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Windsurfing Hydrofoil Motion Technical Measurements

Abstract

As a part of the hydrofoil optimisation project for windsurfing, a system for measuring vessel motions, weather elements and water conditions was developed. By measuring the speed, acceleration, angular velocity, inclination and direction of the vessel movement and weather elements in real time, the hydrodynamic optimisation process of hydrofoils was accelerated. Measurements were performed with a measuring device attached to the observed vessel, while measurements of weather elements and sea conditions were performed with another device on the accompanying vessel. Wind speed, direction and temperature, environmental temperature, atmospheric pressure, surface water current and wave properties were measured. By combining data from both devices, a database was created on the state of the environment and the vessel motions. Analysis of the database provided the necessary data for the hydrodynamic optimisation of the hydrofoil. The polar diagram of the vessel speed in relation to the speed and direction of the wind, together with the data on the inclinations of the hydrofoil and the angle between the direction of movement and the pointing direction at the moments of reaching the maximum speed, accelerate the hydrofoil hydrodynamic optimisation process.

Keywords: measurement, hydrofoil, polar speed diagram

1. Introduction

For the purposes of measuring movement speed, acceleration, angular velocity, inclination and direction of movement of the vessel, as well as weather elements in real time, a system was developed that consists of:

- device for measuring sailing dynamics
(*Sailing Dynamics Measurement Device* - SDMD),
- weather station and receiver for measurements of sailing dynamics
(*Sailing Dynamics Weather Station* - SDWS) and
- Application for the presentation of real-time measurements
(*Measurements Presentation Application* - MPA).

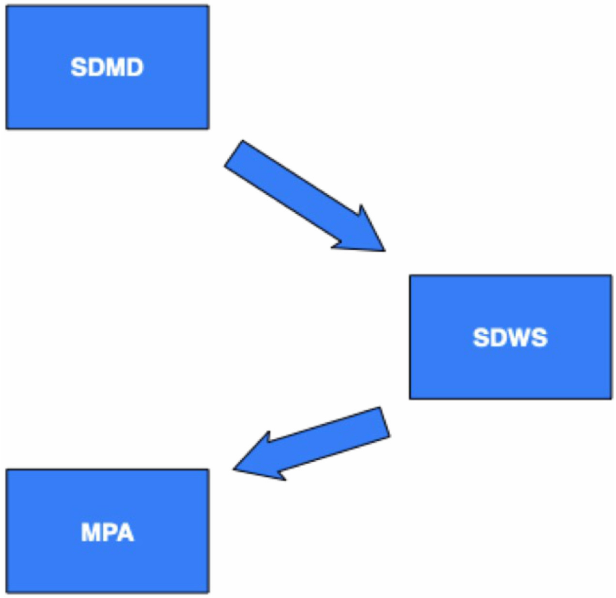

Figure 1: Devices and software for sailing dynamics measurement

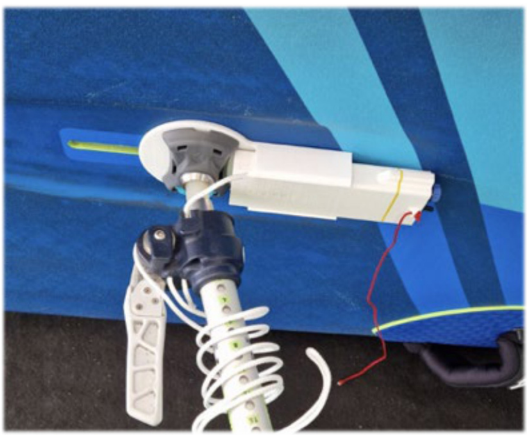

Figure 2: SDMD on the observed vessel

During the measurement process, the SDMD is rigidly attached to the observed vessel in order to make the measurements of acceleration, angular velocities and inclination as accurate as possible.

Figure 3: Measured vessel

During the measurement process, the SDWS was also placed on top of the mast of the accompanying vessel at a height of 2 meters above the sea surface.

In addition to measuring the state of the environment, the SDWS also serves as a communication device for receiving SDMD data and sending combined data from both devices to the MPA.

Figure 4: SDWS on accompanying vessel

Application for the presentation of measurements in real time make it possible to control the measurement process. By measuring the dynamics of sailing and the state of the environment and combining the data from both devices into a single database, the data needed to speed up the optimisation process of hydrofoils for windsurfing were obtained.

