship will actually fly over the wave crest and after some airtime, fall down in the waves. The moment the ship hits the wave again, the highest vertical acceleration peaks are generated. These peaks are positive accelerations.

5.4.1. Active throttle control

Active throttle control decreases the momentary relative speed of the ship and therefore reduces the chance of airtime and the corresponding occurrence of very high acceleration peaks. Figure 12-15 show some examples of active throttle control of RIB KH and RIB DR. Figure 12 and 14 show two examples during run number 4 of RIB KH and RIB DR where active throttle control results in avoiding very high acceleration peaks. Figure 13 and 15 show two examples of a high acceleration peak during run number 2 of RIB KH and RIB DR, with fixed throttle control and free steering control.



Figure 12: Example of active throttle control, which results in a small positive, vertical acceleration peak (RIB KH)



Figure 13: Example of fixed throttle control, which results in a high positive, vertical acceleration peak (RIB KH)

Ministry of Def










Figure 16: RIB KH Rayleigh distribution of the crests of all runs



Figure 17: RIB DR Rayleigh distribution of the crests of all runs

ny of Defe

Ministry of Defence

The interviews with operators made clear the operator will apply his throttle control to avoid large vertical acceleration peaks. It appears the operator manipulates the vertical acceleration level with his throttle control, resulting in an acceptable acceleration level. This acceptance acceleration level is discussed in paragraph 5.4.2.

5.4.2. Acceptance level

An interesting question is: Could it be possible to determine a certain acceptance level for the measured vertical accelerations?

The comments of the operators during the trials and the answers to the questionnaire afterwards, confirm the existence of an vertical acceleration acceptance level. During the trials, the moment the highest vertical acceleration peaks occur, the operators stated that the experienced vertical acceleration was or was not within acceptable limits for the operators.

A few of the highest peaks were too high to be comfortable for crew and ship and therefore not acceptable to the operators. This is how the acceptance level or acceptance limit is determined.

For both ships, a Rayleigh distribution is made of all the measured vertical positive acceleration peaks, also called crests. For both ships, these Rayleigh distributions are shown in figure 16 and 17. A short theoretical background about the Rayleigh distribution is included in appendix E. This Rayleigh distribution illustrates the probability of exceeding a given vertical acceleration amplitude. In these figures, the indicated crests are the accelerations in positive z-direction. The vertical accelerations, indicated by the operator as not-acceptable are illustrated in figures 16 and 17 as well. Only these indicated vertical accelerations are disapproved by the operator, the rest, and majority, of the vertical acceleration peaks are within the designated limits and therefore acceptable for the operator. Rayleigh distributions for the vertical accelerations at the bow are included in appendix K - Rayleigh distributions vertical accelerations bow.

In table 7 the bracket sizes of the acceptance level are shown for both ships for all runs. In this table, the mentioned probability of exceeding refers to the acceptance limit.

Ship	Run number	Acceptance limit (m/s ²)	Probability of exceeding (%)
KH	2	8	0.04
	3	12	0.06
	4	13	0.07
DR	2	23	0.06
	3	23	0.09
	4	23	0.4

Table 7: Acceptance limits of vertical accelerations

Remarkable is the difference in acceptance limit between both ships. The acceptance level of RIB DR's operator is much higher than the acceptance level of RIB KH's operator. Also the chance of exceeding the acceptance limit is higher at RIB DR than at RIB KH. For both ships, this chance of exceeding the acceptance limit slightly increases with higher average speed. However, this increase is obviously very small.

Nevertheless, both operators stated that especially run number 4 was executed with the maximum possible speed given the environmental conditions, even when these runs have been executed for safeguard.

It is expected that the acceptance limits for all runs of one ship are the same. And also the value of the positive acceleration peaks is expected to be more or less the same as the experienced peaks during the run with fixed throttle control. From figure 17, for RIB DR, it can be seen, the maximum generated vertical accelerations during the run with fixed throttle control equal the acceptance limit. Only during the run with free steering and free throttle



Figure 18: Perceived jerk (RIB KH)



Figure 19: Perceived jerk (RIB DR)

Ministry of Defence

control, a few vertical accelerations beyond the acceptance level are generated. The experienced vertical accelerations during run 3 are the same as during run number 2. And the acceptance limits are also the same for all runs. Afterwards, the operator stated to be happy with the throttle position and speed during run number 2. For RIB DR, the proposition about the similarity of the experienced accelerations and the acceptance limits seems to be true, despite a few higher vertical accelerations during run number 4.

This proposition is also true for run number 3 and 4 of RIB KH, despite a few higher vertical acceleration generated during run number 4. However, the positive acceleration peaks during the run with the fixed throttle control, run number 2, are significantly lower than the ones during run number 3 and 4. This is also expressed in the lower acceptance limit in table 7. Although the operator stated afterwards to be happy with the throttle position and speed during run number 2, the setting of the throttle position was probably too careful.

The operators were questioned about the generation of the vertical acceleration peaks beyond their acceptance limit. Two reasons were indicated by the operators for the appearance of the very high acceleration peaks:

- Misjudgement of the incoming wave by the operator
- Loss of concentration. The runs were very intensive and demanding a constant high concentration level.

Based on the comments of the operators and further data analysis, it is certainly possible to determine a acceptance level for the vertical acceleration peaks per operator. However, based on the trials with only two different ships, it is not possible to determine one general operator acceptance level.

Based on the analysis of active throttle control and an acceleration acceptance level, it is obvious that an active throttle control by the operator is absolutely useful:

- The average speed increases considerable, as mentioned in paragraph 5.2.
- Despite the higher average speed, the majority of the positive vertical accelerations remain within acceptable limits. The operator manipulates the acceleration level with his throttle control.

5.4.3. Experienced accelerations by the operator

In general, the measured accelerations (measured with the accelerometers) and perceived accelerations by the operator do not have the same value. The experienced accelerations by the operator are observed by his otoliths in his vestibular system [8] and appeared to be always higher than the measured accelerations, measured by instruments. The difference between the experienced and measured acceleration peak is called "perceived jerk".

Many experiments were executed to determine a transfer function of the human acceleration perception, which describes by the operator experienced accelerations based on the measured accelerations [9].

The transfer function of the otoliths, developed by TNO-HF, is applicable for both horizontal and vertical accelerations [10]. The difference between the experienced and measured vertical accelerations by application of the transfer function is illustrated in figures 18 and 19. Obviously, applying this transfer function to the measured vertical accelerations results in a higher experienced acceleration peak. The acceptance limits in table 7 are based on, by the operator, perceived accelerations, however the value of these limits is determined by using accelerometers. The acceptance limits in table 7 can be transformed using the transfer function to determine the perceived jerk and use the perceived jerk as an additional acceleration on top of the measured acceptance limit. This transformation is illustrated in table 8.



Figure 20: Throttle control as anticipative control (RIB KH)



Figure 21: Throttle control as anticipative control (RIB DR)

MARTECH / MMT D 5050 / 463

Ship	Run number	Acceptance limit (m/s ²) measured accelerations	Transformed acceptance limit (m/s ²) perceived accelerations
KH	2	8	25
	3	12	33
	4	13	35
DR	2	23	55
	3	23	55
	4	23	55

Table 8: Transformed acceptance limits

5.5 Moment of throttle control

In this paragraph, the actual moment of the throttle application is considered. In sub paragraph 5.5.1 the throttle control is described as anticipative control and in sub paragraph 5.5.2 the actual moment of throttle control is discussed with respect to the incoming wave.

5.5.1. Throttle control as anticipative control

An indication for the control type of throttle control is given by the comparison of the moment of the executed throttle control in time, with the moment of the performed vertical acceleration. It appeared throttle control is generally followed by a vertical acceleration. This is illustrated in figure 20 en 21. As mentioned before, the operator actually uses his throttle control to anticipate at the cues and avoiding large vertical acceleration peaks. The vertical acceleration, is a result of the applied throttle control by the operator. Therefore, the vertical acceleration itself cannot be a cue for the operator on which he will base his handling, because the vertical accelerations occur after the operator's response. During the moment of consideration what actions to take, the information about the value of the vertical acceleration peak is still unknown to the operator. Even after a few large vertical acceleration peaks his behaviour remains the same compared with his behaviour before the large acceleration peaks. Based on this, throttle control can be designated as anticipative control.

