2020

Research Report

PROPULSION SYSTEM SIMULATION

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Organisation:	*Solar Boat Sealander*
Client:	*Mr. R. Eijlers*
Tutor:	*Mr. W. Haak*
Date:	*28-01-2021*

Information

This project is being executed by students of the mechatronics course at the HZ University of Applied Sciences, in cooperation with exchange students from the SMU in China. The following sections will state general information about the client and project members.

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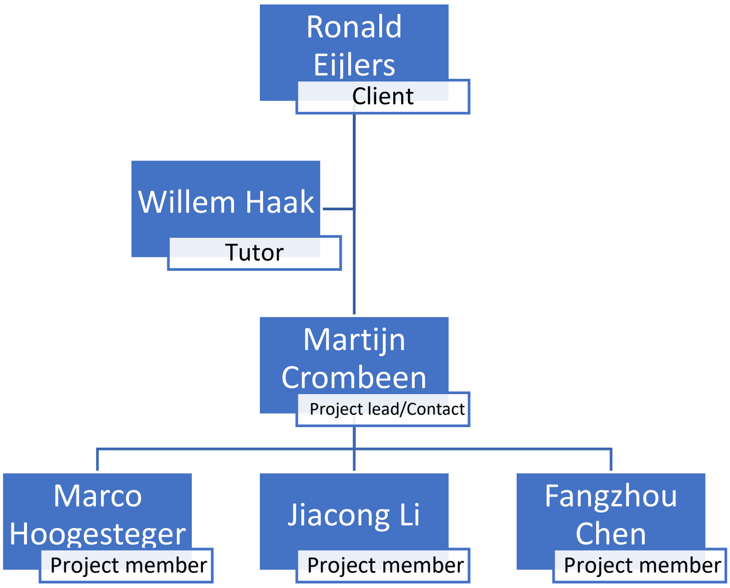
Hierarchy



Abstract

Solar powered travel is something that has been booming for the last few years. It can clearly be seen that current developments such as global warming has a very negative impact on the environment. Many recent studies and projects have been finding and experimenting with different environmentally friendly solutions to combat this rising trend. One of these solutions is the use of solar energy. The HZ also contributes to this research with their solar boat. This boat is being developed by a team of students from different areas and is used to compete in yearly solar boat races. There, the teams have to face off against other students with different boats.

Foreword

Before you lie the research report of the “Propulsion System Simulation of the Solar Boat”. This is the documentation of the research and design of the simulation, verified by empirical data from the MARIN. This report has been written to give the client and the tutor an overview of the project and proving the team’s skill. The complete system design can be found in the appendix, in the chapter “V-model”.

First and foremost, the project team would like to thank the client, Mr. Eijlers, for the opportunity to execute this project and learning lots of information about simulating and the boats’ propulsion system. The nautical background of the client also helped the project team because lots of information could be gathered straight from the client.

Secondly, we would like to thank Mr. Haak for the relevant feedback and support throughout the whole project, which assured the final result was according to the expectations of both the client and assessors from the HZ University of Applied Sciences.

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Marco Hoogesteger
Martijn Crombeen

Vlissingen, January 28th 2021

Abbreviations

Since this is a project performed by an international project team, it is written in English. The client is Dutch, so for the abbreviations, also the Dutch description is given.

Abbreviation	English description	Dutch description
MARIN	Maritime Research Institute Netherlands	Maritiem Onderzoeksinstituut Nederland
MAROF	Maritime Officer	Maritiem Officier
HZ	University Zeeland	Hogeschool Zeeland
UAS	University of Applied Sciences	Universiteit van toegepaste wetenschappen

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1. Introduction

1.1. Background

The Solar boat project has been running since 2008 and multiple changes have been made to the boat. In the current rendition of the boat, the hull and structure are made from fiberglass. Because this material is not eco-friendly, the next generation will be made from mostly biobased materials. Together with this change, the main contents of the boat will get an overhaul eventually. The main drivetrain components will be simulated by two groups of 4th year students.

1.2. Problem statement

The current propulsion system on the solar boat can realize the function of propelling boat and controlling direction. But the narrow and long blades of the propeller cause high friction when the propeller is rotating and in contact with water. Because of the small contact area between the blades and water, the thrust output from propeller cannot be transformed fully into high propulsion speed of the boat. Another issue is that some components of the propulsion system are heavy, which increases the burden of the propulsion system and effects the energy conversion efficiency (rotational kinetic energy as input from motor and output as thrust from propeller).

Basing on the above problem analyzation, three main research direction can be followed:

- Change the size of the propeller to reduce energy consumption caused by friction.
- Change the shape of blades to produce high thrust and increase the propulsion speed.
- Check every component of propulsion system and reduce weights of propulsion system to improve energy conversation efficiency.

To find out what size and shape of the propellor, and what parameters of the drivetrain are optimal, it is needed to perform a simulation of the different components and calculate where the improvements must take place. By simulating the whole system with all its components, tests can be performed with different parameters for different components.

Therefore this project will focus on simulating the current propulsion system and validating it. This is a digital twin. Later different components can be inserted virtually to test its performance.

1.2.1. Main question
What is the verified simulation to calculate the propulsion system of the Solar boat to improve its efficiency (to aid the choice of components)?

1.2.2. Subtopic 1
What is the demo test plan?

1.2.3. Subtopic 2
What is the system test plan?

1.2.4. Subtopic 3
What is the subsystem test plan?

1.2.5. Subtopic 4
What is the component test plan?

1.2.6. Subtopic 5
What is the component test?

1.2.7. Subtopic 6
What is the subsystem test?

1.2.8. Subtopic 7
What is the system test?

1.2.9. Subtopic 8
What is the customer acceptation?

1.3. Goals and objectives

1.3.1. Goal

The goal of this project is to satisfy the client, by developing simulations that will provide information and support not only for this particular project, but for every new version of the boat that will be built.

1.3.2. Objectives

- A verified simulation built in Excel.
    - User-friendly interface.
    - Easy to learn.
- Calculation chain.

1.3.3. Boundaries

In this project, simulations are built and validated focused on designing a new propulsion system. It is easy to go to deep in the project resulting in an inadequate final result. To prevent this, it is very important to set project boundaries. After discussion and consideration with the client and the group members, the project boundary has been set as followed.

Simulations regarding the motor, propeller, shaft, bearings and gearing will be made. With all these simulations, we can calculate the ideal torque and revolutions that the driveshaft has to receive from the motor. The Engineer that is going to design the whole new propulsion system and select components, can use this information to select the desired motor.

The following figure shows a simple block diagram displaying the project boundary.

Figure 1 Calculation chain

In the theoretical framework below, all kind of factors are displayed that could have some kind of influence on the performance of the propulsion system. A very difficult part of this are the variable properties of water. Ocean water can contain current, waves or different compositions, that all can lead to variable outcomes. For this project we stated that we don't take the variables linked to water in account.

1.4. Requirements

Requirements List

List of clients' requirements		Demand	Wish
1.	The final deliverable work surprises the client.		
2.	The prototype is a calculation chain.		
3.	The client thinks the interface of the simulation is user-friendly.		
4.	Data is measured from the real setup for the verification of the calculation chain.		
5.	The propulsion system will be more efficient.		
6.	The errors between the results derived from the calculation chain and the results from the real Solarboat do not exceed 30%.		
7.	The calculation chain only focusses on the propulsion system so external resistances from water are not taken in to account.		
8.	All data are kept to two decimal places.		
9.	Provide some efficient component selection direction for those who design the boat's propulsion system.		
10.	The correct formulas will be chosen to make the calculation chain.		
11.	The V-model is used as method.		
12.	The demo test plan is made.		
13.	The system test plan is made.		
14.	The subsystem test plan is made.		
15.	The component test plan is made.		
16.	The component test is made.		
17.	The subsystem test is made.		
18.	The system test is made.		
19.	The client is satisfied.		

2. Theoretical framework

2.1. Operational characteristics of propulsion components

This paper is aiming to reveal the details of energy conversion through of the solar boat's propulsion system so that researchers can build a calculation chain to simulate and optimize the propulsion system with a higher efficiency. The solar boat's propulsion system which consists of the electric motor (prime mover), the gearbox and shaft (transmission system) and the propeller (propulsor). Furthermore, the thrust delivered by the propeller has to overcome the ship's resistance, which strongly depends upon the external forces that impose to the boat. So the wind and waves have been considered (Shi1 & Grimmelius, 2009).

2.2. Input power

The energy of the propulsion system comes from the electric motor that is powered by the batteries, who in turn are powered by solar panels.

2.3. Factors affecting the propulsion system

In the process of energy transmission, the output power of the motor cannot be completely converted into the output power of the propeller due to the influence of some factors. And due to the influence of other external factors, the propulsion power output by the propeller needs to overcome a series of resistances to result in the force that accelerates the solarboat.

The efficiency of the conversion of solar power to a moving solarboat could be divided into four parts; the hull efficiency, the propeller efficiency, the transmission efficiency and the engine efficiency. Since our boundary does not include the hull and motor, it was decided to use a fixed value to represent the hull resistance, which together with the output power from the motor is used as the input of the system (Shi1 & Grimmelius, 2009).

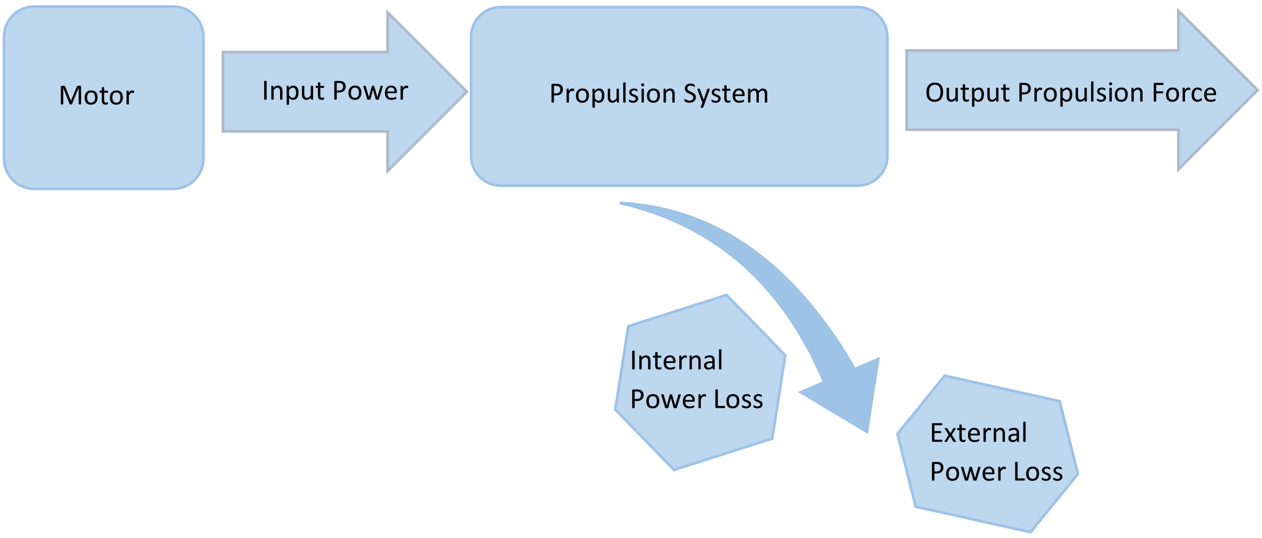


Figure 2 Power distribution

2.3.1. Internal factors

Transmission efficiency and propeller efficiency are the main parts of the internal energy loss factors. The researchers figured out which components mainly caused the energy loss of these two parts. The main energy loss happened in the gearbox and propellers.

2.3.2. External factors

The external energy loss mainly comes from wind and waves and the resistance of the hull. The researchers set the hull's own resistance to a fixed value. For the wind & waves in the ocean, the current intensity value is used, as they related to the Dutch sea area which is used in the simulation of the propulsion system of the solar ship.

2.4. Power loss in the gearbox

The power loss in a gearbox is caused by gears, bearings, and seal and auxiliary losses (Klaus Michaelis, 2011). Gear and bearing losses can be separated into no-load losses, which occur even without power transmission. Except for the working conditions and the air gap in the gearbox, no-load losses are mainly caused due to lubricant viscosity and density, while the immersion depth of the components dipping into the lubricant also contribute to the no-load losses.

Load-losses depend on transmitted load, coefficient of friction and sliding velocity in the contact areas of the components. The power loss in gears is typically dominant in the nominal power transmission situation. For part load and high speed, high no-load losses dominate the total losses. For optimizing the whole operating range of a gearbox, it is needed to simulate the transmission flow using a calculation chain. In the following topics, the major factors that lead to gearbox power losses mainly consider the bearings & gears and shaft.

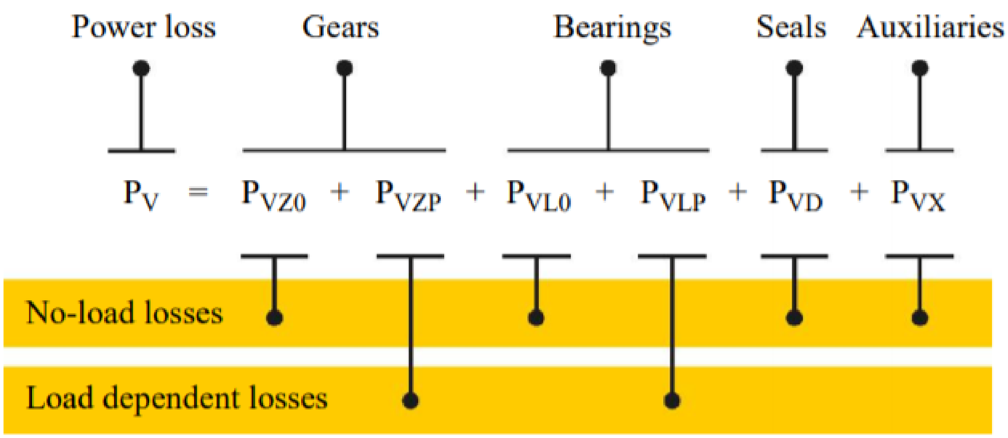


Figure 3 Composing of the power loss

2.4.1. Power loss in the gears

2.4.1.1. No-load gear losses

The no-load gear losses ensue from immersion depth in sump lubricated gearboxes & lubricant viscosity in operating conditions. Since the operating conditions are uncontrollable, the immersion depth in lubricant and lubricant viscosity will be mainly concerned.

For immersion depth in a sump lubricated gearbox, the immersion depth of the gear will affect the meshing of the gear and cause the loss of energy. Therefore, at different immersion depths, the gear loss in this part is different (Lin Zou, 2018).

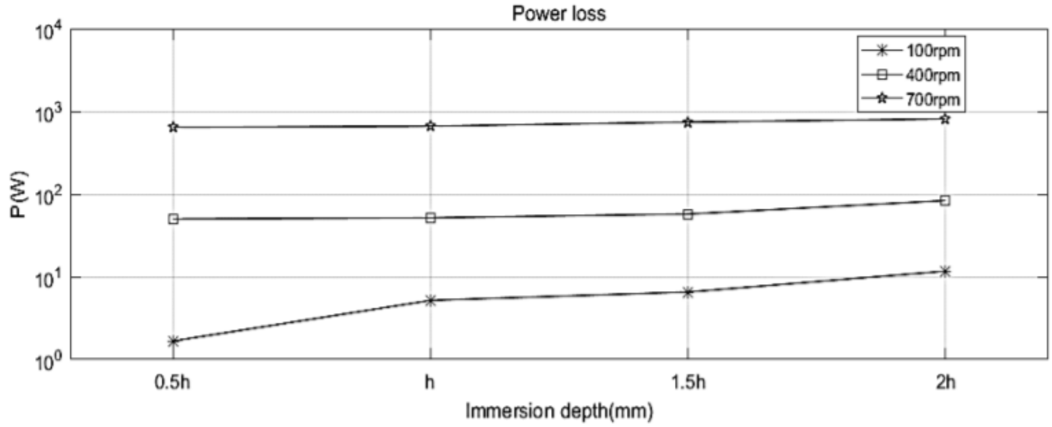


Figure 4 Power loss with different immersion depth

In **Fout! Verwijzingsbron niet gevonden.** it can be seen that high immersion depth may lead to higher energy loss, which is caused by lubricant resistance. But in order to prevent rust, reduce friction, heat dissipation and other disadvantages, we cannot blindly reduce the lubricant immersion depth. It is therefore crucial to find a suitable lubricant immersion depth range, which can achieve less energy loss and satisfy its function (Lauer, 2013).

The energy loss due to the lubricant mainly depends on the viscosity of the lubricant. High-viscosity lubricants will increase churning loss. The viscosity of the lubricant decreases with increasing temperature. When the load is immense, the lubricant with a high viscosity is suitable and when the speed is high, the lubricant with a low viscosity is suitable. Suitable lubricants are therefore needed for the solar boat (k.Michaelis&B.-R.Hohn).

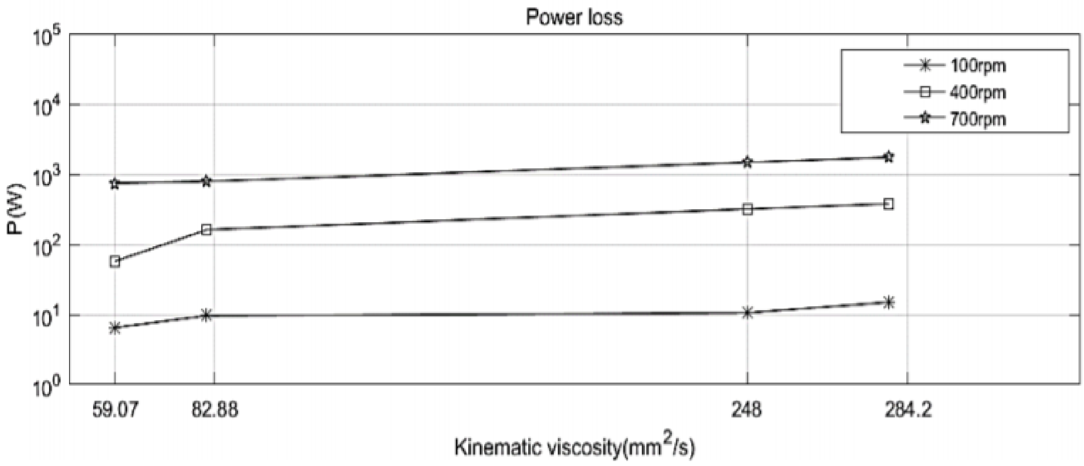


Figure 5 Power loss with different kinematic viscosity

From figure 7, it can be derived that the energy loss of high-speed gears is greater than that of low-speed gears.

2.4.1.2. Load dependent losses

The load gear losses P_{vzp} in the mesh while power is transmitted follow the basic Coulomb law: (Klaus Michaelis, 2011)

Gear friction power loss

$P_{vzp} = F_R(X) * v_{rel}(X)$

with:

$P_{vzp} = load\ gear\ losses\ [kW]$

$F_R = friction\ force\ [kN]$

$v_{rel} = relative\ velocity\ [\frac{m}{s}]$

Friction force

$$F_R = F_n \times \mu_M$$

F_n=Normal force of tooth surface[N].

μ_M=Friction coefficient.

$$F_n = \frac{F_t}{cos\alpha}$$

$$F_t = \frac{2T}{d}$$

F_t=Gear circumferential force [N].

α=Index circle pressure angle, standard gear is 20°.

T=Torque [N*m].

d=Index circle diameter of driving wheel [m].

Relative velocity

The sliding speed is the relative speed of the common contact point between the paired gear teeth in the transverse plane. (Gear Rolling & Sliding velocity) The sliding speed can be approximated as

$$V_{rel} = \frac{(d_1 + d_2)}{2} \times \omega \times 2 \times cos\alpha$$

d_1=Addendum radius[m].

d_2=Deddendum radius[m].

ω= Angular velocity[rpm].

α=Index circle pressure angle, standard gear is 20°.

Gear churning loss

Because of lubricate, the gear will face resistance when it is rotating, resulting in energy loss.

$$P_{loss} = 1.177m^{0.0214} \times z^{0.0106} \times \rho d^5 \times (\frac{1}{Re})^{0.34}(\frac{1}{Fr})^{0.61}(\frac{h}{d})^{0.35}(\frac{b}{d})^{1.21}$$

$$Fr = \frac{\omega d}{g}$$

$$Re = \frac{\rho R^2 \omega}{\mu}$$

m=Modulus.

z=Number of teeth.

ρ=Lubricant density[kg/m^3].

d=Index circle diameter of driving wheel [m].

ω=Rotation speed[rpm].

g=9.8[N/m^2].

μ= Lubricant viscosity.

$\frac{h}{d}$= Gear immersion depth ratio [0.2~1].

$\frac{b}{R}$= Tooth width ratio[$0.2 \sim 1$].

Gear type

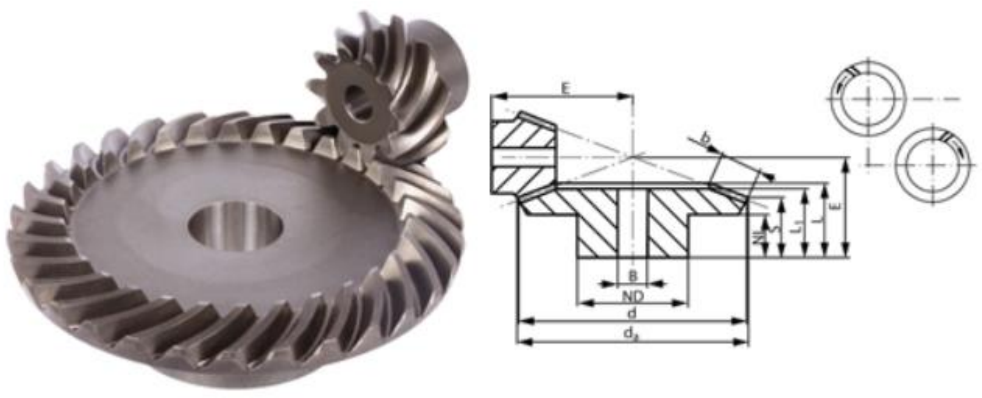


Figure 6 Gear type

Transmission [i]	3 : 1
Module	1,5
No. of Teeth	10 / 30
d_a [mm]	26/66,6
d [mm]	22/66
ND [mm]	17/40
NL [mm]	8/8
L_1 [mm]	19/17
L [mm]	20,1/21,3
S [mm]	9,6/17,8
b [mm]	11/11
B^{H7} [mm]	8/12
E [mm]	42/28
Admissible MD [Nm]	9,1/27,3
Weight/Pair [g]	380

Table 1 Properties of gearing

2.4.2. Power loss in the bearings

The energy loss in the bearings can also be divided into no-load loss and load dependent loss. The no-load loss in a bearing is mainly caused by the type and size of the bearing, the arrangement of the bearing, and the viscosity and supply of the lubricant (Klaus Michaelis, 2011). **Fout! Verwijzingsbron niet gevonden.** shows the no-load power loss difference between bearing types.

The radial bearing has the lowest no-load loss. Roller bearings with a small taper are suitable for no-load bearing arrangements. When considering the cross load, axial preloading is required, which greatly increases the no-load energy loss of the tapered roller.

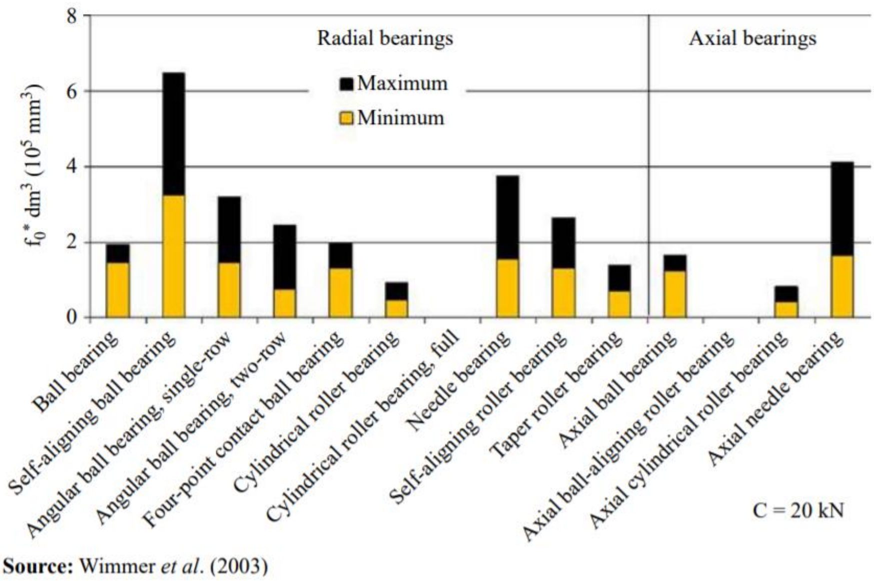


Figure 7 No load loss of bearing

When it comes to load-dependent losses, the causes are different. The load dependent losses depend on bearing type and size, on load and sliding conditions in the bearing and on the lubricant type. **Fout! Verwijzingsbron niet gevonden.** shows load-dependent losses of the bearing with same load capacity C = 20 [kN].

