CONSTANTA MARITIME UNIVERSITY
FACULTY OF NAVAL ELECTROMECHANICS
DOCTORAL SCHOOL OF MECHANICAL AND
MECHATRONIC ENGINEERING

THESIS
-Summary-

Contributions to the study of the dynamics of an unconventional naval propulsion system

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CONTENT

INTRODUCTION

The field of naval propulsion is in continuous development and represents continuous and intense research for the application of the latest technologies.

From the mid-1970s, the complex mathematics required to generalize algorithms began to be understood, and general-purpose CFD programs were developed. These began to appear in the early 1980s and required very powerful computers, as well as an in-depth knowledge of fluid mechanics and a large amount of time to create models. Consequently, CFD programs are widely used tools, both in research and in industry, where their use can greatly reduce the development time of a product, or predict the behavior of technical systems under given conditions.

The propulsion studied in this work is one developed by nature over millions of years and which can be studied within the Constanța Maritime University with the latest software programs but also tested in the laboratory. The study of the unconventional propulsion system with naval application studied is based on the dolphin tail and uses the latest simulation techniques.

The work is developed around three major research directions:

- Simulation using ANSYS software in the CFD environment.
- Validation of ANSYS numerical results based on experimental results obtained in the laboratory.

- Analysis of thrust functions to identify the effect of the unconventional propulsion system.

The Ansys TM-Fluent R1 module year 2022 allows running simulations with the same data but multiple study models with great ease. Numerical research based on ANSYS software was performed in UMC. Numerical simulations were processed at the highest level and I obtained the necessary qualification by participating in the Ansys course. The advantage of these initial calculations is that a large number of simulations and geometric configurations can be run in Ansys Fluent.

The paper contains all the elements of classical propulsion theory and shows how to perform the latest numerical modeling for propulsion installations in relation to turbulent theory and the SKE model.

Through the function [Force_x] we will calculate the pushing force in kg. This function has the role of integrating the pressures appearing on the triangular blade made in the DesignModeller part on the upper and lower surfaces simultaneously. The results of the [Force_x] function are presented in tables and graphs.

The environmental problems generated by naval, land, air and rail traffic are related to gas emissions and vibrations in the marine environment. To reduce the vibrations emitted in the marine environment, the non-conventional propulsion system can be configured for the propulsion of small boats, the limitation being given by the resistance of the materials from which this propeller is made. Energy efficiency is presented for various non-conventional systems and potential fuels to be used for greening shipping.

Chapter 3 contains a description of the Ansys TM Fluent software and how it works for the numerical analysis of unconventional marine propulsion. The scheme of the calculation model of the FLUENT program is presented in detail for a better understanding of the calculation mode. There are various methods for solving problems used in CFD codes, but the most common and the one on which CFX is based is known as the finite volume method, and is the one used in this paper. The Fluent software, which is part of the ANSYS TM program package, allows the modification of working equations through the UDF (user defined function) method, which makes the answers and requirements rise to the highest level.

The better the calculated solutions are, the finer the discretization is done and the more calculation iterations are given. The results obtained were highlighted with the last part of the program, in the sections of interest: entrance and exit, but also in section plans parallel to the original coordinate axes. To those mentioned above, the user can add, depending on the needs, additional conditions for the calculation of the different values of accelerations, speeds, pressures and turbulence. To obtain the figures present in this work, we used the SKE (Standard k-epsilon) model and the standard coefficients defined by the program. SKE is widespread in the calculation and design of industrial applications, but there is room for modifications and improvements with the help of UDF functions for all the presented models.

The determination of the displacement of the "Dolphin tail" propeller blade is carried out based on the assumptions presented in the simulation chapter for the 3D model. The triangular blade simulation scheme is presented and graphically performed in parametric simulation:

Basin research involves the practical realization of the scale structure and the analysis of the results according to the studied models and working frequency. The obtained measurements are close in value to those of the numerical simulations, this confirming the numerical results obtained with Ansys Fluent.

The analysis carried out on the non-conventional naval propulsion includes all the calculation elements to be able to expand the understanding of this type of propulsion to be able to find the most suitable ones for use in the naval field and not only.

The research carried out in this thesis presents numerous elements of analysis of the unconventional naval propulsion system. By plotting and validating the thrust functions for a blade, a complete analysis of how this propulsion works is achieved.

STRUCTURE AND MULTIDISCIPLINARY CHARACTER OF THE THESIS

Through the aspects presented in the thesis entitled ***"CONTRIBUTIONS TO THE STUDY OF THE DYNAMICS OF AN UNCONVENTIONAL NAVAL PROPULSION SYSTEM"*** the understanding of "Dolphin Tail " type propulsion systems is facilitated . The present research has a multidisciplinary character and can contribute to the development of future projects with application in the field of boat propulsion. Important aspects that can be applied to other engineering issues:

The measurements were carried out in the laboratories of the Maritime University of Constanta. For the measurements we used the test pool and we used the clamping mechanisms and sensors described in the paper.

The main objectives of the validation activity on the completed models were:

- ➢ Measurement of thrust forces created for different working frequencies.
- ➢ Calculation of working amplitudes for test models
- ➢ Comparison of the results obtained through numerical simulation with ANSYS Fluent CFD, with those obtained during real tests.
- ➢ Choosing the optimal constructive model among the studied models and explaining the selection.
- ➢ Determination of pressures and dynamics around the "Dolphin tail" propeller blade.

All models used were stored in a database. The Ansys model can later be used for any other size and shape of unconventional propulsion studied.

The use of Ansys simulations was the basis for the creation and realization of the test model and for establishing the dimensions of the triangular Dolphin Tail blades. The simulations were run over several sessions to run each model later tested physically.

The general simulation was materialized by using CFD software (ANSYS program) and the measurement in the modified test basin was done in the laboratories of the Maritime University of Constanta.

Postprocessing is the CFD component used to analyze, visualize and present the results interactively. Post-processing includes everything from obtaining point values to complex animated sequences.

Some examples of important features of CFD postprocessors are:

- Visualization of the 3D system and the volumes involved in the analysis
- Vector graphic visualization showing direction and amplitude of flow
- Visualizing the variation of scalar variables (variables that have only magnitude, not direction, such as temperature, pressure, and velocity) in the domain of study
- Quantitative numerical calculations
- Raising charts according to the chosen parameters
- Possibility of generating reports in physical (paper) and/or electronic format for the sizes characteristic of the studied non-conventional propellant.

The presented results for a triangular blade were made using Ansys Fluent and show a multidisciplinary way and a wide applicability in engineering.

CHAPTER I
CURRENT STATE OF RESEARCH IN UNCONVENTIONAL SHIP PROPULSION SYSTEMS

The first types of boats

The existing documentary data, established approximately before 6000 BC, show that the first boats used were rudimentary canoes obtained by splitting tree trunks. These were propelled and governed at first with the help of the palms of the hands, and later with the help of sticks allowing people to cross the not too deep and, of course, not too wide waters.

Modern ships

The ever-increasing economic role of oil has led to a rapid evolution of ships designed to transport this important category of raw material and fuel. Oil ships recorded the most spectacular jump in terms of tonnage: from about 300t at the end of the 19th century to 45,000t in 1953 (the "Tona Onasis" oil tanker), to 100,000t in 1965 (the "British Admirai" oil tanker), followed by the replica Japanese of which only a few examples are mentioned - "Idemitru Mani" of 210000t in 1966, followed in 1971 by "Nisseki Mani" of 372400t, then by other oil tankers of 500000t, 600000t, 850000t and 1000000t. Currently, there is a tendency to reconsider the tonnage, to abandon the idea of building such giant oil tankers, due to several disadvantages they present, returning to the construction of oil tankers of smaller sizes and displacements.

An important step in naval construction is the use of nuclear energy to propel ships, which considerably increases their cruising range.

Constructive solutions different from the classical ones that appeared in a more recent stage are represented by ships built on dynamic floating principles, among which we mention ships with load-bearing wings and ships on an air cushion, relatively small constructions especially intended for the transport of passengers, transports express goods, postal services and other special purposes. These types of ships achieve high speeds due to the fact that during movement the body rises above the water, either due to the effect of the supporting wings, or by obtaining a substantiation force with the help of air jets created and maintained between the surface of the water and the ship.