To what cues the operator is anticipating, is still unknown in this stage of the data analysis. However, the vertical acceleration is not a cue for the operator. Possible cues are researched thoroughly in chapter 6 - Model development.

5.5.2 Throttle control with respect to the incoming wave

For the runs in which the operator was allowed to apply throttle control, it appeared for both ships, there was some consistency in the actual moment of applying this throttle control. The actual moment of throttle control application was generally the same with respect to the incoming wave. When the operator used his throttle control, the ship generally was positioned in the wave trough of the incoming wave. Table 9 illustrates the actual positions of throttle application in terms of percentage regarding to the wave troughs.

Ship	1.0s-0.5s (before)	0.5s-0.2s (before)	0.2s-trough-0.2s	0.2s-0.5s (after)	0.5s-1.0s (after)
KH	-	-	84.1 %	4.5 %	11.4 %
DR	4.7 %	5.3%	62.2 %	20.6 %	7.2 %

Table 9: Moment of throttle control with respect to the wave trough



Figure 22: Moment of throttle control in wave trough (RIB KH)





Ministry of D



"Before" means throttle application before the wave trough within the indicated time bracket and "after" means throttle application after the wave trough within the indicated time bracket.

Obviously, RIB KH had the highest percentage of throttle control applications in the wave trough. In figure 22-24 some examples are illustrated of moments of throttle control with respect to the wave trough.

5.6 Comparison measured and calculated accelerations

FASTSHIP is a non-linear strip theory based program for the calculation of hydrodynamic loads, motions, and derivatives of planing ships in irregular head waves. For RIB KH, several runs with different speeds are executed in FASTSHIP for comparison of the heave height and wave height as described in paragraph 4.4. These FASTSHIP runs can also be used for comparison between the measured vertical accelerations at RIB KH operator's position and calculated vertical acceleration at RIB KH operator's position. These comparison is discussed in this paragraph.

Two different speeds will be considered: a speed of 18.1 knots and a speed of 21.6 knots. The speed of 18.1 knots is the average speed of run number 2 of RIB KH (fixed throttle control and free steering control) and the speed of 21.6 knots is the average speed of run number 4 of RIB KH (free throttle control and free steering control).

5.6.1 Speed 18.1 knots

In figure 25 the FASTSHIP run with speed of 18.1 knots is illustrated, compared with the measured vertical accelerations.

Comparing the measured vertical accelerations at the operator's positions of run number 2 with the calculated vertical accelerations at the operator's position of the FASTSHIP run with speed of 18.1 knots, it is expected that the measured and calculated vertical accelerations peaks have the same peak values. As mentioned before, run number 2 was executed with "fixed throttle control and free steering control". It is expected these run could be considered as "fixed speed". However, as illustrated in appendix D - Peak statistics, run number 2 still displays some speed fluctuations which are caused by the wave impacts.

As illustrated in figure 25, the calculated vertical accelerations of FASTSHIP are significantly higher than the ones measured during the trials. A possible explanation could be the fluctuations in speed during run number 2, despite the fixed throttle setting. These fluctuations in speed are not taken into account in FASTSHIP and therefore it is likely, FASTSHIP will calculate higher vertical accelerations than measured. An other possible explanation for the differences between measured and calculated accelerations could be the difference in wave input in FASTSHIP, based on the JONSWAP spectrum, and the actual wave conditions during the trials.

5.6.2 Speed 21.6 knots

The comparison between the measured vertical accelerations at the operator's positions of run number 6 with the calculated vertical accelerations at the operator's position of the FASTSHIP run with speed of 21.6 knots, illustrates the influence of the throttle interference by the operator at the vertical acceleration peaks. It is expected that the measured vertical acceleration peaks of run number 6 are considerably smaller, because the operator manipulates this vertical acceleration level with his throttle interference. In figure 26 the FASTSHIP run with speed of 21.6 knots is illustrated, compared with the measured vertical accelerations.



Figure 24: Moment of throttle control after the wave trough (RIB DR)



Figure 25: Calculated vertical acceleration operator positions Vs=18.1 knots (FASTSHIP) (RIB KH)

try of D



Compared to the measured vertical accelerations during run number 6, the calculated accelerations display a significantly higher level of the vertical acceleration peaks. This confirms the expectation stated above. However, based on the findings in the sub paragraph 5.6.1, it is not possible to draw conclusions about the manipulative behaviour of the operator and the consequences of his behaviour. When, in the near future, FASTSHIP is adjusted for the surge motion, the calculations above should be repeated and considered again.

5.7 Differences between the operators regarding throttle application

Besides the similarities in the behaviour of the operators, there are two remarkable differences in their behaviour:

- The duration of the throttle control application. The operator of RIB DR uses a much shorter duration for his throttle control than the operator of RIB KH. The difference in duration is illustrated in the figures 22 (RIB KH's operator with relative long duration of throttle), 23 and 24 (RIB DR's operator with a relative short duration of throttle). This difference in duration is considered in chapter 6 - Model development.
- The throttle frequency. The total number of throttle applications of RIB DR's operator (run 3 and 4 together) was 314, the total number of throttle applications of RIB KH's operator (also run 3 and 4 together) was 104. The throttle frequency of RIB DR's operator was three times higher than the throttle frequency of RIB KH's operator. A possible explanation for this higher frequency could be the difference in environmental conditions, like the wave height and wind conditions and the wave against current situation during the trials with RIB DR.

5.8 Sub conclusions

From data analysis, it appeared throttle control to be dominant with respect to steering control. Because of the small contribution of steering control to the average speed, steering control is neglected during the model development.

Using a helmet with fixed camera, the visual sector of interest for the operator appeared to be 180 degrees in total, 90 degrees off the ship's course at both sides. The instruments are not a cue for the operator, because his focus was just outside the ship and the operator rarely looked at his instruments. The cues are located outside the ship.

The acceptance levels for vertical accelerations with corresponding probabilities of exceeding, differ significantly for both operators. The expectation that the acceptance limits for all runs of one ship are the same is true for all runs of RIB DR and for the run numbers 3 and 4 of RIB KH. For RIB KH, the throttle setting during run number 2 (fixed throttle control) was probably too careful.

Based on the analysis of active throttle control and acceptance levels of vertical accelerations, active throttle control by the operator is absolutely useful. Using active throttle control the average speed increases considerably and the positive vertical accelerations remain within acceptable limits. The operator uses his throttle control to anticipate at the cues and avoiding large vertical acceleration peaks. Therefore, throttle control can be designated as anticipative control. The vertical acceleration itself is not a cue for the operator, because the vertical acceleration occurs after the operator's throttle application. During this moment of throttle application, the value of the vertical acceleration peak is still unknown to the operator. Generally the actual moment of throttle application happened to be in the wave trough.



Figure 26: Calculated vertical acceleration operator positions Vs=21.6 knots (FASTSHIP) (RIB KH)

Ministry of D

Ministry of De

Compared to the measured vertical accelerations during run number 2 and 6, the calculated FASTSHIP accelerations display a significantly higher level of the vertical acceleration peaks. Therefore, it is not possible to draw conclusions about the manipulative behaviour of the operator and the consequences of his behaviour, based on the comparison between measured vertical accelerations and accelerations calculated with FASTSHIP.

Besides the similarities in their behaviour, the operators showed remarkable differences in throttle duration and throttle frequency.



Ministry of Defence

6 – Model development



6.1 General

As mentioned in the introduction, the aim of this thesis is to investigate and analysis operator behaviour and to develop a model for this operator behaviour so that it can be implemented into motion prediction programmes, such as FASTSHIP.

The maximum average speed can be seen as a performance parameter of the ship. The operator had the ability to influence the ultimate performance of the ship by means of throttle control and steering control. As seen in paragraph 5.2 the contribution of steering control to the average speed is relatively small. Therefore, in further data analysis, steering control is not taken into account. Also in the model development process, steering control is neglected.

To gain the required insight into the operator behaviour, the cues for the operator using his throttle control with a certain throttle duration must be determined. Relations between throttle control and throttle duration and possible cues must be designated. After all, a model of the throttle application by the operator, defined as the throttle change, and a model of the throttle duration had to be developed.