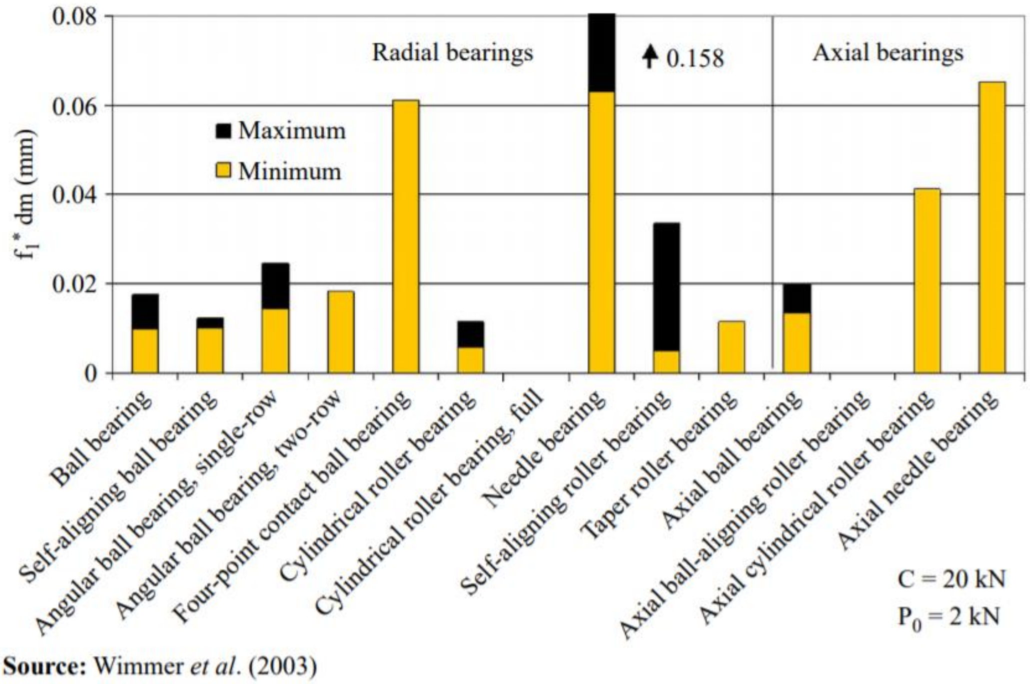


Figure 8 Load-dependent loss of bearing

Cylindrical rollers have the lowest axial power loss. Under the same load, tapered rollers have small energy losses due to their smaller diameter.

The formulas that can be used are as follows:

Friction force

$$F_{friction} = F_{load} * \mu$$

$F_{friction}$=loss due to friction [N]

F_{load}=load from axis on bearing [N]

μ=friction coefficient

Powerloss due to friction

$$\mathrm{P}_{out} = \mathrm{P}_{\mathrm{in}} - \left(\left(F_{friction} * \mathrm{r}_{\mathrm{shaft}}\right) * \omega\right)$$

P_{out}= output power [W].

P_{in}= input power [W].

$F_{friction}$=loss due to friction [N]

r_{shaft}=radius driving shaft [m]

ω=angular velocity [rad/s]

$$T = \frac{60}{2\pi} \times \frac{P}{n}$$

T=torque [Nm].

P=power [W].

n=rotation speed [rpm].

Friction table

Bearing Type	Coefficient of friction μ
Deep Groove Ball Bearing	0,0015
Angular Contact Bearing	0,0020
Cylindrical Roller Bearing, Cage	0,0010
Cylindrical Roller Bearing, Full Comp.	0,0020
Tapered Roller Bearing	0,0020
Spherical Roller Bearing	0,0020
Ball Thrust Bearing	0,0015
Cylindrical Roller Thrust Bearing	0,0050
Tapered Roller Thrust Brg. Cage	0,0020
Tapered Roller Thrust Brg. Full Comp	0,0050

(FRICTION & FREQUENCY FACTORS, sd)

Table 2 Coefficient of friction with different bearings

2.4.3. Power loss in shaft

Since power is a function of speed and torque, the speed will not be affected by the length of the shaft, but the torque will. The length of the shaft has an effect on torsional (twisting) stiffness. The longer it is, the less stiff it will be. If the torque on the shaft is varying a lot, then the changes in torque are damped by the deflection of the shaft. If the shaft is under constant torque, the torque loss is almost zero, but in real life the load is not constant. So the length of the shaft will affect the energy loss.

Friction on the shaft can also cause energy loss, so lubricants are needed to help reduce losses caused by friction.

2.4.4. Power loss in propeller

The propeller is used to generate thrust to overcome the ship resistance. Normally, an open water diagram is used to determine the operational behaviour of the propeller. That is because realistic waters and open waters are rarely the same. Energy loss occurs when the power of the propeller in open water is converted into actual propeller power (Shi1 & Grimmelius, 2009).

2.5. Simulate the resistance caused by wind

Wind is considered an external energy resistance. Since the wind is not fixed and varies from day to day, the researchers found the average wind value of the Dutch sea detected by the testing station. This mean value is used as the input value of the calculation chain.

West Netherlands

Wind speed averages for a year

Days	Place	MPH	KPH
11	Amersfoort	8.3	13.3
56	Amsterdam	11.4	18.4
84	Den Helder	13.0	20.9
44	Goes	10.7	17.3
149	Hook of Holland	16.3	26.3
164	IJmuiden	17.0	27.4
62	Katwijk	11.6	18.7
34	Lopik	9.8	15.8
46	Rotterdam	10.5	16.9
6	Utrecht	7.6	12.2
105	Vlissingen	14.1	22.7

Table 3 Average wind speeds in the Netherlands

(Annual Average Wind Speeds in the Netherlands, 2010)

Table 3 shows the average wind speed for a year in miles per hour [MPH] and kilometres per hour [KPH]. All the numbers here are based on weather data collected from 1981 to 2010.

2.6. Simulation of the resistance caused by waves

A wave is considered an external energy resistance. Since Vlissingen does not have a wave detection point, the researchers decided to use data near Honte nabij Sloehaven as the wave input (Waterinfo-Wave, 2020).

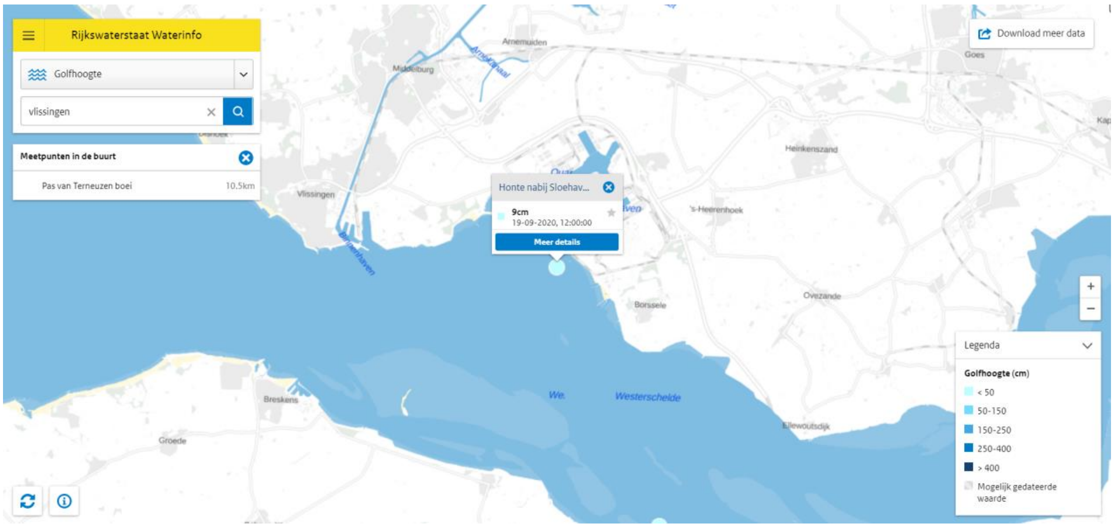


Figure 9 Waterinfo map by Rijkswaterstaat

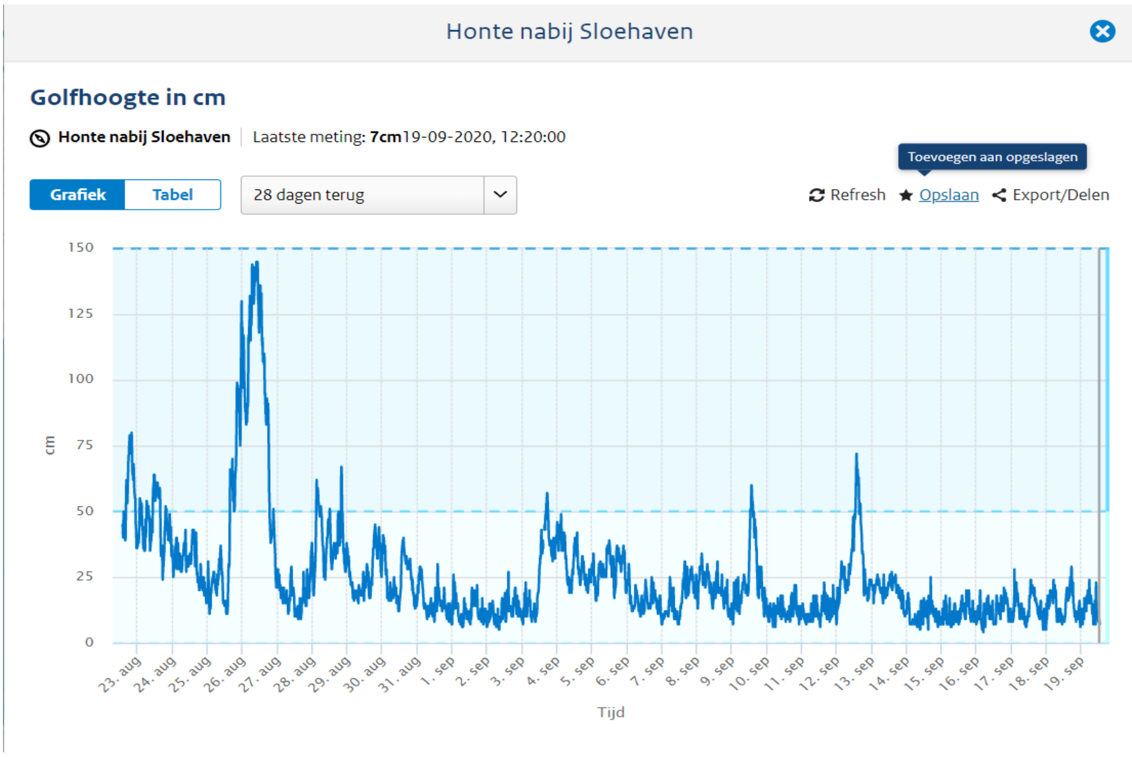


Figure 10 Wave height aug.-sep. in Honte nearby Sloehaven

It can be seen from Figure 10 that the wave data fluctuates greatly, but the data is concentrated around 10cm.

2.7. Simulation of the resistance caused by ocean current

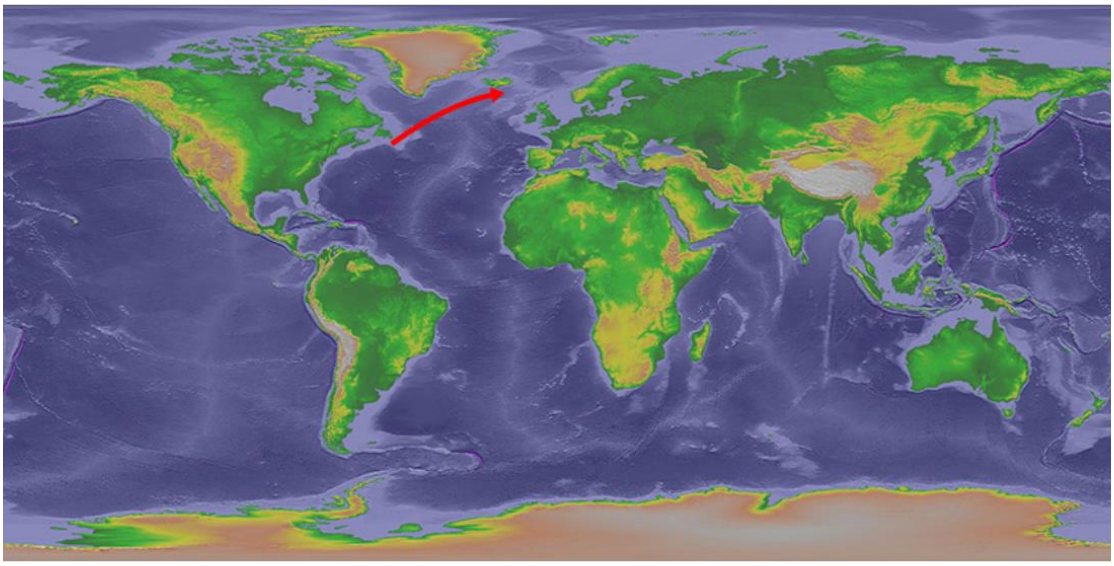


Figure 11 Overview of the water and currents of earth

(Major Ocean Currents, n.d.)

The ocean current surrounding the Netherlands is the North Atlantic Warm Current, the most powerful warm current in the northern Atlantic Ocean and is a continuation of the Gulf Stream. The North Atlantic warm current runs from southwest to northeast (North Atlantic Current). The direction of the ocean current will affect the navigation of the ship. Although the solar boat is driven by a Propeller which is less dependent on ocean currents and winds, all ships can benefit from making good use of ocean currents. According to research, ocean currents in offshore areas can be ignored (Willemsen, 2019).

2.8. Define the output power of a ship's propulsion system

When studying the final output power of the propulsion system, the output power can be calculated by using the following formula.

$$P = F \times v$$

P = output power (W)

F = total resistance force (N)

v = boat velocity(m/s)

The thrust required is related to the rotational speed and torque required by the following formula.

$$K_T = \frac{Ft}{\rho \times n^2 \times d^4} \quad \rightarrow \quad Ft = \rho \times n^2 \times d^4 \times K_T$$

Ft = thrust (N).

ρ = liquid density (kg/m^3).

n = rotating speed (rev/s).

d = diameter (m).

K_T = thrust coefficient.

2.9. Motor characteristic curve

2.9.1. Motor drawings and data provided by suppliers

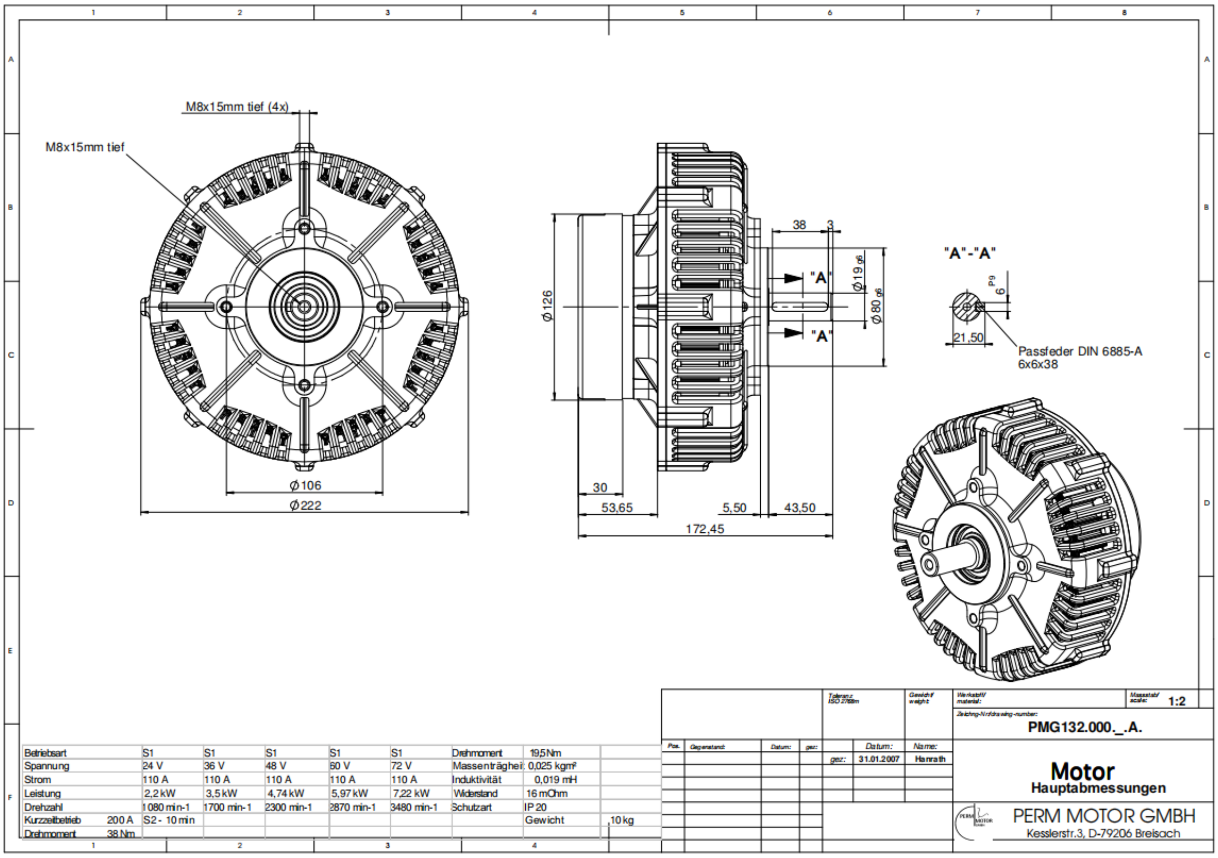


Figure 12 Motor drawing

Motor parameters

Pole pair	Coils	Current
4	20	110A
Voltage (V)	Rotation speed (rpm)	Power (kw)
24	1080	2,2
36	1700	3,5
48	2300	4,74
60	2870	5,97
72	3480	7,22

Table 4 Motor parameters

The motor datasheet is coupled with multiple graphs for different voltages. These are based upon a data set of different rpms at different loads and voltages. These can be seen below.

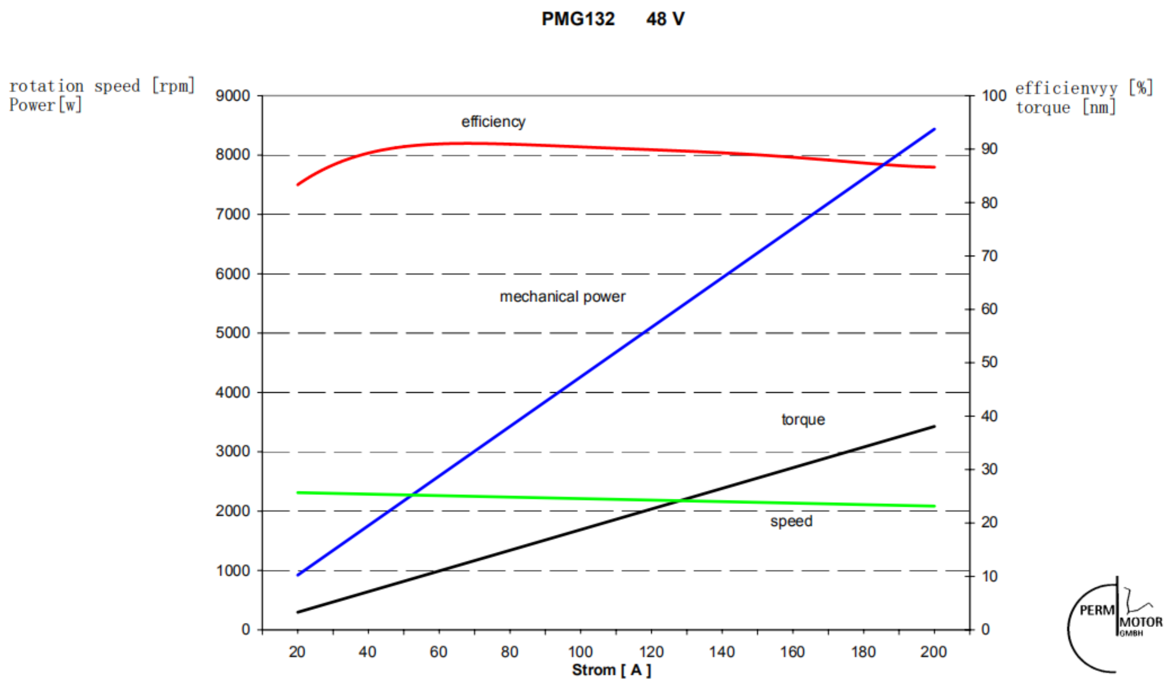
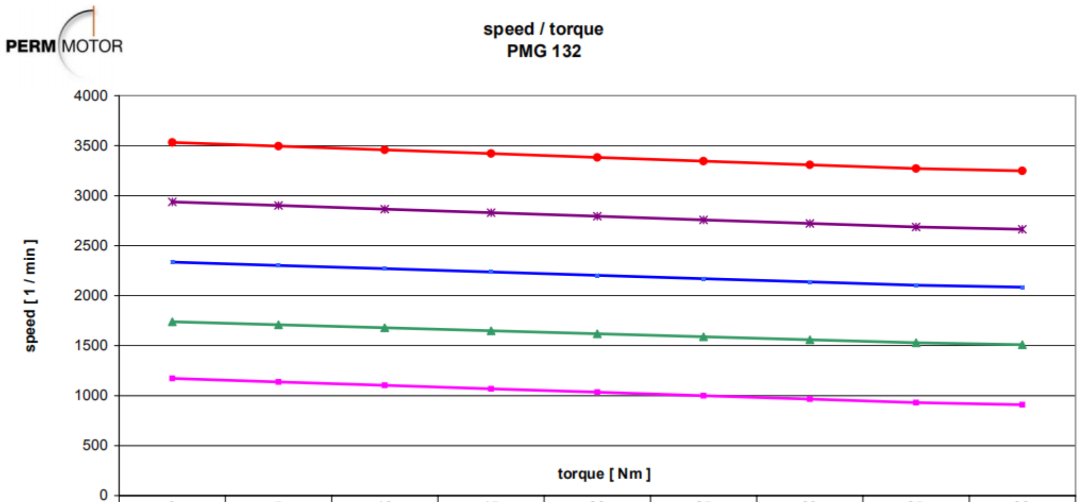


Figure 13 Motor n/P/T-I curve on 48V



	0	5	10	15	20	25	30	35	38
24V	1172	1138	1103	1069	1034	1000	965	931	910
36 V	1739	1709	1679	1649	1619	1588	1558	1528	1510
48 V	2335	2302	2269	2236	2203	2170	2137	2104	2084
60 V	2937	2901	2865	2830	2794	2758	2722	2686	2664
72 V	3532	3495	3458	3420	3383	3346	3308	3271	3249

Figure 14 Motor T-n curve on different voltage

This dataset can be expanded linearly, because the lines in the graph above can be estimated as being linear.

$$y - y1 = \frac{y2 - y1}{x2 - x1} * (x - x1)$$

(x, y) = coordinates of interpolation value

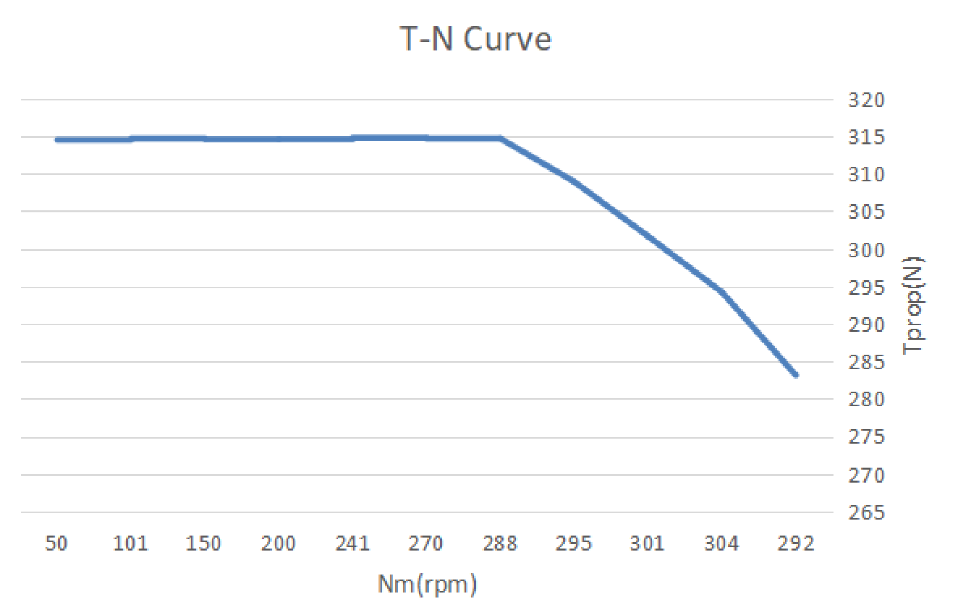


Figure 15 T-N curve of the motor connected to the propellor

2.10. Propeller characteristic curve

The performance of the propeller is usually tested by open water experiments. Normally the performance of the propeller is determined by thrust coefficient (K_T), torque coefficient (K_Q) and the advance ratio (J). Researchers can calculate the thrust and torque by using these coefficients. Moreover, the thrust coefficient and torque coefficient are inversely proportional with the advance ratio. When $J = 0$, the thrust and torque coefficient reaches their peaks.