There are many concerns of shipbuilders to continuously improve the constructive systems of the hull, the propulsion and steering systems, the machinery for the handling of goods, the remote control and automation equipment, as well as for the realization of multi-functional ships.

Regarding the equipment and facilities of modern ships, even in a brief presentation of the evolution of naval constructions, one can mention the improvements made to the navigation equipment (girocompas, radar, automatic pilot, steering the navigation by means of satellites), on-board computers provided for the optimization of calculations of navigation, of the operation of the loading-unloading, propulsion installations, as well as the automation equipment of various commands, signals, etc. All these improvements and modern equipment have made it possible to build ships that are more and more efficient and safer in operation.

In the perspective of the development of naval constructions worldwide, multiple future improvements are expected, facilitated by the continuous progress of science, technique and technology, which will create increasing possibilities for the adoption of more economical solutions to solve problems such as:

- ship propulsion – by expanding the use of nuclear propulsion, gas turbines, other energy systems and types of propulsion;
- reducing the forward resistance for classic ships by optimizing the shape of the hull, especially the shapes in the bow and stern, by using additives applied to the outer surface of the submerged body, etc.;
- increasing the size and tonnage of modern ships built on dynamic floating principles - on load-bearing wings and especially on air cushion ships, which many specialists consider the ships of the future.

The current world economic crisis and especially the energy crisis will determine qualitative changes that will lead to the continuous development and improvement of naval constructions. This objective direction is argued by the fact that ships constitute the basic and at the same time the most economical means of transport for international trade, and for the internal traffic of goods, water transport takes on an ever greater weight.

1.3. Marine propulsion installations - general considerations

The propulsion of the ship, i.e. its movement along the desired path with the imposed speed, is carried out with the help of the propulsion installation.

In order for a ship to be able to move forward at a certain speed, a force must be applied to it, equal and of the opposite direction to the force of water resistance, which arises when the ship moves forward. The force that has the effect of advancing the ship can be created by means of the various energy sources existing on board the ships. Wind energy can also be converted by sails into mechanical work to propel the ship.

According to M. Amorăriței, naval thrusters transform the mechanical energy produced by the main propulsion machines into the ship's kinetic energy, more precisely into a thrust force that drives the ship in motion, a force whose size depends on the value of the ship's forward resistance at the desired speed.

The thrusters used depend on the type and operating conditions of the ship.

According to the way in which the thrust force is achieved, naval thrusters are divided into two categories: active and reactive.

Active thrusters develop thrust through the direct action of the wind (sail, Flettner rotors), and reactive thrusters produce thrust through the reaction of the water mass that is forced to move in the opposite direction to the movement of the ship (frames, paddle wheel, naval propeller , fin thruster, jet thruster).

Steam engines (alternatives or turbines), internal combustion engines (diesel or gas turbines), electric motors powered by generator sets or accumulators are used to propel ships. Atomic power is still used on a large scale, especially for special purpose ships. The need to use wind energy, currently leads to the construction of ships with engines and sails.

In the case of reactive propellers with blades, the reaction of the rejected water is directly taken over by the blades which are fixed on a support. The thrust that arises as a result of the action of the propeller is transmitted to the ship's hull by means of the portelica shaft, the line of shafts and the thrust bearing.

❖ Paddle wheel it is the first thruster used in the era of mechanical propulsion, mechanically driven by an energy production facility, located on board ships. Paddle wheels are propulsors that produce thrust, due to the entrainment of the mass of water, on which the ship floats, by the submerged rotating paddles.

From a kinematic point of view, paddle wheels are divided into two main types:

- wheels with fixed radial paddles;
- wheels with articulated (rotating) radial paddles.

The kinematic type of a paddle wheel is determined by increasing the relative eccentricity using the relation: $e_r = \frac{e}{k}$, where k is a speed factor.

❖ The most common type of propeller is the naval propeller. Propellers are reactive propellers, which were born as a result of the change, mounting the paddles from a position perpendicular to the plane of the wheel to an inclined position and as a result of the arrangement of the wheel in the stern of the ship. The edge of the blades that cuts the stream of fluid is called the leading or leading edge.

CHAPTER II ENERGY EFFICIENCY STUDY OF UNCONVENTIONAL NAVAL PROPELLERS

2.1. Energy efficiency of conventional propulsion systems and their fuels

Diesel engines

The diesel engine is today the main means of marine propulsion. Broadly, engines are classified into engines: slow, two-stroke; medium speed, in four strokes; and high-speed, in four strokes (figures 2.1 and 2.2). While some ships, due to their design and operational profile, use either slow or medium speed diesel engines as their primary mode of propulsion, most ships are equipped with additional high or medium speed diesel engines for auxiliary power consumption . In addition, all commercial ships have the means to generate electricity in an emergency, according to the SOLAS convention.

Fig. 2.1. Slow diesel engine (Wärtsilä RT-flex82T version B, main engine) [28]

The main concern of engine builders is the most efficient method of building various engines. Exhaust gas recirculation is a method that can be used to reduce NO_X in slow and medium diesel engines. In the case of two-stroke engines, slow engines, development programs with exhaust gas recirculation systems have been carried out over the last 20 years. These include operational studies on board the *Alexander Maersk* that have made useful contributions to the understanding of these systems. With the EGR method of reducing NO_X part of the oxygen in the captured air is replaced by CO_2 , because carbon dioxide has a higher calorific capacity, which reduces the peak temperatures inside the cylinders. In-service studies showed that system components such as piston rings, EGR blowers, water vapor collector and control systems performed well. Injection of water into the cylinders at the time of combustion and humidification of the intake air is also useful in reducing the NO_X content of the combustion gases in slow engines. Several methods have been designed and tested for this purpose by various manufacturers of slow and medium speed motors.

Another approach involves injecting ammonia into the flue gas stream, usually in the form of a urea solution. This reacts with the exhaust component NO_X at the surface of the selective catalytic reduction elements to form N and H_2O. This method, however, requires dedicated space for urea storage on the vessel, dosing and control systems, and catalytic reduction elements which can replace the normal shock absorber.

The Green Ship of the Future project undertook a study on a 38,500 tdw oil tanker powered by a slow diesel engine that was planned to spend 13.5% of its voyage time in an emission control area [14].

Three options were considered: using a low-sulphur fuel; placing a flue gas scrubber in the system or using LNG fuel. The low sulfur fuel option involved some lubrication issues. The exhaust gas cleaning alternative based on the use of heavy fuel oil required the installation of a new chimney due to the introduction of the scrubber with its associated mechanism and new tanks. In the latter case, the use of LNG fuel, new pipelines and a fuel supply system were required along with the new LNG tanks; also, in this case, two 350 m^3 tanks were mounted on the deck.

A new class of ultra-long-stroke engines has been introduced to the marine propulsion market. These engines have a lower speed and, if used with a propeller of the optimum diameter, at these low rotational speeds, the overall efficiency of the ships propulsion can be improved. This hydrodynamic benefit can then be matched with the improved fuel consumption characteristics of the engine. Table 1.1 shows the differences in fuel consumption between an ultra-long stroke engine and a conventional engine.

Table 2.1. Comparison between an ultra-long stroke engine and a traditional engine [12]

Engine parameters	The K 98 ME engine	The S 90 ME engine
Piston stroke (mm)	2660	3260
Speed (rpm)	97	84
Specific fuel consumption (g/kWh)	174	167

To reduce fuel consumption there has been a tendency to run large marine engines at part load. Although such restrictions were largely limited to continuous powers above 60% of the maximum continuous rating (MCR), more recently, in container ship operation, these limitations have been reduced to 10% MCR. To achieve these extremely low loads, the supply of lubricating oil must be reduced with the introduction of part-load and reduced engine tuning methods.

Of importance in this context are the bypass of combustion gases, the variable surface of the turbine, the control of fuel injection in the engine and the regulation of high pressure.

Potential advantages and disadvantages of the technology:

- Benefits:
  - i. Diesel engine technology is a well-understood and reliable form of marine propulsion and auxiliary power generation.
  - ii. The training of engineers to operate diesel machinery is well known and there are facilities for the appropriate levels of education.
  - iii. Engine manufacturers have well-established spare parts and repair networks around the world.
  - iv. Diesel, in all its grades, is easily obtained through

the worldwide distribution network.

v. Many primary and secondary methods for reducing emissions that are currently perceived as harmful are available. Moreover, there is an ongoing program of research and development undertaken by engine builders in this regard.

