EXPERIMENTAL INVESTIGATIONS OF ACCELERATIONS AND VIBRATIONS ON VEHICLES AND BOATS

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ABSTRACT

The first objective of this study is to measure the hydrodynamic accelerations of Istanbul AFAD's inflatable boats. They use these boats for life saving purposes at Black Sea coasts and beaches of Istanbul. These types of boats running at high speed in rough seas experience six degrees of freedom (heave, surge, sway, yaw, roll and pitch) which is highly complex and dangerous. The reasons of the accelerations and pressures on the boat are, the wave impact, dead rise angle of the boat, running trim, displacement, speed of the boat and the incident wave heights. All the combination of the parameters make the hydrodynamic problem very complicated. An inertial measurement unit (IMU), was used to measure the accelerations of the boat cruising at rough seas. The second objective is to examine the quality of roads in ITU Ayazaga campus with a car and an ambulance all the while identifying the environmental factors affecting individual susceptibility to motion sickness during the road transport. The second experiment was designed to analyze the quality of roads in Istanbul Technical University Ayazaga Campus while cruising with a car in a convenient speed and measure the accelerations on the stretcher for a sick person during the cruise of ambulance in the event of an emergency case.

Key Words: Vibration Dose Value; IMU Device; Rigid Inflatable Boats; Hydrodynamic Accelerations.

1. Introduction

The mission of the Istanbul AFAD is to ensure the safety of life within its area. These inflatable boats have an important role on this mission. Our study was to measure the dynamic accelerations of these boats at high speed in rough sea conditions. In any urgent case, level of dynamic acceleration is very significant point on motion sicknesses especially while carrying injured person on board to the coast. During this journey comfort of injured person is so important and preventing from any possible motion sickness can save life. Our main object was to measure this hydrodynamic acceleration and at the end to suggest a better design for decreasing it. The second objective of this research was to identify environmental factors affecting individual susceptibility to motion sickness during the road transport.

There are numerous works in the literature investigating the accelerations on land vehicles. Nowadays, the dynamic accelerations of water crafts can also be investigated. Blood et al. [1] measured whole-body vibration exposures in front-end loader operators, and evaluated the effects of traction chains and work tasks on their whole-body vibration exposures.

Allen et al. [2] studied on the shocks and the impacts encountered on small high-speed craft exceed the limits set for safe working practice according to current standards. They set out to highlight the vibration dose values that can be expected during typical transits onboard high-speed craft and attempts to clarify some of the controversy currently surrounding vibration dose measurement in such circumstances. Dawkins et al. [3] investigated the effectiveness of using fractals for generating artificial terrains which can be used for vehicle simulations. Shoop et al. [4] explored a methodology that could quantify the impact of various vehicles, tires, driving speeds and maneuvers on the snow road conditions. Basic maneuvers were used to isolate the impact of turning, acceleration, braking and speed using spirals, circles, and straight-line testing on a flat, smooth snow pavement. Fallah-Fini et al. [5] discussed a dynamic efficiency measurement model for evaluating the performance of high way maintenance policies where the inter-temporal dependencies between consumption of inputs and realization of outputs were explicitly captured. Chan et al. [6] utilized the Tennessee Pavement Management System and Accident History Database to investigate the relationship between accident frequency and pavement distress variables. Shah et al. [7] evaluated two methods for priority ranking of road maintenance; ranking based on subjective rating and ranking based on economic indicator. Erdogan et al. [8] focused on the development and experimental evaluation of a novel adaptive feed forward vibration cancellation based friction estimation system. Nila et al. [9] focused on the hydrodynamic impact of bodies onto the water surface which is a problem of great importance in the design of off-shore and naval structures (wave energy converters, off-shore platforms, high speed boats, etc). Wines [10] focused on an issue for high speed craft that they in general are subject to high levels of vibration. Such vibrations may be harmful to the human body on-board and may reduce the situational awareness. An 11m hull RIB has been investigated experimentally for very high Froude numbers. Having recognized the problems that will most likely occur in calm water and in waves, the actual RIB was instrumented and a series of tests were conducted regarding vibration and maneuverability. Wertheim et al. [11] tested the traditional assumption that sea sickness is uniquely provoked by heave motion characteristics, with pitch and roll movements being ineffective. In an experiment with a ship motion simulator, subjects were exposed to pitch and roll motions in combination with rather weak heave motions that have no motion sickness inducing potential.