In paragraph 6.2 the determination of the ships speed is discussed and in paragraph 6.3 determination of the wave form is illustrated. In paragraph 6.4 the building of a parameter data base is treated and in paragraph 6.5 the regression analysis for the throttle change is discussed. In paragraph 6.6 the regression analysis for throttle duration is treated and in paragraph 6.7 the moments of zero throttle control are considered. In paragraph 6.8 the models for throttle control and throttle duration are presented and the general validity of these models is discussed in paragraph 6.9. This chapter ends with the sub conclusions, presented in paragraph 6.10.

6.2 Determination of the ships speed

Generally, the integration of the acceleration signal in x-direction, will give the speed in xdirection. However, during both trials, the accelerations in the x-direction were recorded with an accelerometer equipped with a frequency range from 2-1000 Hz. The low frequency accelerations were not recorded by this accelerometer. Unfortunately, for the purpose of determining the speed in x-direction, the recorded acceleration in x-direction was insufficient. In figure 27 an example of this acceleration in x-direction is given.

Despite of the low sample rate, the GPS data are used to determine the ship speed. Unfortunately, it appeared these GPS data were the only speed data available.

6.3 Determination of the wave form

In sub paragraph 6.3.1 possible wave form indicators will be considered and in sub paragraph 6.3.2 the wave slope of the incoming waves is determined.

6.3.1 Wave form indicators

One of the indicated cues by the operator is the wave form. Based on the recorded data, two wave form indicators can be designated: the pitch angle and the wave slope.



Figure 27: Example of the acceleration in x-direction (RIB KH)





The first idea was to use the pitch angle of the ship as a wave form indicator. When the ship was sailing from wave trough to wave top, the pitch angle could say something about the wave form. However, the only measured data was the pitch speed of the ship (deg/s). The pitch angle of the ship had to be determined by means of integrating the pitch speed. Eventually, using the pitch angle of the ship does not seem applicable, because of two problems:

- The starting value of the pitch angle at the run start was unknown. After integrating the pitch speed, the absolute values of the pitch angle are still unknown, because of the unknown starting value of the pitch angle. And exactly these absolute values of the pitch angle are needed to identify the wave form.
- The ship showed non-linear behaviour. Because of this non-linear behaviour of the ship, it is not completely clear whether the value of the pitch angles identify the wave form every time. Even when the integrated pitch speed resulted in the correct absolute values of the pitch angle, they were still not usable as wave form indicator because of this non-linearity [11].

The pitch angle is not usable as a wave form indicator and the only wave form indicator left is the wave slope. Therefore, the wave slope is designated to be used as wave form indicator. In figure 28 the definition of the wave slope used in this research is illustrated.

Based on the definition in figure 28, the wave slope, α , is given by:

$$\alpha = a \tan(\frac{H}{\frac{1}{2}\lambda})$$
 (deg)

(6.1)

6.3.2 Determination of the wave slope for each incoming wave

In chapter 4, it was demonstrated, that the heave height can be used as a wave height indicator. The wave height, as illustrated in figure 28, is determined by the value of the heave motion from heave trough to heave crest.

It is assessed the single incoming wave of which the wave slope is determined can be considered as regular.

The water depth is considered to be deep with respect to the wave lengths of the incoming waves.

From the heave motion signal the corresponding "half of the encounter period" $(1/2T_e)$ from trough to crest can be measured, as illustrated in figure 29. "Half of the encounter period" multiplied by two, results in the T_e .

The encounter frequency, ω_e is given by:

$$\omega_e = \frac{2^* \pi}{T_e} \qquad (rad/s) \tag{6.2}$$

The trials are executed in head waves only, so the wave frequency, ω , can be determined, using equation 6.3:

$$\omega_e = \omega + \frac{\omega^2 * U}{g} \tag{6.3}$$

In this equation, U is the ship speed in m/s. The wave speed is determined using equation 6.4:

$$c = \frac{g}{\omega} \tag{(m/s)}$$



Figure 29: Measure the first part of the encounter period (1/2 Te) (RIB KH)

The wave length, λ , is determined using equation 6.5: $\lambda = \frac{c^2 * 2\pi}{m}$ (m)

Finally, the wave slope is determined by using equation 6.1:

$$\alpha = \alpha \tan(\frac{H}{\frac{1}{2}\lambda}) \qquad (deg) \tag{6.1}$$

6.4 Building a parameter data base

To investigate the relations between throttle change, throttle duration and possible cues, a data base with all throttle changes and throttle durations have been build including corresponding parameters, like wave height and wave slope. These parameters can be designated as possible cues. This data base is illustrated in appendix H. In this appendix, a table of different parameters is shown. For all the moments the operator actually used his throttle, the corresponding throttle change, throttle duration, wave height (or heave height), ships speed, vertical acceleration peak, wave slope, encounter period, wave speed and wave length are determined. These parameters are determined for both ships and for run numbers 3 and 4; the runs with free throttle control. Therefore, this table contains all the specific moments the operators used their throttle control.

When equal combinations of parameters occur more than once, this combination of parameters is only showed a single time in the table in appendix H. However, in the regression analysis described in paragraph 6.5 these similar combinations of parameters are taken into account.

6.5 Regression analysis throttle change

In this paragraph, the relations between throttle change and possible cues for the operator are investigated. In sub paragraph 6.5.1 the general procedure of regression analysis is described, in sub paragraph 6.5.2 possible relations of throttle change are investigated and in sub paragraph 6.5.3 multiple regression analysis is discussed.

6.5.1 Procedure of regression analysis

To investigate possible relations, the method of regression analysis will be used, together with the parameter data base (the data base with possible cues) build in paragraph 6.4. When multiple relations with possible cues appear, the multiple regression analysis will be used.

For the regression analysis, two variables are necessary. Here, the aim is to investigate relations between the throttle change and possible cues, so the throttle change is designated as one of the two required variables. The other variable is one of the parameters in the data base.

The possible cue from the parameter data base is called X and designated as the independent or controlled variable. The throttle change is called Y, and is designated as the dependent variable, because its value is depending on X.

The degree of correlation between the variable X and Y can be calculated using the "least squares method". Using this method, the strength of the relation between X and Y can be quantified. The output of that calculation is the called "correlation coefficient" or R. R ranges between values of -1 and 1. A value of 1 indicates perfect positive correlation and likewise, a value of -1 indicates perfect negative correlation. A value of zero indicates zero correlation.



Figure 30: Scatter diagram of the wave height and throttle change (RIB KH) (linear relation)



Figure 31: Scatter diagram of the wave height and throttle change (RIB KH) (quadratic relation)

Ministry of Defend



An other statistic coefficient is the "determination coefficient", or R^2 . This coefficient expresses how much variability in the dependent variable is explained by variability in the independent variable. R^2 ranges between values of 0 and 1.

Before calculating the correlation coefficient, the next step is to produce a scatter or correlation diagram of the variables X and Y. The aim of the regression analysis is to fit a line through the point in the scatter diagram, so that the squared deviations of the observed points from that line are minimized. The line in the scatter diagram is called "regression line". After determining the regression line, the correlation coefficient R and determination coefficient R^2 can be calculated.

6.5.2 Examination of relations

Possible relations will be investigated systematically. For both ships, all the parameters of the database and some combinations of parameters will be examined for possible relations with the throttle change. As mentioned in paragraph 6.4 equal combinations of parameters, however not showed in the table, are taken into account during the regression analysis.

The cues mentioned by the operator are the wave height and wave form (parameter wave slope), these parameters will be examined first.

First the regression analysis if RIB KH is discussed, followed by the regression analysis of RIB DR.

Wave height (RIB KH):

Following the procedure described in sub paragraph 6.5.1, throttle change is designated as variable Y and wave height is designated as variable X. The corresponding scatter diagrams are illustrated in figures 30-33. Both linear and quadratic relations are examined.

In table 10 the corresponding correlation and determination coefficients of the scatter diagrams from figures 30 and 31 (RIB KH) are illustrated as well as the regression line equations.

Type of relation	R	R ²	Equation of regression line	
linear	0.6014	0.3617	y _r = 20.43 * x _r - 11.15	
quadratic	0.6139	0.3768	$y_r = 4.06 * x_r^2 + 12.11$	

Table 10: Correlation and determination coefficients (RIB KH)

From table 10 and from the scatter diagrams above, it is obvious, for RIB KH, that there is not a strong relation between the wave height and throttle change. Although the quadratic relation results in a slightly stronger correlation, the correlation coefficients still are quite small.