- Disadvantages:
  - i. Diesel engines produce CO_2 emissions as well as NO_X, SO_X and volatile organic compounds. They must therefore comply with the requirements of MARPOL Annex VI and be included during the ship's EEDI assessment.
  - ii. SO_X emissions are a function of the sulfur content of the fuel used in the engine and compliance with regulations requires the use of sulfur reduction technology.
  - iii. The possibility of contamination of marine fuel with first-generation biofuels must be carefully managed on board ships.

CHAPTER III
NUMERICAL MODELING METHODS OF UNCONVENTIONAL PROPELLERS

3.1. Ansys TM Fluent software characterization

Ansys TM offers a full range of simulation solutions and contains engineering suites that provide access to almost any area of engineering simulation that requires a pre-design process. Ansys TM for provides the best solution in engineering simulation software. The Ansys TM company pioneered the development and application of simulation methods to solve difficult engineering problems. Ansys TM software solutions, combined with value-added and support services, have been catalysts for innovation and faster time to resolution for thousands of engineering teams around the world.

Ansys TM-Fluent is a modern computer program that allows the modeling of fluid flows, heat transfer and chemical reactions around or in different bodies with complex geometries.

The Ansys TM Fluent software allows the analysis of fluid flow around bodies and its action on different surfaces. For different regions, pressure and velocity variation graphs can be plotted, being a useful source in fluid flow optimization.

Fig. 3.1 Ansys TM V 2022 Program

Ansys TM-Fluent is written in the C language and makes full use of the flexibility and power offered by the programming language. Consequently, dynamic memory allocation, efficient data structures, control and flexible resolution are all possible. In addition, the Ansys TM-Fluent program uses a client/server architecture, which allows it to run separate simultaneous processes on desktop workstations and computationally powerful client servers. This architecture allows efficient execution, interactive control and complete flexibility between different types of machines or operating systems.

3.2. Results of Ansys TM Fluent simulations

To model the fluid-structure interaction forces, we used the Ansys TM Fluent program. Fluent is a program based on the method of finite volumes.

Solving the CFD problem

The complex system of equations that solves the CFD problem is called the Solver. It produces the required results in a discontinuous but non-interactive process. A CFD problem is solved as follows:

1. The partial differential equations are solved in all control volumes in the region of interest. This is equivalent to applying a basic conservation law (eg for mass or momentum) to each partitioned volume during the mesh.

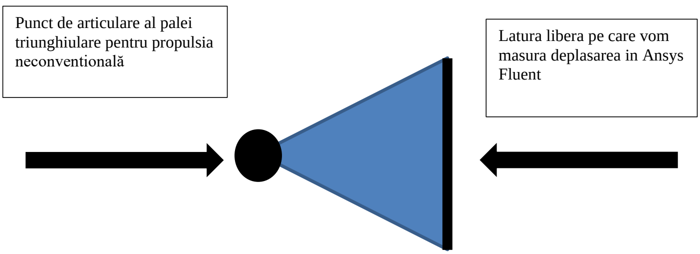
2. This system of integral equations is converted to a system of algebraic equations by generating a set of approximations for the terms in the integral equations.

3. Algebraic equations are solved iteratively.

An iterative solution is necessary because of the nonlinear nature of the equations, and as the solution approaches the exact solution, it is said to converge. For each iteration, an error or residual is reported as a measure of the overall conservation of the flow properties.

The resolution process does not require user interaction and is therefore usually performed as a batch process.

The solver produces a result file that is then passed to the postprocessor.

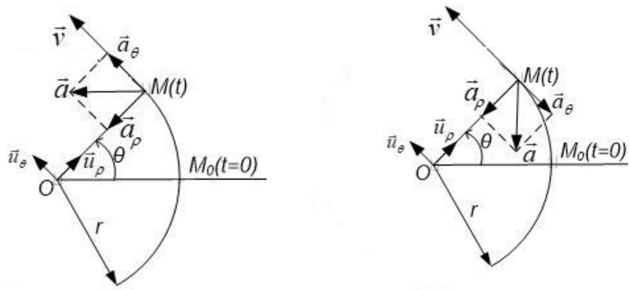


The position vector of the material point at time *t* has the expression:

$$\vec{r} = r \cdot \vec{u}_\rho \quad (3.9)$$

from which, by derivation, the speed expression results:

$$\vec{v} = \dot{r} \cdot \vec{u}_\rho + r \cdot \dot{\vec{u}}_\rho = \dot{\theta} \cdot r \cdot \vec{u}_\theta = \omega \cdot r \cdot \vec{u}_\theta \quad (3.10)$$



a) b)

Fig. 3.12

From the relation (3.10)it can be seen that the speed of the material point in the circular motion is a vector in the direction of the versor $\vec{u}_\theta$(tangent to the trajectory) and has the magnitude:

$$|\vec{v}| = \omega \cdot r$$

The acceleration is obtained by deriving the speed expression:

Through the function [Force_x] we will calculate the pushing force in kg. This function has the role of integrating the pressures appearing on the triangular blade made in the DesignModeller part on the upper and lower surfaces simultaneously. Function results _ [Force_x] are shown in Table 3.1.

Table 3.1. Results of function [Force_x] for thrust force [kg]

Thrust force	**Test 1**	**Test 2**	**Test 3**	**Test 4**
ANSYS simulation [kg]	1,200	8,874	0.770	9,854

The results presented in Fig. 3.24. can be updated by changing the simulation input parameters and can generate results for any size of triangular blade used.

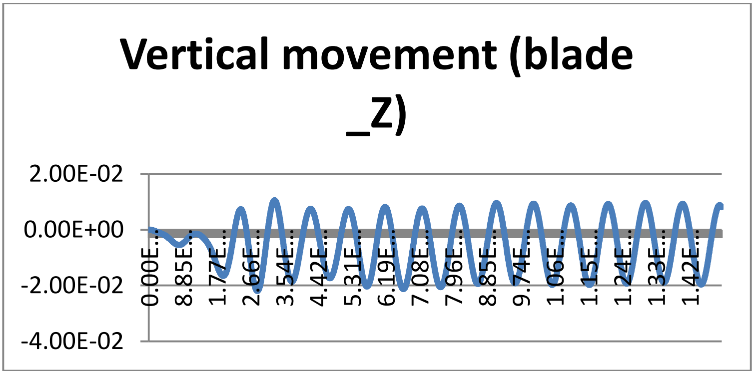


Fig. 3.24. The vertical oscillation of the free side in the Z direction

The biggest challenge for conducting simulations of this type is defining the theoretical tools for a clear and robust prediction and validating them experimentally at scale or using similarity criteria.

CHAPTER IV EXPERIMENTAL METHODS FOR DETERMINING THE CHARACTERISTIC QUANTITIES OF UNCONVENTIONAL NAVAL PROPELLERS

4.1. Organization of measurements to determine the characteristic sizes of non-conventional naval thrusters

The measurements were carried out in the laboratories of the Maritime University of Constanta. For the measurements we used the test basin and we used the clamping mechanisms and sensors described below.

To complete the study of non-conventional naval thrusters, the hypotheses and theoretical calculations regarding the flow of water, the values of the parameters resulting from the numerical simulation with Computational Fluid Dynamics ANSYS-Fluent, were experimentally validated.

The main objectives of the validation activity on the completed models were:

- Measurement of thrust forces created for different working frequencies.
- Calculation of working amplitudes for test models
- Comparison of the results obtained through numerical simulation with ANSYS Fluent CFD, with those obtained during real tests.
- Choosing the optimal constructive model among the studied models and explaining the selection.

• Determination of the pressures and dynamics around the "Dolphin tail" propeller blade.

4.2. Description of the test stand

The test stand is made of an electric motor with 2 speed steps that drives the test models in oscillatory motion according to the diagram in figure 4.1.

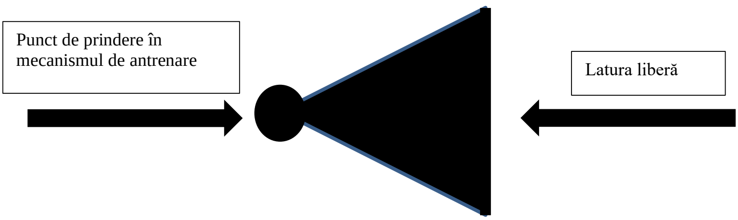


Figure 4.1.: Clamping scheme in the test stand

5 different models were mounted on the test stand:

- 4 equilateral triangles with size l - side of: 5, 10, 15 and 20 cm (black color),
- an additional model with a side of 20 cm (blue).