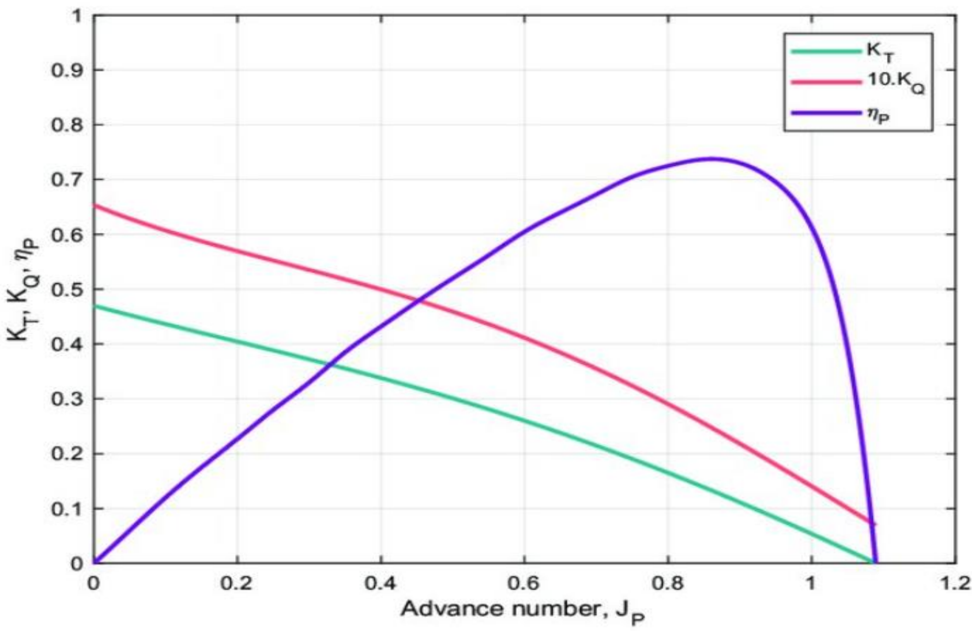


Figure 16 Propeller characteristic curve

η_p Represents the efficiency of a propeller in an open water experiment, which is relevant to the thrust coefficient, torque coefficient and advance ratio. The formula of this coefficient will be introduced later.

The main formulas used for the propellor calculation are listed below.

Force equilibrium (speed is constant)

$$Ft = Fr$$

Ft = thrust (N).

Fr = resistance (N).

Resistance force

$$Rtotal = (1 - t) * Fr$$

Rtotal = total boat resistance (N)

T = thrust deduction factor

Fr = resistance (N).

Interpolation formula

$$y - y1 = \frac{y2 - y1}{x2 - x1} * (x - x1)$$

(x, y) = coordinates of interpolation value

Thrust coefficient

$$K_T = \frac{Ft}{\rho \times n^2 \times d^4} \quad \rightarrow \quad Ft = \rho \times n^2 \times d^4 \times K_T$$

Ft = thrust (N).

ρ = liquid density (kg/m^3).

n = rotating speed (rev/s).

d = diameter (m).

K_T = thrust coefficient.

Torque coefficient

$$K_Q = \frac{Q_R}{\rho \times n^2 \times d^5} \quad \rightarrow \quad Q_R = \rho \times n^2 \times d^5 \times K_Q$$

$$Q_E = Q_R - Q_I$$

Q_E = torque difference(Nm).

Q_R = torque required (Nm).

Q_I = torque input (Nm).

ρ = liquid density (kg/m^3).

n = rotating speed (rev/s).

d = diameter (m).

K_Q = torque coefficient.

Power output

$$P = F \times v$$

P = output power (W)

F = force (N)

v = velocity(m/s).

Power input

$$P = T \times \omega$$

P = input power (W)

T = torque (Nm)

ω = radial velocity (rad/s).

Stream velocity

$$Va = (1 - w) \times Vb$$

Va = inflow stream velocity (m/s)

Vb = boat speed (m/s)

W = wake fraction

Propellor efficiency

$$\eta = (Ft * Va)/(n * Q)$$

Ft = thrust (N)

Va = inflow stream velocity (m/s)

N = radial velocity (rad/s)

Q_R = torque required (Nm)

Propulsive efficiency

$$\eta = (Rtotal * Vb)/(n * Q)$$

Rtotal = total boat resistance (N)

Vb = boat speed (m/s)

N = radial velocity (rad/s)

Q_R = torque required (Nm).

Required rpm

$$\left.\begin{aligned} P = T * n * \frac{2\pi}{60} \\ T = Q_R = \rho \times (n/60)^2 \times d^5 \times K_Q \end{aligned}\right\} n = \left(\frac{P * 60^3}{\rho * d^5 * K_Q * 2\pi}\right)^{\frac{1}{3}}$$

P = input power (W)

n = radial velocity (rpm)

T = Q_R = torque required (Nm).

ρ = liquid density (kg/m^3).

d = diameter (m).

K_Q = torque coefficient.

3. Method

3.1. Overview

The method used in this project is the V-Model method with the main structure shown in **Fout! Verwijzingsbron niet gevonden.**.

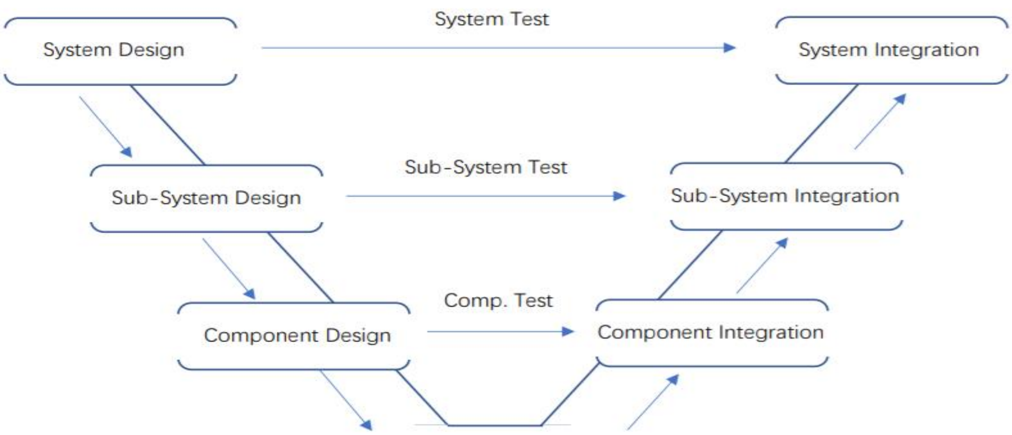


Figure 17 V-model structure

The V-Model can be divided into two main phases: ‘Design Phase’ and ‘Integration Phase’.

In the Design Phase, the behaviours and edges of the final product should be decided and evaluated. In the Integration Phase, focus lies on assembling components, verifying designs in Design Phase and realizing the final product.

The core of V-Model is operating tests and verification. There are several progressive layers in both phases from system to sub-system to component. In the Design Phase different test plans are designed which are used in the corresponding layers in the Integration Phase.

3.2. Reasons of choice

In this propulsion system design project, there is a clear final product idea (fixed component composition, fixed working principle) which gives the team chances to optimize the same idea and guarantee a better functionality of the result. The reason we chose the V-model, is because you do a lot of testing when following the model. Excessive testing is needed to verify our simulation. Especially for this particular propulsion system, every component in every sub-system has close connections. They play different essential roles in the process of generating thrust (components or sub-systems are all related to energy input, output and transmission).

Because every part of the calculation chain has a close connection to each other, we must make sure that the relationship between every part is correct. We must recall and check if there are errors in previous parts before starting a new part. This regularly means going backwards checking for mistakes is necessary. Compared with other methods, the progressive layers of V-Model ensures that the problem and its direction will be recalled and changed effectively. The team can detect the error sources and make targeted improvements easily.

3.3. Usage of method

First, the team has to make the system overview. In order to figure out how system works, disassembling the main system into sub-systems and into components is needed. For every layer, a system description, sub-system descriptions or component descriptions should be taken as the start of the layer. All these descriptions should contain all variables which are related to the input and output of the systems or components. According to these descriptions, the reactions within systems and components can be known and vague elements can be eliminated.

From the system and component descriptions, the design concepts and test plans can be created. In the main system layer, tests will be designed to show the working state of system such as working efficiency and thrust generated by whole propulsion system. In the sub-system layer, tests will be designed, proving relationships between certain sub-systems. For example, the energy transmission/consumption and the power transmission system. In the component layer, the calculation chain will be designed. Tests will be designed to find out the characteristic of every component such as the relationship between the number of gear teeth and the rotation speed.

After finishing all the designs, the components should be reassembled into sub-systems and into a system. The test results from deeper layers will be used in tests from shallower layers. All designs can be validated. When errors appear, the error sources can be found in the corresponding deeper layers.

The following list shows the deliverables of every phase and layer:

Layer	Deliverables
Design Phase	
System Design	1. List of demands. 2. Function overview. 3. Analysis of the current situation. 4. System description. 5. System test plan.
Sub-System Design	1. System division. 2. Formula overview. 3. Subsystem description. 4. Subsystem test plan.
Component Design	1. List of components. 2. Component description. 3. Component test plan
Integration Phase	
Component Integration	1. Component ordering. 2. Component test.
Sub-System Integration	1. Subsystem assembly plan. 2. Subsystem assembly. 3. Subsystem simulation.
System Integration	1. System assembly plan. 2. System assembly. 3. System test.

Table 5 Deliverables list in different phases of V-model

4. Results

After completing all the design and integration phases following the V-model (appendix 7.1-7.7), a complete overview of the system is created. This contains all the variables, properties and formulas to use as a guideline while developing a simulation of the propulsion system of the Solar Boat.

The project basically had three phases apart from the V-model. During the first part of the project research has been done about propulsion systems and calculations based on that. This is all shown in the V-model “component design” (appendix 7.4). Using all the information and separate calculations, the simulation is build up. This is done with the help of the V-model “integration” (appendix 7.5-7.7). The last step is to simulate and validate the current propulsion system of the Solar Boat, Sealander. For that all the components have been checked and the corresponding properties are inserted in the system.

4.1 Designing

The complete design of the simulation can be depicted in a flowchart containing all the different components and order of calculations. This flowchart is shown below. The arrows give the direction of the data flow. This is used for coupling the calculations into a calculation chain. Different values for different components can be calculated with formulas retrieved from physics.

Each calculation has basically three types of values. The first ones are the variables that are inserted, coming from the user or the previous calculation. The second set of values are the values transmitted back to the user-interface, so the user can read them. The third and last set of values are the values that will be transmitted on to the next component with the corresponding calculations.

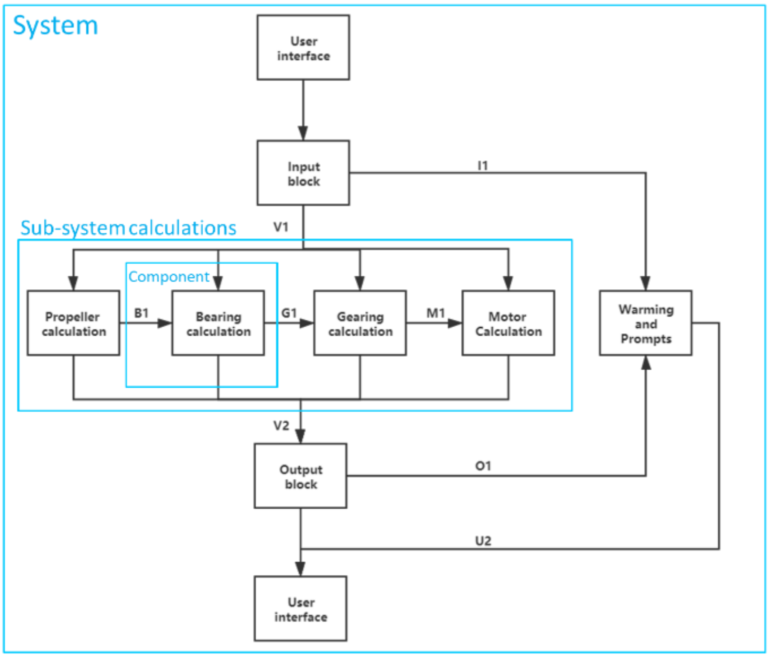


Figure 18 Propulsion simulation system flowchart

4.2 Integrating

After this is all set up individually, the links are being connected into a calculation chain. To interact with the user, a user-interface is designed. This is a user-friendly front panel where only the relevant values are being shown. Therefore the user does not need any technical knowledge to use the simulation. Some relevant values are used to give more insight into the performance of the propulsion system. An example of this are the energy outputs and accompanying graph displayed at the bottom.

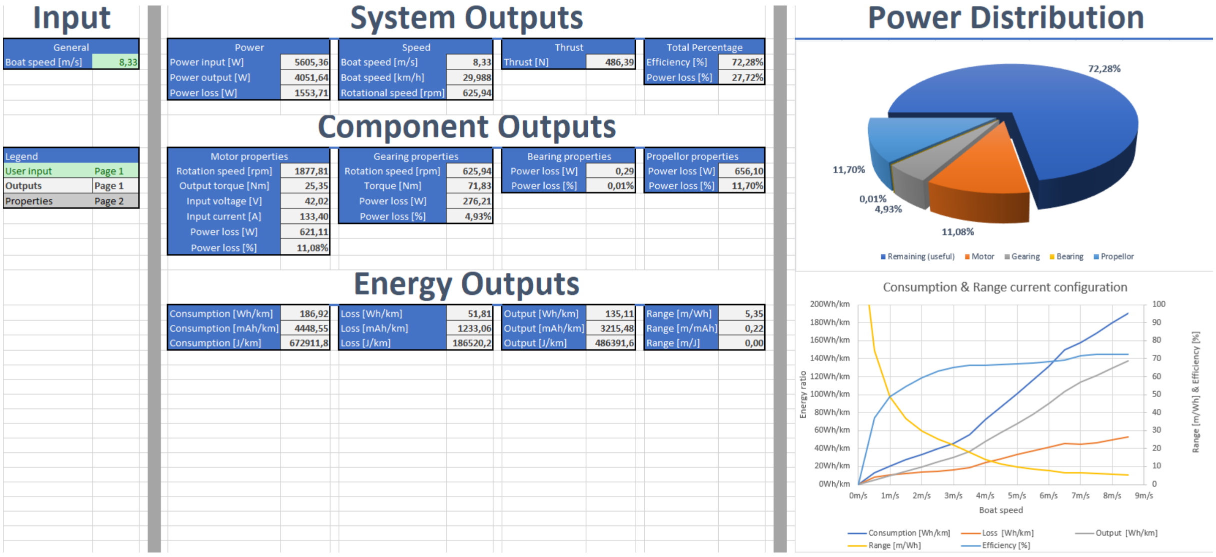


Figure 19 User-interface in simulation

The last step is simulating the current propulsion system and making a digital twin. The properties of the components used in the current propulsion system can be found in the corresponding datasheets. It has also been verified that the datasheets attached belong to the components. There are 4 main physical components; The motor, the transmission (gearing), the bearings, and the propellor.

4.3 Simulating

Verifying the motor was relatively easy, which has been done by comparing the motor nameplates. Attached with the main datasheet were extensive curves showing the load and rotational speed behaviour at different voltages. This dataset was used and expanded using linear inter- and extrapolation. This could be done because the rpm-voltage and rpm-load behaviour is almost linear with a DC motor. This makes swapping the motor easy if the same data array is provided.

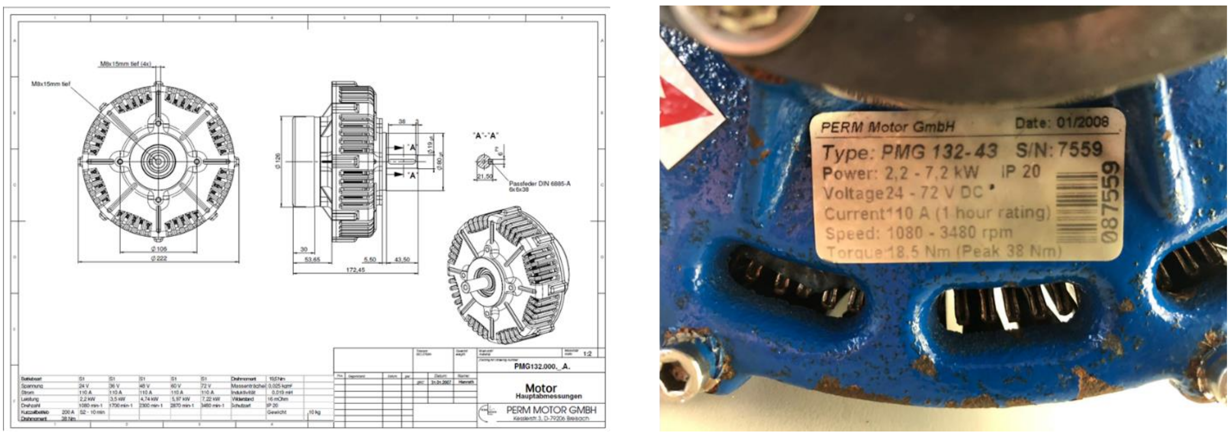
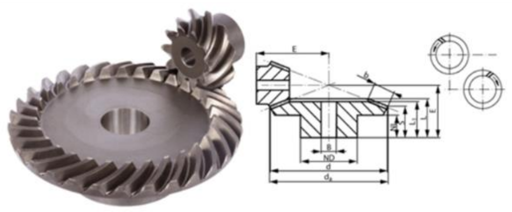


Figure 20 Motor used in the solarboat

The gearing is verified by opening the strut, counting teeth and measuring the diameters. All other properties are either from the datasheet, or using generic standard values. This allows for extensive customizing of the gearing system.



Transmission [i]	3 : 1
Module	1,5
No. of Teeth	10 / 30
d_a [mm]	26/66,6
d [mm]	22/66
ND [mm]	17/40
NL [mm]	8/8
L_1 [mm]	19/17
L [mm]	20,1/21,3
S [mm]	9,6/17,8
b [mm]	11/11
B^{H7} [mm]	8/12
E [mm]	42/28
Admissible MD [Nm]	9,1/27,3
Weight/Pair [g]	380

Figure 21 Gearing used in the solarboat

The bearings used in the propulsion system were confirmed by using SOLIDWORKs drawings of the strut. Combined with generic friction coefficients belonging to different bearing types, and an estimation of the load on them, the bearing properties were selected.

The last component is the propellor. Since the propellor used is not labelled with a name or code, it was a little bit harder to verify this component. But by diving into the SolidWorks drawings of the solarboat, information about the propellor was found. Using the diameter and shape, the propellor could be confirmed. Coupled with the propellor, a data array of different propellor properties varying by boat speed was provided.

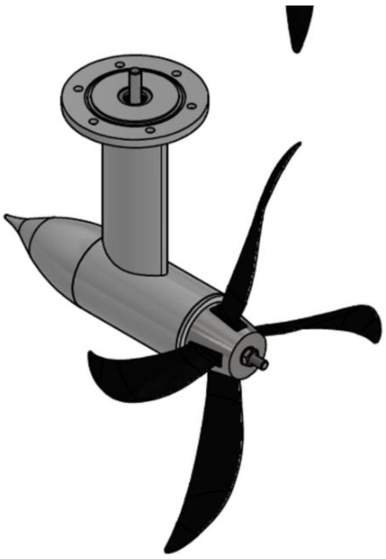


Figure 22 Propeller used in the solarboat

4.4 Validating

Now that all the properties of the different components are determined and inserted into the simulation, calculations can be made. The simulation should be validated with its error margin being less than 10%. The MARIN did a lot of tests years ago and gathered empirical data. This data is stored in this file: *"propdesign_algemene_sheet marof v3 HZ pr"*. A project group from a previous year made calculations with this empirical data and stored them in the same file, under the page: "*propulsion ENG"*. This sheet has some of the same outputs as the simulation so they can be compared and a deviation can be calculated based on that. On the table below is shown how the simulated in-/output power and thrust deviates from the MARIN sheet for different boat speeds. Since none of the deviation is more than 10%, there can be stated that this simulation is valid and very accurate.

Boat speed [m/s]	Input power [W]		Deviation [%]	Output power [W]		Deviation [%]	Thrust [N]		Deviation [%]
0,00	0	0	0	0	0	0	0	0	0
0,28	9,55	9,54	0,10%	2,63	2,809168	6,95%	9,95	10,03274	0,80%
0,56	29,58	28,71	2,95%	10,51	11,24	6,99%	19,91	20,07	0,82%
0,83	56,07	52,86	5,73%	23,64	24,68	4,41%	29,86	29,7	0,53%
1,11	93,62	88,14	5,85%	42,02	44,15	5,06%	39,81	39,77	0,11%
1,39	138,60	130,5	5,85%	65,66	69,23	5,43%	49,77	49,81	0,09%
1,67	187,46	176,63	5,78%	94,55	99,93	5,68%	59,72	59,84	0,20%
1,94	238,49	228,24	4,30%	128,70	134,85	4,78%	69,67	69,51	0,23%
2,22	301,44	289,07	4,10%	168,10	176,59	5,05%	79,62	79,55	0,09%
2,50	370,08	355,61	3,91%	212,75	223,95	5,27%	89,58	89,58	0,00%
2,78	447,82	431,13	3,73%	262,65	276,92	5,43%	99,53	99,61	0,08%
3,06	531,31	512,48	3,54%	317,81	335,52	5,57%	109,48	109,65	0,15%
3,33	623,82	599,42	3,91%	378,97	398,11	5,05%	119,67	119,55	0,10%
3,61	803,01	773,54	3,67%	486,91	512,06	5,17%	141,93	141,84	0,07%
3,89	999,88	966,58	3,33%	606,56	638,97	5,34%	164,18	164,26	0,05%
4,17	1164,44	1155,31	0,78%	726,34	766,15	5,48%	183,50	183,73	0,13%
4,44	1365,39	1351,07	1,05%	856,34	899,13	5,00%	202,82	202,51	0,15%
4,72	1585,70	1574,15	0,73%	999,74	1051,1	5,14%	222,85	222,69	0,07%
5,00	1819,67	1812,05	0,42%	1153,71	1214,43	5,26%	242,89	242,89	0,00%
5,28	2085,83	2083,66	0,10%	1328,22	1399,65	5,38%	264,91	265,09	0,07%
5,56	2357,32	2362,21	0,21%	1514,83	1598,01	5,49%	287,02	287,41	0,14%
5,83	2659,93	2662,25	0,09%	1726,11	1814,2	5,10%	311,48	311,18	0,10%
6,11	2972,08	2984,25	0,41%	1950,29	2051,97	5,21%	335,94	335,84	0,03%
6,39	3325,95	3350,5	0,74%	2200,64	2317,55	5,31%	362,58	362,68	0,03%
6,67	3690,68	3727,54	1,00%	2465,29	2597,64	5,37%	389,26	389,45	0,05%
6,94	3890,92	3929,31	0,99%	2675,10	2812,29	5,13%	405,49	405,23	0,06%
7,22	4168,14	4215,46	1,14%	2893,39	3043,8	5,20%	421,71	421,58	0,03%
7,50	4487,60	4546,04	1,30%	3120,23	3284,46	5,26%	437,93	437,93	0,00%
7,78	4819,23	4890	1,47%	3355,64	3534	5,32%	454,15	454,28	0,03%
8,06	5163,15	5247,69	1,64%	3599,61	3793,25	5,38%	470,37	470,63	0,06%
8,33	5519,51	5605,36	1,56%	3852,14	4051,64	5,18%	486,59	486,39	0,04%
	Average deviation		2,27%			5,17%			0,14%

	Real data
	Simulation results
	Deviation

Figure 23 Final results validation

5. Discussion

5.1. Discrete discussion of results

As seen in chapter 4.4, none of the deviation is more than 10%. This means that all the outputs from the designed simulation are validated and very accurate. Since this is the case, the simulation is ready to be operated.

5.2. Conclusion

The results of the current simulation meet the previous set goal for validation. Therefore, the simulation can be seen as valid and useable. This simulation can thus be used to calculate properties of the solar boat at different speeds. This will help the solar boat project to gain insight into the propulsion system losses and requirements.

5.3. Recommendation

5.3.1 Physical experiments

First, due to the current pandemic and the maintenance of the solar boat, we could not perform physical experiments on the solar boat to measure the data, so the simulation system was verified based on empirical data from the MAROF sheet. The success of the validation of the simulation system depends on the accuracy of the empirical data and the gearing and motor datasheets. It is recommended to perform physical experiments on the solar boat, such as the initial test that were designed.

The importance of these physical experiments is justified because reality is most always different than the theory. What has been calculated in excel can be different compared to reality due different reasons. One major reason is because the theory could be missing other influences, such as weather disturbances and human error. Another reason could be that the datasheets do not correspond 100% with reality, due to the degradation of components and their performance. To sum up, if the end product is being used in reality, it is preferred that it is also validated using reality.

5.3.2 Accuracy

Secondly, for improving the accuracy of the simulation, the inclusion of the before mentioned types of influences (weather, human error, degradation of components) could be added. It was not considered for this project, focusing only on the propulsion system of the solar boat under uniform speed and sufficient battery power, but it would add more value to the simulation.