Turner and Griffin [12] identified personal and environmental factors influencing individual susceptibility to motion sickness during road transport. A questionnaire survey of 3256 coach travelers was conducted. Diaz et al. [13] presents the design of a monovariable robust controller with quantitative feedback theory (QFT) for reducing the vertical movement on a high-speed ferry. Kim et al. [14] investigated the response of the human body to the amounts, frequencies, directions, and exposure times of exerted forces. Processes have been developed to standardize these factors, and the typical examples are ISO 2631-1 and BS 6841, which are related to whole-body vibration and ISO 5349-1, which is related to hand transmitted vibration. Ahn [15] focused on discomfort of vertical whole-body shock-type vibration in the frequency range of 0.5 to 16 Hz. In this experimental study, various shock signals were systematically produced using the response of a one degree-of-freedom vibration model to hanning-windowed half-sine force input. Zhao and Schindler [16] investigated the evaluation of the WBV (Whole-body-vibration) exposure using ISO 2631-1 and ISO2631-5 standards and the results were compared in their study. Turkay and Akcay [17] utilized the response of the vehicle to profile imposed excitation with randomly varying traverse velocity and variable vehicle forward velocity with using the quarter car model. Misol et al. [18] investigated the different active structural acoustic control (ASAC) concepts for the reduction of interior noise in an automobile passenger compartment. For the control experiments, a medium-class test car was used, which had been equipped with an active windshield. Belgacem et al. [19] focused on the cancellation of road noise, from the analysis of vibration transmission paths for an automotive suspension to the design of an active control system using inertial actuators on a suspension to reduce the vibrations transmitted to the chassis. Matilainen and Tuononen [20] determined the the tyre contact length on dry and wet roads measuring the accelerations of the inner liner with a three-axial accelerometer. Aranda et al. [21] improved the design of a multivariable robust controller so that it will be able to reduce incidences of motion sickness on high speed ferries. Kuznetsov et al. [22] analyzed an improved suspension system with the incorporated inerter device of the quarter-car model to obtain optimal design parameters for maximum comfort level for a driver and passengers. Ahn [15] focused on the discomfort of vertical whole-body shock-type vibration in the frequency range of 0.5 to 16 hz. Kim et al. [14] evaluated driven two passenger cars at several speeds over several road profiles to evaluate the subjective rating of ride comfort.

The first objective of this study is to measure the hydrodynamic accelerations of Istanbul AFAD's inflatable boats. The measurements in seas can lead the future researchers to design proper hull shapes and seating that can help people from severe impact injuries. The second objective of this research is to identify the environmental factors affecting individual susceptibility to motion sickness during the road transport. The measurements can be used to analyze the quality of roads.

2. Vibration Analyses

For generations, boaters have experienced the danger of slamming at high speeds in rough conditions. Currently, a number of national and international regulatory and certification organizations have published specific standards intended to limit impact exposure on boat passengers and operators. While it is well known in the scientific community that acute injury in slamming events results from impact, not form vibration, most of these standards are based on different methods of reducing complex whole-body vibration (WBV) exposure data to simple single-figure values.

There is no doubt that being exposed to vibration is healthy. Vibration can cause various health problems including accelerated aging of spinal disks and cartilage. Those problems contribute to cumulative injuries that can weaken structures and increase the risk of acute injury. However acute injury is most commonly triggered by impacts.

The most severe injuries caused by slamming in high-speed boats include fractures in vertebrae and extremities, and ruptures of intervertebral disks including those in the neck. A fast boat in motion even on a relatively calm sea is bafflingly dynamic, making it difficult to accurately predict the slamming loads passengers in a particular boat in particular conditions will be exposed to. It is safe to say that risk of acute injury is proportional to the level of energy absorbed form a particular slam but accurately predicting the magnitude of any slam is practically impossible.

2.1 Motion Sickness

By definition motion sickness or kinetosis is a condition in which a disagreement exists between visually perceived movement and the sensory system's sense of movement. It may be caused by different type of motion environments (e.g., cars, boats, planes, funfair rides, etc.). Factors which are conducting motion sickness sensitivity can be divided into two groups:

- Those related to inducement, ie. motion type and provocative property of inducement,
- Those related to the persons themself, ie. orientation, sensitization, hypersensitivity or individual differences.

