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Hydrodynamic Jet Reaction Analysis for Marine Propulsion Control Units

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***Abstract*— Modern requirements in shipbuilding and marine engineering necessitate continuous improvement of propulsion systems, with particular emphasis on waterjet propulsors due to their high manoeuvrability and efficiency at elevated speeds. This study presents an analysis of hydrodynamic reaction forces generated during the interaction of a high-speed water jet with deflector surfaces of varying geometries. The results demonstrate that the jet deflection angle strongly influences efficiency, with the semi-circular surface achieving the highest energy utilization.**

The experimental investigation was conducted using a specialized laboratory test stand (HM 150.08), enabling precise measurement and quantitative assessment of momentum change. Four deflector geometries were examined: flat (90° deflection), semi-circular (180°), oblique (45°), and conical (135°). Experimental results were compared with theoretical predictions based on the conservation of momentum.

The results confirm that the jet deflection angle plays a critical role in system efficiency, with the semi-circular surface achieving the highest energy utilization and the oblique surface the lowest.

Keywords—conservation of momentum, deflector surfaces hydrodynamic jet reaction, marine waterjet propulsion, mechatronic control system.

I. Introduction

In fluid dynamics, changes in momentum during the acceleration, deceleration, or deflection of a flowing fluid lead to the generation of significant mechanical forces. These fundamental principles, theoretically described by Bernoulli's equation and the law of momentum conservation, form the basis for the design of both classical Pelton turbines and modern high-tech marine waterjet propulsion systems [1], [2].

Detailed control volume analysis is a critical element for accurately calculating reaction forces arising from fluid interaction with surfaces of varying geometry [1]. The methodology for visualization and quantitative measurement of jet momentum, enabling a precise transition from theoretical models to practical engineering calculations, is described in [2].

In the context of marine engineering and shipbuilding, understanding jet hydrodynamics is essential for optimizing thrust and propulsion system efficiency. The characteristics of waterjet systems are closely related to the profile of blades and guide vanes, where each degree of deflection affects the overall efficiency coefficient [3]. In the design of high-speed vessels, where reaction force is the primary principle for achieving design speed, precise analysis of the interaction between the jet and deflector systems is essential for improving hydrodynamic stability and energy efficiency [4].

Modern requirements for marine machinery, however, go beyond purely mechanical design, necessitating the integration of complex mechatronic control solutions. Reaction force data are no longer merely of static laboratory interest; they serve as input parameters for automated control systems. These hydrodynamic forces can be successfully modelled and transformed into algorithms for dynamic positioning and motion control [5]. The transition from physical force measurement to electronic control is further described in [6], where precise regulation of reactive flows through feedback systems is essential for achieving high manoeuvrability under complex marine conditions.

II. Materials and Methods

The experimental investigation was conducted using the HM 150.08 module, which includes a transparent tank, a nozzle with a diameter of 10 mm, and a lever mechanism with calibrated weights.

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The experimental setup and procedure are summarized as follows:

1. Deflectors: Four interchangeable aluminium deflectors were used: flat surface (*90°*), semi-circular surface (*180°*), inclined surface (*45°*), and conical surface (*135°*).

2. Measurement: The jet force was measured using a lever mechanism with calibrated weights to the lever mechanism (ranging from *0.2 N to 5 N*).

3. Flow rate: The volumetric flow rate ($\dot{V}$) was determined by measuring the time (t) required to fill *10 liters* of water in the measuring tank of the base HM 150 module.

4. Calculations: The jet velocity (v) was determined from the volumetric flow rate and nozzle cross-sectional area, while the theoretical force (F) was derived from the momentum conservation principle.

III. Results and discussion

A. Results

The experimental data (Tables 1-4) reveal a direct relationship between the flow rate and the generated force for all investigated surfaces at a volume of *10 liters*.

TABLE 1 DEVIATION 90° AT FLAT SURFACE

Specification	Measured	Calculated
Force, F [N]	Measurement time t for 10 L [s]	Flow rate, $\dot{V}$ [L/s]
0.5	46	0.21
1	32	0.31
2	22	0.45
3	17	0.59
4.5	13	0.77

TABLE 2 DEVIATION 180° AT SEMI-CIRCULAR SURFACE

Specification	Measured	Calculated
Force, F [N]	Measurement time t for 10 L [s]	Flow rate, $\dot{V}$ [L/s]
0.5	59	0.17
1	40	0.25
2	30	0.33
3	24	0.42
4.5	19	0.53

TABLE 3 DEVIATION 45° AND 135° AT INCLINED SURFACE

Specification	Measured	Calculated
Force, F [N]	Measurement time t for 10 L [s]	Flow rate, $\dot{V}$ [L/s]
0.2	52	0.19
0.5	40	0.25
0.8	25	0.40
1.0	21	0.48
1.5	17	0.59

TABLE 4 DEVIATION 135° AT CONICAL SURFACE

Specification	Measured	Calculated
Force, F [N]	Measurement time t for 10 L [s]	Flow rate, $\dot{V}$ [L/s]
0.5	49	0.20
1	35	0.29
2	27	0.37
3	22	0.45
4.5	16	0.63

Table 5-8 presents the values of the calculated force F_{th} and measured force F_{meas} for the different types of deflectors.