Some of the data given in the empirical data about the motor did not match the data in the motor datasheet, which made the process of building the simulation system complicated and confusing, but eventually we found a suitable solution but could not ensure absolute accuracy, if future researchers want to make the system more accurate than the 5% error, it is recommended to test the solar boat to get the accurate parameters. parameters.

5.3.3 Simulation limitations & improvements

A main limitation or the current simulation is the exchangeability of different components. The properties don't give the whole picture of each component. For example, the motor requires a data set to be manually inputted in the motor calculations. Changing the motor would mean changing this data set, along with updating the range of the inter- and extrapolation. This manual change is not very user friendly. This limitation also applies to the gearing, which allows for different parameters to be changed, but an extra conversion or different type of gearing setup is not supported. This might require an update for the different gearing formulas, or addition of parameters.

A more important limitation is the propellor component. This component uses empirical test data of the propellor to calculate its performance. Changing the propellor now would mean changing the whole data set, which has to be generated first. Because of the fact that this data incorporates the hull and pod resistance, a change to these components would also require a revamp of the data set. This could be greatly improved by using open water characteristics derived from flow simulation. If the data set would be automatically generated based on a 3D model of the propellor and boat, the changing of the propellor would be much more user friendly. Such an implementation of flow simulation requires an combination of for example SOLIDWORKS or MATLAB simulations into Excel. This perhaps raises the question of what the desired platform would then be for the simulation. To answer this question, research should be done regarding such implementations and different kinds of simulation programs/languages.

Another limitation of our design in combination with the Excel software, is the fact that the system cannot automatically update the consumption, range & efficiency graph of the system after changing the characteristics of the propulsion system. These characteristics are properties of the motor, gears, bearings, and propeller. This limitation is caused by the fact that the graph uses a set of boat speeds (array) to calculate the curve values. Our design only accounted for 1 value per iteration, and after extensive research, there is no standard function in Excel to simply use an array as an input for one cell and iterate the worksheet based on that array. Such a functionality might be added using the visual basic coding language supported in Excel, but that was out of reach for our project due to time constraints. Another solution would be to use a different platform to perform the simulation. The simulation could be coded in Python, or other programming languages to upgrade the system, making it more user-friendly and practical to use. For updates to the simulation, this will require proper knowledge of these languages.

5.3.4 Combination of multiple simulations

The researchers of this project focused on the study of the simulated solar boat propulsion system, while the researchers of the second group focussed on the study of the simulated battery system of the solar boat. If the results of both projects were to be combined, the value of the simulation would greatly improve. More accurate time of use of the solar boat can be predicted, along with the ability to find more key improvement points. Especially during the races, complete simulations give a better picture of the different scenarios.

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7. Appendices

7.1 V-model design phase (demo)

7.1.1. Demo test plan

Aim & Hypothesis

Aim

The aim of this test is to let the client use the simulation interface to calculate different aspects of the propulsion system.

Hypothesis

The client can use this validated simulation to design an improved the propulsion system.

Variables

These are the constants and variables that will be used during the test. The constants are the same for both situations and define the testing environment.

We will be testing two situations to check the borders of the system. The first situation is a situation where normal values will be put in, between the stated limits. For the second situation we stress the system a bit and put in exceptional values and show how the simulation will react on that.

Constants	Keep constant at...
Ambient temperature	Standard indoor temperature with lower and upper limits (20 °C ± 5°C).
Battery level computer	Constant power source.
Software Excel	Newest version.
All input variables	Real positive numbers & ISO-notation.
Properties	Same as MAROF sheet [worksheet ENG].

Table 6 Constants demo test

Common situation

The limits stated are the limits of the real world. If values are put in out of this range, the outputs will be unreliable.

Inputs	Value
Boat speed [m/s]	Change value from 0 to 2 to 4,56 to 8

Table 7 Inputs common situation

Unusual situation

Inputs	Value
Boat speed [m/s]	Input the letter 'h'
Beat speed [m/s]	-100.000
Gear addendum radius [m]	Input the letter 'f'
Gear addendum radius [m]	-8
Liquid density [kg/m^3]	Input the letter 'g'
Liquid density [kg/m^3]	-200

Table 8 Inputs unusual situation

Outputs

The outputs monitored will be the same for both situations and will be used to see variations or changes in the system.

Outputs	Value
Thrust [N]	Indicator between 0 & 500
Power input [W]	Indicator between 0 & 6000

Power output [W]	Indicator between 0 & 4100
Propellor speed [rpm]	Indicator between 0 & 640

Table 9 Outputs monitored

Tools

Below are the tools listed that will be used during this test.

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version.
Keyboard	No limit.
Mouse	No limit.

Table 10 Testing tools

Method

This section consists of actions that need to be performed during the test in order to conclude a result. The conditions of the constants stated in chapter "2. Variables" have to be met before executing the simulation. To execute the simulation, follow the steps stated in "4.1. Steps".

To validate our design, we can compare it to the datasheet: "propdesign_algemen_sheet marof v3 HZ [worksheet propulsion ENG]". This is a datasheet with a lot of empirical data retrieved from testing and calculations based on that. This is performed by the MAROF, which is the study: Marine Officer. This data is carefully retrieved so we can use this data to validate our simulation.

The boat is not available for testing, so therefore we use data from a sheet instead of building a test setup and measuring data from that.

Steps

1. Power up the laptop and open Microsoft Excel.
2. Load in the: "Propulsion system simulation" file in Excel.
3. Modify the value of the different inputs.
4. Perform a simulation for every input value modification.
5. Load in the: "propdesign_algemen_sheet marof v3 HZ" file in Excel.
6. Compare the results with the empirical data from the MAROF sheet.
7. Close Excel.

Expected results

The expected results of the outputs are as followed.

The outputs from the simulation is within a 10% deviation from the corresponding outputs on the MAROF sheet mentioned above, while inserting the same boat speeds.
We also expect successful prompts.

Conclusion

When boat speed is being changed within the given range, the output values are changing accordingly within 10% deviation of the MAROF sheet, we then consider the test as reliable and passed.

When the outputs are more than 10% deviation, we consider that it failed the test.

When the inputs are like stated at "2.2 Unusual situation" (out of range or incorrect values) and the system does give warnings, we consider that it passes the test.

7.2 V-model design phase (system)

7.2.1 System description

Flowchart

Figure 24 Flowchart system

Unique identifiers

Unique ID	Long Name
U1	User input
U2	Simulation output
O1	Impact to environment
O2	Impact from environment

Table 11 Unique identifiers system

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> U1				
User input				
Boat speed	v_{boat}	0	8,5	m/s
<- U2				
Simulation output				
Thrust	F_T	0	500	N
Boat velocity	V	0	30	Km/h
Rotational speed propeller	n_P	0	2300	rpm
Power input	P_{input}	0	6000	W
Power output	P_{output}	0	4100	W
Power loss	P_{loss}	0	810	W
Current required	I	0	250	A
Voltage required	U	0	72	V
Efficiency	η	0	100	%
Prompts for successful simulation	-	Simulate successfully		-
Warnings for unsuccessful simulation	-	Simulate unsuccessfully		-
Prompts for how to optimize unsuccessful simulation	-	Input error. Input values should be numeric.		-
-> O1				
Impact to the environment				
Heat	Q_{heat}	Will not be considered in the design		W
Noise	N_{noise}			dB
<- O2				
Impact from environment				
Temperature	T_E	Will not be considered in the design		°C
Humidity	H_E			%RH

Table 12 Table of limits system

Table of properties

Generator	Symbol	Min.	Max.	Unit
User interactions				
Motor subsystem				
Motor properties	*Will not be considered in the design.*			
Motor data array (U-T)	n_{motor}	0	5000	rpm
Current-Torque coefficient	ct	0	100	-
Shaft subsystem				
Shaft density **(Exhibition, 2019)**	*Will not be considered in the design.*			
Diameter				
Length				
Shaft torsional stiffness				
Bearing subsystem				
Type	*Will not be considered in the design.*			
Inner diameter				
Outer diameter				
Friction				
Friction coefficient **(Bearing friction coefficient, 2018)**	$\mu_{bearing}$	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Seal coefficient	μ_{seal}	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Load	F	0	1000	N
Shaft radius	r_{shaft}	0	0,05	m
Gearing subsystem				
Gear material hardness **(Hardness of general gears, 2017)**	*Will not be considered in the design.*			
Diameter				
Tooth shape				
Friction coefficient	μ_{gear}	0,1	0,15	-
Ratio	R_g	0,1	10	#
Index circle pressure angle	α	15	25	°
Index circle diameter of driving wheel	d	0	-	m
Addendum radius	d_1	0	-	m
Deddendum radius	d_2	0	-	m
Lubricant viscosity **(Viscosity index)**	μ	0	-	mm^2/s
Tooth number **(Standard gear tooth number, 2019)**	z	0	-	-
Modulus	m	0	-	-
Lubricant density	ρ	0	-	g/m^3
Immersion depth ratio	h	0	-	#
Tooth width ratio	b	0	-	#
Propeller subsystem				
Diameter	d_{prop}	0,1	0,5	m
Thrust deduction coefficient	t	0	1	-
Wake fraction coefficient	w	0	1	-
Liquid density (water)	ρ	980	1000	Kg/m^3
Propeller properties table: Changing according to Vb.	R_{total}	0	500	N
	η	0	100	%
	K_T	0	1	-
	K_Q	0	1	-

User interface subsystem	
User interface properties	*Will not be considered in the design.*
Environmental impacts	
Air thermal coefficient	*Will not be considered in the design.*
Airpressure	
Heat	
Noise	
Temperature	
Humidity	

Table 13 Table of properties system

7.2.2 System test plan

Aim & Hypothesis

Aim

The aim of this test is to verify the simulation of the propulsion system of the Solar boat.

Hypothesis

The simulation will be verified according to the performed tests.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Ambient temperature	Standard indoor temperature with lower and upper limits (20 ℃ ± 5℃).
Battery level computer	Constant power source.
Software Excel	Newest version.
All input variables	Real positive numbers & ISO-notation.
Properties	Same as MAROF sheet [worksheet ENG].

Table 14 Constants system test

Inputs

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable.

Inputs	Value
Boat speed [m/s]	Change value between 0 & 8,5.

Table 15 Inputs system

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system.

Outputs	Value
Thrust [N]	Indicator between 0 & 500
Power input [W]	Indicator between 0 & 6000
Power output [W]	Indicator between 0 & 4100
Prompts or warnings for successful or failed simulation	Simulate successfully / unsuccessfully

Table 16 Outputs monitored

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper

Table 17 Testing tools system

Method

This section consists of actions that need to be performed during the test in order to conclude a result. The conditions of the constants stated in chapter "2. Variables" have to be met before executing the simulation. To execute the simulation, follow the steps stated in "4.1. Steps".

To validate our design, we can compare it to the datasheet: "propdesign_algemen_sheet marof v3 HZ [worksheet propulsion ENG]". This is a datasheet with a lot of empirical data retrieved from testing and calculations based on that. This is performed by the MAROF, which is the study: Marine Officer. This data is carefully retrieved so we can use this data to validate our simulation.

The boat is not available for testing, so therefore we use data from a sheet instead of building a test setup and measuring data from that.

Steps

1. Set up computer and load in simulation.
2. Insert different boat speeds.
3. Run the simulation for every boat speed.
4. Compare results with the corresponding outputs on the excel datasheet.

Expected results

The expected results of the outputs are as followed.

The outputs from the simulation is within a 10% deviation from the corresponding outputs on the MAROF sheet mentioned above, while inserting the same boat speeds.
We also expect successful prompts.

Conclusion

When boat speed is being changed within the given range, the output values are changing accordingly within 10% deviation of the MAROF sheet, we then consider the test as reliable and passed.

When the outputs are more than 10% deviation, we consider that it failed the test.

7.3 V-model design phase (sub-system)

7.3.1 Subsystem description (user interface)

Flowchart

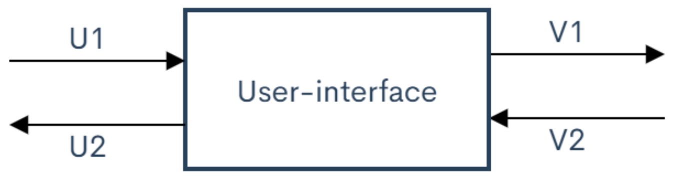


Figure 25 Flowchart user-interface

Unique identifiers

Unique ID	Long Name
U1	User input
U2	Simulation output
V1	User-interface sub-system output
V2	Calculation sub-system output

Table 18 Unique identifiers user-interface

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> U1				
Data from normal users				
Limit input				
Boat speed	v_{boat}	0	8,5	m/s
Data from administrators				
Properties input (used to set up calculation)				
Motor data array (U-T)	n_{motor}	0	5000	rpm
Motor current-torque coefficient	ct	0	100	-
Bearing friction coefficient	$\mu_{bearing}$	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing seal coefficient	μ_{seal}	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing load	F	0	1000	N
Bearing shaft radius	r_{shaft}	0	0,05	m
Gear friction coefficient	μ_{gear}	0,1	0,15	-
Gear transmission ratio	R_g	0,1	10	#
Gear index circle pressure angle	α	15	25	°
Gear index circle diameter of driving wheel	d	0	-	m
Gear addendum radius	d_1	0	-	m
Gear dedendum radius	d_2	0	-	m
Gear tooth number	z	0	-	-
Gear tooth width ratio	b	0	-	#
Gear modulus	m	0	-	-
Gear immersion depth ratio	h	0	-	#
Gear lubricant viscosity	μ	0	-	mm^2/s
Gear lubricant density	ρ	0	-	kg/m^3
Propellor diameter	d_{prop}	0,1	0,5	m
Propellor thrust deduction coefficient	t	0	1	-
Propellor wake fraction coefficient	w	0	1	-

Propellor liquid density (water)	ρ	980	1000	Kg/m^3
Propeller properties table: Changing according to Vb.	R_{total}	0	500	N
	η	0	100	%
	K_T	0	1	-
	K_Q	0	1	-
<- U2				
Data to normal users and administrators				
Limit output				
Thrust	F_T	0	500	N
Boat velocity	V	0	30	Km/h
Rotational speed propeller	n_P	0	2300	rpm
Power input	P_{input}	0	6000	W
Power output	P_{output}	0	4100	W
Power loss	P_{loss}	0	810	W
Current required	I	0	250	A
Voltage required	U	0	72	V
Efficiency	η	0	100	%
Prompts for successful simulation	-	*Simulate successfully*		-
Warnings for unsuccessful simulation	-	*Simulate unsuccessfully*		-
Prompts for how to optimize unsuccessful simulation	-	*Input error. Input values should be numeric.*		-

Table 19 Table of limits user-interface

Interaction	Symbol	Min.	Max.	Unit
<- V1				
Data to calculation sub-system				
Limit output				
Boat speed	v_{boat}	0	8,5	m/s
Properities output (used to set up calculation)				
Motor data array (U-T)	n_{motor}	0	5000	rpm
Motor current-torque coefficient	ct	0	100	-
Bearing friction coefficient	$\mu_{bearing}$	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing seal coefficient	μ_{seal}	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing load	F	0	1000	N
Bearing shaft radius	r_{shaft}	0	0,05	m
Gear friction coefficient	μ_{gear}	0,1	0,15	-
Gear transmission ratio	R_g	0,1	10	#
Gear index circle pressure angle	α	15	25	°
Gear index circle diameter of driving wheel	d	0	-	m
Gear addendum radius	d_1	0	-	m
Gear dedendum radius	d_2	0	-	m
Gear tooth number	z	0	-	-
Gear tooth width ratio	b	0	-	#
Gear modulus	m	0	-	-
Gear immersion depth ratio	h	0	-	#
Gear lubricant viscosity	μ	0	-	mm^2/s
Gear lubricant density	ρ	0	-	kg/m^3
Propellor diameter	d_{prop}	0,1	0,5	m
Propellor thrust deduction coefficient	t	0	1	-
Propellor wake fraction coefficient	w	0	1	-

Propellor liquid density (water)	ρ	980	1000	Kg/m^3
Propeller properties table: Changing according to Vb.	R_{total}	0	500	N
	η	0	100	%
	K_T	0	1	-
	K_Q	0	1	-
-> V2				
Data from calculation sub-system				
<u>Limit input</u>				
Thrust	F_T	0	500	N
Boat velocity	V	0	30	Km/h
Rotational speed propeller	n_P	0	2300	rpm
Power input	P_{input}	0	6000	W
Power output	P_{output}	0	4100	W
Power loss	P_{loss}	0	810	W
Current required	I	0	250	A
Voltage required	U	0	72	V
Efficiency	η	0	100	%

Table 20 Table of properties user-interface

7.3.2 Subsystem test plan (user interface)

Aim & Hypothesis

Aim

The aim of this test is to verify the user interface of the propulsion system of the Solar boat.

Hypothesis

The user interface will be verified according to the performed tests.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Ambient temperature	Standard indoor temperature with lower and upper limits (20 °C ± 5°C).
Battery level computer	Constant power source.
All input variables	Real positive numbers & ISO-notation.

Table 21 Constants user-interface

Normal Input

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable.

Inputs	Value
Boat speed [m/s]	A numeric number
Properties setting values	Nonzero numeric numbers

Table 22 Normal inputs user-interface

Unusual Input

Inputs	Value
Boat speed [m/s]	A non-numeric symbol or a letter
Properties setting values	Zeros or non-numeric symbols or letters

Table 23 Unusual input user-interface

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system.

Outputs	Value
Prompts for successful simulation	-
Warning for unsuccessful simulation and wrong inputs	-

Table 24 Outputs monitored user-interface

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper

Table 25 Testing tools user-interface

Method

This section consists of actions that need to be performed during the test to conclude a result. The conditions of the constants stated in chapter “2. Variables” have to be met before executing the simulation. To execute the simulation, follow the steps stated in “4.1. Steps”.

This test will use an independent part which has no relationship with the calculation sub-system which will be used in the final design. We create a new calculation part to check if user-interface sub-system can give correct prompts or waring in different situations.

Steps

1. Set properties first, give all properties nonzero and numeric values.
2. Input a numeric boat speed. Record the message box result.
3. Input a non-numeric value to boat speed. Record the message box result.
4. Change one of the properties into a non-numeric value of zero. Record the message box result.
5. Input a random boat speed (no matter what type the input is). Record the message box result.

Expected results

The expected results of the outputs are as followed.

With normal inputs, after changing the input boat speed, there should be message boxes with a prompt: Successful simulation.

With unusual inputs, after changing the input boat speed, there should be message box with WARNING in it. And there are following situations:

<table>
<tr><th>Properties</th><th>Boat speed</th><th>Message box outputs (In input-output sheet)</th><th>Message box outputs (In properties setting sheet)</th></tr>
<tr><td>With zero values</td><td rowspan="2">No matter what types of value it is.</td><td>WARNING: Input error. All property inputs shouldn't be zero</td><td rowspan="2">WARNING: Simulation can't be processed. There should be no zero or unumerice value in properties setting</td></tr>
<tr><td>With non-numeric values</td><td>WARNING: Input error. All property inputs should be numeric</td></tr>
<tr><td rowspan="2">With numeric values</td><td>With non-numeric values</td><td rowspan="2">-</td><td>WARNING: Input error. Input should be a numeric number</td></tr>
<tr><td>With numeric values</td><td>Successful simulation</td></tr>
</table>

Table 26 Expected results user-interface test

Conclusion

When we input different boat speeds and properties, there are corresponding prompts and waring message boxes which follow the list in desired results. We state the tests successful.

If the output message boxes have results which are not mentioned in the desired results list, we state the tests failed.

7.3.3 Subsystem description (calculations)

Flowchart

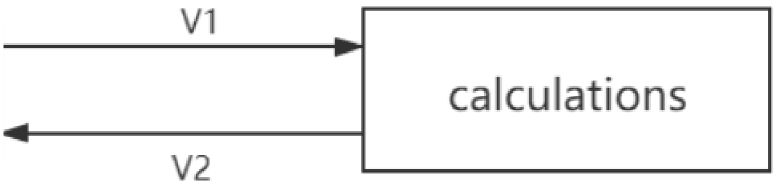


Figure 26 Flowchart calculations

Unique identifiers

Unique ID	Long Name
V1	User-interface sub-system output
V2	Calculation sub-system output

Table 27 Unique identifiers calculations

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> V1				
Data from user interface sub-system				
Limit input				
Boat speed	v_{boat}	0	8,5	m/s
Properities input (used to set up calculation)				
Motor data array (U-T)	n_{motor}	0	5000	rpm
Motor current-torque coefficient	ct	0	100	-
Bearing friction coefficient	$\mu_{bearing}$	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing seal coefficient	μ_{seal}	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing load	F	0	1000	N
Bearing shaft radius	r_{shaft}	0	0,05	m
Gear friction coefficient	μ_{gear}	0,1	0,15	-
Gear transmission ratio	R_g	0,1	10	#
Gear index circle pressure angle	α	15	25	°
Gear index circle diameter of driving wheel	d	0	-	m
Gear addendum radius	d_1	0	-	m
Gear dedendum radius	d_2	0	-	m
Gear tooth number	z	0	-	-
Gear tooth width ratio	b	0	-	#
Gear modulus	m	0	-	-
Gear immersion depth ratio	h	0	-	#
Gear lubricant viscosity	μ	0	-	mm^2/s
Gear lubricant density	ρ	0	-	kg/m^3
Propellor diameter	d_{prop}	0,1	0,5	m
Propellor thrust deduction coefficient	t	0	1	-
Propellor wake fraction coefficient	w	0	1	-
Propellor liquid density (water)	ρ	980	1000	Kg/m^3
Propeller properties table: Changing according to Vb.	R_{total}	0	500	N
	η	0	100	%
	K_T	0	1	-

	K_Q	0	1	-
<- V2				
Data to user interface sub-system				
Limit output				
Thrust	F_T	0	500	N
Boat velocity	V	0	30	Km/h
Rotational speed propeller	n_P	0	2300	rpm
Power input	P_{input}	0	6000	W
Power output	P_{output}	0	4100	W
Power loss	P_{loss}	0	810	W
Current required	I	0	250	A
Voltage required	U	0	72	V
Efficiency	η	0	100	%

Table 28 Table of limits calculations

7.3.4 Subsystem test plan (calculations)

Aim & Hypothesis

Aim

The aim of this test is to verify that the calculation chain of the propulsion system of the Solar boat works.

Hypothesis

The calculation chain will work.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Ambient temperature	Standard indoor temperature with lower and upper limits (20 °C ± 5°C).
Battery level computer	Constant power source.
All input variables	Real positive numbers & ISO-notation.

Table 29 Constants calculations

Inputs

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable.

Inputs	Value
Boat speed [m/s]	0 – 8,5 m/s

Table 30 Inputs calculations

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system.

Outputs	Value
Power input [W]	0 - 5600
Power output [W]	0 - 3900
Thrust [N]	0 - 500
Power loss [W]	0 - 2000
Efficiency [%]	0 - 100

Table 31 Outputs monitored calculations

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper

Table 32 Testing tools calculations

Method

This section consists of actions that need to be performed during the test to conclude a result. The conditions of the constants stated in chapter " Variables" have to be met before executing the simulation. To execute the simulation, follow the steps stated in "Steps".

Steps

1. Set up computer and load in simulation.
2. Set all the properties setting values.
3. Insert boat speed in steps.
4. Run the simulation for every input.
5. Note the output values for every input.
6. Compare the simulation output with real data

Expected results

The expected results of the outputs are as followed.

The following list give the real data of the real solar boat, all simulation outputs have errors less than 30% compared with real data.

Boat speed [m/s]	Input power [W]	Output power [W]	Power loss [W]	Effciency [%]
0.00	0	0	0	-
0.28	9.549877181	2.626517242	6.923359939	0.275031521
0.56	29.58182605	10.50606897	19.07575708	0.355152821
0.83	56.07264864	23.63865518	32.43399346	0.421571938
1.11	93.62110446	42.02427588	51.59682858	0.448876096
1.39	138.6012586	65.66293106	72.93832757	0.473754219
1.67	187.4628336	94.55462073	92.90821283	0.504391291
1.94	238.4933127	128.6993449	109.7939679	0.539635025
2.22	301.4359299	168.0971035	133.3388264	0.557654502
2.50	370.0760455	212.7478966	157.3281489	0.574876162
2.78	447.8166166	262.6517242	185.1648924	0.586516254
3.06	531.3080376	317.8085863	213.4994512	0.59816258
3.33	623.8167042	378.9666984	244.8500058	0.607496875
3.61	803.0108177	486.9090015	316.1018161	0.606354224
3.89	999.884613	606.5644402	393.3201727	0.606634438
4.17	1164.436104	726.3399469	438.0961569	0.623769689
4.44	1365.386872	856.335529	509.0513428	0.627174281
4.72	1585.703691	999.7364993	585.9671913	0.630468672
5.00	1819.67002	1153.711587	665.9584332	0.634022419
5.28	2085.829805	1328.22445	757.6053543	0.636784673
5.56	2357.317715	1514.826463	842.4912514	0.642605981
5.83	2659.934658	1726.106156	933.8285024	0.648928029
6.11	2972.075259	1950.294264	1021.780995	0.656206218
6.39	3325.946844	2200.638397	1125.308447	0.661657717
6.67	3690.679838	2465.290567	1225.389271	0.667977358
6.94	3890.923301	2675.097727	1215.825574	0.687522606
7.22	4168.136314	2893.385701	1274.750612	0.694167725
7.50	4487.59742	3120.233988	1367.363432	0.695301672
7.78	4819.227311	3355.642588	1463.584723	0.696303032
8.06	5163.15442	3599.611501	1563.542919	0.697172931
8.33	5519.510444	3852.140726	1667.369718	0.697913477

Table 33 Expected results calculations (within margin)

Conclusion

When the outputs of the calculation chain do not deviate more than 30% of the measured values, we state that the simulation passes the test.