It is observed that the thrust force has almost constant values when the non-conventional propulsion is stabilized during the test. Higher or lower values are observed when the propulsion blade changes its angle of inclination with respect to the horizontal. That is why in all tests the blade is kept in a horizontal position to avoid these effects.

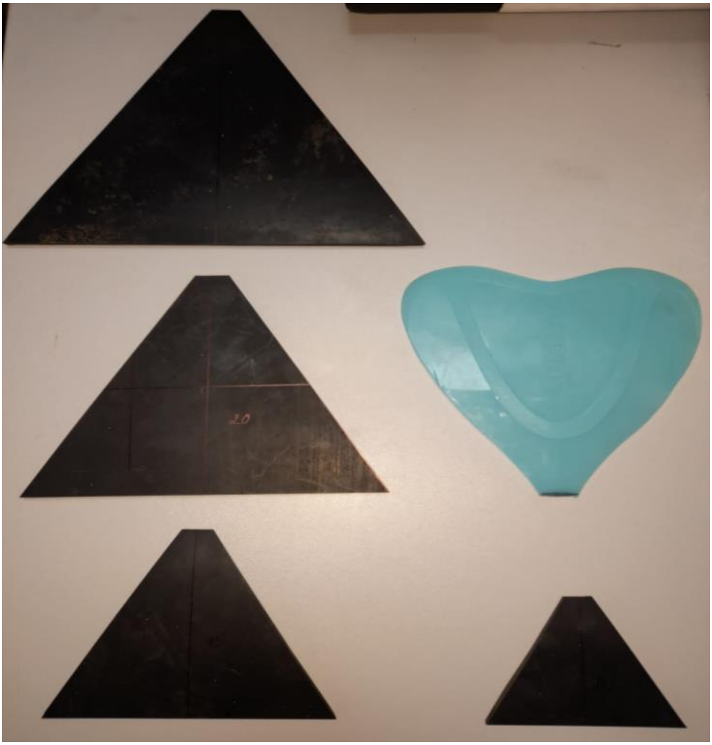


Fig. 4.2. Physical models for basin tests

4.3. The method of measuring the characteristic sizes of non-conventional naval thrusters

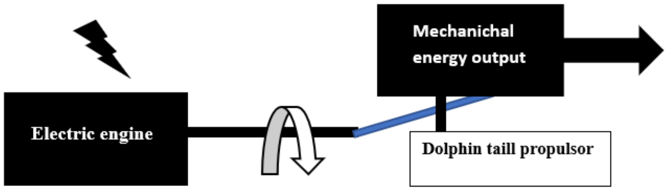


Fig. 4.7. Work schedule for performing basin tests

Fig. 4.8. Initial testing with standard propellers for comparative analysis

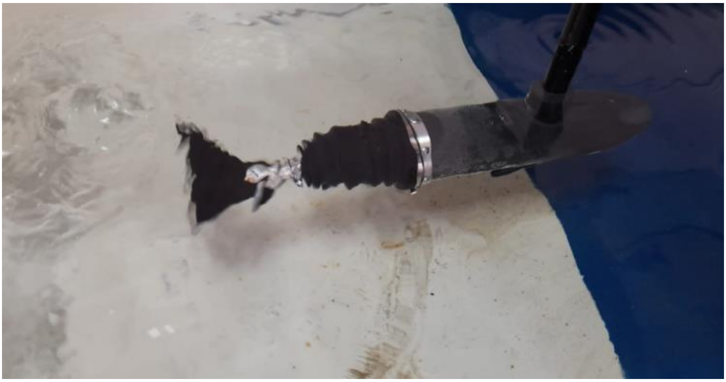


Fig. 4.9. Measurement of the characteristic sizes of non-conventional naval thrusters

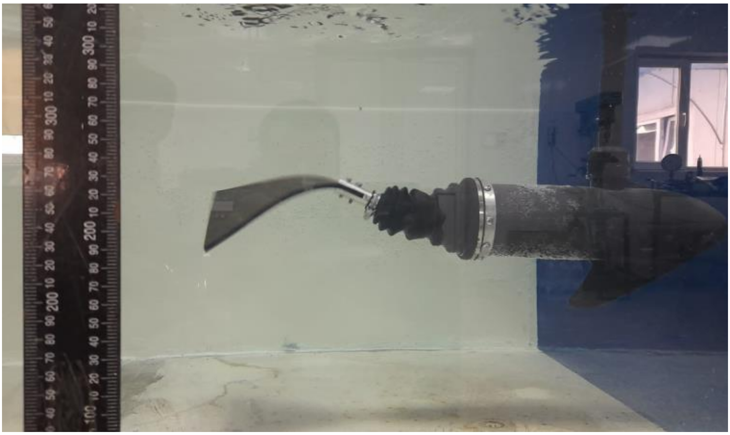


Fig. 4.10. Measurement of pala_z movement amplitudes (test 1)

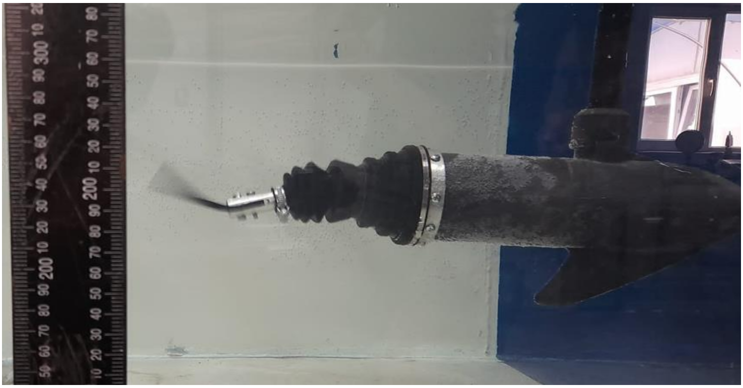


Fig. 4.11. Measurement of pala_z movement amplitudes (test 2)

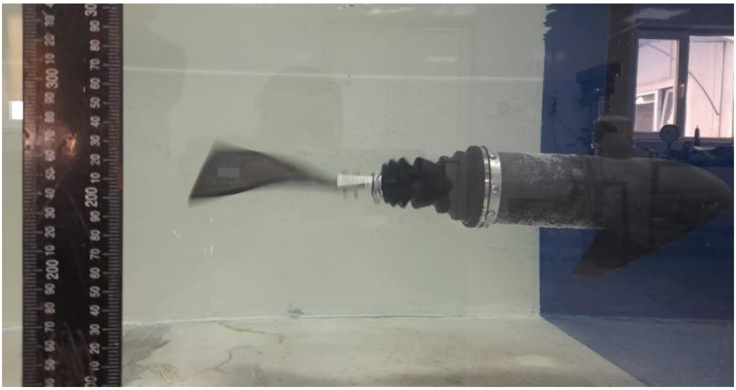


Fig. 4.12. Measurement of pala_z movement amplitudes (test 3)

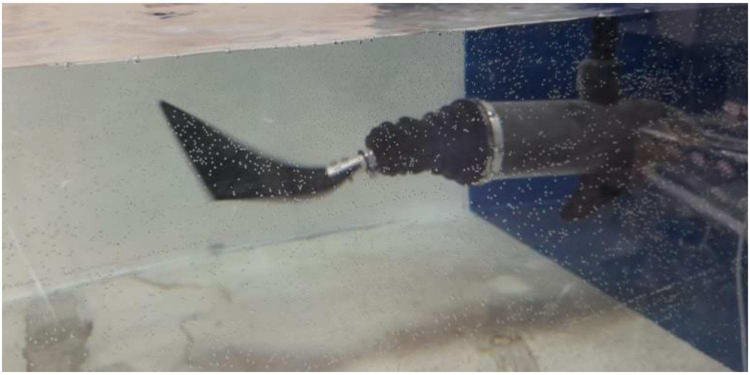


Fig. 4.13. Measurement of pala_z movement amplitudes (test 4)