The last years innovation of transport and industry have extended the range of provocative motion environments, to cars, tilting trains, aircrafts and high speed boats. This general term "motion sickness" is best applied across all of those stimulus specific terms such as travel sickness, car sickness, air sickness or sea sickness.

2.2 Analyzing Accelerations

To measure the dynamics of a moving craft, it is the best option the measurement device at a position where we expect the least (smallest) transients accelerations. This is typically close to the centre of gravity (CG) of the craft since any rotations around the centre of gravity into centripetal accelerations at any point of rotation, which is usually close to the CG. There are some existing standards that might help boat designers and builders determine limits for "how much" and "what kind of exposure" is safe or dangerous.

Some of the existing standards are,

- European Union Directive 2002/44/EC,
- ISO 2631-1 [23],
- ISO 2631-5 [24],
- Annex 10 of 2000 HSC CODE,
- Root mean square (RMS) value,
- The acceleration dose,
- Vibration dose value(VDV),
- Crest Factor,
- Impact Count Index(ICI),
- Sed 8,
- Peak Over Threshold(POT)

2.3 Vibration Dose Values

Vibration Dose Values (VDV) were determined for each axis the VDV was calculated by

$$VDV = \left[\int_0^T a^4(t)dt\right]^{1/4} \tag{1}$$

where T is the duration of the exposure and a is the frequency weighted acceleration.

The unit of measure of VDV is $ms^{-1.75}$. The weightings used were Wd for the X and Y axes, and *W*b for the Z axis. The combined VDV in all axes was determined by

$$VDV_{xyz} = (VDV_x^4 + VDV_y^4 + VDV_z^4)^{1/4} \tag{2}$$

and the total VDV of both trials by,

$$VDV_{TOTAL} = (VDV_1^4 + VDV_2^4)^{1/4} \quad (3)$$

where $VDV1$ and $VDV2$ are the combined axis VDVs of trials 1 and 2, respectively, as given by Equation 2. Since VDV is sensitive to both shocks and vibration, it is interesting to note the estimated contribution to VDV of vibration alone, i.e., without the effects of impacts, and to determine the dosage a person would have received had they been on the boat in calm water with the engine running for the same length of time as the trials.

3. Experiment

Inertial Measurement Unit (IMU) is an electronic device that measures and reports on a body's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes. It works by detecting the current rate of acceleration using one or more accelerometers, and detects changes in rotational attributes like pitch, roll and yaw using one or more gyroscopes. General view of Body Rotation of IMU Device is shown in Figure 1. All the experiment steps have been discussed below.

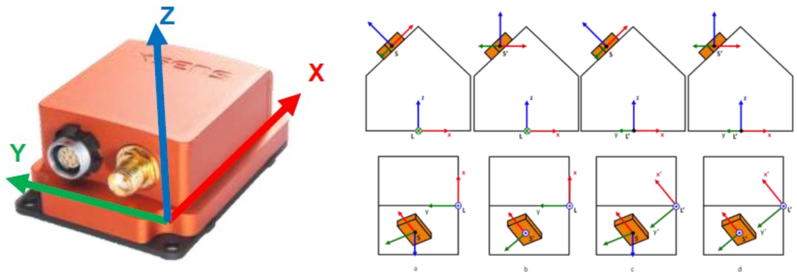

Figure 1: Body Rotation of IMU Device

3.1 Measuring The Impacts On ITU Campus Roads

Both an automobile and an ambulance on ITU Ayazaga Campus roads were undertaken on board. The duration of each trial was approximately 10 minutes. Both trials contained very hard and rough road conditions. On the car, one passenger accompanied with the driver. On the ambulance, three passengers, two was in the stretcher compartment, accompanied with the driver. The average speed during the car cruise is 20.5 km/h and the average speed during the ambulance cruise is the 25.9 km/h.

3.1.1 Automobile trial

Our experiment had done with a car (VW Passat Variant) on ITU Ayazaga Campus. The aim was to measure the accelerations during the cruise on the campus roads. The car was equipped with a tri-axial accelerometer (Xsens GT700). The axes of the accelerometer were aligned such that the Z axis measured vertical acceleration or heave, the Y axis measured transverse or lateral acceleration and the X axis fore-aft accelerations. The X, Y and Z axes of the rate gyros were aligned to measure roll, pitch and yaw, respectively. Basic vehicle parameters of the car are given in Table 1.