When the outputs of the calculation chain deviate more than this range, we state that the simulation failed the test.

7.4 V-model design phase (component)

7.4.1 Component description (motor)

Flowchart

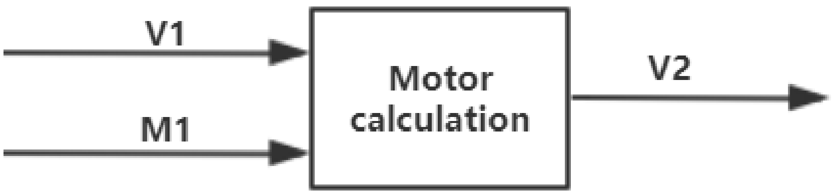


Figure 27 Flowchart motor

Unique identifiers

Unique ID	Long Name
V1	Input from user-interface sub-system
M1	Input from gearing component
V2	Output to user-interface sub-system

Table 34 Unique ID motor

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> V1				
Input from user-interface sub-system				
Boat speed	v_{boat}	0	8,5	m/s
Current-Torque coefficient	ct	0	1000	-
-> M1				
Feedback from gearing component				
Rotational speed required	$n_{Gearing-out}$	0	5000	rpm
Torque required	$T_{Gearing-out}$	0	2000	Nm
<- V2				
Output to user-interface sub-system				
Current required	I	0	250	A
Voltage required	U	0	72	V
Efficiency	η	0	100	%
Power loss	P_{Loss}	0	1000	W

Table 35 Table of limits motor

7.4.2 Component test plan (motor)

Aim & Hypothesis.

Aim

Establish a mathematical model for the relationship between the output and input of the motor

Hypothesis

The output power, torque, rotation speed can be calculated by the input velocity and digital twin can be made.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Ambient temperature	Standard indoor temperature with lower and upper limits (20 ℃ ± 5℃).
Battery level computer	Constant power source.
All input variables	Real positive numbers & ISO-notation.

Table 36 Variables motor

Inputs

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable. Due to the impact of the epidemic, we will use Plan B to simulate the system based on the data sheet.

General input	Value
Motor efficiency	0.84-0.88
Current torque relation coefficient:	0.18

Table 37 General input motor

Inputs for realistic calculation	Value
Boat velocity	[0,17] [Km/h]

Table 38 Inputs for realistic calculation motor

Inputs for theoretical calculation	Value
Feedback torque from gear	-
Feedback rotation speed from gear	-
Gearing power loss	-

Table 39 Inputs for theoretical calculation motor

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system. Due to the impact of the epidemic, we will use Plan B to simulate the system based on the data sheet.

Outputs from realistic calculation	Value
Motor power output	[0,8800] [w]
Motor torque output	[0,40] [Nm]
Motor rotation speed ouput	[0,2400] [rpm]
Motor power input	[0,8800] [w]

Table 40 Outputs for realistic calculation motor

Output from theoretical calculation	Value
Motor input voltage	-
Motor input current	-
Motor input power	

Table 41 Output from theoretical calculation motor

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper
Datasheet	Solar boat relevant data

Table 42 Tools motor

Methods

Realistic calculation

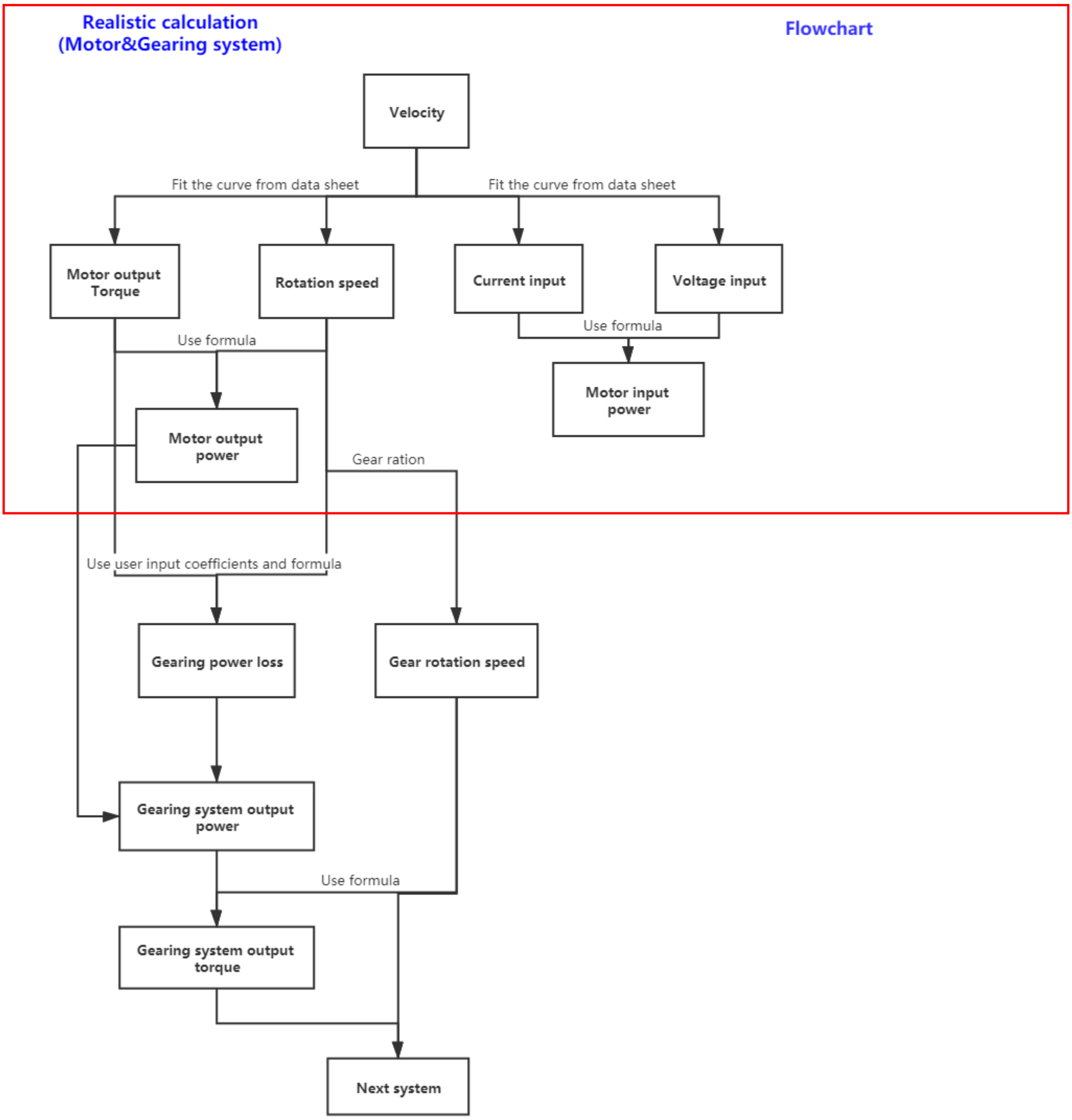


Figure 28 Realistic calculation motor

Theoretical calculation

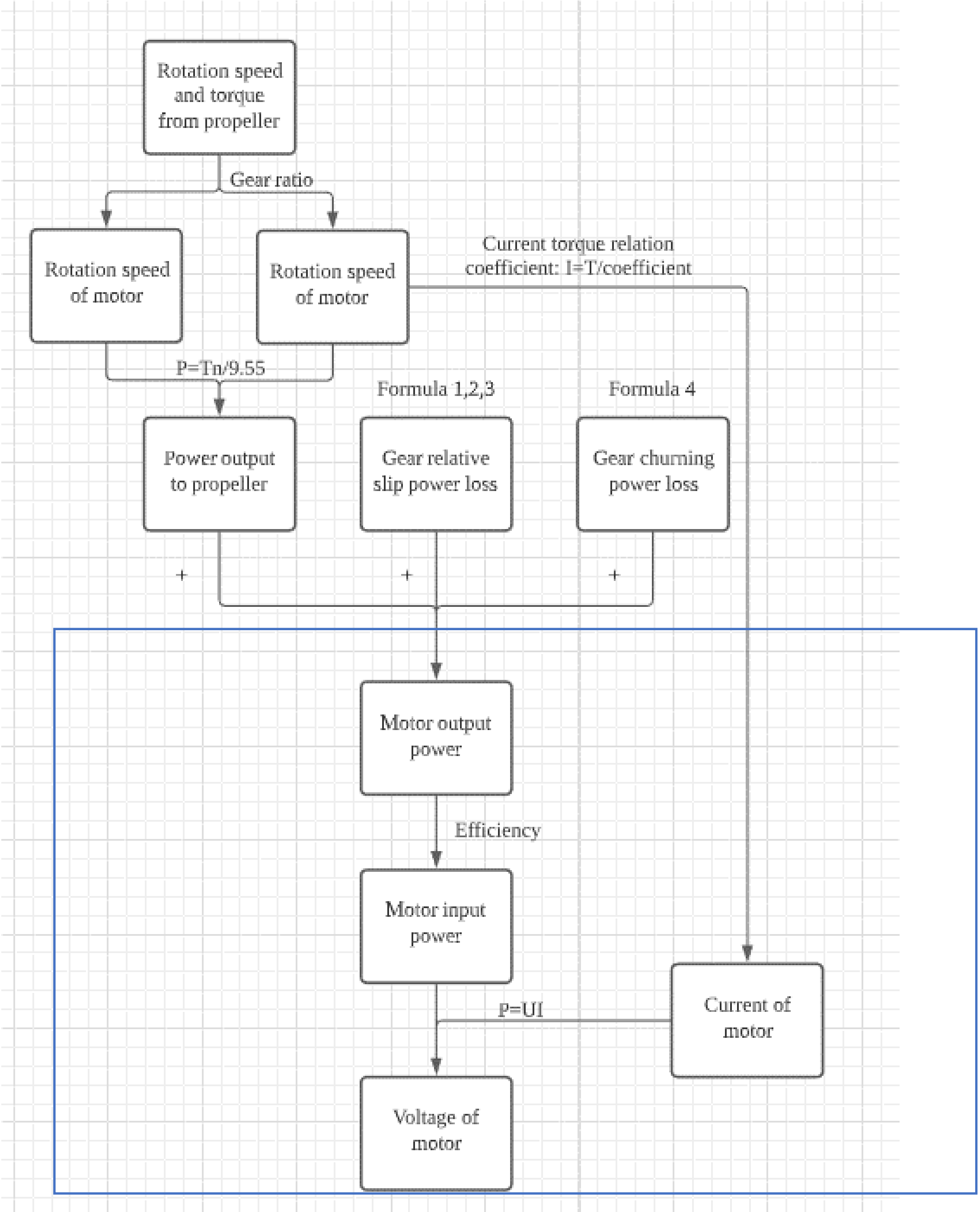


Figure 29 Theoretical calculation motor

When inputting the speed of the ship, compare the motor input and output voltage and current calculated by fitting the curve with the theoretically calculated motor input and output voltage and current. If the error is less than 30%, the digital twin is considered to be successfully established and the fitted curve is used in subsequent calculations.

Steps

- Enter target ship velocity in realistic calculation part.
- Obtain the motor output speed, torque, input voltage and current.
- Record these data and enter the theoretical calculation part.
- In the theoretical calculation section, enter the speed and torque fed back to the motor by the gear system at the corresponding ship speed.
- The approximate efficiency of the motor is automatically inferred from the realistic calculated input voltage.
- Get the input voltage and current of the motor.
- Verify the above calculations' results by paper and pen.
- Determine whether the experiment is successful or not by comparing the results of the data table, theoretical calculation, and theoretical calculation.

Expected results

After the user collects data and enters it into the calculation chain, user enters the motor's input voltage, the motor's output power, torque and speed can be calculated.

7.4.3 Component description (gearing)

Flowchart

Figure 30 Flowchart gearing

Unique identifiers

Unique ID	Long Name
V1	Input from user-interface sub-system
G1	Input from bearing component
V2	Output to user-interface sub-system
M1	Output to motor component

Table 43 Unique ID gearing

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> V1				
Data from user interface sub-system (input block)				
Gear friction coefficient	μ_{gear}	0,1	0,15	-
Gear transmission ratio	R_g	0,1	10	#
Gear index circle pressure angle	α	15	25	°
Gear index circle diameter of driving wheel	d	0	-	m
Gear addendum radius	d_1	0	-	m
Gear dedendum radius	d_2	0	-	m
Gear tooth number	z	0	-	-
Gear tooth width ratio	b	0	-	#
Gear modulus	m	0	-	-
Gear immersion depth ratio	h	0	-	#
Gear lubricant viscosity	μ	0	-	mm^2/s
Gear lubricant density	ρ	0	-	kg/m^3
-> G1				
Data from bearing component				
Rotational speed required	$n_{Bearing-out}$	0	2300	rpm
Torque required	$T_{Bearing-out}$	0	3500	Nm
<- V2				
Data to user interface sub-system (output block)				
Gear power loss	$P_{Gear-loss}$	0	1000	W
<- M1				
Data to motor component				
Rotational speed required	$n_{Gearing-out}$	0	5000	rpm
Torque required	$T_{Gearing-out}$	0	2000	Nm

Table 44 Table of limits gearing

7.4.4 Component test plan (gearing)

Aim & Hypothesis

Aim

The aim of this test is to establish a mathematical model of gear energy loss.

Hypothesis

Power, speed and torque after passing through the gear can be calculated by the input value.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Ambient temperature	Standard indoor temperature with lower and upper limits (20 °C ± 5°C).
Battery level computer	Constant power source.
All input variables	Real positive numbers & ISO-notation.

Table 45 Variables gearing

Inputs

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable.

General input	Value
Gear friction coefficient(a)	0.2
Gear transmission ratio	3
Gear index circle pressure angle(l)	30
Gear index circle diameter of driving wheel(d)	0.3
Gear addendum radius(e)	0.32
Gear dedendum radius(f)	0.28
Gear tooth number(z)	15
Gear tooth width ratio(b)	0.2
Gear modulus(m)	2
Gear immersion depth ratio(h)	0.4
Gear lubricant viscosity (u)	2
Gear lubricant density(p)	4

Table 46 General input gearing

Inputs for realistic calculation	Value
Motor power output	[0,8800] [w]
Motor torque output	[0,40] [Nm]
Motor rotation speed ouput	[0,2400] [rpm]

Table 47 Inputs for realistic calculation gearing

Inputs for theoretical calculation	Value
Feedback rotation speed from propeller	-
Feedback torque from propeller	-

Table 48 Inputs for theoretical calculation gearing

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system.

Outputs from realistic calculation	Value
Gearing power output	[0,8800] [w]
Gearing torque output	[0,40] [Nm]
Gearing rotation speed ouput	[0,2400] [rpm]
Outputs from theoretical calculation	**Value**
Feedback rotation speed to motor	-
Feedback torque to motor	-
Gearing power loss	-

Table 49 Outputs gearing

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper
Mathematical model	Consists of formulas

Table 50 Tools gearing

Methods

Realistic calculations

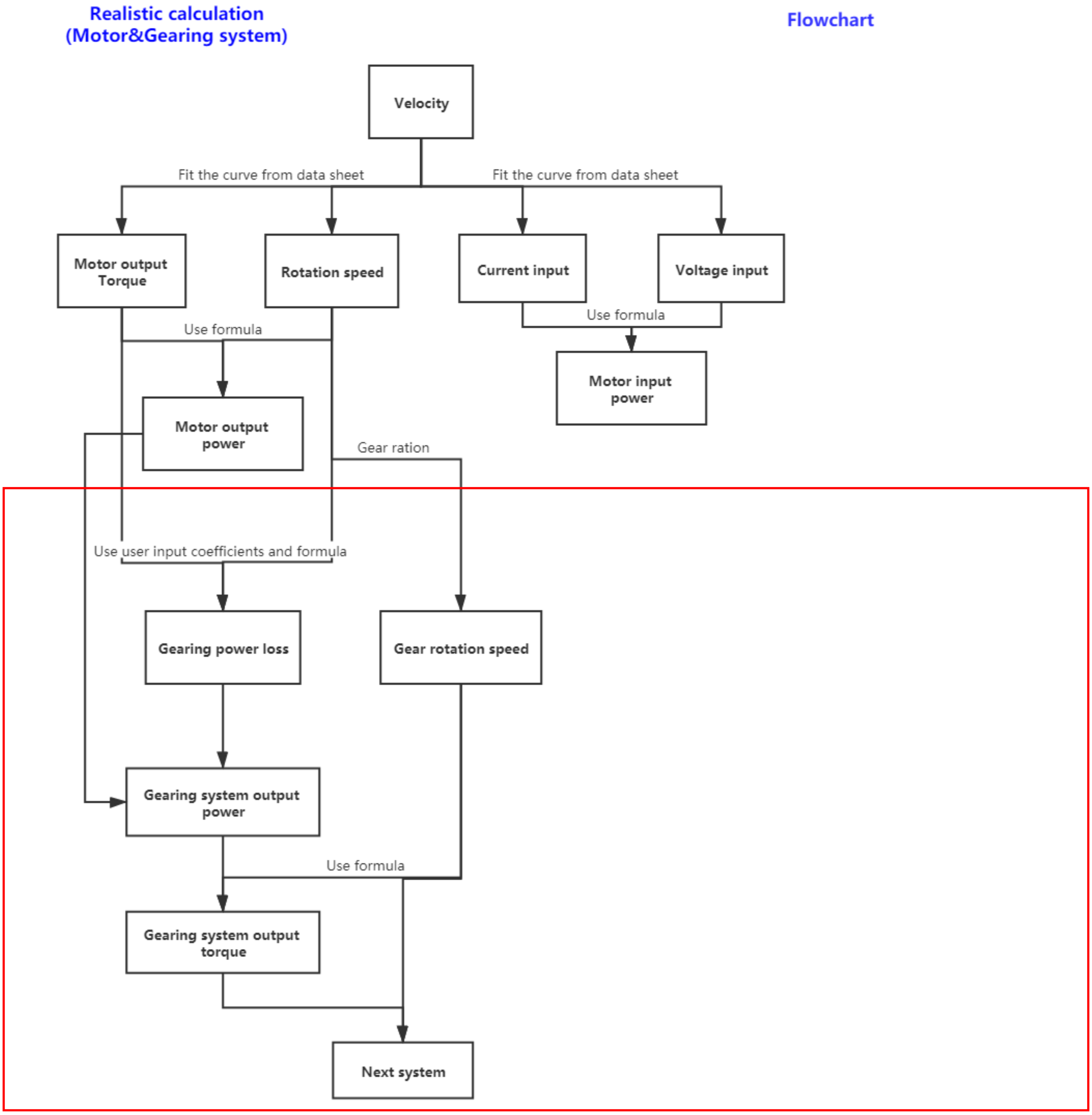


Table 51 Realistic calculation gearing

Theoretical calculation

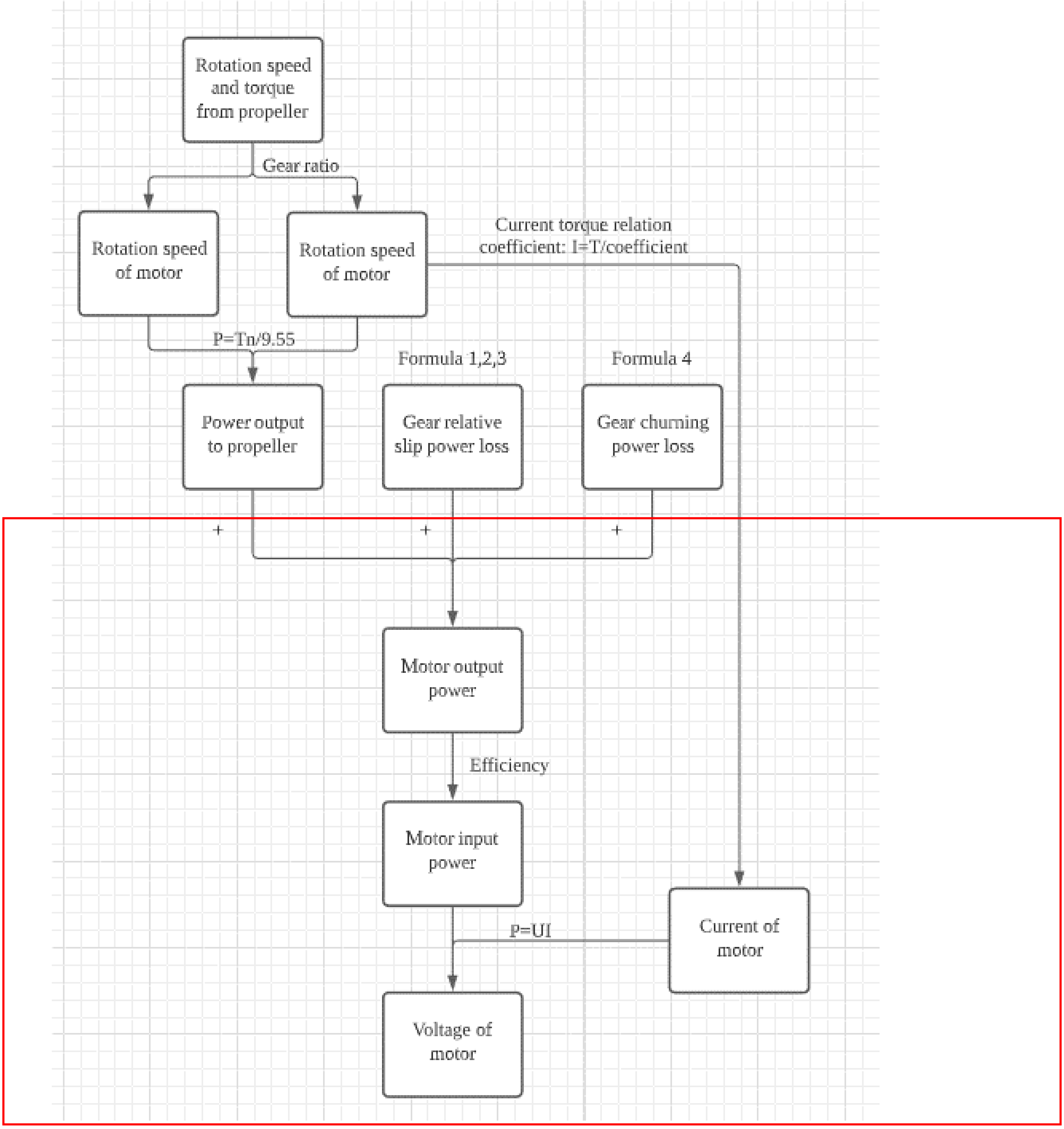


Table 52 Theoretical calculation gearing

When inputting the speed of the ship, compare the motor input and output voltage and current calculated by fitting the curve with the theoretically calculated motor input and output voltage and current. If the error is less than 30%, the digital twin is considered to be successfully established and the fitted curve is used in subsequent calculations. Since the process output value of the gear system is difficult to compare, the output value of the motor system is used as the comparison standard.

Steps

- Get the input torque and speed from the motor part.
- Calculate energy loss and rotation speed.
- Calculate output torque from energy loss and speed.
- Record the energy loss and the output speed and torque of the gear system.
- In the theoretical calculation part, input the torque and speed fed back from the propeller to the gear.
- Calculate the speed and speed of the gear feedback to the motor.
- Verify the above calculations' results by paper and pen.
- The success of the verification of the gear system determines the success or failure of the verification of the motor system. Since the gear system and the motor system are closely connected, the verification of the gear system and the motor system will be combined.

Expect result

When power, speed, and torque are transferred from the motor component system to the gear component system, the output power, speed, and torque of the gear system can be calculated according to the set parameters. The gear calculation system can use the data to correctly calculate the result.

Conclusion

If the outputs have the same values as their calculated counterparts, the test is considered as passed. If not, the test is considered as failed.

Appendix

The energy loss on the gear consists of the meshing between the gears and the gear churning loss. In the gear component, the loss of these two parts will be calculated.

Gear friction power loss

$$P_{VZP} = F_R \times V_{rel}$$

P_{VZP}= load gear losses (kW).

F_R=friction force (kN).

V_{rel}=relative velocity (m/s).

Friction force

$$F_R = F_n \times \mu_M$$

F_n=Normal force of tooth surface[N].

μ_M=Friction coefficient.

$$F_n = \frac{F_t}{cos\alpha}$$

$$F_t = \frac{2T}{d}$$

F_t=Gear circumferential force [N].

α=Index circle pressure angle, standard gear is 20°.

T=Torque [N*m].

d=Index circle diameter of driving wheel [m].