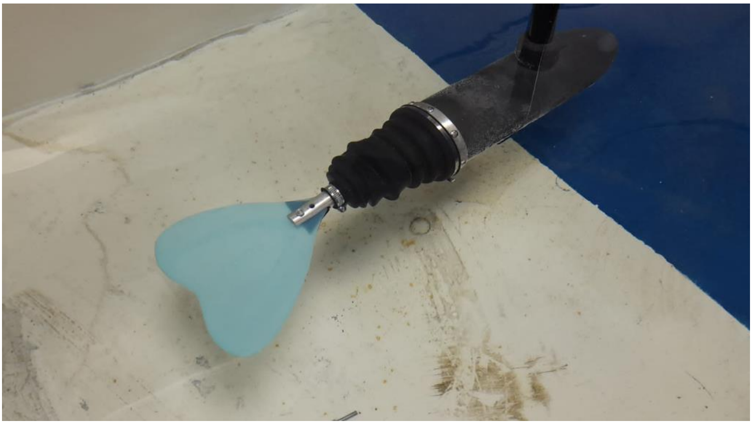


Fig. 4.14. Measurement of pala_z movement amplitudes (test 5)

4.4. Measurement results of the characteristic sizes of non-conventional naval thrusters

Table 4.1. Measurement results of the characteristic sizes of non-conventional naval thrusters

	Model 1 Queue 15/15/15	Model 2 Tail 20/20/20	Model 3 Queue 25/25/25	Model 4 Blue ABS plastic 20/20/20	Model 5 standard propeller
Step 1 [kg]	1,285	0.210	0.495	0.805	7,000
Step 2 [kg]	0.565	0.865	1,777	0.965	10,000
Step 1 [%]	18,357	3,000	7,071	11,500	100,000
Step 2 [%]	5,650	8,650	17,770	9,650	100,000

Table 4.2. Electrical power measurement results of tested non-conventional naval thrusters

	Model 1 Queue 15/15/15	Model 2 Tail 20/20/20	Model 3 Queue 25/25/25	Model 4 Blue ABS plastic 20/20/20	Model 5 standard propeller
Step 1 [w]	70,700	79,770	102,480	69,310	62,830
Step 2 [w]	121,400	160,800	180,000	162,000	120,000
Step 1 [%]	112,526	126,962	163.107	110,314	100,000
Step 2 [%]	101,167	134,000	150,000	135,000	100,000
Step 1 [η]	1,818	0.263	0.483	1,161	11,141
Step 2 [η]	0.465	0.538	0.987	0.596	8,333

Figure 4.15 graphically shows the thrust measurement results [kg] of non-conventional naval thrusters for the 4 test models according to table 4.1

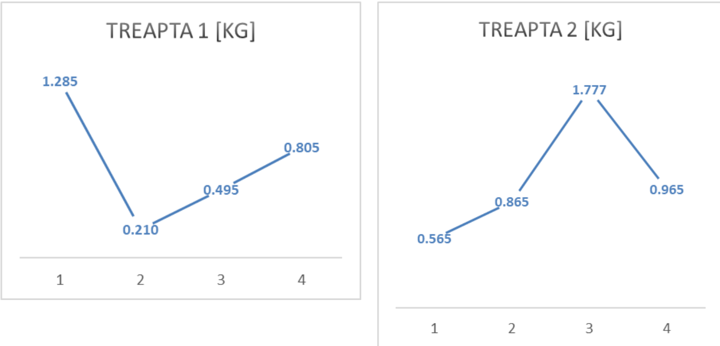


Fig. 4.15. Graphical thrust measurement results [kg] of non-conventional naval thrusters

Figure 4.16 graphically shows the thrust measurement results [%] of non-conventional naval thrusters compared to propeller thrusters for the 4 test models according to table 4.1

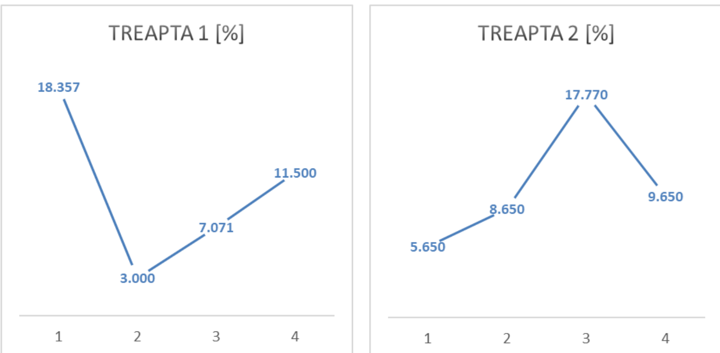


Fig. 4.16. Graphic results of thrust measurement [%] of non-conventional naval thrusters compared to propeller thrusters

Figure 4.17 shows graphically the results of measuring the power consumption [W] of non-conventional naval thrusters for the 4 test models according to table 4.2

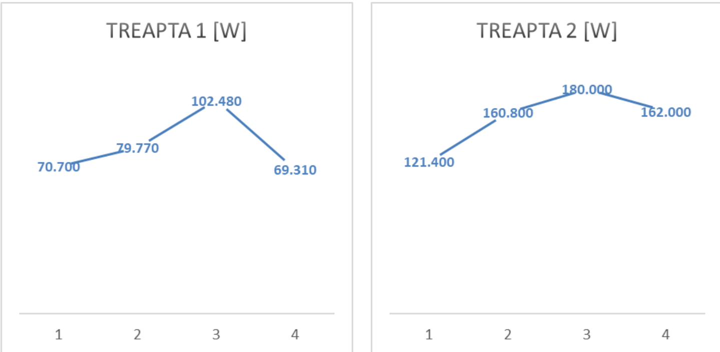


Fig. 4.17. Graphic results of measuring power consumption [W] of non-conventional naval thrusters

Figure 4.18 shows graphically the results of measuring power consumption [%] of non-conventional naval thrusters compared to propeller thrusters for the 4 test models according to table 4.2

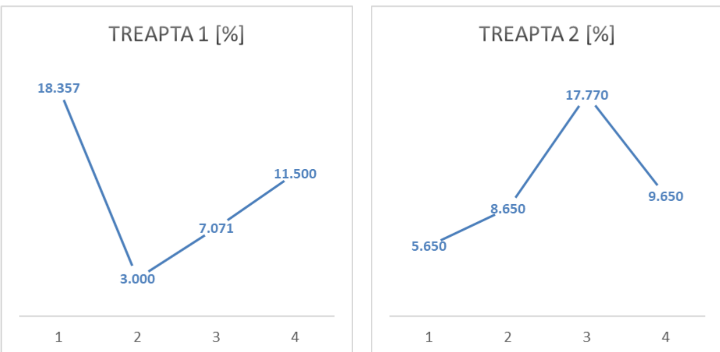


Fig. 4.18. Graphic results of measurement of power

consumption [%] of non-conventional naval thrusters compared to propeller thrusters

Figure 4.19 graphically shows the measurement results for the efficiency [η] of non-conventional naval thrusters according to table 4.2

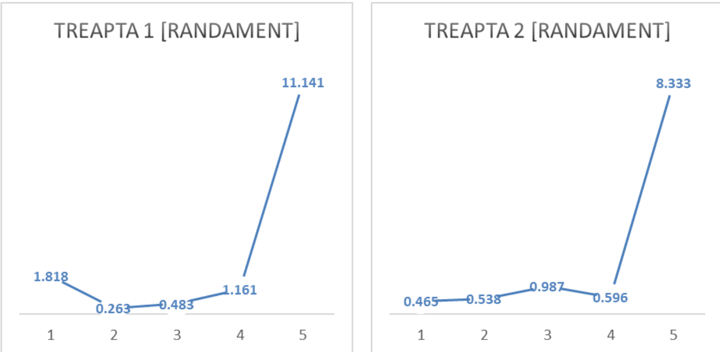


Fig. 4.19. Graph measurement results for the efficiency [η] of non-conventional naval thrusters

CHAPTER V
ANALYSIS AND OPTIMIZATION OF THE "TAIL TYPE" OR "DOLPHIN TAIL" PROPULSION SYSTEM

5.1. Analysis of the results obtained for model validation

To analyze the studied non-conventional propulsion of the "Dolphin Tail" (DT) type and to understand how it works, I used the CFD simulator to analyze a parametric model. The resulting forces and amplitudes in the simulation were limited by the dimensions and capacity of the test pool. The description of the models used was already made in chapter IV.