Wave height (RIB DR):

In table 11 the corresponding correlation and determination coefficients of the scatter diagrams from figures 32 and 33 (RIB DR) are illustrated as well as the regression line equations.

Type of relation	R	R ²	Equation of regression line	
linear	0.5294	0.2803	y _r = 14.47 * x _r + 40.59	
quadratic	0.5005	0.2505	$y_r = 3.17 * x_r^2 + 55.96$	

Table 11: Correlation and determination coefficients (RIB DR)

From table 11 and from the scatter diagrams above, it is obvious, also for RIB DR, that there is again not a strong relation between the wave height and throttle change. Although the linear relation results in a slightly stronger correlation, the correlation coefficients still are quite small. The correlation and determination coefficients are even smaller than the one of RIB KH.



Figure 32: Scatter diagram of the wave height and throttle change (RIB DR) (linear relation)



Figure 33: Scatter diagram of the wave height and throttle change (RIB DR) (quadratic relation)

Ministry of De

The blue dotted ellipses in figure 30 and 31 (RIB KH) represent throttle changes in the range of 15-85 % at a wave height of 2.5 meters and the blue dotted ellipses in figures 32 and 33 (RIB DR) represent throttle changes in the range of 40-90 % at a wave height of 1.5 meters. Because of different throttle applications at one particular wave height, it is difficult to determine one throttle change belonging to one wave height.

There must be another cue or cues the operator is responding to. Despite the fact both operators indicated the wave height as a cue, apparently the wave height is not the strong cue the operators were thinking it was.

Also remarkable is the minimum wave height of 1.0 meters as can be seen in the table in appendix H. The operator did not respond to wave heights smaller than 1.0 meters.

Wave slope (RIB KH):

The throttle change is variable Y and the wave slope is variable X. The corresponding scatter diagrams are illustrated in figures 34-37. Both linear and quadratic relations are examined. In table 12 the corresponding correlation and determination coefficients of the scatter diagrams from figures 34 and 35 (RIB KH) are illustrated as well as the regression line

equations. Type of relation R R^2 Equation of regression line

Type of relation	R	R^2	Equation of regression line
linear	0.9200	0.8464	y _r = 15.23 * x _r - 47.54
quadratic	0.9359	0.8759	$y_r = 1.31 * x_r^2 - 6.21$

 Table 12: Correlation and determination coefficients (RIB KH)

From table 12 and from the scatter diagrams above, it is obvious, for RIB KH, here is a strong relation between the wave slope and throttle change. The values of the correlation and determination coefficient are both high. The quadratic relation results in the highest correlation coefficient.

Wave slope (RIB DR):

In table 13 the corresponding correlation and determination coefficients of the scatter diagrams from figures 36 and 37 (RIB DR) are illustrated as well as the regression line equations.

Type of relation	R	R ²	Equation of regression line	
linear	0.8575	0.7353	y _r = 12.28 * x _r + 1.23	
quadratic	0.8635	0.7456	$y_r = 1.10 * x_r^2 + 34.19$	

Table 13: Correlation and determination coefficients (RIB DR)

From table 13 and from the scatter diagrams above, it is obvious, also for RIB DR, there is again a strong relation between the wave slope and throttle change. The values of the correlation and determination coefficient are both high. The quadratic relation results in the highest correlation coefficient.

Remarkable is the difference between operators regarding the starting point of their throttle change. The throttle change of RIB KH's operator ranges from 10-95 % and the throttle change of RIB DR's operator ranges from 40-95 %.



Figure 34: Scatter diagram of the wave slope and throttle change (RIB KH) (linear relation)



Figure 35: Scatter diagram of the wave slope and throttle change (RIB KH) (quadratic relation)

stry of Defe



Figure 36: Scatter diagram of the wave slope and throttle change (RIB DR) (linear relation)



Figure 37: Scatter diagram of the wave slope and throttle change (RIB DR) (quadratic relation)

stoy of D

Ministry of Defence

Remaining parameters:

The relations between the remaining parameters and the throttle change are examined in the same way as above. Also both linear and quadratic relation are considered. In table 14 the relations with corresponding coefficients is illustrated. The corresponding scatter diagrams are illustrated in appendix I -Scatter diagrams throttle change.

Ship	Parameter	Relation type	R	R ²	Regression line
KH	ships speed	linear	0.0348	0.0012	$y_r = 0.4549 * x_r + 23.07$
		quadratic	0.0455	0.0021	$y_r = 0.01 * x_r^2 + 26.19$
	vertical acceleration	linear	0.2132	0.0455	$y_r = 0.9859 * x_r + 23.68$
		quadratic	0.1922	0.0369	$y_r = 0.0408 * x_r^2 + 28.30$
	encounter period	linear	-0.2392	0.0572	$y_r = -15.06 * x_r + 68.62$
		quadratic	-0.2359	0.0556	$y_r = -3.18 * x_r^2 + 51.26$
	wave speed	linear	-0.1134	0.0128	$y_r = -2.78 * x_r + 56.76$
		quadratic	-0.0888	0.0078	$y_r = -0.13 * x_r^2 + 42.39$
	wave length	linear	-0.0887	0.0078	$y_r = -0.20 * x_r + 42.38$
		quadratic	-0.0319	0.0010	$y_r = -0.0007 * x_r^2 + 34.73$
	ships speed + wave	linear	-0.0510	0.0026	$y_r = -0.80 * x_r + 48.83$
	speed				
		quadratic	-0.0346	0.0012	$y_r = -0.01 * x_r^2 + 38.51$
DR	ships speed	linear	0.0345	0.0019	$y_r = 0.29 * x_r + 65.37$
		quadratic	0.0260	0.0007	$y_r = 0.01 * x_r^2 + 68.37$
	vertical acceleration	linear	0.1304	0.0170	$y_r = 0.49 * x_r + 66.59$
		quadratic	0.1019	0.0104	$y_r = 0.02 * x_r^2 + 68.95$
	encounter period	linear	-0.1791	0.0321	y _r = -6.11 * x _r + 85.48
		quadratic	-0.1959	0.0383	$y_r = -1.22 * x_r^2 + 78.05$
	wave speed	linear	-0.1612	0.0259	$y_r = -2.64 * x_r + 91.44$
		quadratic	-0.1723	0.0297	$y_r = -0.17 * x_r^2 + 81.11$
	wave length	linear	-0.1728	0.0298	$y_r = -0.26 * x_r + 81.15$
		quadratic	-0.1882	0.0354	$y_r = -0.003 * x_r^2 + 75.46$
	ships speed + wave	linear	-0.0843	0.0071	$y_r = -0.92 * x_r + 85.56$
	00000	quadratic	-0.1688	0.0285	$y_r = -0.16 * x_r^2 + 82.20$

Table 14: Correlation and determination coefficients for remaining parameters

Obviously, there are no strong relations between the throttle change and the remaining parameters, because of the small correlation and determination coefficients in table 14.

6.5.3 Multiple regression analysis

In paragraph 6.5.2. a small correlation and determination coefficient of the relation between the wave height and throttle change was found and therefore a very weak relation between the throttle change and wave height is expected. To confirm this weak relation, a multiple regression analysis with three variables have been executed. The throttle change is variable Z, the wave height is variable X and the wave slope is variable Y. Only the linear relation is considered.

The graphical results of the multiple regression analysis are shown in figures 38 en 39.

As a result of this multiple regression analysis, the calculated correlation coefficients were 0.9115 (RIB KH) and 0.8330 (RIB DR). The corresponding determination coefficients were



0.8313 (RIB KH) and 0.6949 (RIB DR). So the strength of correlation decreases with three variables involved, compared to the linear correlation coefficient of the relation wave slope and throttle change.

The corresponding regression equations are: RIB KH: y_r = -3.18 * wave height + 16.33 * wave slope - 46.44 RIB DR: y_r = 0.07 * wave height + 12.25 * wave slope + 1.20

The contribution factors of the wave height are -3.18 (RIB KH) and 0.07 (RIB DR). For both ships, the contribution of the wave height to the total throttle change is considerably small. This confirms the results of paragraph 6.5.2; there is no significant relation between the wave height and the throttle change. Finally, it can be concluded, the results of the regression analysis of the throttle change, produced only one cue; the wave slope.