Relative velocity

The sliding speed is the relative speed of the common contact point between the paired gear teeth in the transverse plane. (Gear Rolling & Sliding velocity) The sliding speed can be approximated as

$$V_{rel} = \frac{(d_1 + d_2)}{2} \times \omega \times 2 \times cos\alpha$$

d_1=Addendum radius[m].

d_2=Deddendum radius[m].

ω= Angular velocity[rpm].

α=Index circle pressure angle, standard gear is 20°.

Gear churning loss

Because of lubricate, the gear will face resistance when it is rotating, resulting in energy loss.

$$P_{loss} = 1.177m^{0.0214} \times z^{0.0106} \times \rho d^5 \times (\frac{1}{Re})^{0.34}(\frac{1}{Fr})^{0.61}(\frac{h}{d})^{0.35}(\frac{b}{d})^{1.21}$$

$$Fr = \frac{\omega d}{g}$$

$$Re = \frac{\rho R^2 \omega}{\mu}$$

m=Modulus.

z=Number of teeth.

ρ=Lubricant density[kg/m^3].

d=Index circle diameter of driving wheel [m].

ω=Rotation speed[rpm].

g=9.8[N/m^2].

μ= Lubricant viscosity.

$\frac{h}{d}$= Gear immersion depth ratio [0.2~1].

$\frac{b}{R}$= Tooth width ratio[0.2~1].

Gear type

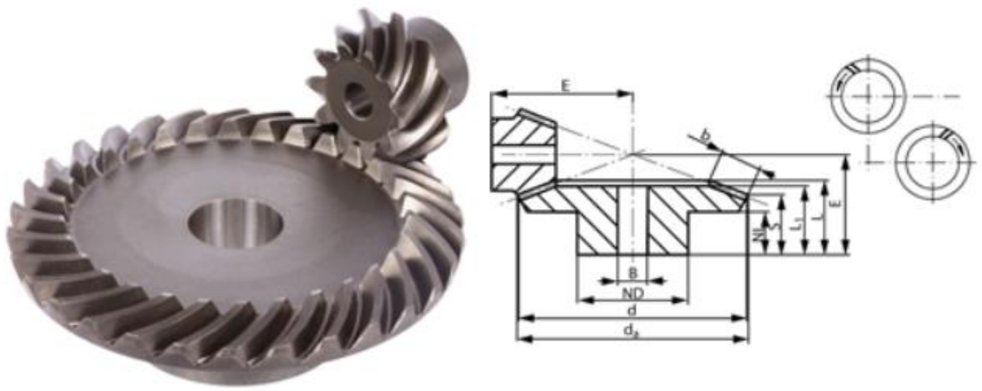


Figure 31 Gear type

Transmission [i]	3 : 1
Module	1,5
No. of Teeth	10 / 30
d_a [mm]	26/66,6
d [mm]	22/66
ND [mm]	17/40
NL [mm]	8/8
L_1 [mm]	19/17
L [mm]	20,1/21,3
S [mm]	9,6/17,8
b [mm]	11/11
B^{H7} [mm]	8/12
E [mm]	42/28
Admissible MD [Nm]	9,1/27,3
Weight/Pair [g]	380

Figure 32 Data gearing

7.4.5 Component description (bearing)

Flowchart

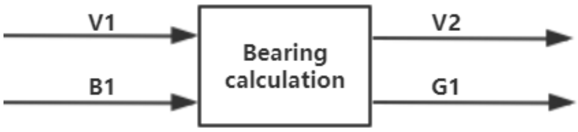


Figure 33 Flowchart bearing

Unique ID	Long Name
V1	Input from user-interface sub-system
B1	Input from propellor component
V2	Output to user-interface sub-system
G1	Output to gearing component

Table 53 Unique ID bearing

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> V1				
Input from user-interface sub-system				
Bearing friction coefficient	$\mu_{bearing}$	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing seal coefficient	μ_{seal}	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing load	F	0	1000	N
Bearing shaft radius	r_{shaft}	0	0,05	m
-> B1				
Input from propellor component				
Rotational speed required	$n_{Prop-out}$	0	2300	rpm
Torque required	$T_{prop-out}$	0	3500	Nm
<- V2				
Output to user-interface sub-system				
Power loss	$P_{Bearing-loss}$	0	100	W
<- G1				
Output to gearing component				
Rotational speed required	$n_{Bearing-out}$	0	2300	rpm
Torque required	$T_{Bearing-out}$	0	3500	Nm

Table 54 Table of limits bearing

Bearing Type (FRICTION & FREQUENCY FACTORS, sd)	Friction coefficient µ
Deep Groove Ball Bearing	0,0015
Angular Contact Bearing	0,0020
Cylindrical Roller Bearing, Cage	0,0010
Cylindrical Roller Bearing, Full Comp.	0,0020
Tapered Roller Bearing	0,0020
Spherical Roller Bearing	0,0020
Ball Thrust Bearing	0,0015
Cylindrical Roller Thrust Bearing	0,0050
Tapered Roller Thrust Brg. Cage	0,0020
Tapered Roller Thrust Brg. Full Comp	0,0050

Table 55 Friction coefficients bearing

7.4.6 Component test plan (bearing)

Aim & Hypothesis

Aim

The aim of this test is to verify the simulated mathematical model of the bearing calculations.

Hypothesis

The bearing simulation has the same desired output values, compared to the calculations.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Battery level computer	Constant power source.
All input variables	Real positive numbers & ISO-notation.

Table 56 Variables bearing

Inputs

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable.

Inputs	Value
Rotational speed [rpm]	0 - 2200
Bearing friction coefficient	0,0015 – 0,0050
Seal friction coefficient	0,0015 – 0,0050
Load [N]	0 – 1000
Radius shaft [m]	0 – 0,2

Table 57 Inputs bearing

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system.

Outputs	Value
Bearing power output [W]	0 - 8400
Bearing torque output [Nm]	0 - 3500
Power loss [W]	0 – 8400
Power loss [%]	0 – 100

Table 58 Outputs bearing

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper

Table 59 Tools bearing

Methods

The simulation will be compared to the actual calculations to see if they are the same.

Steps

1. Put the different values from 2.1 in the simulation
2. Note the outputs
3. Calculate the outputs based on the mathematical model (7.Appendix) using pen, paper and calculator
4. Note the answers.
5. Compare the two answers

Expected results

The expected outputs are according to the mathematical models and between the range stated in the table 2.2

Conclusion

If the outputs have the same values as their calculated counterparts, the test is considered as passed.

If not, the test is considered as failed.

Appendix

Friction force

$$F_{friction} = F_{load} * \mu$$

$F_{friction}$=loss due to friction [N]

F_{load}=load from axis on bearing [N]

μ=friction coefficient

Powerloss due to friction

$$\mathrm{P}_{out} = \mathrm{P}_{\mathrm{in}} - \left(\left(F_{friction} * \mathrm{r}_{\mathrm{shaft}}\right) * \omega\right)$$

P_{out}= output power [W].

P_{in}= input power [W].

$F_{friction}$=loss due to friction [N]

r_{shaft}=radius driving shaft [m]

ω=angular velocity [rad/s]

$$T = \frac{60}{2\pi} \times \frac{P}{n}$$

T=torque [Nm].

P=power [W].

n=rotation speed [rpm].

7.4.7 Component description (propeller)

Flowchart

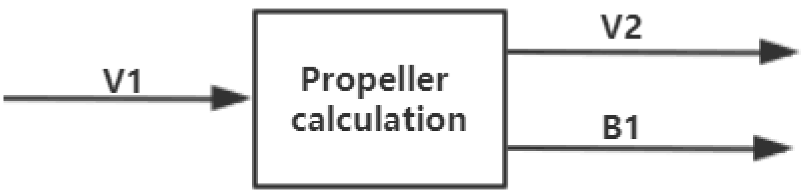


Figure 34 Flowchart propellor

Unique ID	Long Name
V1	Input from user-interface sub-system
V2	Output to user-interface sub-system
B1	Output to bearing component

Table 60 Unique ID propellor

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> V1				
Input from user-interface sub-system				
Boat speed	Vb	0	8,5	m/s
Propeller diameter	d_{prop}	0,1	0,5	m
Liquid density	ρ	980	1000	kg/m^3
Thrust deduction coefficient	t	0	1	-
Wake fraction coefficient	w	0	1	-
<- V2				
Output to user-interface sub-system				
Thrust	F_T	0	500	N
Rotational speed propeller	n_P	0	2300	rpm
Power output	P_{output}	0	5000	W
Power loss	P_{loss}	0	1000	W
<- B1				
Feedback to bearing component				
Rotational speed required	$n_{Prop-out}$	0	2300	rpm
Torque required	$T_{Prop-out}$	0	3500	Nm

Table 61 Table of limits propellor

7.4.8 Component test plan (propeller)

Aim & Hypothesis

Aim

The aim of this test is to verify the simulated mathematical model of the propellor calculations.

Hypothesis

The propellor simulation has the same output as the calculations.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Battery level computer	Constant power source.
All input variables	Real positive numbers & ISO-notation.

Table 62 Variables propellor

Inputs

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable.

Inputs	Value
Boat speed [m/s]	0 – 8,5
Propellor diameter [m]	0,1 - 0,5
Liquid density [kg/m^3]	980 - 1000
Thrust deduction coefficient	0 - 1
Wake fraction coefficient	0 - 1
Propellor properties: Rtotal at Vb	0 - 500
Propellor properties: η at Vb	0 – 100
Propellor properties: Kt at Vb	0 – 1
Propellor properties: Kq at Vb	0 – 1

Table 63 Inputs propellor

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system.

Outputs	Value
Thrust [N]	0 - 500
Rotational speed propeller [rpm]	0 - 2200
Torque required [Nm]	0 - 3500
Power output [W]	0 - 8400
Power loss [W]	0 - 8400

Table 64 Outputs propellor

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper
Mathematical model	Using correct formulas

Table 65 Tools propellor

Method

The simulation will be compared to the actual calculations to see if they are the same.

Steps

1. Put the different values from 2.1 in the simulation
2. Note the outputs
3. Calculate the outputs based on the mathematical model (7.Appendix) using pen, paper and calculator
4. Note the answers.
5. Compare the two answers.

Expected results

The expected outputs are according to the mathematical models and between the range stated in the table 2.2.

Conclusion

If the outputs have the same values as their calculated counterparts, the test is considered as passed. If not, the test is considered as failed.

Explanation

The experiment of propeller alone in uniform water flow is called open water experiment. The following formulas and coefficients can be applied in these circumstances.

Formulas

Force equilibrium (speed is constant)

$$Ft = Fr$$

Ft = thrust (N).
Fr = resistance (N).

Resistance force

$$Rtotal = (1 - t) * Fr$$

Rtotal = total boat resistance (N)
T = thrust deduction factor
Fr = resistance (N).
Interpolation formula

$$y - y1 = \frac{y2 - y1}{x2 - x1} * (x - x1)$$

(x, y) = coordinates of interpolation value

Thrust coefficient

$$K_T = \frac{Ft}{\rho \times n^2 \times d^4} \quad \rightarrow \quad Ft = \rho \times n^2 \times d^4 \times K_T$$

Ft = thrust (N).
ρ = liquid density (kg/m^3).
n = rotating speed (rev/s).
d = diameter (m).
K_T = thrust coefficient.

Torque coefficient

$$K_Q = \frac{Q_R}{\rho \times n^2 \times d^5} \quad \rightarrow \quad Q_R = \rho \times n^2 \times d^5 \times K_Q$$

$$Q_E = Q_R - Q_I$$

Q_E = torque difference(Nm).
Q_R = torque required (Nm).
Q_I = torque input (Nm).
ρ = liquid density (kg/m^3).
n = rotating speed (rev/s).
d = diameter (m).
K_Q = torque coefficient.

Power output

$$P = F \times v$$

P = output power (W)
F = force (N)
v = velocity(m/s).

Power input

$$P = T \times \omega$$

P = input power (W)
T = torque (Nm)
ω = radial velocity (rad/s).

Stream velocity

$$Va = (1 - w) \times Vb$$

Va = inflow stream velocity (m/s)
Vb = boat speed (m/s)
W = wake fraction

Propellor efficiency

$$\eta = (Ft * Va)/(n * Q)$$

Ft = thrust (N)
Va = inflow stream velocity (m/s)
N = radial velocity (rad/s)
Q_R = torque required (Nm).

Propulsive efficiency

$$\eta = (Rtotal * Vb)/(n * Q)$$

Rtotal = total boat resistance (N)
Vb = boat speed (m/s)
N = radial velocity (rad/s)
Q_R = torque required (Nm).

Required rpm

$$\left.\begin{array}{r} P = T * n * \dfrac{2\pi}{60} \\ T = Q_R = \rho \times (n/60)^2 \times d^5 \times K_Q \end{array}\right\} n = \left(\frac{P * 60^3}{\rho * d^5 * K_Q * 2\pi}\right)^{\frac{1}{3}}$$

P = input power (W)
n = radial velocity (rpm)
T = Q_R = torque required (Nm).
ρ = liquid density (kg/m^3).
d = diameter (m).
K_Q = torque coefficient.

7.4.9 Component description (input block)

Flowchart

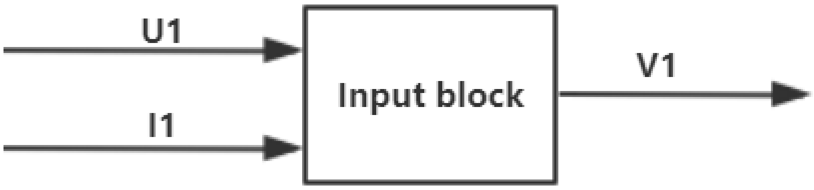


Figure 35 Flowchart input block

Unique ID	Long Name
U1	User input
I1	Simulation input state signal
V1	User-interface sub-system output (input block output)

Table 66 Unique ID input block

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> U1				
Data from normal users				
Limit input				
Boat speed	v_{boat}	0	8,5	m/s
Data from administrators				
Properties input (used to set up calculation)				
Motor current-torque coefficient	ct	0	100	-
Bearing friction coefficient	$\mu_{bearing}$	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing seal coefficient	μ_{seal}	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing load	F	0	1000	N
Bearing shaft radius	r_{shaft}	0	0,05	m
Gear friction coefficient	μ_{gear}	0,1	0,15	-
Gear transmission ratio	R_g	0,1	10	#
Gear index circle pressure angle	α	15	25	°
Gear index circle diameter of driving wheel	d	0	-	m
Gear addendum radius	d_1	0	-	m
Gear dedendum radius	d_2	0	-	m
Gear tooth number	z	0	-	-
Gear tooth width ratio	b	0	-	#
Gear modulus	m	0	-	-
Gear immersion depth ratio	h	0	-	#
Gear lubricant viscosity	μ	0	-	mm^2/s
Gear lubricant density	ρ	0	-	kg/m^3
Propellor diameter	d_{prop}	0,1	0,5	m
Propellor thrust deduction coefficient	t	0	1	-
Propellor wake fraction coefficient	w	0	1	-
Propellor liquid density (water)	ρ	980	1000	Kg/m^3

-> I1				
Simulation input state signal	-	0 (false)	1(true)	-
<- V1				
Data to different calculation components				
Limit output				
Boat speed	v_{boat}	0	8,5	m/s
Properities output (used to set up calculation) to motor calculation				
Motor current-torque coefficient	ct	0	100	-
Properities output (used to set up calculation) to bearing calculation				
Bearing friction coefficient	$\mu_{bearing}$	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing seal coefficient	μ_{seal}	$1{,}5 * 10^{-3}$	$5 * 10^{-3}$	-
Bearing load	F	0	1000	N
Bearing shaft radius	r_{shaft}	0	0,05	m
Properities output (used to set up calculation) to gearing calculation				
Gear friction coefficient	μ_{gear}	0,1	0,15	-
Gear transmission ratio	R_g	0,1	10	#
Gear index circle pressure angle	α	15	25	°
Gear index circle diameter of driving wheel	d	0	-	m
Gear addendum radius	d_1	0	-	m
Gear dedendum radius	d_2	0	-	m
Gear tooth number	z	0	-	-
Gear tooth width ratio	b	0	-	#
Gear modulus	m	0	-	-
Gear immersion depth ratio	h	0	-	#
Gear lubricant viscosity	μ	0	-	mm^2/s
Gear lubricant density	ρ	0	-	kg/m^3
Properities output (used to set up calculation) to propeller calculation				
Propellor diameter	d_{prop}	0,1	0,5	m
Propellor thrust deduction coefficient	t	0	1	-
Propellor wake fraction coefficient	w	0	1	-
Propellor liquid density (water)	ρ	980	1000	Kg/m^3

Table 67 Table of limits input block

7.4.10 Component test plan (input block)

Aim & Hypothesis

Aim

The aim is to verify that the data can be transmitted from the user to the calculation.

Hypothesis

The user input is transmitted to the calculation.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Battery level computer	Constant power source.
All input variables	Real positive numbers & ISO-notation.

Table 68 Variables input block

Inputs

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable.

Inputs	Value
Value 1 (input variables)	1-10
…	-
Value 2 (constant coefficient)	1-10
…	-

Table 69 Inputs input block

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system.

Outputs	Value
Output value 1	1-100
…	-

Table 70 Outputs input block

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper

Table 71 Tools input block

Methods

This section consists of actions that need to be performed during the test to conclude a result. The conditions of the constants stated in chapter "2. Variables" have to be met before executing the simulation. To execute the simulation, follow the steps stated in "4.1. Steps".

This part is a general test method which should be test several times to make sure when input block is connected to all different formulas which will be used in calculation component, the data can be transmitted from input block successfully.

In this general test method part, the formula P =U*I is used to give an example. We set **U (value 1)** as an input variable and **I (value 2)** is a constant which can be seen as a coefficient. **P** is the **output value 1**. According to different formulas, there can be several input variables, coefficients, and outputs.

Steps

1. Create a new form in Excel.
2. Take the grid A2 as the input block of **U**. Take the grid B2 as the input block of **I**.
3. Take the grid AC2 as the indicator of calculation result. And add a formula to C2: = B2 * A2.

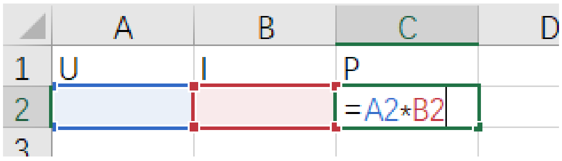


Figure 36 Formula input block

4. Choose a numeric value of **I** and input this value to B2
5. Choose several numeric values of **U** and input values to A1 and record results from C2.
6. Calculate several results according to different values of **U** on paper.
7. Compare the results from paper calculation and C2.
8. Input a non-numeric value to A2 and record the result from C2

Expected results.

When numeric values of A2 is input, the values of C2 should be equal to results from paper calculation.

When a non-numeric value of A2 is input, text '#VALUE' (specify text of Excel which means the calculation result is not a numeric value) should be shown in C2.

Conclusion

When numeric values of A2 is input, if the values of C2 are not equal to results from paper calculation or text '#VALUE' appears in C2, the test is failed.

When a non-numeric value of A2 is input, a numeric value appears in C2, the test is failed.

If other all conditions which meet the expect results appear, the tests are successful.

7.4.11 Component description (Output block)

Flowchart

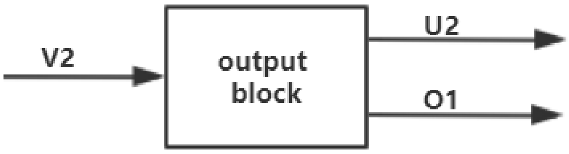


Figure 37 Flowchart output block

Unique ID	Long Name
V2	Calculation sub-system output
U2	Simulation output
O1	Simulation state signal

Table 72 Unique ID output block

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> V2				
Data from calculation sub-system				
Limit input				
Thrust	F_T	0	500	N
Boat velocity	V	0	30	Km/h
Rotational speed propeller	n_P	0	2300	rpm
Power input	P_{input}	0	6000	W
Power output	P_{output}	0	4100	W
Power loss	P_{loss}	0	810	W
Current required	I	0	250	A
Voltage required	U	0	72	V
Efficiency	η	0	100	%
<- U2				
Data to normal users and administrators				
Limit output				
Thrust	F_T	0	500	N
Boat velocity	V	0	30	Km/h
Rotational speed propeller	n_P	0	2300	rpm
Power input	P_{input}	0	6000	W
Power output	P_{output}	0	4100	W
Power loss	P_{loss}	0	810	W
Current required	I	0	250	A
Voltage required	U	0	72	V
Efficiency	η	0	100	%
<- O1				
Simulation state signal	-	0 (false)	1 (true)	-

Table 73 Table of limits output block

7.4.12 Components test plan (Output block)

Aim & Hypothesis

Aim

The aim is to verify the outputs from the calculations components can be shown correctly by the output block.

Hypothesis

The results shown by the output block are same as calculation results.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Battery level computer	Constant power source.
All input variables	Real positive numbers & ISO-notation.

Table 74 Variables output block

Inputs

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable.

Inputs	Value
Value 1 (input power)	Random positive numeric numbers
Value 2 (efficiency)	Random positive numeric numbers between 0 and 1

Table 75 Inputs output block

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system.

Outputs	Value
Output value 1 (output power)	Random positive numeric numbers
Output value 2 (power loss)	

Table 76 Outputs output block

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper

Table 77 Tools output block

Methods

This section consists of actions that need to be performed during the test to conclude a result. The conditions of the constants stated in chapter "2. Variables" have to be met before executing the simulation. To execute the simulation, follow the steps stated in "4.1. Steps".

In this test, the output value will be shown with a pie chart which consists of output power and power loss.

Steps

1. Create a new form in Excel.
2. Take the grid A2 as the input block of **value 1 (input power)**. Take the grid B2 as the input **value 2 (efficiency).**
3. Take the grid C2 as the indicator of **output value 1 (output power)**. Take the grid D2 as the indicator of **output value 2 (power loss)**. And add a formula to C2: = A2 * B2. Add a formula to D2: =A2 * (1 – B2).

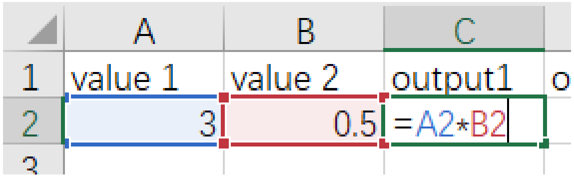


Figure 38 Formula 1 output block

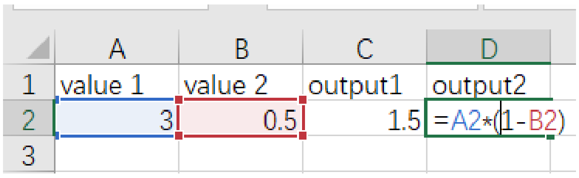


Figure 39 Formula 2 output block

4. Choose a numeric value of **value 1 (input power)** and input this value to A2
5. Choose a numeric value between 0 and 1 of **value 2 (efficiency)** and input this value to B2
6. Calculate **output value 1 (output power)** and **output value 2 (power loss)** on paper.
7. Use the data from C2 and D2 to create a pie chart.

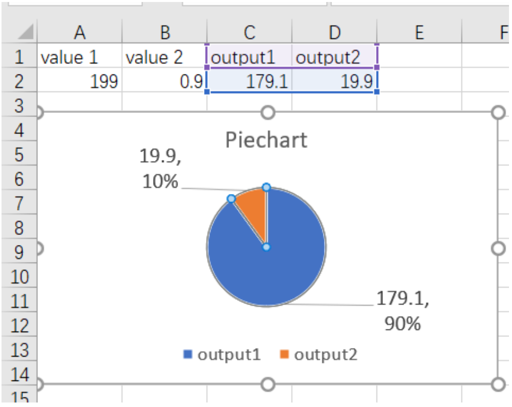


Figure 40 Piechart output block]

8. Compare the results from paper calculation and C2, D2 and pie chart.

Expected results.

The values of C2 and D2 are equal to results of paper calculation.

The ratio between C2 and D2 is equal to the value of efficiency.

The ratio of areas of **output value 1 (output power)** and **output value 2 (power loss)** in the pie chart is equal to the value of effiency.

The values of **output value 1 (output power)** and **output value 2 (power loss)** shown in pie chart are equal to values from C2 and D2.

Conclusion

If every condition in '5. Expect result' is met, the test is successful.

If one of the conditions in'5. Expect result' can't be met, the test is failed.

7.4.13 Component description (Warning and prompts)

Flowchart

Figure 41 Flowcharts prompts

Unique ID	Long Name
U2	Simulation output
I1	Simulation input state signal
O1	Simulation state signal

Table 78 Unique ID prompts

Table of limits

Interaction	Symbol	Min.	Max.	Unit
-> U2				
Data to normal users and administrators				
Limit output				
Prompts for successful simulation	-	Successful simulation		-
Warnings for unsuccessful simulation	-	Simulation failed		-
Prompts for how to optimize unsuccessful simulation	-	Input error. Insert numeric values		-
-> I1				
Simulation input state signal	-	0	1	-
-> O1				
Simulation state signal	-	0	1	-

Table 79 Table of limits prompts

7.4.14 Component test plan (Warning and prompts)

Aim & Hypothesis

Aim

Verify the warnings and prompts component can clearly inform users the state of the simulation.

Hypothesis

Warnings and prompts appear on the right time when simulations are failed or successful.