The use of Ansys simulations was the basis for the creation and realization of the test model and for establishing the dimensions of the triangular Dolphin Tail blades. The simulations were run over several sessions to run each model later tested physically.

Initial conditions:

- the speed of the ship is considered to be zero;
- orientation of the test blade in the horizontal direction
- The drive motor always works at 100%
- simulation conditions and test pool: the water surface is calm
- The working position in the pool/simulated fluid domain is always the same for the center of the blade of the propulsion system.

During each type of test, the correctness of the measurements was monitored and a minimum of 3 measurements were performed in each situation. The values shown are an average of the measurements considered valid during pool tests.

The adjustments made for the pool tests have the role of calibrating the measurements and obtaining an indication as accurate as possible on the models tested compared to the classic propulsion propeller.

Checks and inspections during each test were done in the following order to ensure rigorous testing:

1. Verification of fixation in the measuring stand
2. Setting the oscillator to position 0
3. Start force measuring instruments
4. Checking and adjusting the starting angle to get the blades in the horizontal plane when starting the tests
5. Measurement of amplitudes and thrust forces generated as in fig 5.1.

It is observed that the thrust force has almost constant values when the non-conventional propulsion is stabilized during the test. Higher or lower values are observed when the propulsion blade changes its angle of inclination with respect to the horizontal. That is why in all tests the blade is kept in a horizontal position to avoid these effects.

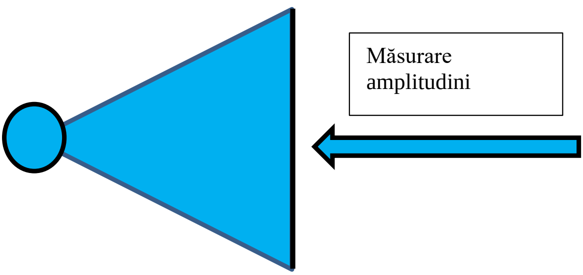


Figure 5.1.: Amplitude measurement scheme in tests

5 different models were mounted on the test stand and Ansys simulations were run for the existing dimensions of the models:

- 4 equilateral triangles with side dimensions of: 5, 10, 15 and 20 (black),
- an additional model with a side of 15 cm (blue).

All models used were stored in a database. The Ansys model can later be used for any other size and shape of unconventional propulsion studied.

The parameters of the model could be changed during the simulations for all the dimensions requested and possible to use in the test basin.

The changes were relevant for understanding the data differences between the input and output of the test system presented in figure 5.2.

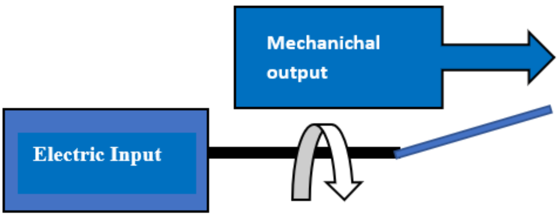


Fig. 5.2. Input/Output measurement system

The general simulation was materialized by using CFD software (ANSYS program) and the measurement in the modified test basin was done in the laboratories of the Maritime University of Constanta.

Postprocessing is the CFD component used to analyze, visualize and present the results interactively.

Post-processing includes everything from obtaining point values to complex animated sequences.

Some examples of important features of CFD postprocessors are:

• Visualization of the 3D system and the volumes involved in the analysis

• Vector graphic visualization showing flow direction and amplitude

• Visualizing the variation of scalar variables (variables that have only magnitude, not direction, such as temperature, pressure, and velocity) in the studied domain

• Quantitative numerical calculations

• Animation

• Elevation of diagrams according to the chosen parameters

• Possibility of generating reports in physical (paper) and/or electronic format for the sizes characteristic of the studied non-conventional propellant.

5.2. Presentation of simulation and measurement results overlaid

In table 5.1. the thrust functions for the studied models starting from the horizontal plane ($\alpha = 0$) are presented.

Table 5.1. Comparative results for the characteristic sizes of non-conventional naval thrusters (stage 1)

Thrust force	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Pool tests [kg]	1,285	0.210	0.495	0.805
ANSYS simulation [kg]	1,200	8,874	0.770	9,854

The following notations were used:

- the amplitude of the vertical movements of the blade, pala_ z [m];
- amplitude of angular movements of the experimental model, θ[degrees];
- frequency of angular movements of the experimental model, f_w [Hz].

Based on these physical quantities, the amplitudes for the vertical movement of the experimental model were graphically plotted.

Drawing the graphs from fig 5.3. and 5.4. it will be done by linear interpolation using the Microsoft Excel application for the values presented in table 5.1.

The difficulty of generating physical models for all the values in the graphs is alleviated for this validation by easily changing the ANSYS Fluent TM software parameters. Thus, we will be able to evaluate the vertical displacements of the tip of the blade that appear in the software with the help of pool tests. Percentage differences of less than 10% confirm a correct software interpretation of unconventional thruster dynamics.

In the comparisons we have identified differences and variations in some frequency areas that come from the fact that the UMC pool is small and has certain limitations when using large models.

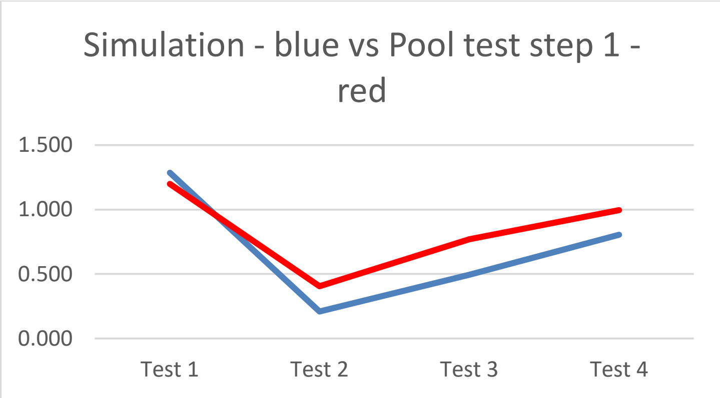


Fig. 5.3. Overlay values for Ansys simulations and basin measurements

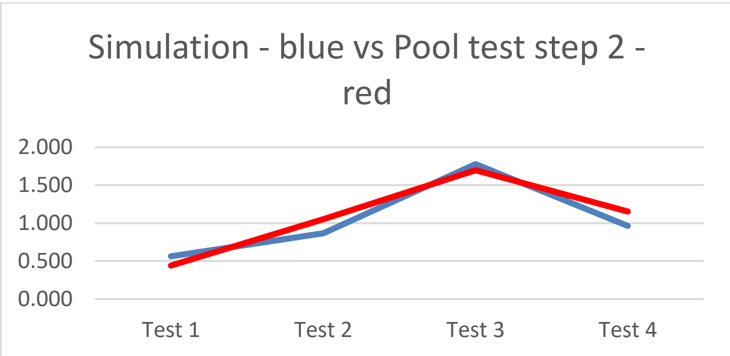


Fig. 5.4. Overlay values for Ansys simulations and basin measurements

To compare the results for the simulated models and for the pool tests on the model we will compare the obtained amplitudes.

The tests thus confirm the results of the simulations through small differences for the value of the thrust generated and the percentage differences noticed between the experimental model and the CFD model represent usual differences. It can be seen in figure 5.3 that the values obtained in the basin tests follow the trend and approach the values obtained in the numerical simulations. Thus the measured data confirm the graphs obtained by linear interpolation of the simulation data.

5.3. Interpretation of results obtained through numerical simulation with ANSYS Fluent CFD and real tests

To complete the study on the dynamic behavior of the unconventional propulsion in the horizontal plane , the hypotheses and theoretical calculations regarding the values of the parameters resulting from the numerical simulation with Computational Fluid Dynamics ANSYS-Fluent, were experimentally validated. The variations of the models and dimensions of the working blades allowed the measurement in the laboratory of the Constanța Maritime University.

The validation of the mathematical model of the dynamic behavior of the non-conventional propulsion in the horizontal plane was carried out through experimental tests on a model built according to the pool's specifications. The presented model and the circular motion-oscillation conversion equipment was made by the author of the thesis in the laboratories of the Constanța Maritime University.

The comparative analysis of the results obtained from simulations and pool tests for the study of non-conventional propulsion refers to their behavior in calm water and in the assumption of horizontal placement. In this case, the largest differences of up to 10% occurred in the large-sized models due to the interaction with the walls of the test basin.