Table 1: The specifications of VW Passat Variant

Engine Output	85.75 kW
Wheelbase	2709 mm
Tire Size	205/55 R16
Front Suspension	The depreciated rack
Rear Suspension	Helical spring

The main objective of our experiments was to analyse the quality of roads in Istanbul Technical University Ayazaga campus with a car. During our cruise in ITU campus we have met 14 of speed bump and we turned 15 road bends. The loop for driving over different road surfaces is shown in Figure 2. The road sections include asphalt, only some parts of it has rough gravel surface and short slopes. The length of the loop is around 3.5 km. The speed bumps were fixed on a smooth asphalt road. All speed bumps have the same dimensions. The height of the obstacle is 0.08 m; the width is 0.5 m; and the length is 5m as shown in Figure 3. During our cruise on 10th of March 2015 in ITU campus we have met 14 speed bumps. While passing by on different speed bumps we have met different acceleration values.

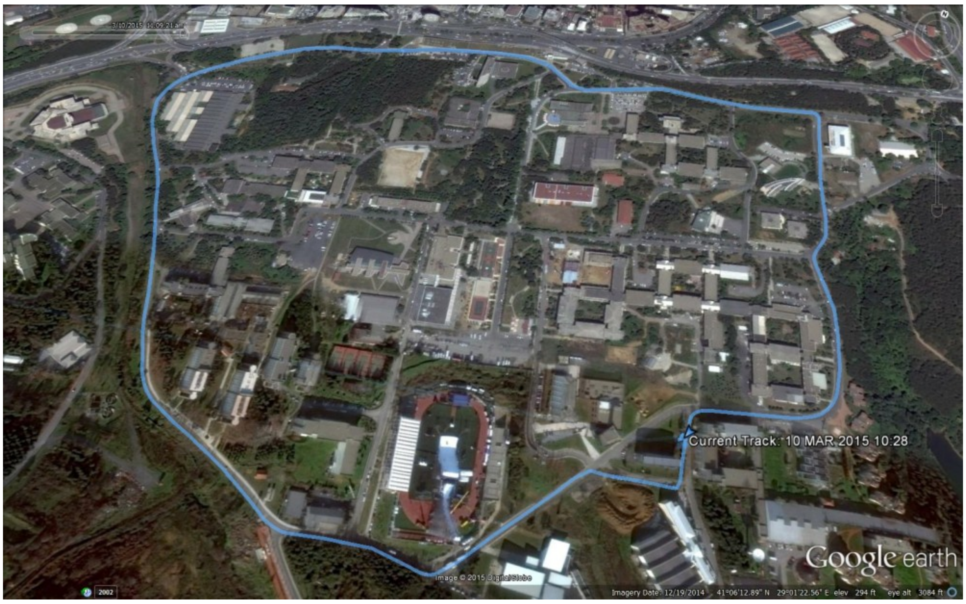

Figure 2: The aerial view of the test route at ITU Ayazaga Campus

During the trial, the peak acceleration magnitude for the Z axis was 14.79 m/s^2 - 1.508 g, while its rms value was 9.797 m/s^2. While passing through the 1st speed bump, the maximum acceleration is 1.23 g which is 12.1 m/s^2. The photograph and the real time accelerations on the 1st Speed Bump is given in Figure 6. The average speed was 20.5 km/h, the average speed while moving was 23.4 km/h, the minimum speed was 0.2 km/h and the maximum speed was 56 km/h during the cruise in the campus. The properties of campus track on 10th of March 2015 are given in Table 2, the Photograph of the 7th Speed Bump and the accelerations on the 7^{th} Speed Bump is shown in Figure 3 respectively.

Table 2: The properties of campus track on 10^{th} of March 2015

Property	Value
Elapsed Time (min/sec)	09:32
Moving Time (min/sec)	08:20
Distance (km)	3.3
Average Speed (km/h)	20.5
Average Moving Speed (km/h)	23.4
Minimum Speed (km/h)	0.2
Maximum Speed (km/h)	56.0

Table 3: The speed and maximum acceleration values of the speed bumps on 10^{th} of March 2015 track.