6.6 Regression analysis throttle duration

As mentioned before, some differences in the behaviour between the operators occurred. Generally, this is expressed in the throttle duration and the starting point of the throttle change. RIB KH's operator starts with his throttle change at 10 % with a significantly longer throttle duration than RIB DR's operator. RIB DR's operator, however, starts at 40 % throttle change combined with a short duration.

Throttle change times throttle duration can be designated as the total effect of the throttle application. If regression analysis produces a relation for this combination of throttle change and throttle duration (the total effect) consequently this results into a relation for throttle duration alone, because of the expression for throttle change found in sub paragraph 6.5.2.

Possible relations will be investigated systematically. For both ships, all the parameters of the database and some combinations of parameters will be examined for possible relations with the throttle duration. Again, the cues mentioned by the operator, the wave height and wave form (parameter wave slope), will be examined first. The aim of this paragraph is to find an suitable relation similar for both ships. Only if the relations are similar for both ships, the throttle duration can be described.

Wave height (both RIBs):

The throttle duration times throttle change is variable Y and the wave height is variable X. The corresponding scatter diagrams are illustrated in figures 40 and 41. Both linear and quadratic relations are examined.

In table 15 the corresponding correlation and determination coefficients of the scatter diagrams from figures 40 and 41 are illustrated as well as the regression line equations.

Ship	Type of relation	R	R ²	Equation of regression line	
KH	linear	0.5320	0.2830	y _r = 98.57 * x _r - 100.80	
	quadratic	0.5341	0.2853	$y_r = 19.25 * x_r^2 + 13.09$	
DR	linear	0.5046	0.2546	$y_r = 41.19 * x_r + 6.70$	
	quadratic	0.5153	0.2655	$y_r = 9.55 * x_r^2 + 48.02$	

 Table 15: Correlation and determination coefficients



Figure 38: Multiple regression analysis (RIB KH)



Figure 39: Multiple regression analysis (RIB DR)

Ministry of Defe



Figure 40: Scatter diagram of throttle duration times throttle change and wave height for both ships (linear relation)



Figure 41: Scatter diagram of throttle duration times throttle change and wave height for both ships (quadratic relation)

MARTECH / MMT D 5050 / 463 istry of De

From table 15 and from the scatter diagrams above, it is obvious, for both RIBs, there is a small relation between the wave height and throttle duration times throttle change. Although the quadratic relation results in a slightly stronger correlation, the correlation coefficients still are quite small.

Wave slope (both RIBs):

The throttle duration times throttle change is variable Y and the wave slope is variable X. The corresponding scatter diagrams are illustrated in figures 42-45. Both linear and quadratic relations are examined.

In table 16 the corresponding correlation and determination coefficients of the scatter diagrams from figures 42 and 43 are illustrated as well as the regression line equations.

Ship	Type of relation	R	R ²	Equation of regression line
KH	linear	0.6274	0.3936	y _r = 75.95 * x _r - 289.38
	quadratic	0.6410	0.4109	$y_r = 6.75 * x_r^2 - 90.22$
DR	linear	0.6475	0.4193	y _r = 21.97 * x _r - 32.45
	quadratic	0.6660	0.4436	$y_r = 2.06 * x_r^2 + 23.64$

Table 16: Correlation and determination coefficients

From table 16 and from the scatter diagrams above, it is obvious, for both RIBs, there is a significantly larger relation between the wave slope and throttle duration times throttle change than the relation with the wave height. The correlation coefficients of the quadratic relation are slightly larger than the ones of the linear relation. However, the equations of the linear and quadratic regression lines are not really similar for both ships and to find a relation similar for both ships was the aim of this paragraph. From figures 42 and 43 it appears, until a wave slope of 7 degrees, the scatter points are comparable for both ships. In figure 44 and 45 the scatter diagrams of the linear and quadratic relations are illustrated again, without the points beyond wave slope of 7 degrees.

In table 17 the corresponding correlation and determination coefficients of the scatter diagrams from figures 44 and 45 are illustrated as well as the regression line equations.

Ship	Type of relation	R	R ²	Equation of regression line
KH	linear	0.6299	0.3968	$y_r = 31.50 * x_r - 85.80$
	quadratic	0.6648	0.4420	$y_r = 3.31 * x_r^2 - 13.75$
DR	linear	0.6675	0.4456	y _r =19.35 * x _r - 19.50
	quadratic	0.6865	0.4713	$y_r = 2.53 * x_r^2 + 11.19$

 Table 17: Correlation and determination coefficients

From the figures 44 and 45 and the table 17 it can be concluded that the quadratic relation of the wave slope < 7 degrees has the strongest relation so far.

If for example the relations are tested with a wave slope of 5 degrees, the relations will produce the following throttle duration times throttle change: RIB KH: 69 RIB DR: 74 These values are comparable to each other.



Figure 42: Scatter diagram of throttle duration times throttle change and wave slope for both ships (linear relation)





Ministry of Def



Figure 44: Scatter diagram of throttle duration times throttle change and wave slope <7 degrees for both ships (linear relation)



Figure 45: Scatter diagram of throttle duration times throttle change and wave slope <7 degrees for both ships (quadratic relation)



Remaining parameters:

The relations between the remaining parameters and the throttle duration times throttle change are examined in the same way as above. Also both linear and quadratic relation are considered. In table 18 the relations with corresponding coefficients are illustrated. The corresponding scatter diagrams are illustrated in appendix J -Scatter diagrams throttle duration.

Ship	Parameter	Relation type	R	R ²	Regression line
KH	ships speed	linear	-0.0346	0.0012	$y_r = -2.47 * x_r + 166.33$
		quadratic	-0.0270	0.0007	$y_r = -0.05 * x_r^2 + 134.44$
	vertical acceleration	linear	0.2818	0.0794	$y_r = 7.11 * x_r + 45.02$
		quadratic	0.2414	0.0583	$y_r = 0.28 * x_r^2 + 80.02$
	encounter period	linear	-0.2335	0.0545	$y_r = -80.22 * x_r + 301.96$
		quadratic	-0.2267	0.0514	$y_r = -16.69 * x_r^2 + 207.95$
	wave speed	linear	-0.1199	0.0144	$y_r = -16.00 * x_r + 249.22$
		quadratic	-0.0943	0.0089	$y_r = -0.73 * x_r^2 + 166.62$
	wave length	linear	-0.0943	0.0088	$y_r = -1.14 * x_r + 166.58$
		quadratic	-0.0388	0.0015	$y_r = -0.005 * x_r^2 + 123.66$
	ships speed + wave	linear	-0.0979	0.0090	$y_r = -0.80 * x_r + 48.83$
	speed				
		quadratic	-0.0947	0.0089	$y_r = -0.01 * x_r^2 + 38.51$
DR	ships speed	linear	0.0389	0.0015	$y_r = 0.95 * x_r + 75.02$
		quadratic	0.0410	0.0017	$y_r = 0.03 * x_r^2 + 82.51$
	vertical acceleration	linear	0.1240	0.0154	$y_r = 1.37 * x_r + 80.93$
		quadratic	0.1135	0.0129	$y_r = 0.06 * x_r^2 + 86.89$
	encounter period	linear	0.1062	0.0113	$y_r = 10.62 * x_r + 64.53$
		quadratic	0.0898	0.0080	$y_r = 1.63 * x_r^2 + 80.53$
	wave speed	linear	0.1229	0.0151	$y_r = 5.89 * x_r + 43.62$
		quadratic	0.1121	0.0126	$y_r = 0.32 * x_r^2 + 70.26$
	wave length	linear	0.1115	0.0124	$y_r = 0.49 * x_r + 70.37$
		quadratic	0.0852	0.0073	$y_r = 0.004 * x_r^2 + 84.08$
	ships speed + wave	linear	0.1079	0.0116	$y_r = -0.92 * x_r + 85.56$
	speed	quadratic	0.1135	0.0128	$y_r = -0.16 * x_r^2 + 82.20$

 Table 18: Correlation and determination coefficients for remaining parameters

Although the relation is not as strong as the relation between the throttle change and wave slope, the relation between the throttle duration times throttle change and the wave slope is the best relation found with the regression analysis.