2. Device for measuring sailing dynamics

The device for measuring the dynamics of sailing consists of a series of sensors necessary to measure the speed of movement, acceleration, angular velocity, inclination and direction of movement of the observed vessel:

- **GPS** - speed and direction of movement,
- **Inclinometer** - slope,
- **Accelerometer** - acceleration,
- **Gyroscope** - angular velocity and
- **Magnetometer** - bow direction (heading).

Measurement data from all mentioned sensors is collected, filtered, connected and stored by the microcontroller on a data storage device - micro SD card.

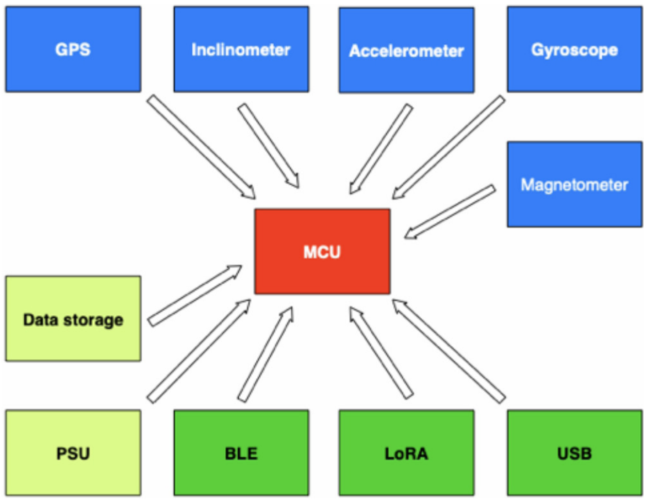

Figure 5: SDMD block diagram

LoRA (Long RAnge) radio communication technology is used for data transmission to the meteorological station, while Bluetooth LE radio communication technology is used for direct data transmission to the MPA.

The USB communication port is used to download complete measurement data saved on the SD card and to upgrade the device's software.

The measuring device is powered by a rechargeable LiPo battery and has a built-in battery charging system via a USB port and battery protection against complete discharge, overcharging and overheating.

2.1 Sensor fusion

Sensor data fusion procedures are used to reduce measurement errors. As a large number of errors appear when measuring the magnetic field, in order to determine the true direction of the bow of the observed vessel, an algorithm based on the Kalman filter is used, combining data from the accelerometer, gyroscope and magnetometer.

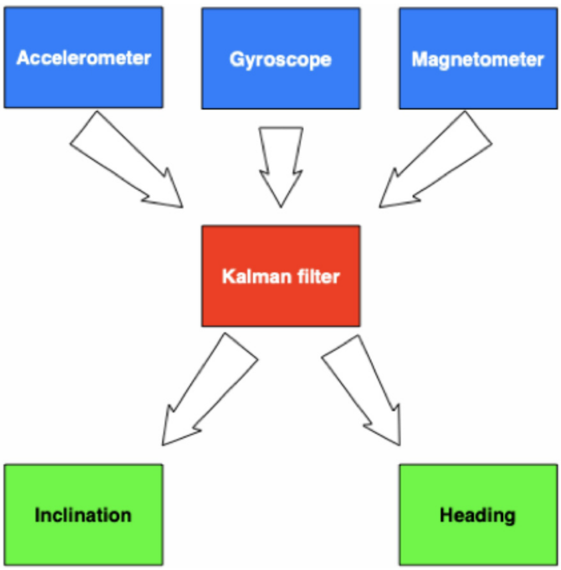

Figure 6: Kalman filter

In order to reduce the errors of other sensors, the Gauss process algorithm was used.

Both Kalman filter and Gauss process agorithm are implemented into SDMD firmware.

3. Weather station

The weather station and receiver for measurements of sailing dynamics consists of sensors necessary for measuring wind speed and direction, movement speed, acceleration, angular velocity, inclination, direction of movement of the accompanying vessel, temperature and atmospheric pressure:

- **GPS** - speed and direction of movement,
- **Anemometer** - apparent wind speed and direction,
- **Accelerometer** - acceleration,
- **Gyroscope** - angular velocity,
- **Magnetometer** - bow direction,
- **Temperature** sensor and
- **Atmospheric** pressure sensor.