These tests can be repeated for any constructive forms thus providing possibilities to use the thrust functions in different applications.

Table 5.2. Percentage differences for the characteristic sizes of non-conventional naval thrusters

	Test 1	**Test 2**	**Test 3**	**Test 4**
Percentage differences d [%]	7.08	2.3	4.5	9

The analysis of the results presented in table 5.2, obtained by numerical simulation and those from experimental measurements show differences of 5 - 10%. 2 of the tests are below 5% and 2 between 5 and 10%. These results confirm the simulations performed and support the research of non-conventional propulsion systems. The possible causes of the appearance of these usual differences in CFD simulations come from the simplifying hypotheses presented in chapter III of this thesis. The values from the experimental data are generally higher than the simulated values because in the basin tests the real phenomenon is studied and the integration of the pressures does not fully cover the phenomenon of the non-conventional dolphin tail propulsion.

Analyzing the influencing factors of the discretization in the numerical analysis, a clear distinction can be made between:

1. discretization of structures that have a physical support,
2. the discretization of solid or fluid bodies which is a purely mathematical process (Fluent).

A series of identified factors that condition the discretization of the triangular plate are:

- the type of finite elements: they are chosen according to the type of problem and the domain of analysis, the desired precision, the variation of the unknown quantity, etc. Parabolic elements are preferred to linear elements, since for the same number of nodes the discretization solution with parabolic elements is more accurate than the one with linear elements. If there are several types of finite elements at the border between them, continuity must be ensured;

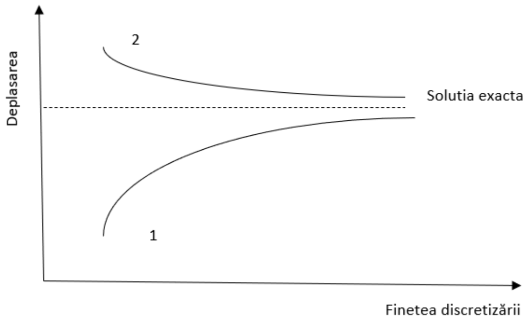


Fig. 5.5. The influence of the number of elements (nodes) on the accuracy in CFD analysis

- the size and number of finite elements influence the convergence of the solution (it is observed that with a larger number of elements the result approaches the exact solution but the excessive increase only leads to a very large volume of calculations and therefore increases the analysis time. The convergence of rule corresponds to curve 1 but there are finite elements for which the convergence is of the type of curve 2 or even with oscillating convergence;
- the positioning of the nodes, which is generally done uniformly in the structure. Discontinuities in the geometry or in the load require the selection of additional nodes. The transition from an area with fine discretization to one with modest discretization is done progressively, not suddenly;

  - the degree of uniformity of the network of finite elements. The use of elements with an exaggeratedly distorted shape, i.e. elongated elements and/or elements with faces that do not fit into a plane, is avoided. It would be preferable for the discretization with triangles to contain only equilateral triangles, the discretization with quadrilaterals to contain only squares and the spatial one with bricks to contain cubic elements, etc.;
- the establishment of border areas, for the correct introduction of border conditions;
- the maximum number of nodes or elements allowed by the Ansys Fluent program.

The differences identified between the performed simulations had differences of maximum 10% compared to the data presented in the simulation chapter. The data presented helped to validate the correct way of working on a simple triangular blade and verified the proper operation of ANSYS Fluent. The differences shown come from the impossibility of achieving very fine discretizations for the domain used within Fluent. The software compromise was the discretization of the areas of interest (the proximity of the structure and the free surface of the liquid) and a coarser analysis for the rest of the domain, all of which were done in order not to exceed the current hardware possibilities that limit the number of cells used in a simulation to a maximum of 4,000,000 cells. The VoF method involves adding a density feature and solving a CFD domain with a pressure difference based solver.

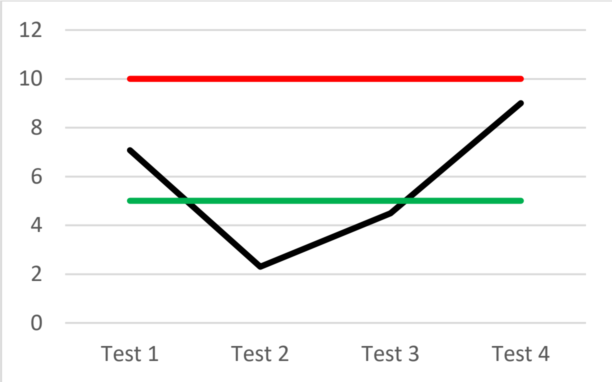


Fig. 5.4. Presentation of percentage differences (black) and the limits of 5% (green) and 10% (red)

The results presented for a triangular blade were made with the help of Ansys Fluent and reveal a behavior similar to that presented in the specialized literature and confirmed by the way nature has developed the tail of marine fauna. The alignment of the graphs shown for a triangular blade takes into account the effects of additional masses and Krylov forces.

There is no software that does not perform interpolation for plotting the graph of the function 5.4. In other words, any software will consider a number of points in the study interval, perform the calculation for those values and later by interpolation plot the graph. It should be taken into account that a small number of values to interpolate can lead to a low accuracy of the graphical results.

Functions 5.2 and 5.3 are an abstract notion for the considered speed steps that include all the characteristics of some hydrodynamic effects that are quite difficult to draw in mathematical equations. Therefore, verifying their validity is difficult. The pool test provides comparison data from a real scale structure and helps to validate numerical data obtained in Fluent.

The triangular blade at high frequency has a behavior dictated by the inertial forces and these suppress the thrust force response, which makes the thrust function value tend to 0 for high frequencies (high speed in the basin).

Also, in the case of long period motions (more than 30 seconds), the structure tends to behave as a reduced size structure due to the pressure reduction on the triangular blade.

In the numerical simulations, we removed the friction on the walls of the study domain in ANSYS Fluent of the respective areas, which corresponds to the behavior of propulsion in the open sea. The basin studies took place in a space of limited width which may influence the thrust/propulsion behavior under study through the thruster-basin interaction.

The field of non-conventional propulsion is in permanent development and involves research with the help of: numerical calculation programs dedicated to engineering, basin tests and tests on pilot structures.

5.4. Optimizing the performance of the "tail" or "dolphin tail" propulsion system

To improve the response characteristics of the "tail" or "dolphin tail" propulsion system in calm water, additional mechanisms and systems can be used in various passive or active forms. These mechanisms have the role of reducing the movements induced by the dolphin tail type propulsion in the body of the powered boat.

Passive systems do not have an external power source and do not require special control. These systems have the role of creating a moment/force opposite to the hull of the ship or semi-submersible structure to reduce or dampen movement in the desired direction. The most well-known passive systems that can be attached to the propelled body to increase the performance of the "tail" or "dolphin tail" propulsion system are:

- Chilli roll
- passive fins,
- Passive tank system and
- Passive system of moving masses.

Active systems are those in which the moments created are realized with the help of an external energy source and which are created/controlled with modern control systems. The most known active systems are:

- Active anti-roll stabilizers,
- active tank system,
- Active mass systems and
- Gyroscopes.

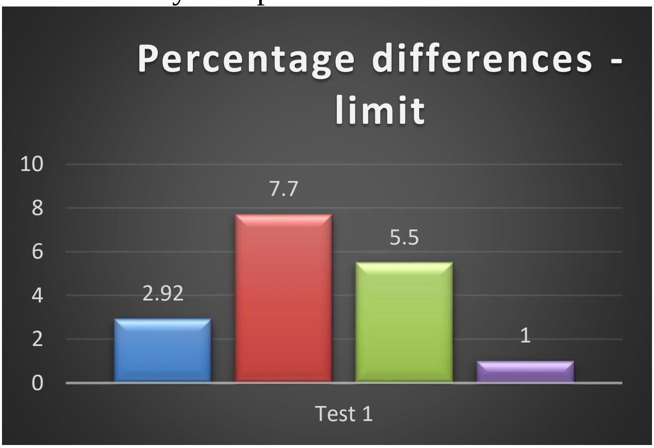


Fig. 5.4. Percentage differences relative to the limit established in test 1

The evaluation of the behavior of each propulsion blade will be done with the help of thrust functions for different operating situations and their plotting will be done for different working frequencies to identify the optimal working areas and will be validated with the help of basin tests. It is recommended to use in practice pool tests with the lowest possible percentage differences (fig 5.4 is the example given for test 1) for a high accuracy of the validation results.