Variables

These are the constants and variables that will be used during the test.

Constants simulation	Keep constant at...
Battery level computer	Constant power source.
All input variables	Real positive numbers & ISO-notation.

Table 80 Variables prompts

Inputs

The limits stated are the limits of the real world. If values out of this range are entered, the outputs will be unreliable.

Inputs	Value
Input value [U]	Random numbers, letters, and signals
Simulation input state signal	True or False

Table 81 Inputs prompts

Outputs

These are the outputs that will be monitored and will be used to see variations or changes in the system.

Outputs	Value
Prompts for successful simulation	Successful simulation
Warnings for unsuccessful simulation	Simulation failed
Prompts for how to optimize unsuccessful simulation	Input error. Please insert numeric values.

Table 82 Outputs prompts

Tools

Testing tools	Demand
Computer	Windows 10 compatible
Excel	Newest version
Keyboard	No limit
Mouse	No limit
Calculator	Basic calculator
Pen & Paper	Basic pen & paper

Table 83 Tools prompts

Methods

This section consists of actions that need to be performed during the test to conclude a result. The conditions of the constants stated in chapter “2. Variables” have to be met before executing the simulation. To execute the simulation, follow the steps stated in “4.1. Steps”.

In this test, a simulation in Excel with the same structure as the following graph is needed.

Input value [U]	Simulation input state signal	Coefficient [I]		Output value [P]	Simulation state signal
0	TRUE	99		0	TRUE

Figure 42 Structure prompts

Input value [U] is the value we need to change. Coefficient [I] is a constant which will be set before test. Output value [P] is equal to ‘input value * coefficient [I]’. The simulation input state signal shows the state of input value [U]. If input value [U] is a numeric number, simulation input state signal is True, otherwise it will be False. The simulation state signal shows the state of output value [P]. If output value [p] is a numeric number, simulation state signal is True, otherwise it will be False.

Steps

1. Create a new form in Excel.
2. Take the grid A2 as the input block of **Input value [U]**. Take the grid B2 as the indicator of **simulation input state signal.**
3. Take the grid C2 as the indicator of **coefficient [I]**. Take the grid E2 as the indicator of **output value [p]**. Take the grid F2 as the indicator of **simulation state signal**. And add a formula to E3: = A2 * C2.
4. Add the function ‘Isnumber()’ to grid B2 and monitor the value of A2. Add the function ‘Isnumber()’ to grid F2 and monitor the value of e2.
5. Input all the codes in following graph in ‘Developer >> Visual Basic >> Sheet1 (Sheet1)’.

```
Dim OldValue

Private Sub Worksheet_Change(ByVal Target As Range)
    If Range("F2") = True Then
        If Range("E2").Value <> OldValue Then
            MsgBox "Simulate successfully"
        End If
    End If

    If Range("b2").Value = False Then
        MsgBox "Input error. Simulate unsuccessfully. Please input a numerric number"
    End If
End Sub

Private Sub Worksheet_SelectionChange(ByVal Target As Range)
    OldValue = Range("E2").Value
    If Range("b2").Value = False Then
        OldValue = 0
    End If
End Sub
```

Figure 43 Code prompts

6. Set the value of coefficient with a random numeric number.
7. Choose a numeric value for **input value [U]** and input this value to A2
8. Record the results from B2 and F2. Also record the messages from the message boxes.
9. Choose a non-numeric value for **input value [U]** and input this value to A2
10. Record the results from B2 and F2. Also record the messages from the message boxes.

Expected results.

When a numeric value is input in A2. The values of B2 and F2 are both True and message box should be same as the following picture:

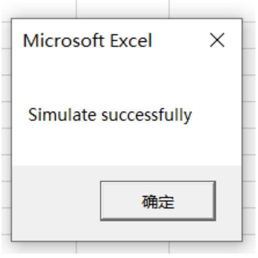


Figure 44 Successful simulation

When a non-numeric value is input in A2. The values of B2 and F2 are both False and message box should be same as the following picture:

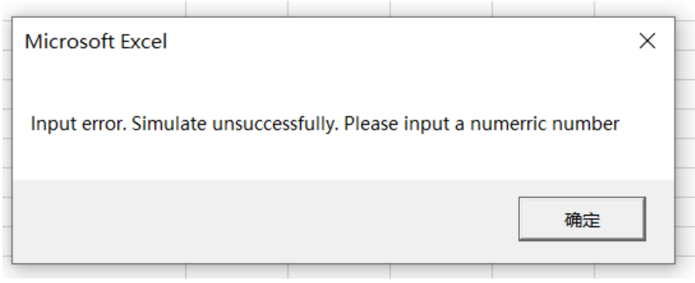


Figure 45 Unsuccessful simulation

Conclusion

When a numeric value is input in A2, there is no prompts of successful simulation, and when a non-numeric value is input in A2, there is no warning, the test are failed.

Otherwise, the tests are successful.

7.5 V-model integration phase (component)

7.5.1 Component integration (motor)

Build up

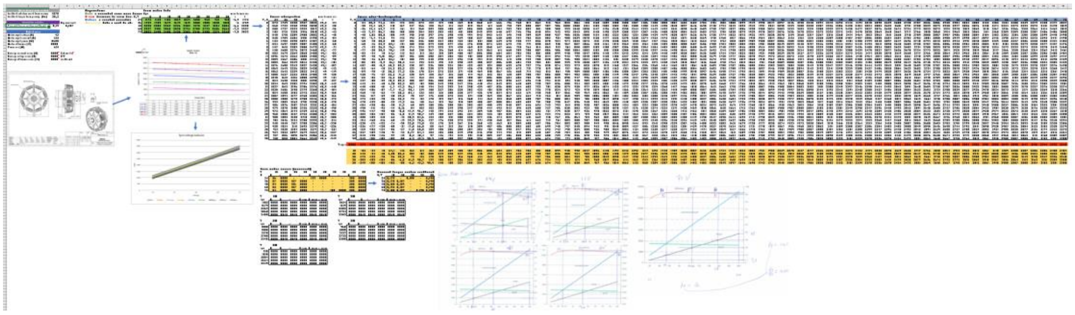


Figure 46 Buildup motor

Log test data

Performed steps

1. Open up simulation.
2. Insert variables.
3. Calculate with the same variables.
4. Compare results.

Results

This is the result with the simulation:

In realistic calculation when the input boat velocity is 10km/h.

Input value(motor system)		Output values(input values for gearing system)	
Velocity (km/h)	10	Motor output Torque (Nm)	2.39436
		Rotation speed (Rpm)	1420.36298
		Motor output power (w)	356.1110267
		Voltage input (V)	32.569723
		Current input (A)	13.3173
		Motor Input power (w)	433.7407721

Figure 47 Realistic result motor

In theoretical calculation:

Motor efficiency:	0.86				
Current torque relation coefficient:	0.18				
Gear ratio	3				
Feedback value from gearing to motor	Rotation speed [rpm]	Torque [Nm]	Motor input:	Voltage [V]	Current [A]
	1430.7	2.3		31.35589918	14.07940809
Total power loss	35.10				
Motor output power [W]:	379.6663506		Motor input power [W]:	441.4725007	

Figure 48 Theoretical result motor

This is the result of the calculations:

$$P_{in} = \frac{P_{out}}{\eta}$$

$$T \propto I$$

$$P = UI = \frac{TN}{9.55}$$

Conclusion

In conclusion, the outputs from the realistic calculation match the outputs from the theoretical calculation and data sheet. Therefore, the hypothesis:

"the motor simulation has the same output as the calculations"

is correct and the simulation works as intended.

7.5.2 Component integration (gearing)

Build up

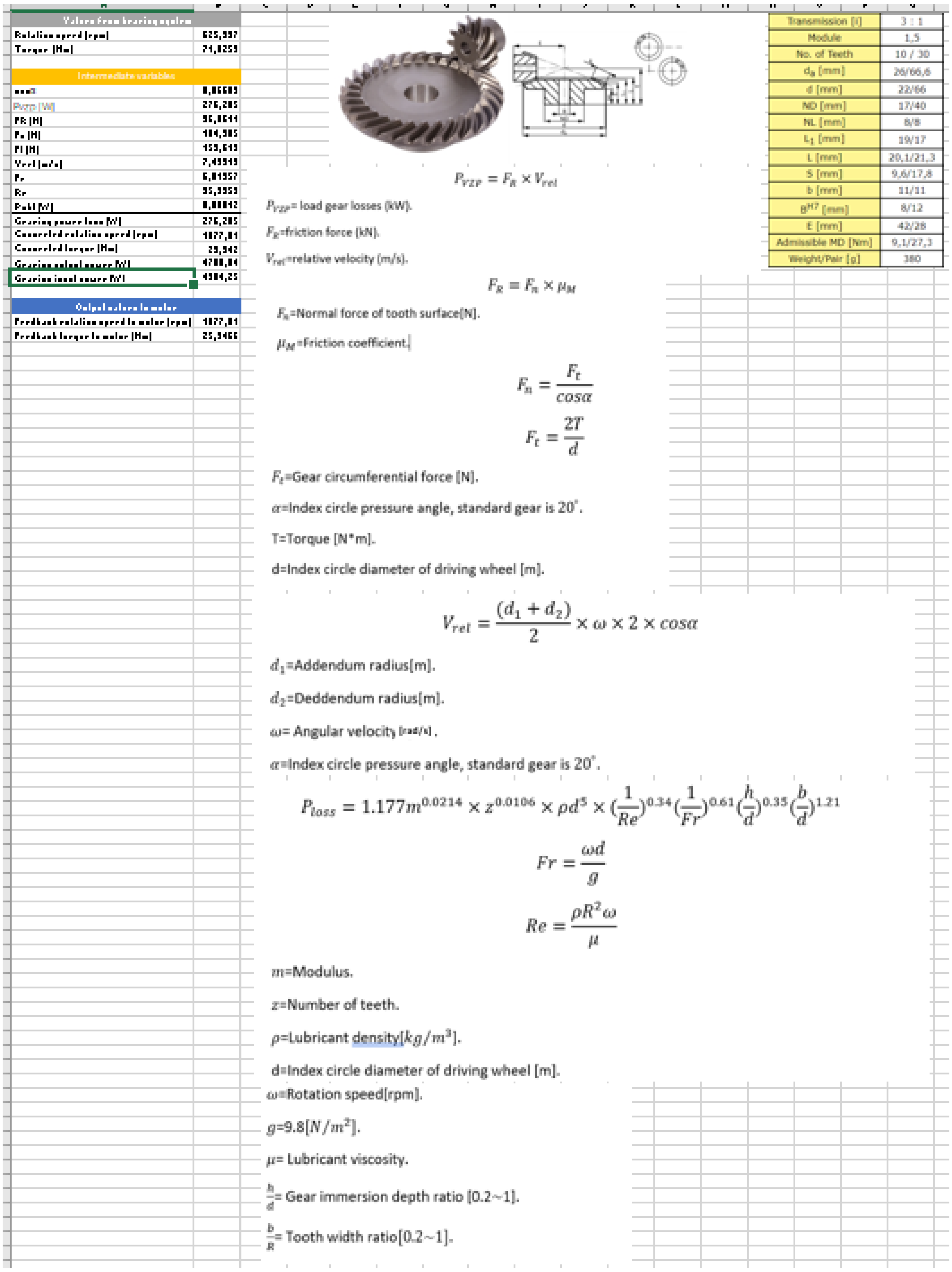


Figure 49 Buildup gearing

Log test data

Performed steps

1. Open up simulation.
2. Insert variables.
3. Calculate with the same variables.
4. Compare results.

Results

This is the result with the simulation:

In realistic calculation when the input boat velocity is 10km/h.

Input value(motor system)		Output values(input values for gearing system)		User values(gearing system)		Gearing system output value	
Velocity (km/h)	10	Motor output Torque (Nm)	2.39436	Gear friction coefficient(-)	0.2	Gearing power loss (W)	14.94014665
		Rotation speed (Rpm)	1420.36298	Gear transmission ratio (-)	3	Rotation speed (Rpm)	473.4543267
		Motor output power (w)	356.1110267	Gear index circle pressure angle(deg)	20	Torque (Nm)	6.881723792
		Voltage input (V)	32.569723	Gear index circle diameter of driving wheel(m)	0.3		
		Current input (A)	13.3173	Gear addendum radius (m)	0.26		
		Motor Input power (w)	433.7407721	Gear dedendum radius (m)	0.22		
				Gear tooth number(-)	10		
				Gear tooth width ratio(-)	0.2		
				Gear modulus(-)	1.5		
				Gear immersion depth ratio(-)	0.4		
				Gear lubricant viscosity (-)	2		
				Gear lubricant density(-)	4		

Figure 50 Realistic result gearing

In theoretical calculation:

Theoretical calculation			Motor efficiency	0.86	
			Current torque relation coefficient:	0.18	
			Gear ratio	3	
Feedback value from propeller to gearing	Rotation speed [rpm]	Turque [Nm]	Feedback value from gearing to motor	Rotation speed [rpm]	Torque [Nm]
	476.9	6.9		1430.7	2.3
			Total power loss	35.10	
			Motor output power [W]:	379.6663506	

Figure 51 Theoratical result gearing

This is the result of the calculations:

$$P_{loss} = P_{VZP} + P_{churning}$$

$$= F_R * V_{rel} + 1.177m^{0.0214} \times z^{0.0106} \times \rho d^5 \times (\frac{1}{Re})^{0.34} (\frac{1}{Fr})^{0.61} (\frac{h}{d})^{0.35} (\frac{b}{d})^{1.21}$$

$$= \frac{\frac{2T}{d}}{cos\alpha} \times \mu \times \frac{(d_1+d_2)}{2} \times \omega \times 2 \times cos\alpha + 1.177m^{0.0214} \times z^{0.0106} \times \rho d^5 \times \left(\frac{1}{Re}\right)^{0.34} \left(\frac{1}{Fr}\right)^{0.61} \left(\frac{h}{d}\right)^{0.35} \left(\frac{b}{d}\right)^{1.21}$$

$$= 14.94(w)$$

$$N = \frac{N_{motor}}{r} = 473.45(rpm)$$

$$T = 9.55 \times \frac{P_{in} - P_{loss}}{N} = 6.88(Nm)$$

Conclusion

In conclusion, the outputs from the realistic calculation match the outputs from the theoretical calculation and data sheet. Therefore, the hypothesis:

"the gearing simulation has the same output as the calculations"

is correct and the simulation works as intended.

7.5.3 Component integration (bearing)

Build up

Values from propellor system	
Rotation speed [rpm]	405,9443
Torque [Nm]	31,80407
Intermediate variables	
Bearing output power [W]	1352,003
P_loss [W]	0,191297
Bearing input power [W]	1352,194
P_loss [%]	6,88E-05
Output values to gearing	
Feedback rotation speed to gearing [rpm]	405,9443
Feedback torque to gearing [Nm]	31,80857

Figure 52 Buildup bearing

Log test data

Performed steps

1. Open up simulation.
2. Insert variables.
3. Calculate with the same variables.
4. Compare results.

Results

This is the result with the simulation:

Bearing and seal calculation							
Values from system		Properties		User values		Output values	
P_gear-out [W]	5000	Load [N]	100	Bearing f coefficient	0,0015	P_loss [W]	0,45
T_gear-out [Nm]	50	r_shaft [m]	0,015	Sealing f coefficient	0,0015	P_loss [%]	0,0090%
n_gear-out [rpm]						P_bearing-out [W]	4999,55
n_gear-out [rad/s]	100					T_bearing-out [Nm]	49,9955

Figure 53 Result bearing

This is the result of the calculations:

$$F_{friction} = F_{load} * \mu = 100 * (0{,}0015 + 0{,}0015) = 0{,}3\ [N]$$

$$\mathrm{P_{out}} = \mathrm{P_{in}} - \left((\mathrm{F_{friction}} * \mathrm{r_{shaft}}) * \omega\right) = 5000 - \left((0{,}3 * 0{,}015) * 100\right) = 4999{,}55\ [\mathrm{W}]$$

Conclusion

In conclusion, the outputs from the simulation match the outputs from the calculations. Therefore, the hypothesis*:*

"The bearing simulation has the same desired output values, compared to the calculations."

is correct and the simulation works as intended.

7.5.4 Component integration (propellor)

Build up

Values from front panel			
Boat speed (Vb) [m/s]	8,33		
Intermediate variables		Averag	Median
Propellor diameter [m]	0,48		
Propellor coefficient (Kt)	0,0852	0,094	0,0933
Propellor coefficient (Kq)	0,0262	0,0263	0,0276
Thrust deduction coefficient (t)	0,05		
wake fraction coefficient (w)	0,02		
Liquid density (ρ) [kg/m^3]	988		
Thrust [N]	486,39		
Water speed (Va) [m/s]	8,1634		
Power output [W]	4051,6		
Propellor efficiency	86,06%		
Power input [W]	4707,7		
Power loss [W]	656,1		
Propulsive efficiency	81,76%		
Output values to bearing			
Feedback rotation speed to bearing [rpn	625,94		
Feedback torque to bearing [Nm]	71,821		

Emperical data

Speed [km/h]	[m/s]	[kts]	Rtotal [N]	Fresistance [N]	Kt	10Kq	propeller efficiency [%]
-6	-1,67	-3,24	-56,73	-59,7187	-0,105	-0,269	65,16%
-5	-1,39	-2,70	-47,28	-49,7656	-0,106	-0,267	61,20%
-4	-1,11	-2,16	-37,82	-39,8125	-0,11	-0,264	57,99%
-3	-0,83	-1,62	-28,37	-29,8594	-0,115	-0,262	54,46%
-2	-0,56	-1,08	-18,91	-19,9062	-0,116	-0,257	45,88%
-1	-0,28	-0,54	-9,455	-9,95312	-0,122	-0,253	35,53%
0	0,00	0,00	0	0	0	0	0%
1	0,28	0,54	9,4555	9,953118	0,122	0,2535	35,53%
2	0,56	1,08	18,911	19,90624	0,1157	0,2566	45,88%
3	0,83	1,62	28,366	29,85935	0,1149	0,2617	54,46%
4	1,11	2,16	37,822	39,81247	0,1096	0,2644	57,99%
5	1,39	2,70	47,277	49,76559	0,106	0,2667	61,20%
6	1,67	3,24	56,733	59,71871	0,1046	0,269	65,16%
7	1,94	3,78	66,188	69,67183	0,1029	0,2711	68,09%
8	2,22	4,32	75,644	79,62494	0,1011	0,273	70,37%
9	2,50	4,86	85,099	89,57806	0,0996	0,2748	72,54%
10	2,78	5,40	94,555	99,53118	0,0976	0,2756	74,01%
11	3,06	5,94	104,01	109,4843	0,096	0,2763	75,48%
12	3,33	6,48	113,69	119,6737	0,0943	0,2762	76,66%
13	3,61	7,02	134,84	141,933	0,0945	0,2762	76,51%
14	3,89	7,56	155,97	164,1829	0,0944	0,2762	76,55%
15	4,17	8,10	174,32	183,4964	0,0939	0,2762	76,92%
16	4,44	8,64	192,68	202,8163	0,0933	0,2761	77,34%
17	4,72	9,18	211,71	222,8515	0,0928	0,276	77,75%
18	5,00	9,72	230,74	242,8866	0,0922	0,2759	78,19%
19	5,28	10,26	251,66	264,909	0,0918	0,2758	78,53%
20	5,56	10,80	272,67	287,0198	0,0917	0,276	79,24%
21	5,83	11,34	295,9	311,4778	0,0919	0,2764	80,02%
22	6,11	11,88	319,14	335,9359	0,0921	0,2767	80,92%
23	6,39	12,42	344,45	362,5766	0,0923	0,277	81,59%
24	6,67	12,96	369,79	389,2564	0,0925	0,2773	82,37%
25	6,94	13,50	385,21	405,4885	0,0933	0,2782	84,78%
26	7,22	14,04	400,62	421,708	0,0921	0,2758	85,60%
27	7,50	14,58	416,03	437,9276	0,0903	0,2722	85,74%
28	7,78	15,12	431,44	454,1471	0,0885	0,2687	85,87%
29	8,06	15,66	446,85	470,3667	0,0868	0,2653	85,97%
30	8,33	16,20	462,26	486,5862	0,0852	0,2621	86,06%
31	8,61	16,74	477,81	502,9571	0,0852	0,2648	86,48%
32	8,89	17,28	493,36	519,3274	0,0851	0,267	86,89%
33	9,17	17,82	508,91	535,6978	0,085	0,2691	87,31%
34	9,44	18,36	524,46	552,0681	0,0849	0,2713	87,72%
35	9,72	18,90	540,02	568,4384	0,0848	0,2734	88,14%
36	10,00	19,44	555,57	584,8087	0,0846	0,2756	88,55%

Figure 54 Buildup propellor

Log test data

Performed steps

1. Open up simulation.
2. Insert variables.
3. Calculate with the same variables.
4. Compare results.

Results

This is the result with the simulation:

Input				Output			
User variables				**User output**			
Boat speed	Vb [m/s]	3,33		Thrust	Ft [N]	119,5514215	
Propellor diameter	dprop [m]	0,48		Water speed	Va [m/s]	3,2634	
Propellor coefficient T	Kt	0,0943		Power output	P_output [W]	398,1062335	
Propellor coefficient Q	Kq	0,0276		Propellor efficiency	η_prop	0,766425903	
Thrust deduction coefficient	t	0,05		Power input	P_input [W]	519,4321228	target power
wake fraction coefficient	w	0,02					
				Feedback to bearing			
User properties				Speed required	n_prop [rpm]	295,1051743	
Liquid density	ρ [kg/m^3]	988		Torque required	T_req [Nm]	16,80828338	If motor can't provide, Vb can't be reached
Channel area (water stream)	A [m^2]	0,18096					
Input from bearing							
Rotation speed	n_Bearing_out [rpm]	300					
Torque	T_Bearing_out [Nm]	1					

Figure 55 Result propellor

This is the result of the calculations:

$$F_t = \rho * n^2[rps] * d^4 * K_T = 988 * \frac{295{,}63^2}{60} * 0{,}48^4 * 0{,}0943 = 119{,}6[N]$$

$$P = F * v = 119{,}6 * 3{,}33 = 398{,}3$$

Conclusion

In conclusion, the outputs from the simulation match the outputs from the calculations. Therefore, the hypothesis:

“the propellor simulation has the same output as the calculations”

is correct and the simulation works as intended.

7.5.5 Component integration (warnings and prompts)

Log test data

Performed steps

1. Open up simulation.
2. Insert variables.
3. Compare results with expected results from “test plan”.

Results

This is the result with the simulation when a numeric value is inserted:

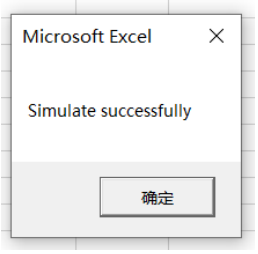


Figure 56 Result warning numeric

This is the result with the simulation when a non-numeric value is inserted:

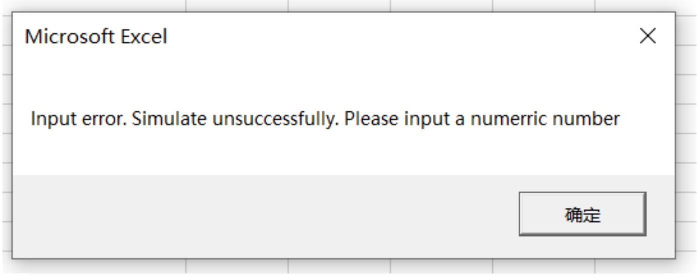


Figure 57 Result warning non-numeric

Conclusion

In conclusion, the outputs from the simulation match the outputs from the calculations. Therefore, the hypothesis:

“Warnings and prompts appear on the right time when simulations are failed or successful.”

is correct and the simulation works as intended.

7.5.6 Component integration (input block)

Log test data

Performed steps

1. Open up simulation.
2. Insert variables.
3. Compare results with expected results from "test plan".

Results

This is the formula. Block A1 is an input block. Block B1 is the output block. For the formula "=", they are both the same. Therefore the input and output blocks both work.

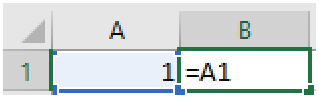


Figure 58 Result input block

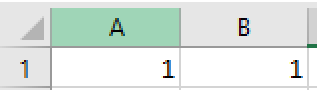


Figure 59 Result 2 input block

Conclusion

In conclusion, the outputs from the simulation match the outputs from the calculations. Therefore, the hypothesis:

"The user input is transmitted to the calculation."

is correct and the simulation works as intended.

7.5.7 Component integration (output block)

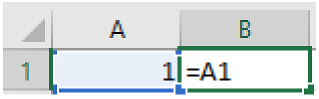
Log test data

Performed steps

1. Open up simulation.
2. Insert variables.
3. Compare results with expected results from “test plan”.

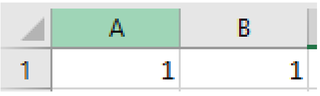
Results

This is the formula. Block A1 is an input block. Block B1 is the output block. For the formula “=”, they are both the same. Therefore the input and output blocks both work.