TABLE 5 FLAT SURFACE

Flow rate, $\dot{V}$ [L/s]	Flow, $\dot{V}$ [m³/s]	Velocity, w_1 [m/s]	Calculated force, F_{th} [N]	Measured force, F_{meas} [N]
0.21	0.00021	2.67	0.56	0.5
0.31	0.00031	3.94	1.22	1.0
0.45	0.00045	5.72	2.58	2.0
0.59	0.00059	7.49	4.42	3.0
0.77	0.00077	9.78	7.56	4.5

TABLE 6 SEMI-CIRCULAR SURFACE

Flow rate, $\dot{V}$ [L/s]	Flow, $\dot{V}$ [m³/s]	Velocity, w_1 [m/s]	Calculated force, F_{th} [N]	Measured force, F_{meas} [N]
0.17	0.00017	2.16	0.73	0.5
0.25	0.00025	3.18	1.59	1.0
0.33	0.00033	4.20	2.77	2.0
0.42	0.00042	5.35	4.51	3.0
0.53	0.00053	6.75	7.19	4.5

TABLE 7 INCLINED SURFACE

Flow rate, $\dot{V}$ [L/s]	Flow, $\dot{V}$ [m³/s]	Velocity, w_1 [m/s]	Calculated force, F_{th} [N]	Measured force, F_{meas} [N]
0.19	0.00019	2.41	0.22	1.19
0.25	0.00025	3.18	0.30	1.57
0.38	0.00038	4.84	0.46	2.39
0.48	0.00048	6.11	0.58	3.02
0.59	0.00059	7.52	0.71	3.72

TABLE 8 CONICAL SURFACE

Flow rate, $\dot{V}$ [L/s]	Flow, $\dot{V}$ [m³/s]	Velocity, w_1 [m/s]	Calculated force, F_{th} [N]	Measured force, F_{meas} [N]
0.20	0.00020	2.54	1.26	0.5
0.29	0.00029	3.68	2.03	1.0
0.37	0.00037	4.69	2.59	2.0
0.45	0.00045	5.72	3.16	3.0
0.63	0.00063	8.01	4.42	4.5

B. Results Analysis

Table 9 presents the difference between the calculated theoretical force (F_{th}) and the experimentally measured force (F_{meas}) for four surface types. The conical surface yields the highest theoretical value (*2.03 N*), while the inclined surface shows the lowest (*0.30 N*), compared to a constant measured force of *1 N*.

TABLE 9 COMPARATIVE DATA BETWEEN THEORETICAL AND MEASURED FORCE UNDER A WEIGHT OF 1 N

Surface	**Calculated Force, F_{th} [N]**	**Measured Force, F_{meas} [N]**
Flat surface	1.22	1.0
Semi-circular surface	1.59	1.0
Inclined surface	0.30	1.0
Conical surface	2.03	1.0

- The semi-circular surface (*180°*) demonstrates the closest agreement between theoretical and measured values, indicating higher efficiency and lower energy losses.

- The inclined surface shows a significant deviation between theoretical and measured force, indicating increased losses due to geometry-related factors.

- The conical surface, despite producing the highest theoretical force, also exhibits a notable discrepancy from the measured value, which may indicate limitations of the theoretical model under these conditions.

Figure 1 and Figure 2 illustrate the variation of the flow rate $\dot{V}$ for the four deflectors relative to the theoretical force F_{th} and the measured force F_{meas}, respectively.

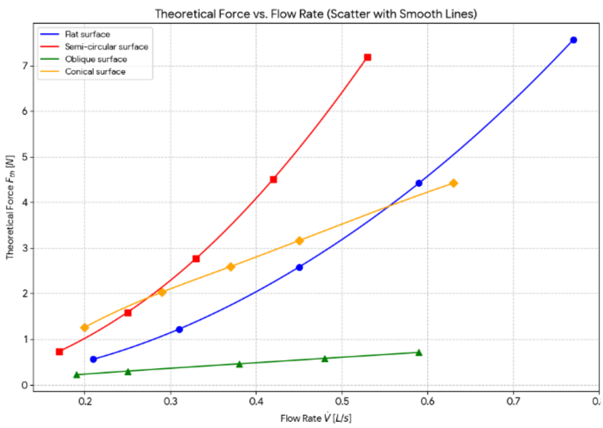

Fig. 1. Flow rate variation versus theoretical force.