6.7 Moments during the trials with zero throttle control

The regression analysis is based on all the moments the operator is actually applying his throttle. From the data analysis, it is known both operators do not use their throttle for wave slopes smaller than respectively 2.9 degrees (RIB DR) and 3.3 degrees (RIB KH). Also the minimum wave height (heave height) the operators were responding to is 1.0 meter for both ships. These wave heights of 1.0 meter have higher wave slopes than the minimum wave slopes of 2.9 degrees.

However, there are many moments the operator is not using his throttle. To analyse these moments, the minimum wave height of 1.0 meter is chosen as departure point: first because

a wave height of 1.0 meter is the minimum wave height at which the operator used his throttle control and second as seen from paragraph 4.4.2, heave heights smaller than 1.0 meter showed considerable large deviations from the actual wave heights and are therefore not usable as indicator for the wave height.

If combinations of "zero throttle" and "wave heights larger than 1.0 meter" are found, it is expected these waves will have wave slopes smaller than the minimum wave slopes of 2.9 degrees and 3.3 degrees respectively. Otherwise, the operator would have used his throttle. When these particular wave slopes are smaller than the minimum wave slope, the operator is not supposed to respond to this wave, based on the relation between the throttle use and wave slope found during the regression analysis. When the particular wave slopes are larger than the minimum wave slopes, the operator should have responded to that wave. If too many moments with zero throttle control and wave slopes larger than 2.9 degrees or 3.3 degrees are found, the relation between the throttle use and wave slope found in paragraph 6.5.2 is unfortunately not valid. A maximum of 10 % moments with zero throttle control exceeding the wave slopes of 2.9 or 3.3 degrees is considered to be still acceptable.

For both ships, the trial data were analysed for combinations of "zero throttle control", "wave heights of 1.0 meter or larger" and the corresponding wave slopes. The results of this data analysis in terms of percentage are presented in table 19. The results are fully illustrated in appendix H. For RIB KH a total number of 6 waves slopes exceeding the minimum wave slope are found. The total number of throttle applications for RIB KH was 104. The percentage of wave slopes exceeding the minimum wave slope is calculated by using both previous numbers ((6 /104)*100%). For RIB DR a total number of 17 wave slopes exceeding the minimum wave slope are found. The total number of throttle applications for RIB DR was 314. The percentage of wave slopes exceeding the minimum wave slope is calculated by using both previous numbers ((17/314)*100%).

Ship	Wave slopes ≥ 2.9 (DR) / 3.3 (KH) deg
KH	5.8 %
DR	5.4 %

 Table 19: Zero throttle and corresponding wave slopes exceeding minimum wave slopes

The percentages illustrated in the red cells, represent the moments of zero throttle control, with wave slopes exceeding the minimum wave slopes, where throttle control was to be expected however not applied. The percentages are small in regard to the total number of throttle applications by the operator. The percentages for both ships remain within the defined limit.

6.8 Operator models for throttle change and throttle duration

Based on the regression analysis in the previous paragraphs and the analysis of moments with zero throttle control, in this paragraph an operator model for the throttle change and throttle duration will be designated.

6.8.1 Operator model for throttle change

The best description of the throttle change was found in paragraph 6.5.2. In this paragraph, a strong relation between the wave slope and throttle change was found. For both ships, it appeared the quadratic relation between the wave slope and throttle change produced the highest correlation and determination coefficients. The configuration of the operator models is equal for both ships, using different parameters.



Both operator models have one important constraint: they are only valid for wave heights (heave heights) \geq 1.0 meter.

For both ships, the operator models for throttle change are given by:

<u><i>RIB KH (reference table 12, quadratic expression):</i></u> wave slope < 3.3 deg : throttle change = 0 wave slope \ge 3.3 deg : throttle change = 1.31 * (wave slope) ² - 6.22	(%) (%)	(6.6)
<u>RIB DR (reference table 13, quadratic expression):</u> wave slope < 2.9 deg : throttle change = 0	(%)	

wave slope $\geq 2.9 \text{ deg}$: throttle change = 1.10 * (wave slope)² + 34.19 (%) (6.7)

These operator models are visualised in figures 46-48. In figures 47 and 48 the red dots represent the moments of zero throttle control with corresponding wave slopes larger than 2.9 or 3.3 deg. The green dots represent the moments of zero throttle control with corresponding wave slopes smaller than 2.9 or 3.3 deg.

6.8.2 Operator model for throttle duration

The best description for the throttle duration was found in paragraph 6.6. In this paragraph, a relation between the throttle duration times the throttle change (the total "effect" of throttle application) and wave slope was found. For both ships, it appeared the quadratic relation between the wave slope and throttle duration times throttle change produced the highest correlation and determination coefficients, although these correlation and determination coefficients are considerably smaller than the ones found for the model of the throttle change. The configuration of the operator models for throttle duration times throttle change is equal for both ships, using different parameters.

Both operator models for throttle duration times throttle change have two important constraints: they are only valid for wave slopes < 7 degrees and wave heights \geq 1.0 meter.

For both ships, the operator models for throttle duration times throttle change are given by:

<u>*RIB KH (reference table 17, quadratic expression):*</u> throttle duration times throttle change = $3.31 * (wave slope)^2 - 13.75$ (%) (6.8)

<u>*RIB DR (reference table 17, quadratic expression):*</u> throttle duration times throttle change = $2.53 * (wave slope)^2 + 11.19$ (%) (6.9)

These models are illustrated in figure 45.

Using the expressions 6.6 and 6.7 for throttle change, the operator model for throttle duration alone is given by:

<u>RIB KH:</u>

throttleduration =
$$\frac{3.31^* (waveslope)^2 - 13.75}{1.31^* (waveslope)^2 - 6.22}$$
 (s) (6.10)



Figure 46: Operator models of throttle change with constraints



Figure 47: Operator model throttle change (RIB KH)


Figure 48: Operator model throttle change (RIB DR)



Figure 49: Operator model for throttle duration

istry of De

RIB DR:

throttleduration =
$$\frac{2.53 * (waveslope)^2 + 11.19}{1.10 * (waveslope)^2 + 34.19}$$
 (s) (6.11)

This operator model for throttle duration is illustrated in figure 49.

The brackets of the throttle duration are small, as can be seen in figure 49, especially for RIB KH. However, looking at the variation in applied throttle duration for the RIB KH's operator, these variations seemed also to be small. Therefore, it can be concluded, these operator models for throttle duration are usable for both ships. However, because of the smaller correlation and determination coefficients, further investigation about relations of throttle duration is necessary.

6.9 General validity of the operator model for throttle change

The operator models for throttle change and throttle duration are based on the data base mentioned in paragraph 6.4. This data base is build by considering each incoming wave separately. For each individual incoming wave the wave characteristics are determined, like wave length, wave speed and wave slope. As can be seen in appendix H many different waves with many different characteristics have passed the operator. From short waves with high wave slopes till long waves with relative small wave slopes. Because of this variety in wave characteristics and the consistency in operator behaviour responding or not responding to the incoming waves, the range of application for the operator models is broad.

During other environmental conditions (for example another wind force), the individual waves with corresponding wave characteristics as experienced during the trials, will also be produced.

At high seas the wave characteristics of the incoming waves could be different than the ones in coastal conditions (JONSWAP spectrum).

Therefore the operator models for throttle change and throttle duration are generally valid for coastal conditions, for all sort of environmental conditions in which the RIB can be operated safely and for wave heights larger than 1.0 meter. The operator models for throttle duration are only valid for wave slopes smaller than 7 degrees. In addition, the operator models for throttle duration are only valid for the corresponding RIB.

6.10 Sub conclusions

Based on the recorded data, two parameters were appropriate to be used as wave form indicator: the pitch angle and the wave slope. However, the pitch angle was unusable as wave form indicator because of limitations of the integration process to obtain this pitch angle and the non-linear behaviour of the RIBs. Therefore, the wave slope is used as wave form indicator.

For the purpose of determining the ships speed, the recorded accelerations in x-direction were insufficient. The GPS data are used to determine the ships speed.

Possible relations between the throttle change and different parameters (based on the data base of possible cues) were investigated using regression analysis. It appeared the wave slope had a strong relation with the throttle change. However, the wave height showed a very weak relation with the throttle change. Although the operators indicated the wave height as a cue for their actions, only the wave slope can be designated as a cue for the operator.