	A	B
1	1	=A1

Figure 60 Result output block



	A	B
1	1	1

Figure 61 Result 2 output block

Conclusion

In conclusion, the outputs from the simulation match the outputs from the calculations. Therefore, the hypothesis:

“The results shown by the output block are same as calculation results”

is correct and the simulation works as intended.

7.6 V-model integration phase (subsystem)

7.6.1 Subsystem integration (user interface)

Build up

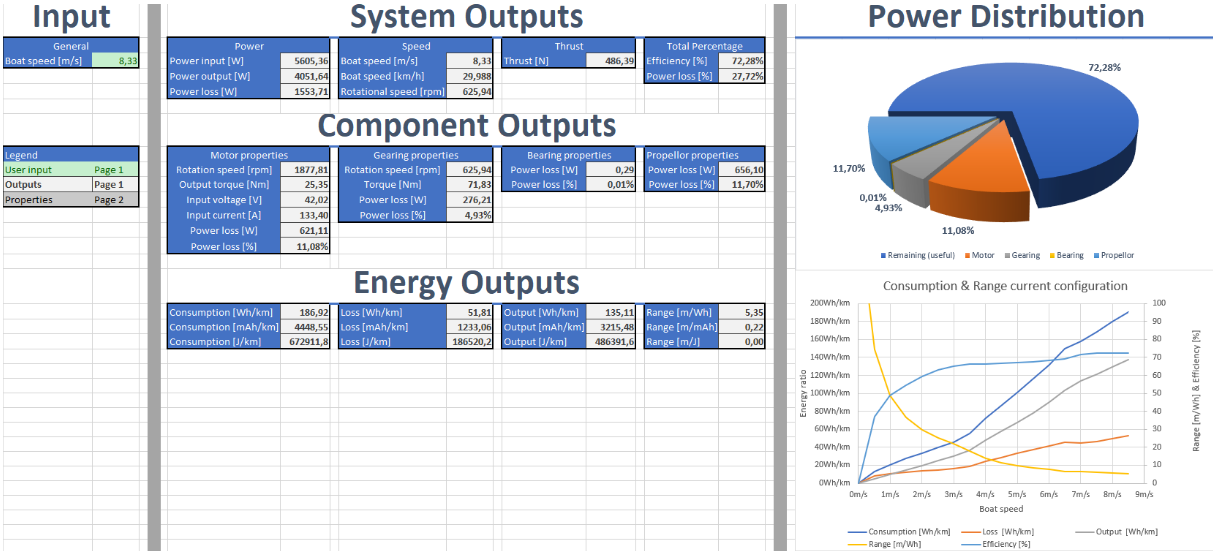


Figure 62 Buildup user interface

Gearing		Bearing		Propellor	
Gear friction coefficient(a)	0	Friction coefficient	0,0015	Propellor diameter [m]	0,48
Gear transmission ratio	1	Seal coefficient	1	Thrust coefficient (Kt)	0,0943
Gear index circle pressure angle(l)	1	Load [N]	100	Torque coefficient (Kq)	5
Gear index circle diameter of driving wheel(d)	1	r_shaft [m]	0,015	Thrust deduction coefficient (t)	2
Gear addendum radius(e)	0,32			Wake fraction coefficient (w)	0,02
Gear dedendum radius(f)	0,28			Liquid density [kg/m^3]	988
Gear tooth number(z)	15				
Gear tooth width ratio(b)	0,2				
Gear modulus(m)	1				
Gear immersion depth ratio(h)	1				
Gear lubricant viscosity (u)	2				
Gear lubricant density(p)	4				

Figure 63 Buildup properties

Input value [U]	Simulation input state signal	Coefficient [I]	Output value [P]	Simulation state signal
2	WAAR	99	198	WAAR
1	WAAR			
		#OVERLOOP!		

Figure 64 Buildup warnings and prompts

Log test data

Performed steps

1. Open the user-interface simulation.
2. Set all properties setting value with numeric numbers (without 0)
3. Input a numeric boat speed and record the message box.
4. Input a non-numeric value to boat speed and record the message box.
5. Change some of properties setting values into zero or non-numeric value and record the message box.
6. With the setting in step 5, input any value of boat speeds. Record the message box.

Results

This are the results with the simulation:

Properties setting value with numeric numbers:

Gearing		Bearing		Propellor	
Gear friction coefficient(a)	1	Friction coefficient	0.0015	Propellor diameter [m]	0.48
Gear transmission ratio	1	Seal coefficient	1	Thrust coefficient (Kt)	0.0943
Gear index circle pressure angle(l)	1	Load [N]	100	Torque coefficient (Kq)	5
Gear index circle diameter of driving wheel(d)	1	r_shaft [m]	0.015	Thrust deduction coefficient (t)	2
Gear addendum radius(e)	0.32			Wake fraction coefficient (w)	0.02
Gear dedendum radius(f)	0.28			Liquid density [kg/m^3]	988
Gear tooth number(z)	15				
Gear tooth width ratio(b)	0.2				
Gear modulus(m)	1				
Gear immersion depth ratio(h)	1				
Gear lubricant viscosity (u)	2				
Gear lubricant density(p)	4				

Figure 65 Results properties

Input a numeric boat speed:

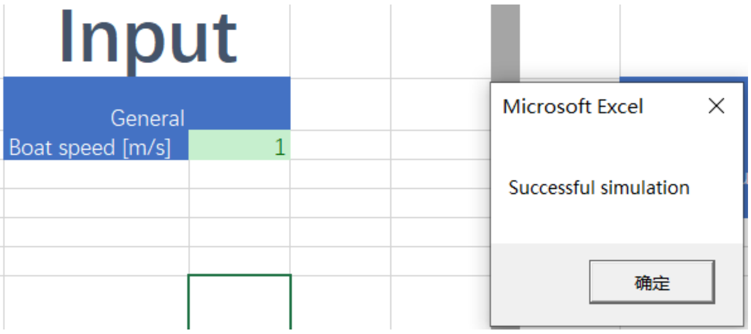


Figure 66 Results numeric boat speed

Input a non-numeric value to boat speed:

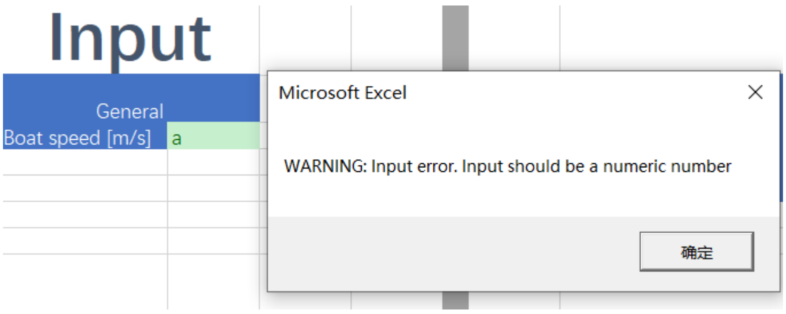


Figure 67 Result non-numeric boat speed

Change some of properties setting values into zero or non-numeric values:

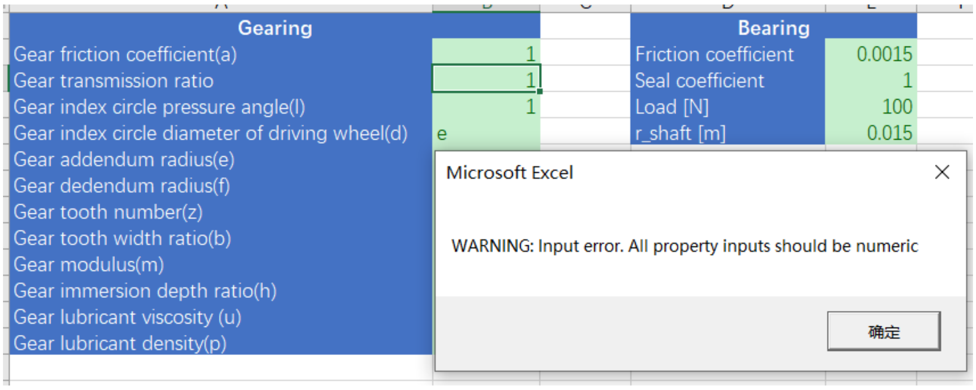


Figure 68 Result properties non-numeric

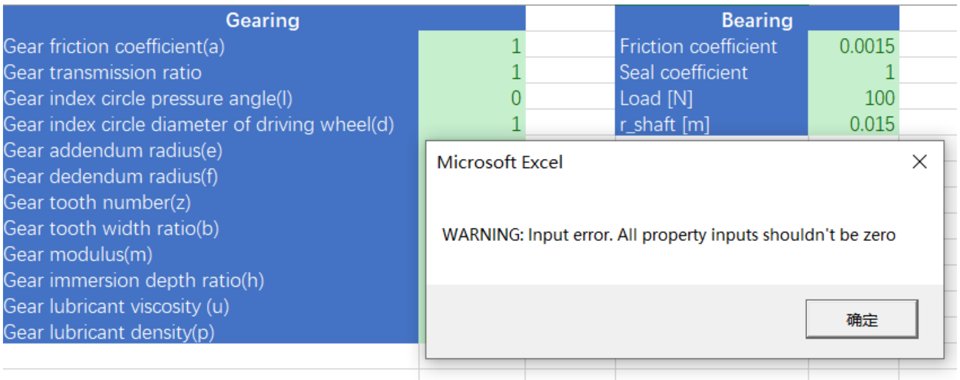


Figure 69 Results properties 0

With the setting in step 5, input any value of boat speeds.

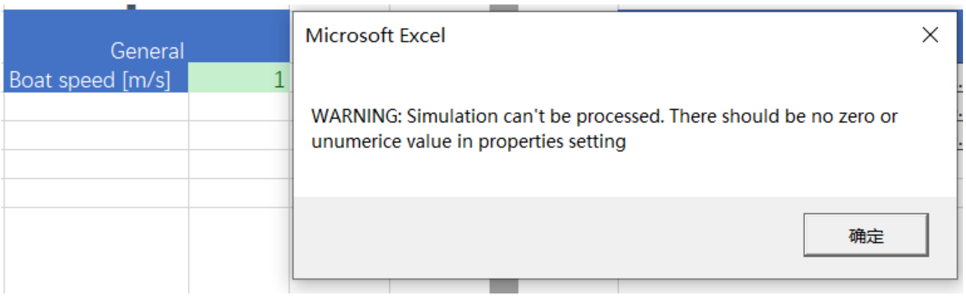


Figure 70 Result prompts

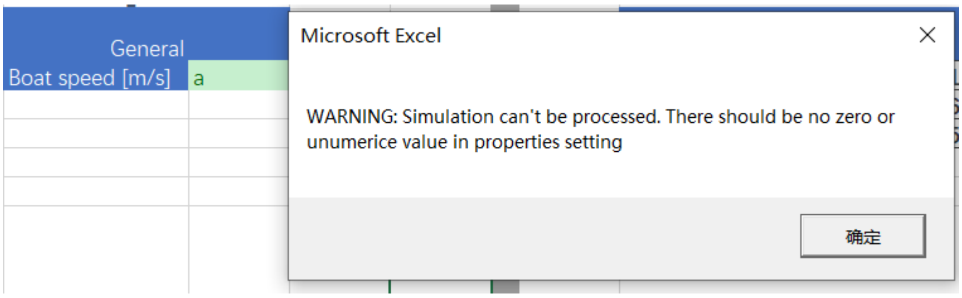


Figure 71 Result 2 prompts

Conclusion

The result of this test is same to the desired result list, with different types of inputs, there will be different correct corresponding prompts or warning shown to users. This can remind users the result of simulations and the sources of problems.

Properties	Boat speed	Message box outputs (In input-output sheet)	Message box outputs (In properties setting sheet)
With zero values	No matter what types of value it is.	WARNING: Input error. All property inputs shouldn't be zero	WARNING: Simulation can't be processed. There should be no zero or non-numeric value in properties setting
With non-numeric values		WARNING: Input error. All property inputs should be numeric	
With numeric values	With non-numeric values	-	WARNING: Input error. Input should be a numeric number
	With numeric values		Successful simulation

Table 84 Conclusion test user interface

7.6.2 Subsystem integration (calculations)

Build up

This is directly integrated in the user interface.

Log test data

Performed steps

1. Open the calculation simulation.
2. Set all properties setting values.
3. Input 6 numeric boat speeds and record the output.
4. Compare the simulation results with real data.

Results

This are the results with the simulation:

Boat speed [m/s]	Input power [W]			Output power [W]			Power loss [W]			Effciency [%]		
0.00	0			0			0			-		
0.28	9.549877181	9.54	0.10%	2.626517242	2.81	6.95%	6.923359939	6.73	2.77%	0.275031521	0.29444	7.06%
1.94	238.4933127	228.24	4.30%	128.6993449	134.85	4.78%	109.7939679	93.39	14.94%	0.539635025	0.59084	9.49%
3.89	999.884613	966.5777679	3.33%	606.5644402	638.972	5.34%	393.3201727	327.606	16.71%	0.606634438	0.66107	8.97%
5.56	2357.317715	2362.2119	0.21%	1514.826463	1598.01	5.49%	842.4912514	764.206	9.29%	0.642605981	0.67649	5.27%
7.22	4168.136314	4215.463734	1.14%	2893.385701	3043.8	5.20%	1274.750612	1171.67	8.09%	0.694167725	0.72205	4.02%
8.33	5519.510444	5605.355164	1.56%	3852.140726	4051.64	5.18%	1667.369718	1553.71	6.82%	0.697913477	0.72282	3.57%
			1.77%			5.49%			9.77%			6.40%
		Real data										
		Simulation result										
		Deviation ratio										

Figure 72 Results sub system calculations

This picture shows the simulation results. Blue blocks contain real data, red block simulation results and yellow blocks contain deviation ratio. The deviation ratios of four outputs are all lower than 10%.

Conclusion

The results of this test are same to the desired result, with different inputs, there will be different correct corresponding input power, output power, power loss and efficiency. And all results have deviations less than 10%.

7.7 V-model integration phase (system)

7.7.1 System integration

Buildup

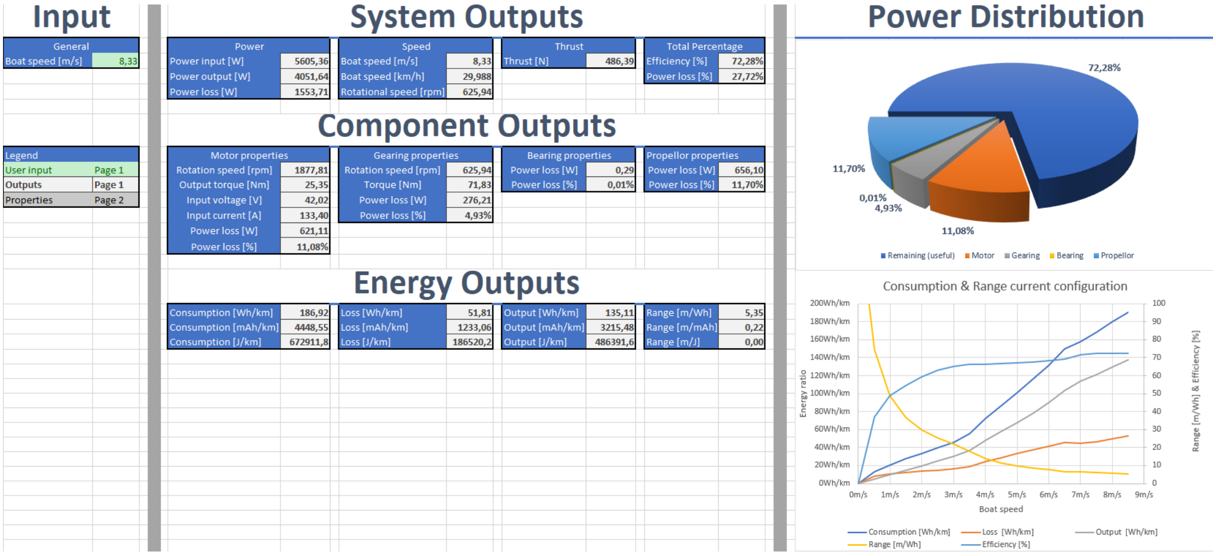


Figure 73 Buildup system

Log test data

Performed steps

1. Set up computer and load in simulation.
2. Insert different boat speeds.
3. Run the simulation for every boat speed.
4. Compare results with the corresponding outputs on the excel datasheet.

Results

This are the results with from the simulation:

Boat speed [m/s]	Input power [W]		Deviation [%]	Output power [W]		Deviation [%]	Thrust [N]		Deviation [%]
0.00	0	0	0	0	0	0	0	0	0
0.28	9.55	9.54	0.10%	2.63	2.80917	6.95%	9.95	10.0327	0.80%
0.56	29.58	28.71	2.95%	10.51	11.24	6.99%	19.91	20.07	0.82%
0.83	56.07	52.86	5.73%	23.64	24.68	4.41%	29.86	29.7	0.53%
1.11	93.62	88.14	5.85%	42.02	44.15	5.06%	39.81	39.77	0.11%
1.39	138.60	130.5	5.85%	65.66	69.23	5.43%	49.77	49.81	0.09%
1.67	187.46	176.63	5.78%	94.55	99.93	5.68%	59.72	59.84	0.20%
1.94	238.49	228.24	4.30%	128.70	134.85	4.78%	69.67	69.51	0.23%
2.22	301.44	289.07	4.10%	168.10	176.59	5.05%	79.62	79.55	0.09%
2.50	370.08	355.61	3.91%	212.75	223.95	5.27%	89.58	89.58	0.00%
2.78	447.82	431.13	3.73%	262.65	276.92	5.43%	99.53	99.61	0.08%
3.06	531.31	512.48	3.54%	317.81	335.52	5.57%	109.48	109.65	0.15%
3.33	623.82	599.42	3.91%	378.97	398.11	5.05%	119.67	119.55	0.10%
3.61	803.01	773.54	3.67%	486.91	512.06	5.17%	141.93	141.84	0.07%
3.89	999.88	966.58	3.33%	606.56	638.97	5.34%	164.18	164.26	0.05%
4.17	1164.44	1155.31	0.78%	726.34	766.15	5.48%	183.50	183.73	0.13%
4.44	1365.39	1351.07	1.05%	856.34	899.13	5.00%	202.82	202.51	0.15%
4.72	1585.70	1574.15	0.73%	999.74	1051.1	5.14%	222.85	222.69	0.07%
5.00	1819.67	1812.05	0.42%	1153.71	1214.43	5.26%	242.89	242.89	0.00%
5.28	2085.83	2083.66	0.10%	1328.22	1399.65	5.38%	264.91	265.09	0.07%
5.56	2357.32	2362.21	0.21%	1514.83	1598.01	5.49%	287.02	287.41	0.14%
5.83	2659.93	2662.25	0.09%	1726.11	1814.2	5.10%	311.48	311.18	0.10%
6.11	2972.08	2984.25	0.41%	1950.29	2051.97	5.21%	335.94	335.84	0.03%
6.39	3325.95	3350.5	0.74%	2200.64	2317.55	5.31%	362.58	362.68	0.03%
6.67	3690.68	3727.54	1.00%	2465.29	2597.64	5.37%	389.26	389.45	0.05%
6.94	3890.92	3929.31	0.99%	2675.10	2812.29	5.13%	405.49	405.23	0.06%
7.22	4168.14	4215.46	1.14%	2893.39	3043.8	5.20%	421.71	421.58	0.03%
7.50	4487.60	4546.04	1.30%	3120.23	3284.46	5.26%	437.93	437.93	0.00%
7.78	4819.23	4890	1.47%	3355.64	3534	5.32%	454.15	454.28	0.03%
8.06	5163.15	5247.69	1.64%	3599.61	3793.25	5.38%	470.37	470.63	0.06%
8.33	5519.51	5605.36	1.56%	3852.14	4051.64	5.18%	486.59	486.39	0.04%
	Average deviation		2.27%			5.17%			0.14%

Figure 74 Results system test

	Real data
	Simulation results
	Deviation

Figure 75 Legend system test

This picture shows the simulation results. Blue blocks contain real data, red block simulation results and yellow blocks contain deviation ratio. The deviation ratios of three outputs are all lower than 10%. And most deviations are lower than 5% which shows the system is reliable.

During the usage of simulation. After we input correct values and there are prompts to show successful simulation. When the wrong types of values are entered, there are warnings to remind users to input values in range and with right types of values.

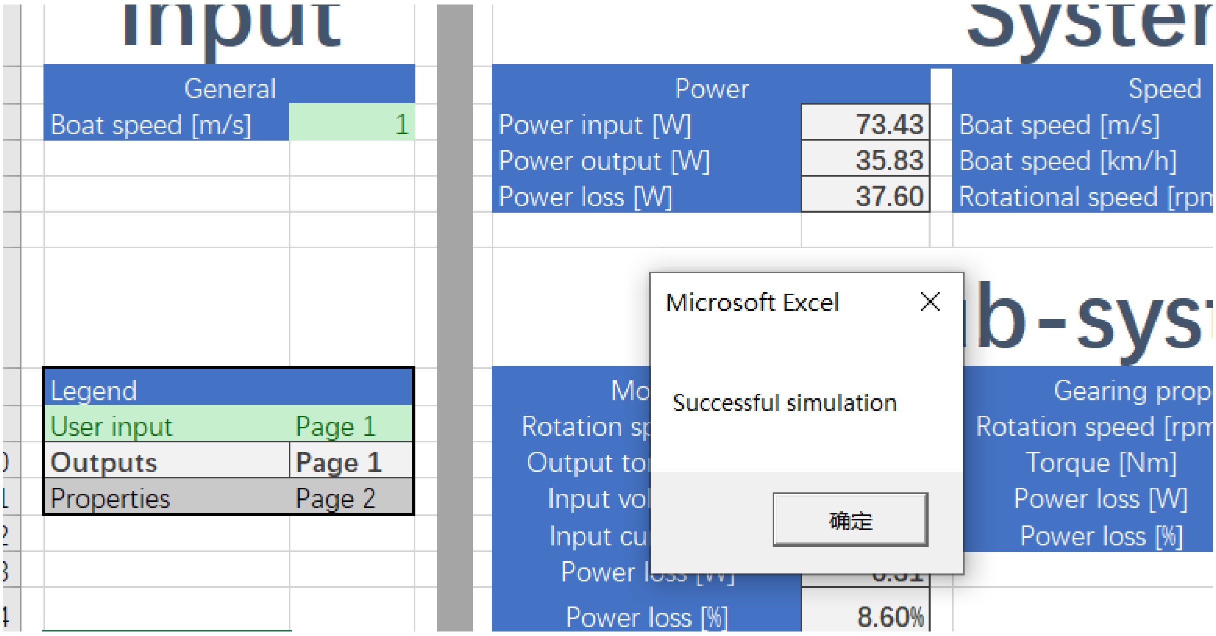


Figure 76 System test successful simulation

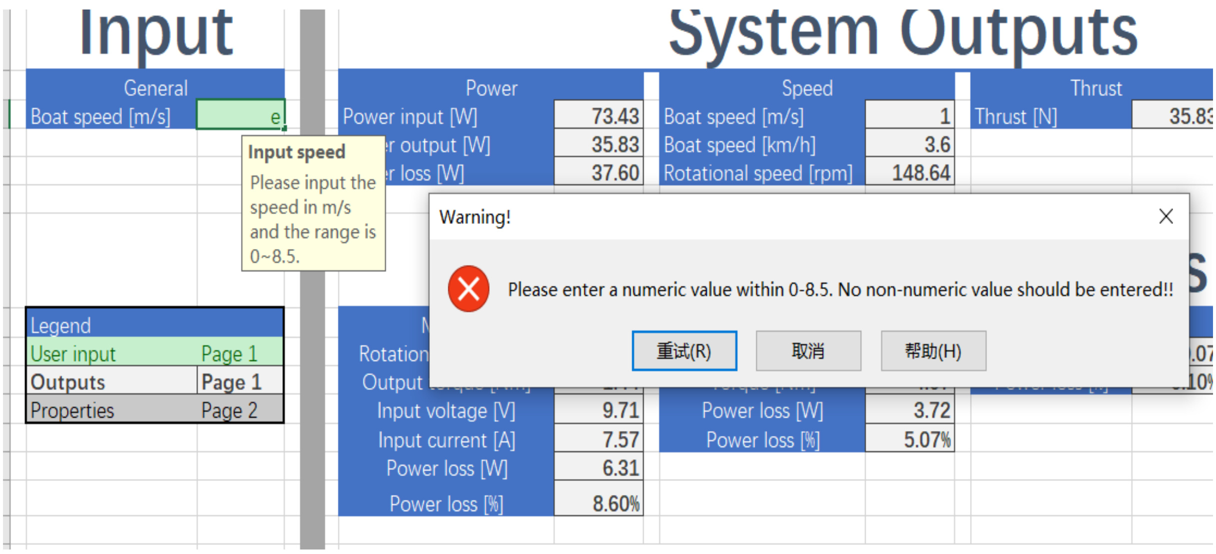


Figure 77 System test unsuccessful simulation

Conclusion

The results of this test meet the expectation of the desired results, with different inputs, there will be different correct corresponding input power, output power, and thrust. And all results have deviations less than 10%. Meanwhile, with correct inputs, there are prompts for successful simulation. And with wrong inputs, there are different warnings.