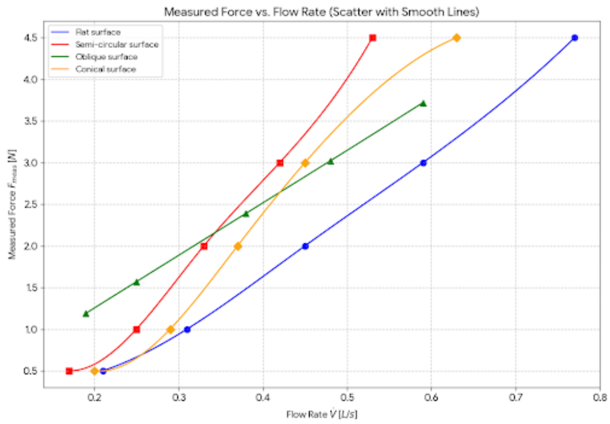

Fig. 2. Flow rate variation versus measured force

The graphical results suggest that, for the same force level, the lowest flow rate is required for the semi-circular surface.

This plot, shown in Fig. 2, illustrates the actual experimental results. The data presented correspond to the measured force (F_{meas}) and the associated flow rate ($\dot{V}$) for the four types of bodies.

- Flat surface: data from Table 1;
- Semi-circular surface: data from Table 2;
- Inclined surface: data from Table 3;
- Conical surface: data from Table 4.

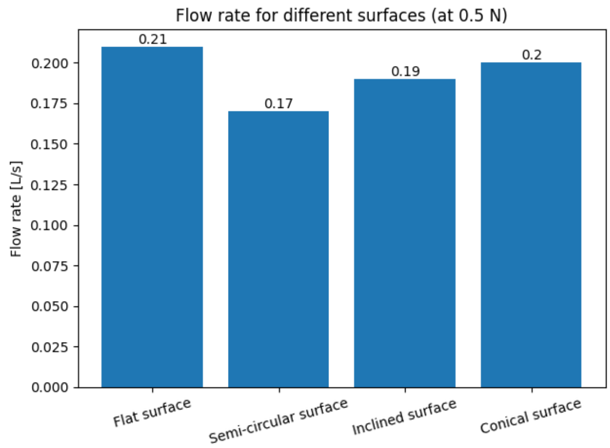

Fig. 3. Flow rate ratio for the four types of deflectors under a weight of 0.5 N

The graph clearly shows that, for generating the same force, the semi-circular surface requires the lowest flow rate, confirming its highest efficiency.

The conical surface exhibits the highest theoretical potential, but its actual efficiency depends strongly on the accuracy of jet deflection.

Table 10 illustrates the required volumetric flow rate ($\dot{V}$) in *L/s* to maintain a force of *0.5 N*. The highest flow rate is observed for the flat surface (*0.21 L/s*), while the lowest is associated with the semi-circular surface (*0.17 L/s*).

TABLE 10 COMPARATIVE DATA FOR FLOW RATE UNDER A WEIGHT OF 0.5 N.

Surface	Force, 0.5 [N]	Flow rate, [L/s]
Flat surface	0.5	0.21
Semi-circular surface	0.5	0.17
Inclined surface	0.5	0.19
Conical surface	0.5	0.20

C. Discussion

The analysis of the results indicates that the semi-circular surface utilizes the energy of the water jet most efficiently, as it deflects the fluid by *180°*, thereby maximizing the change in momentum. In contrast, the inclined surface demonstrates the lowest level of energy utilization, requiring a significantly higher flow rate to achieve the same reaction force.

These differences in hydrodynamic performance are relevant for the design of Marine Propulsion Control Units. Reaction force data are transformed into control algorithms that regulate pump speed and nozzle angle in waterjet propulsion systems [5]. Accurate modelling of these forces enables automation systems to compensate for nonlinearities and improve vessel manoeuvrability. The use of high-efficiency deflectors (such as semi-circular geometries in Pelton turbine buckets) can be applied in the design of more efficient reversing devices in shipbuilding.

IV. CONCLUSIONS

The conducted study successfully demonstrates the principle of momentum and its practical application in marine engineering. The results indicate that surface geometry is a determining factor in hydrodynamic reaction efficiency. The semi-circular geometry proves to be the most efficient, while the inclined surface offers the least resistance and consequently generates the smallest force.

The obtained data can be used as a basis for calibration of sensors and control systems in waterjet propulsion applications.

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