Regression analysis was also used to investigate possible relations between the throttle duration and the data base parameters. The strongest relation for throttle duration was found for the wave slope. Although this relation was not as strong as the one found between the throttle change and wave slope, the values of the calculated correlation and determination coefficients were sufficient enough to indicate a significant relation between the throttle duration and the wave slope.

The moments with zero throttle control and corresponding wave slopes were investigated. It was expected these investigated waves will have wave slopes smaller than the minimum wave slopes of 2.9 degrees (RIB DR) or 3.3 degrees (RIB KH). Otherwise, based on the operator models for throttle change, the operator should have used his throttle. The number of moments with zero throttle application combined with waves slopes exceeding the minimum wave slopes are small and therefore the operator models for throttle change are still valid.

The operator models for throttle change and throttle duration are valid for all sort of environmental, coastal, conditions in which the RIB can be operated safely and for wave heights larger than 1.0 meter. The operator models for throttle duration are only valid for wave slopes smaller than 7 degrees. In addition, the operator models for throttle change and throttle duration are only valid for the corresponding RIB.

MARTECH / MMT D 5050 / 463 Ministry of Def



7 – Conclusions and Recommendations

7.1 Conclusions

The aim of this thesis is to investigate and analysis operator behaviour and to develop a model for this operator behaviour on board of fast RIBs. To attain this aim, full scale trials were conducted and different data were recorded. These recorded data are incorporated and analysed, which resulted in two operator models for both ships: an operator model for throttle change and an operator model for throttle duration. Based on this thesis research, the following conclusions can be made:

- In non-linear models, the motions of fast RIBs can be predicted with given wave conditions, but only without the important influence of the operator. Eventually, such non-linear models give a pessimistic view of the craft, since such models neglect the beneficial actions of a good helmsman. Especially calculations of vertical accelerations of the ship will show unrealistic high values and just these vertical accelerations are of high interest during a design or procurement process.
- The significant wave height during the runs with the RIB 2000 (RNIN) appeared to be not enough for sufficient "throttle position changes" by the operator. The recorded throttle data showed only a few throttle applications. Therefore, the RIB 2000 data was not used during the rest of the research. The data analysis and model development are based on the trials with both RIBs of the RNLBS.
- The present state of techniques appeared to be insufficient to measure the wave height, wave form or wave pattern in front of the ship during the run. Because of the importance of knowledge about the wave height and wave form, another way of collecting the required wave characteristics had to be considered. In this thesis the heave height is used as wave height indicator. The heave motion is calculated by the double integration of the recorded vertical acceleration signal at the operator's position. The feasibility of the heave height as wave height indicator is demonstrated in two independent ways, by FASTSHIP calculations for RIB KH and by the determination of the heave spectra for both ships. Only the first part of the heave motion is usable as wave height indicator, because of the possibility of airtime. Airtime will result in a heave motion which is no longer related to the wave height. Heave motions smaller than 1.0 meter are unusable as wave height indicator because of the large error between these small heave heights and the corresponding wave heights. Other constraints which occur using the heave height as wave height indicator are the neglected hydrodynamic effects of the ship and the neglected contribution of the pitch angle to the vertical accelerations.
- The contribution of steering control to the average speed is very small. Throttle control is dominant with respect to steering control. The contribution of steering control to the average speed is very small and therefore neglected in this investigation. Based on the analysis of active throttle control and acceptance levels of vertical accelerations, active throttle control by the operator is absolutely useful. Using active throttle control, the average speed increases considerably and the positive vertical accelerations remain within acceptable limits. The operator uses his throttle control to avoid large vertical acceleration peaks.
- During interviews, the operators indicated the wave height and wave form as cues for their actions and responses. The wave slope is used as wave form indicator. The main cue for the operator to use his throttle control is the wave slope, as defined in this thesis. Although the operators indicated the wave height as a cue as well, the

relation between the throttle change and wave height is weak. Also the instruments are not a cue for the operator, because his focus was just outside the ship and the operator rarely looked at his instruments. Finally, the vertical acceleration itself is also not a cue for the operator, because the vertical acceleration occurs after the operator's throttle application. During this moment of throttle application, the value of the vertical acceleration peak is still unknown to the operator. Generally the actual moment of throttle application happened to be in the wave trough.

- Both operators did not use their throttle for wave slopes smaller than respectively 2.9 degrees (RIB DR) and 3.3 degrees (RIB KH). Also the minimum wave height (heave height) the operators were responding to is 1.0 meter for both ships. These wave heights of 1.0 meter have higher wave slopes than the minimum wave slopes of 2.9 degrees and 3.3 degrees.
- Based on the data analysis and regression analysis, operator models for operator behaviour are developed. Because of the small influence of steering control at the average speed, steering control is neglected and the first operator model is based on the throttle control. The main difference in behaviour of the operators is the used throttle duration. Therefore, a second operator model for throttle duration is developed. The operator models for throttle change and throttle duration are valid for all sort of environmental, coastal, conditions in which the RIB can be operated safely and for wave heights larger than 1.0 meter. The operator models for throttle duration are only valid for wave slopes smaller than 7 degrees. In addition, the operator models for throttle change and throttle duration are only valid for the corresponding RIB.
- After the data analysis and the model development process, the following about the operator behaviour is known:
 - To what he reacts (the wave slope)
 - How he reacts (by throttle application)
 - When he reacts (in the wave trough)
 - How long he reacts (throttle duration)

7.2 Recommendations

The results of this thesis have to contribute to the main goal of the research program as mentioned in the introduction. Based on the contribution to this main goal and the conclusions in paragraph 7.1 the following recommendations can be made:

- To gain insight in the differences in operator behaviour it is recommended for future trials to switch operators. When achievable, RIB KH's operator should execute the trials on board of the RIB DR and RIB DR's operator should execute the trials on board of RIB KH. With this operator switch, differences in throttle duration and vertical acceleration acceptance limits can be validated and evaluated.
- To validate the operator models, more trials should be executed, with different RIBs, different operators and different environmental conditions. Trials on board of the RIBs for the NA&ACG could also be used for validation purposes.
- To extend the operator models, less experienced operators and the use of bucket control should be considered. Also different headings, different speeds and different propulsion types should be investigated.

- To evaluate the throttle setting during run number 2 (the run with fixed throttle control and free steering control), for future trials, the run schedule has to be extended and run number 2 has to be repeated after run number 6 (the run with the free throttle and steering control). The difference between the "first" run number 2 and the "second" run number 2 indicates the caution of the throttle setting during the "first" run number 2.
- When, in the near future, FASTSHIP is adjusted for the surge motion, the comparison between the measured vertical accelerations and the calculated vertical accelerations (FASTSHIP) should be repeated and considered again.
- Because of the relative small correlation and determination coefficients, found for the relation between the throttle duration and the wave slope, further investigation about relations of throttle duration is recommended.
- To share the outcome of trials regarding operator behaviour it is recommended to build a data base with the outcome of the corresponding operator trials. Also the outcome of operator trials executed by other countries could be included in the data base. Finally, sharing a data base with information about operator behaviour will contribute to the evaluation, validation and improvement of operator models.
- To improve the quantitative comparison of alternative designs of fast RIBs, it is recommended to implement the operator models for throttle change and throttle duration, as described in this thesis, in the motion-prediction program FASTSHIP.