Speed Bump	Speed before the bump [km/h]	Acceleration Z [m/s^2]	Acceleration Z in g
1^{st} Speed Bump	13	12.1	1.23
2^{nd} Speed Bump	20	14.2	1.45
3^{rd} Speed Bump	20	13.7	1.39
4^{th} Speed Bump	16	13.3	1.35
5^{th} Speed Bump	18	14.4	1.47
6^{th} Speed Bump	14	12.7	1.29
7^{th} Speed Bump	17	14.1	1.44
8^{th} Speed Bump	21	12.6	1.28
9^{th} Speed Bump	10	13.0	1.32

Figure 3: The Photograph and the accelerations of the 7th Speed Bump.

The speed before the bumps and maximum acceleration values of the speed bumps are given in Table 3. The acceleration values on the speed bumps directly related to the speed of the vehicle before the bump. If the speeds are higher, the acceleration values are getting higher. Trial 1 was the first 1.9 km of the track, and Trial 2 was the rest of the track as depicted in Figure 2. VDV of Mti700 in each axis and totals for both trials on 10th of March 2015 track is shown in Table 4. The total VDV are calculated using Equations (1)-(3). It can be seen that VDV due to vibration was calculated to be 5.02 $ms^{-1.75}$ and 5.47 $ms^{-1.75}$ for trials 1 and 2, respectively and the total VDV is 6.26.

Table 4: VDV of Mti700 in each axis and totals for both trials on 10th of March 2015 track.

VDV	Trial 1	Trial 2	Total
X-Axis	139.26	409.16	410.53
Y-axis	188.12	241.75	261.39
Z-axis	308.22	245.67	335.49
Total	5.02	5.47	6.26

3.1.2 Ambulance trial

The second experiment has done with an ambulance in ITU Ayazaga Campus. Our aim is to measure the accelerations on the stretcher for a sick person during the cruise of ambulance. The ambulance was equipped with two tri-axial accelerometers. The axes of the accelerometer were aligned such that the Z axis measured vertical acceleration or heave, the Y axis measured transverse or lateral acceleration and the X axis fore-aft accelerations. The X, Y and Z axes of the rate gyros were aligned to measure roll, pitch and yaw, respectively. Basic vehicle parameters of the ambulance are given in Table 5. Also experimental setup for the ambulance trial is shown in Figure 4 and the aerial view of the test route at ITU Ayazaga Campus is shown in Figure 5.

Table 5: Ambulance Specifications Ford Transit

Engine Output	99.29 kW
Wheelbase	3300 mm
Tire Size	215/55 R16
Front Suspension	Coil Spring
Rear Suspension	Leaf spring

Figure 4: Experimental setup for the ambulance trial.

The second main objective of the experiment was to analyse the quality of roads in Istanbul Technical University Ayazaga campus with an ambulance in an emergency situation. During the cruise on ITU campus roads, 16 speed bumps and 19 road bends have encountered. The road sections include asphalt, some parts has rough gravel surface and short slopes. The length of the loop is around 3.6 km. The photograph and accelerations of the 1st imperfection is shown in Figure 6, the maximum acceleration values of the speed bumps is given in Table 6. Besides VDV of Mti200 in each axis and total VDV for road trials is given in Table 7.