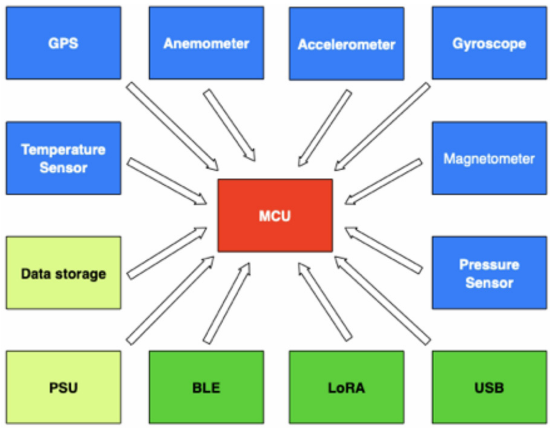

Figure 7: Blok shema SDWS

Measurement data from all mentioned sensors is collected, filtered, connected and stored by the microcontroller on a data storage device - micro SD card.

LoRA (Long RAnge) radio communication technology is used to receive data from the device for measuring sailing dynamics, while Bluetooth LE radio communication technology is used for direct data transmission to the MPA.

The USB communication port is used to download complete measurement data saved on the SD card and to upgrade the device's software.

The weather station is powered by a rechargeable LiPo battery and has a built-in battery charging system via a USB port and battery protection against complete discharge, overcharging and overheating.

3.1 True wind direction and speed

While the accompanying vessel is stationary, the apparent wind speed is equal to the measured wind speed on the anemometer. The measured wind direction is the wind angle in relation to the bow of the accompanying vessel, and the true wind direction is determined using the bow direction obtained from magnetometer measurements and corrected using the Kalman filter and additional accelerometer and gyroscope data.

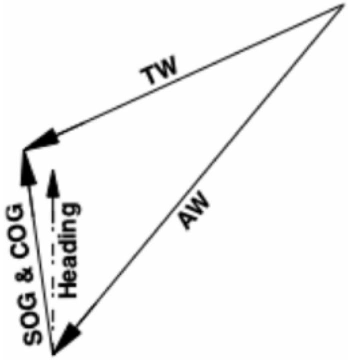

Figure 8: Apparent and true wind

- **AW** - Apparent Wind vector
- **TW** - True Wind vector
- **SOG & COG** - motion vector of the accompanying vessel (Speed Over Ground & Course Over Ground)
- **Heading - the direction of the bow**

Figure 9: True Wind Algorithm

While the accompanying vehicle is moving, the actual wind speed and direction are calculated from the apparent wind vector and the follow vehicle movement vector obtained from GPS measurements.

The direction of the wind is determined by the direction of the bow, as in the case of the accompanying vessel at rest.

The results of the true wind calculation algorithm are:

- **TWS** - True Wind Speed i
- **TWD** - True Wind Direction.

True wind calculation algorithm is implemented at the level of presentation application as it integrates data from two different measurement devices.

4. Application for presentation of measurements

The measurement presentation application is designed to work on smartphones and tablets regardless of the type of operating system and was tested on Android smartphones.

The application connects to the weather station via Bluetooth LE connection and displays measurement results in real time.

Application is specialy developed for data collection and presentation from SDWS and SDMD measurement devices.

Figure 10: Real time data

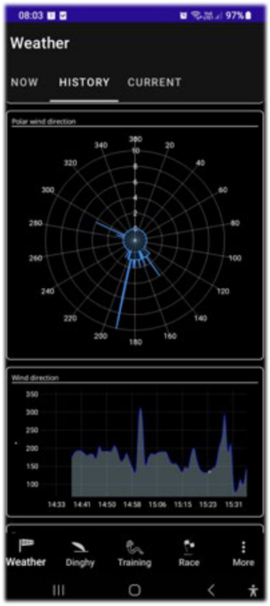

Figure 11: Measurement history

The previous two pictures show the pages of the application for displaying meteorological measurement data.

Current data and changes in wind speed and direction are displayed with the current change trend (increase or decrease in wind speed compared to average and change in wind direction to the left or right compared to the average direction).

The measurement history shows the distribution of the change in wind direction in the polar diagram for a given period of time, as well as the wind direction and speed for a given period of time.