CHAPTER VI
CONCLUSIONS

The present work collected and used all the updated information about unconventional propulsion systems and processed them in a numerical and practical way and represents a research for the application of the latest technologies. The propulsion studied in this work was studied at the Constanța Maritime University with the latest ANSYS programs and tested in the laboratory.

The work covered three major research directions:

- Simulation using ANSYS software in the CFD environment.
- Validation of ANSYS numerical results based on experimental results obtained in the laboratory.
- Analysis of thrust functions to identify the effect of the unconventional propulsion system.

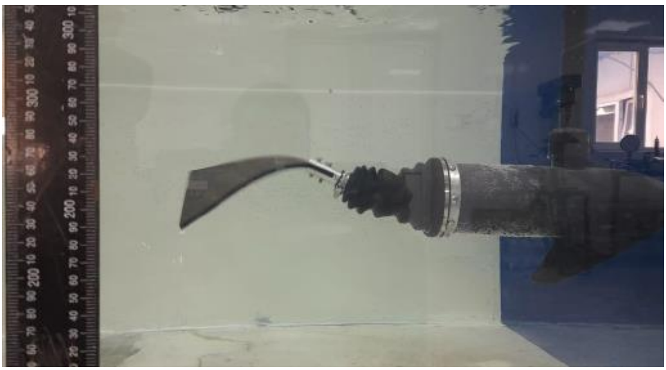


Fig. 6.1. Validation of ANSYS numerical results based on experimental results obtained in the laboratory

The paper contains all the elements of classical propulsion theory and shows how to perform the latest numerical modeling for propulsion installations in relation to turbulent theory and the SKE model.

The results of the thesis will be used for the following directions of study:

- Thrust force graphs for other similar systems
- Graphs of the yield functions shown
- Graphs of the identified percentage differences
- Analyzes relevant to the future needs of industry or academia

Chapter 3 contained a characterization of the Ansys TM Fluent software and how it works for the numerical analysis of unconventional marine propulsion. The calculation model scheme of the FLUENT program has been presented in detail for a better understanding of the calculation mode. These aspects can be used for any other type of propulsion.

The determination of the displacement of the "Dolphin tail" propeller blade was made based on the assumptions presented in the simulation chapter for the 3D model. The simulation scheme of the triangular blade was presented and graphically realized in the parametric simulation.

It is observed in the paper that the thrust force has almost constant values when the non-conventional propulsion is stabilized during the test. Higher or lower values are observed when the propulsion blade changes its angle of inclination with respect to the horizontal. That is why in all tests the blade is kept in a horizontal position to avoid these effects. The simulations performed and the laboratory tests all have the blade in the initial horizontal position.

During each type of test, the correctness of the measurements was monitored and a minimum of 3 measurements were performed in each situation. The presented values are the values that validate the numerical model.

During the tests, calibration is mandatory for each test to obtain the clearest possible indication of the result. Checks and inspections during each test should be done in the following order to ensure rigorous testing:

1. Verification of fixation in the measuring stand
2. Setting the oscillator to position 0
3. Start force measuring instruments
4. Checking and adjusting the starting angle to get the blades in the horizontal plane when starting the tests

The research carried out in this thesis presents numerous elements of analysis of the unconventional naval propulsion system. By plotting and validating the thrust functions for a blade, a complete analysis of how this propulsion works was achieved. The thrust functions or graphs drawn in this thesis can serve to provide the necessary information to design such a propulsion system or represent a starting point in naval propulsion projects

The results of the thesis were disseminated in various articles and prestigious scientific events in the field and accepted following a review process.

CHAPTER VII
PERSONAL CONTRIBUTIONS. RESEARCH DIRECTIONS

The research carried out in this thesis presents numerous elements of analysis of the unconventional naval propulsion system. Through the results of the thesis, we have identified the following possibilities for future research

1. Simulation of the action of non-conventional propulsion systems in waves
2. Continuation of experiments on the existing model
3. Studying other mathematical models and other software tools for numerical estimation of these problems

7.1. Simulation of the action of non-conventional propulsion systems in rough seas

As other analysis situations become available, along with the development of UMC's hardware resources, current simulations can be resumed and reanalyzed. New concepts in the field of naval propulsion can be evaluated.

For the analysis of naval propulsion, other systems and fields such as:

- Thrust force graphs for other similar systems
- Graphs of the yield functions shown
- Graphs of the identified percentage differences
- Presenting analysis relevant to future industry or academic needs

7.2. Continuation of experiments on the existing model

The existence of the test stand and scale models allows the evaluation of new situations for frequencies or working modes with various particularities.

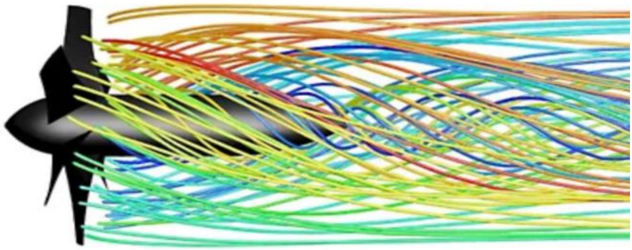


Fig. 7.2. Carrying out similar analyzes on other naval propulsions

Future research possibilities may include contributions regarding shape optimization on a multi-criteria basis taking into account in particular the thrust functions of the nalave propulsion, but also the structural strength of the blade. The existence of this stand for testing scale models within the Constanța Maritime University can be used to carry out experiments by teachers and students.

The triangular shape of the working blade and the constructional peculiarities may pose a challenge for future research projects and even for university students' degree projects.

7. 3. Studying other mathematical models and other software tools for numerical estimation of these problems

The functions drawn in this work can serve various applications or future research projects. They represent a direction that must be developed on a large number of mathematical models and experimental results to be able to develop the field of unconventional naval propulsion. Further research may include the study of phenomena related to the studied field in order to find appropriate solutions for the naval and renewable energy fields.

The electrical-mechanical conversion of the non-conventional marine thruster (Fig. 7.1) requires an electrical power source. That is why I believe that there is the possibility of developing a mixed system with a renewable resource (solar, wind, wave)

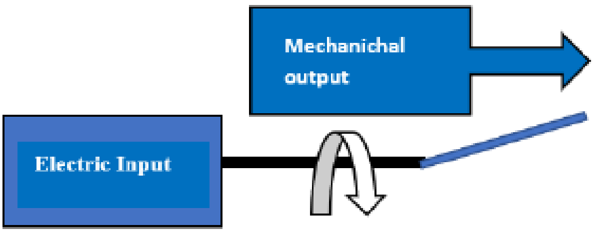


Fig. 7.2. The electrical-mechanical conversion of the non-conventional naval propulsion

The thrust functions or graphs drawn in this thesis can serve to provide the information needed to design such a propulsion system or represent a starting point in naval propulsion projects.

List of main abbreviations

3D	dimensional	dimensional
CFDs	Computational Fluid Dynamics	Numerically realized Fluid Mechanics
DNV	Det Norske Veritas	
DT	Dolphin Tail	"tail type" propulsion
dwt	Deadweight (of a ship)	Tonnage
IT'S LIKE	Issue control area	Emission control area
EEDI	Environmental energy design index	
EEOI	Energy efficiency operational index	Operational energy efficiency index
HFO	Heavy fuel oil	Heavy fuel
IMO	International Maritime Organisation	International Maritime Organization
LNG	Liquid natural gas	Liquid natural gas
LPG	Liquid petroleum gas	Liquefied petroleum gas
MARPOL	Marine Pollution Convention (IMO)	International Convention for the Prevention and Reduction of Pollution from Ships (IMO)

it	Edge length	side of: 5,10, 15 and 20
pala_ z [m]	Edge amplitude	the amplitude of the vertical movements of the blade
SOLAS	Safety of Life at Sea Convention (IMO)	Convention on the Protection of Life at Sea
T-square	Twenty-foot equivalent (container) units	20' container
UMC	Constanta Maritime University	Constanța Maritime University
θ[degrees]	angle amplitude	the amplitude of the angular movements of the blade
f_w [Hz]	frequency	the frequency of the angular movements of the blade
[η]	efficiency	yield
d [%]	Percentage difference	Percentage differences

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