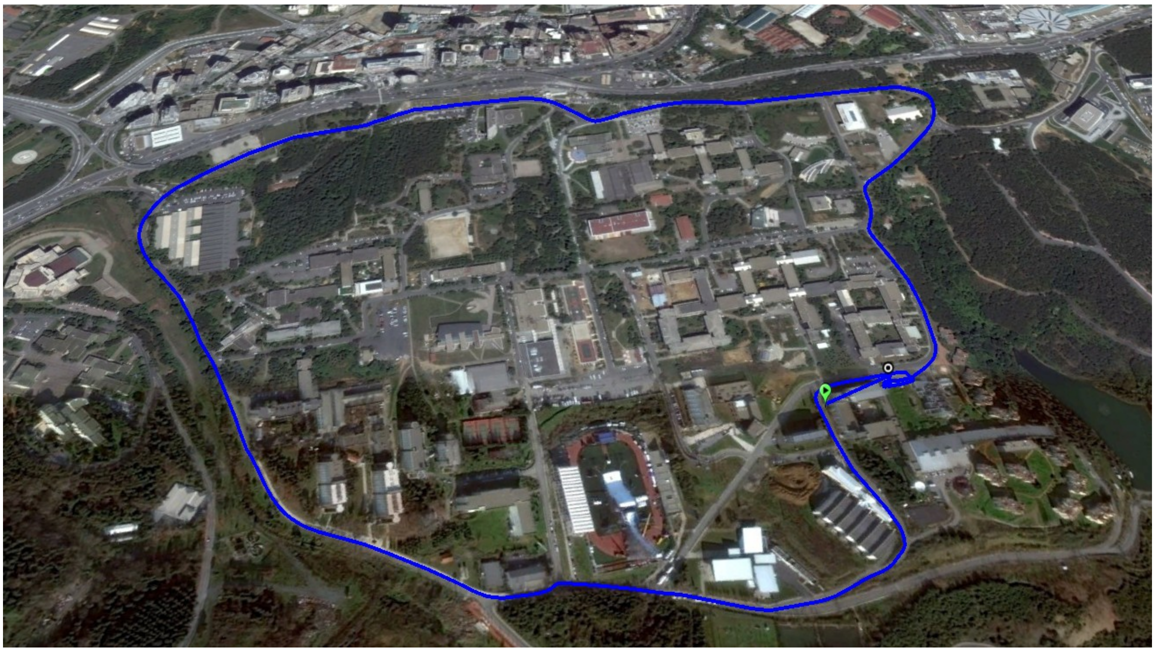

Figure 5: The aerial view of the test route at ITU Ayazaga Campus

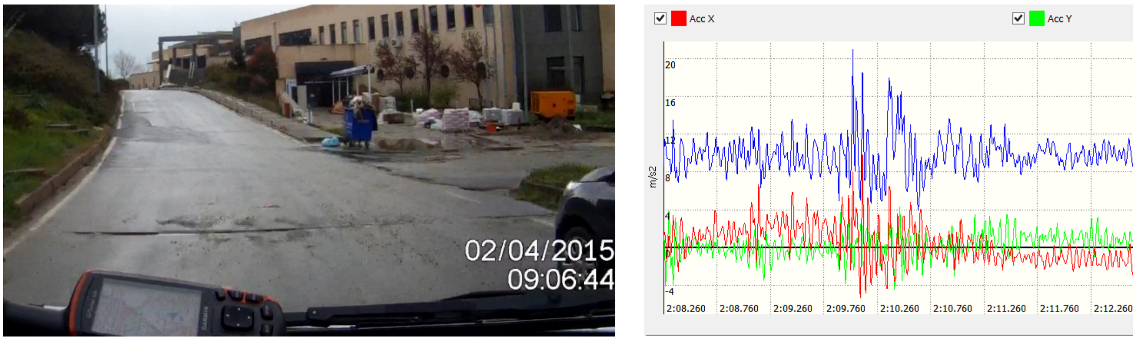

Figure 6: The Photograph and accelerations of the 1st Imperfection

Table 6: The maximum acceleration values of the speed bumps

Speed Bumper	Speed before the bump or imperfections [km/h]	Acceleration Z [m/s^2]	Acceleration Z in g
1st Imperfection	34	22	2.24
2nd Imperfection	48	25	2.55
3rd Speed Bump	12	16	1.63
4th Speed Bump & Imperf.	9	20	2.04
5th Imperfection	50	35	3.56

Table 7: VDV in each axis and totals for both devices.

VDV	Mti 200[m/s$^{1.75}$]	Mti 700[m/s$^{1.75}$]	Total[m/s$^{1.75}$]
X-Axis	2500.975	20120.73	20121.93
Y-axis	2049.075	24756.79	24757.08
Z-axis	43831.63	80178.02	81911.29
Total	14.831	18.805	20.41

The track is given in Figure 5 and VDV of Mti200 and Mti700 in each axis and totals on 2nd of April 2015 track is shown in Table 7. It can be seen that VDV due to vibration was calculated to be 14.83 ms$^{-1.75}$ and 18.81 ms$^{-1.75}$ for Mti200 and Mti700 respectively, and the total VDV is 20.41.