Figure 12: Observed vehicle I

Figure 13: Observed vehicle II

The data of the observed vessel are displayed on the application pages shown above in real time, and as with meteorological data, it is also possible to display the measurement history.

5. Measurements

The measurements were taken at sea in front of Volosko in Preluk bay during May and June 2023. The observed vessel, a hydrofoil windsurfing board, was piloted by Enrico Marotti.

The image shown shows the distance traveled based on GPS data for June 1, 2023.

Figure 14: The distance traveled during the measurement

- Average wind direction: 353.39º
- Average wind speed: 6.78 m/s (13.18 kn)
- Maximum speed of the observed vessel: 15.59 m/s (30.30 kn)
- Ratio of vessel speed and average wind speed: 2.30.

At the moments when the maximum speed of movement of the observed vessel was achieved, the wind speed was higher than the average.

SDWS and SDMD measurement devices data are transfered to MySQL database via USB port and specially designed serial data transfer application.


```
SD:0:2:2022:07:28:05:28:57:800:0:1:0:4201275563:423260908:0:0:9651375:0.00:-6.7836:3.391
SD:0:2:2022:07:28:05:28:58:400:0:1:38:144875251:453065428:0:0:298230:0.00:-6.4327:4.0936
SD:0:2:2022:07:28:05:28:58:800:0:1:115:144875219:453065285:0:0:298459:0.00:-5.4971:3.391
SD:0:2:2022:07:28:05:28:59:400:0:1:81:144875210:453065331:0:0:298075:0.00:-5.9649:3.6257
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SD:0:2:2022:07:28:05:29:06:000:1:0:15:144881547:453064323:144881547:453064323:49170:0.00
```


Figure 15: Raw data sample

5.1 Wind speed

The following figure shows the Gaussian distribution of wind speed for three measurement days, including the average distribution for all three days.

	Prosjek	Maksimalno
01.06.2023.	6,78	10,24
02.06.2023.	8,45	13,22
03.06.2023.	7,25	12,04
	7,50	11,83

Figure 16: The table shows the average and maximum wind speeds for all three measurement days.

The ratios of average and maximum speeds are uniform for all three days of measurement and are around 1.7.

Gaussian wind distribution was used for the purpose of determining the range of wind speed within which data on the observed vessel movement can be considered acceptable for the hydrofoil optimization process.

5.2 Observed vessel speed

The following figure shows the Gaussian distribution of the speed of movement of the observed vessel for three days of measurement, including the average distribution for all three days.

	Prosjek	Maksimalno
01.06.2023.	8,91	15,59
02.06.2023.	10.51	17,37
03.06.2023.	8,93	17,49
	9,45	16,82

Figure 17: The table shows the average and maximum speeds of the observed vessel for all three measurement days.

5.3 The tilt of the hydrofoil fuselage

The pitch angle of the hydrofoil fuselage between the horizontal plane (sea surface) and the longitudinal axis was measured with a high-precision inclinometer.

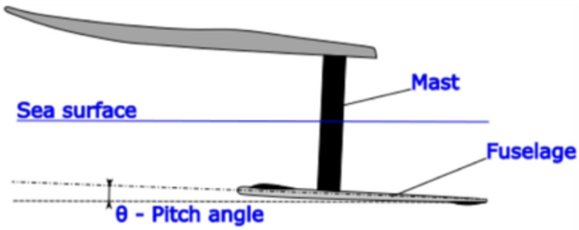

Figure 18: Hydrofoil fuselage pitch angle

The difference between the actual and measured angle is calculated by the difference between the inclination of the hydrofoil body and the device for measuring sailing dynamics. The difference was measured with the same device used for the measurements themselves.