MARTECH / MMT D 5050 / 463 ł

Ministry of Defen



- [1] Zarnick, E.E. A Nonlinear Mathematical Model of Motions of a Planing Boat in Regular Waves, DTNSRDC, Report 78/032,1978
- [2] Keuning, J.A. Nonlinear Motions of Fast Ships and the Effect on Operability, MARIN Jubilee Meeting, Report 930-P, 1992
- [3] Keuning, J.A. *The Nonlinear behaviour of fast monohulls in head waves,* PhD Thesis, Delft University of Technology, ISBN 90-370-0109-2, 1994
- [4] <u>www.actuelewaterdata.nl</u>
- [5] Dijkshoorn, J. *Slamming en trillingen van een KNRM-RIB,* Royal Netherlands Navy, Report MKC 3101, 2003
- [6] Finch, G.R. *Comparison between the predicted and measured response of a planing vessel,* Industrial Research Limited, New Zealand, 2004
- [7] Vermeulen K.J., Keuning J.A. *Fastship calculations on three fast monohulls*, Delft University of Technology, 2004
- [8] <u>www.nasa.gov/audience/forstudents/912/features/F_Human_Vestibular</u> System in Space.html
- [9] Hosman R.J.A.W, van der Vaart J.C. Vestibular Models and Thresholds of Motion Perception, Results of Tests in a Flight Simulator, - Delft University of Technology, Faculty of Aerospace Engineering, Report LR-265,1978
- [10] Hosman R.J.A.W. Pilot's Perception and Control of Aircraft Motions, PhD thesis -Delft University of Technology, Faculty of Aerospace Engineering, ISBN 90-407-1384-7, 1996
- [11] Keuning, J.A. *Nonlinear Heave and Pitch Motions of Fast Ships in Irregular Head Seas,* Intersociety High Performance Marine Vehicle Conference and Exhibit, 1992

The following literature is not referred to in the thesis, however they contributed considerably to the conceptualisation of the subject:

- [12] Peterson R. Dr, Pierce E., Price B., Bass C. Dr. Shock Mitigation for the Human on High Speed Craft: Development of an Injury Design Rule, Naval Surface Warfare Center, RTO-MP-AVT-110, 2004
- [13] Rasmussen J. Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinction in Human Performance Models, IEEE Transactions on Systems, Man, and Cybernetics, Vol SMC-13, No3., 1983
- [14] Keuning, J.A. Seakeeping of High Speed Craft, WEGEMT, Workshop Small Craft Design, 1997
- [15] Nieuwenhuis, M.R.A. *The Ultimate Performance of Fast RIBs An Experimental Investigation into the Influence of the Helmsman, Ministry of Defence, The Netherlands, RINA Conference "Rigid Inflatables", 2005*
- [16] U.S. Coast Guard, Response Boat Training Team *Trim & Throttle Control Master* Lesson Plan
- [17] Hodgdon J.A., Walsh B.J., Hackney A.C., *Microhematuria Associated with a Special Operations Craft Mission*, Naval Health Research Center, RTO-MP-AVT-110, 2004
- [18] www.mathworld.wolfram.com
- [19] www.knrm.nl
- [20] Ullman, J. Sea Rescue Missions Must Not Slow Down, Ullman Human Design, Sweden, RINA Conference "Rigid Inflatables", 2005
- [21] Dobbins T., Pierce E., *Developing a Human Factors Design Standard for High Speed Planing Craft*, Human Sciences & Engineering Ltd, UK, RINA Conference "Rigid Inflatables", 2005
- [22] Dobbins T., Hill J., Claphan J., *Enhancing RIB Operational Performance Through the use of User-Focused-Design,* Equipment Capability Wing, Royal Marines Poole, UK, RINA Conference "Rigid Inflatables", 2005

MARTECH / MMT D 5050 / 463 of D

Tables and Figures

J

Table 1: Environmental conditions during trials	5
Table 2: Different control types	6
Table 3: Recorded data with corresponding sensor position	7
Table 4: Errors between wave height and heave height from FASTSHIP calculations	. 15
Table 5: Error between wave height and heave height based on heave spectrum	. 17
Table 6: Differences in average speed	. 21
Table 7: Acceptance limits of vertical accelerations	. 27
Table 8: Transformed acceptance limits	. 31
Table 9: Moment of throttle control with respect to the wave trough	. 31
Table 10: Correlation and determination coefficients (RIB KH)	. 45
Table 11: Correlation and determination coefficients (RIB DR)	. 45
Table 12: Correlation and determination coefficients (RIB KH)	. 47
Table 13: Correlation and determination coefficients (RIB DR)	.47
Table 14: Correlation and determination coefficients for remaining parameters	.50
Table 15: Correlation and determination coefficients	51
Table 16 ⁻ Correlation and determination coefficients	54
Table 17: Correlation and determination coefficients	54
Table 18: Correlation and determination coefficients for remaining parameters	57
Table 19: Zero throttle and corresponding wave slopes exceeding minimum wave slopes	58
Table 10. Zero (motile and conceptioning wave slopes exceeding minimum wave slopes .	
Figure 1. Definition of axes and degrees of freedom	8
Figure 2: Location of sensors (RIB KH)	8
Figure 3: Reduction of the signal bandwidth when throttle decreases	10
Figure 4: Rough and filtered vertical acceleration signal	10
Figure 5: No phase shift after filtering the signal	12
Figure 6: Double integration process, from vertical acceleration to vertical position	14
Figure 7: Comparison of wave beights and heave beights (speed 21.6 knots)	16
Figure 8: Comparison of wave heights and heave heights (speed 21.0 knots)	16
Figure 9: Spectra of run number 4 (RIB KH)	18
Figure 10: Spectra of run number 4 (RIB DR)	18
Figure 11: Helmet with fixed camera	23
Figure 12: Example of active throttle control, which results in a small positive	
vertical acceleration peak (RIB KH)	24
Figure 13: Example of fixed throttle control, which results in a high positive	
vertical acceleration peak (RIB KH)	24
Figure 14: Example of active throttle control, which results in a small positive	
vertical acceleration peak (RIB DR)	25
Figure 15: Example of fixed throttle control, which results in a high positive	
vertical acceleration neak (RIB DR)	25
Figure 16: RIB KH Rayleigh distribution of the creats of all runs	26
Figure 17: RIB DR Rayleigh distribution of crests of all runs	26
Figure 18: Perceived jerk (PIR KH)	28
Figure 10: Perceived jerk (RIB DR)	28
Figure 20: Throttle control as anticipative control (PIR KH)	30
Figure 21: Throttle control as anticipative control (RIB RP)	30
Figure 22: Memort of throttle control in wave trough (PIP KH)	32
Figure 22: Moment of throttle control in wave trough (NID NI)	32
Figure 23. Moment of throttle control after the wave trough (RIB DR)	31
Figure 25: Calculated vertical acceleration operator position Vo=19.1 knots (EASTSUID)	.04
(PIR KH)	34
Figure 26: Calculated vertical acceleration operator position Va=21.6 kpote (EASTSHID)	
(PIR KU)	36
(תום תה)	

Ministry of Defence

м	inistry of Defence
	M
Figure 27: Example of the acceleration in x-direction (RIB KH)	
Figure 28: Definition of the wave slope	40
Figure 29: Measure the first part of the encounter period (1/2 Te) (RIB KH)	
Figure 30: Scatter diagram of the wave height and throttle change (RIB KH)	
(linear relation)	44
Figure 31: Scatter diagram of the wave height and throttle change (RIB KH)	
(quadratic relation)	44
Figure 32: Scatter diagram of the wave height and throttle change (RIB DR)	
(linear relation)	46
Figure 33: Scatter diagram of the wave height and throttle change (RIB DR)	
(quadratic relation)	46
Figure 34: Scatter diagram of the wave slope and throttle change (RIB KH)	
(linear relation)	48
Figure 35: Scatter diagram of the wave slope and throttle change (RIB KH)	10
(quadratic relation)	48
(linear relation)	40
(inear relation)	49
(quadratic relation)	10
Figure 38: Multiple regression analysis (PIR KH)	
Figure 30: Multiple regression analysis (RIB DR)	
Figure 40: Scatter diagram of throttle duration times throttle change and wave height	
for both ships (linear relation)	. 53
Figure 41: Scatter diagram of throttle duration times throttle change and wave height	
for both ships (quadratic relation).	53
Figure 42: Scatter diagram of throttle duration times throttle change and wave slope	
for both ships (linear relation)	55
Figure 43: Scatter diagram of throttle duration times throttle change and wave slope	
for both ships (quadratic relation)	55
Figure 44: Scatter diagram of throttle duration times throttle change and wave slope	
< 7 degrees for both ships (linear relation)	56
Figure 45: Scatter diagram of throttle duration times throttle change and wave slope	
< 7 degrees for both ships (quadratic relation)	56
Figure 46: Operator model of throttle change with constraints	60
Figure 47: Operator model throttle change (RIB KH)	60
Figure 48: Operator model throttle change (RIB DR)	61
Figure 49: Operator model for throttle duration	61