3.2 Measuring Impacts on 4.7m Inflatable Lifesaving Boat

The experiment has done with a rigid inflatable 4.70 meters Mercury boat of Istanbul AFAD at Marmara Sea. The boat was equipped with two tri-axial accelerometers. Two trials on the same day approximately five minutes apart were undertaken on board. The duration of each trial was approximately 7 and 8 minutes, respectively. Both trials contained a mixture of head, beam and following seas. The sea state was estimated to be 1 on both trials. Two passengers accompanied an experienced Istanbul AFAD pilot on both trials. The average speed in open water during both trials was between 15 knots and 20 knots depending on the direction of travel relative to the waves. The axes of the accelerometer were aligned such that the Z axis measured vertical acceleration or heave, the Y axis measured transverse or lateral acceleration and the X axis fore-aft accelerations. The X, Y and Z axes of the rate gyros were aligned to measure roll, pitch and yaw, respectively. Basic vehicle parameters of the boat are given in Table 8. Similar measurements can be found on Riley[25] and Ullman [26].

Table 8: Boat Specifications Heavy-Duty 470 XS

Specification	Value
Engine Output	25 kw
Overall length	470 cm
Length inside	332 cm
Overall beam	216 cm
Maximum Load	1200 kg
Boat’s Weight	160 kg
Beam Inside	108 cm
Tube Diameter	54 cm

The total VDV of 12.10 $ms^{-1.75}$ experienced by the crew during the trials far exceeded the action limit of 15 $ms^{-1.75}$ recommended in BS and the maximum daily dose of 21 $ms^{-1.75}$ permitted by the European Directive. The higher VDV of the first trial in comparison to that of the second was to be expected given the increased sea state during the former. It is also interesting to note that the total VDVs were dominated by the VDV of the Z axis and that the impacts in Y axis had very little effect on the VDV despite the relative importance suggested by anecdotal evidence that lateral impacts have on discomfort. This would appear to support the argument that, although it is generally held to be measure of discomfort, based on translational accelerations alone, VDV does not adequately represent the level of discomfort reported onboard high-speed craft. During our cruise on 14th of April 2015 on Ağaçlı, Black Sea coast of Istanbul, the maximum acceleration value on z direction is around 35 m/s^2 which is almost 3.6 g. The real time accelerations of the cruise is given in Figure 7 and Figure 8 respectively. It can be seen from the figures that, when the boat speed is getting high, the measured acceleration values in z direction is getting high as expected. The properties of sea trial is given in Table 9.

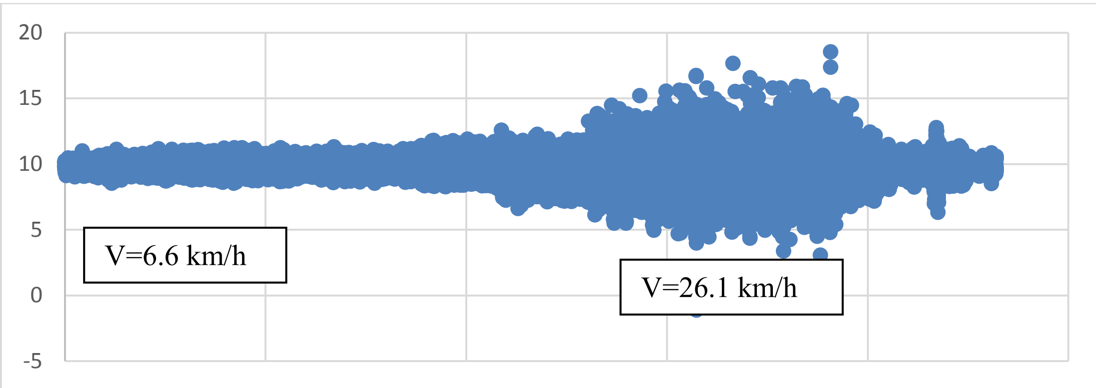

Figure 7: The first part plots of the raw accelerometer signal of z direction.

The boat travelled around the coast of Ağaçlı and during the cruise, the sea state was 1 and there was no significant waves which would affect our acceleration measurements. We increased the speed at every 20 seconds in first trial and additionally we have moved on a curvy line 6 times at our second trial. Approximately 15 minutes after the start of the trial, the boat returned to the starting point.