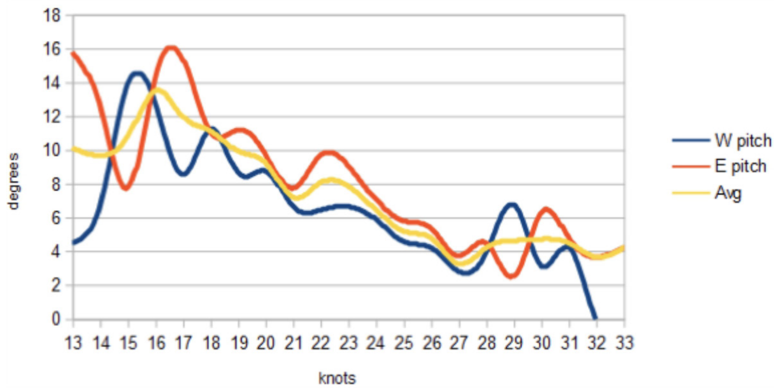

Figure 19: The pitch angle in relation to the speed of movement

The figure above shows the pitch angle of the hydrofoil fuselage in relation to the speed of movement of the observed vessel during movement from east to west (line W pitch) and during movement from west to east (line E pitch).

The average inclination of the hydrofoil body in relation to the movement speed is shown by the yellow line.

5.4 Front wing heel angle

The inclination (heel) of the hydrofoil wing between the horizontal plane (sea surface) and the lateral axis of the hydrofoil body was measured with a high-precision inclinometer.

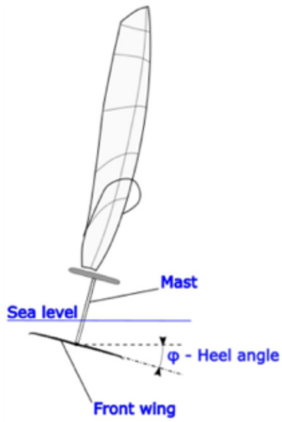

Figure 20: Front wing heel angle

The difference between the actual and measured angle is calculated by the difference between the inclination of the front wing of the hydrofoil and the device for measuring sailing dynamics. The difference was measured with the same device used for the measurements themselves.

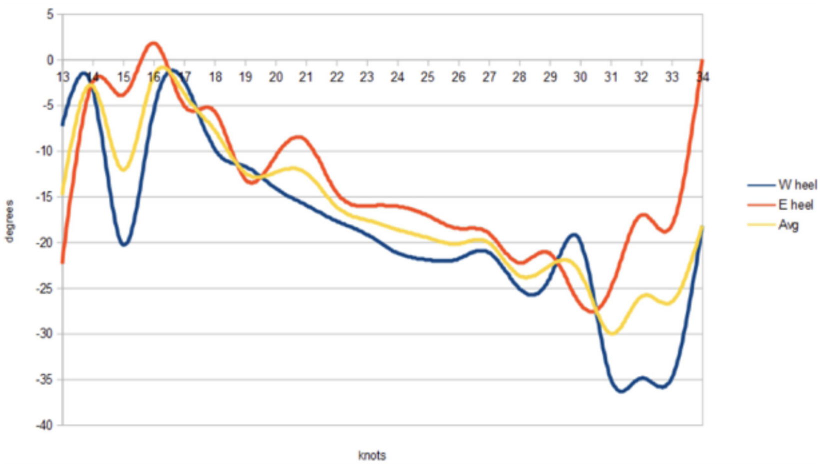

Figure 21: Front wing heel in relation to the speed of movement

The previous picture shows the heel angle of the front wing in relation to the speed of movement of the observed vessel during movement from east to west (line W heel) and during movement from west to east (line E heel). The average heel angle of the front wing in relation to the movement speed is shown by the yellow line.

6. Conclusion

Measurement data from both devices (SDMD & SDWS) are combined using timestamps and stored in a database. Analysis of the database provided the necessary data for hydrofoil optimisation.

Vessel speed versus wind speed and direction, along with hydrofoil pitch data, speed up the optimisation process.

The same measurement system can be used for measurements to optimise various properties of other similar vessels.

All data were collected in the same place within three days. In order to compare the data, it would be interesting to repeat the measurements in another place with different weather conditions.

Both measurement devices save sensor data every 200 milliseconds. From which it follows that within an hour of measurement, each device saves 18,000 records of 210 bytes in size. With a maximum data transfer speed of 115200 bps, it is necessary to wait a long time for data transfer from measurement devices to the PC.

For this reason, in future versions of measuring devices, data will be transferred to a PC wirelessly via Bluetooth, where it is possible to achieve significantly higher speeds compared to serial data transfer via the USB interface.

7. Abbreviations

- **SDMD** - Sailing Dynamics Measurement Device
- **SDWS** - Sailing Dynamics Weather Station
- **MPA** - Measurements Presentation Application

8. Literature

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