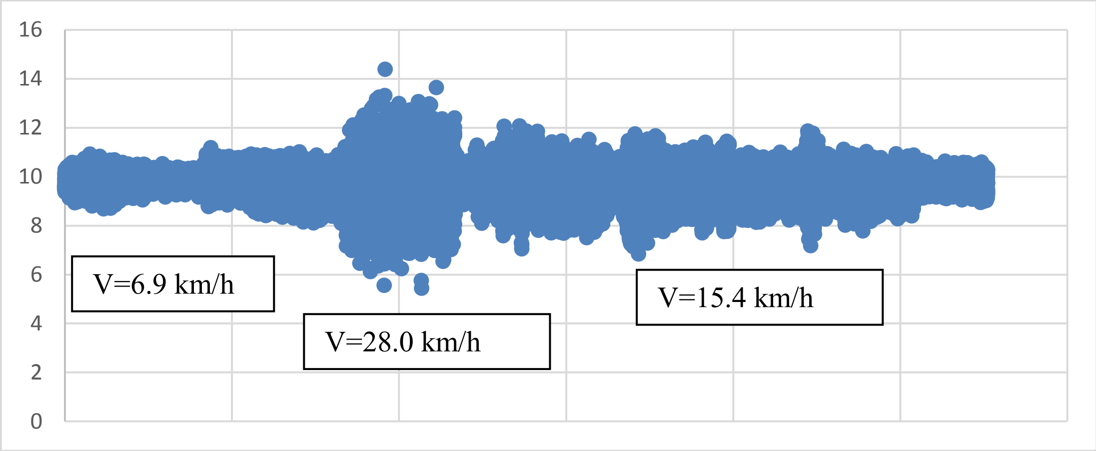

Figure 8: The second part plots of the raw accelerometer signal of z direction.

The average speed was 12.1 km/h, the average speed while moving was 12.2 km/h, the minimum speed was 0.2 km/h and the maximum speed was 32 km/h during the cruise on the sea. increasing speed, a mechanical failure or handling error will introduce an increasing risk of capsizing with increasing speed. To ensure safe operations, the following essential moments should be considered. VDV of Mti700 and Mti200 in each axis and totals for both trials are given in Tables 10-12.

Table 9: The properties of sea trial.

Property	**Value**
Elapsed Time (min/sec)	13:36
Moving Time (min/sec)	13:27
Distance (km)	2.7
Average Speed (km/h)	12.1
Average Moving Speed (km/h)	12.2
Minimum Speed (km/h)	0.2
Maximum Speed (km/h)	32.0

Table 10: VDV of Mti700 in each axis and totals for both trials.

VDV	Trial 1	Trial 2	Total
X-Axis	1080.886	541.474	1097.52
Y-axis	2927.196	382.441	2927.41
Z-axis	8438.258	3742.779	8518.75
Total	10.5623	8.265	11.44

Table 11: VDV of Mti200 in each axis and totals for both trials.

VDV	Trial 1	Trial 2	Total
X-Axis	272.806	293.322	337.28
Y-axis	107.436	299.165	300.40
Z-axis	3031.841	313.885	3031.93
Total	7.643	5.487	8.11

Table 12: VDV in each axis and totals for both trials.

VDV	Trial 1-Avg	Trial 2-Avg	Total-Avg
X-Axis	1097.52	337.28	1099.96
Y-axis	2927.41	300.40	2927.49
Z-axis	8518.75	3031.93	8552.72
Total	11.44	8.11	12.10

4. Conclusions

This paper has highlighted the Vibration Dose Values (VDV) that can be expected on a car, an ambulance and a RIB high speed marine craft, and how these values relate to limits set by current standards and legislation. By comparing the impacts encountered to the boat motions, it has been possible to determine which are the more dominant axes and show that it is not necessary to weight axes and show that it is not necessary to weight certain axes more than others. In further work, the experiments should be repeated in higher sea states. Also different type of boats can be used. The magnitudes of impacts reported in this work are lower than those in other works. However, it is not clear how their data were collected and analysed, and therefore it is not easy to gauge the accuracy of their results. It is reasonable to assume though that the impacts encountered would have been larger due to the higher sea states. It is also possible to evaluate an impact formula for RIB high speed marine crafts by using the parametric sea tests. It is also intended to apply the algorithms and analysis reported here to a series of model tank test experiments involving a variety of hull forms. From these experiments it should be possible to determine each hull's VDV and motion characteristics in a variety of sea conditions, which could prove useful to naval architects designing RIBs that exhibit better performance regarding the new legislation.

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