

Comprehensive Experimental Study on the Effect of Flow Direction, Pitch Angle, and Waves on Tidal Turbine Performance

A. Farhoudi, R. Shafaghat *, B. Alizadeh Kharkeshi

Sea-Based Energy Research Group, Babol Noshirvani University of Technology, Babol, Iran.

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*Corresponding author: mogshu@gmail.com (R. Shafaghat)

Abstract

The performance of tidal turbines depends on geometric characteristics and wave-current properties. This study investigates the performance of a three-bladed, 1:6 scale horizontal-axis tidal turbine (HATT), with particular emphasis on the underexplored influence of flow direction—a critical factor for bi-directional tidal sites. The effects of various variables, including pitch angle, flow direction, electrical load, and wave-current interaction under different tip speed ratios, were systematically examined. Power and moment of force coefficients (C_p and C_m), along with their TSRs, were considered as the objective functions. The wave characteristics of the Khoran Strait were scaled using Froude's methodology. The C_p and C_m at the optimal pitch angle range for downstream flow do not exceed a maximum increase of 6.5% compared to the no-wave mode. When the HATT operates at its optimal variables, the power coefficient increases by 35% relative to the lowest level. However, due to the generator's characteristics, the increases in power and moment of force follow a non-linear trend. Variations in C_p and C_m at different TSRs also exhibit a parabolic pattern. A key novel contribution of this study is the comprehensive comparison of upstream versus downstream flow configurations, revealing that the turbine's power and moment of force coefficients in the upstream flow state increase by 36.1% and 18.1%, respectively, compared to the same pitch angles in the downstream flow state, due to the absence of the nacelle impeding the current. This finding provides crucial guidance for the design of bi-directional tidal turbine installations.

Keywords: Horizontal axis tidal turbine, Pitch angles, Wave, Upstream/Downstream flow, Moment coefficients.

Nomenclature and abbreviation

A	Rotor area (m^2)	ω_R	Rotor's rotational velocity (RPM)	C_m	Moment of force coefficient (-)
C_p	Power coefficient (-)	ω_{ang}	Rotor's angular velocity (rad/s)	k_d	Wave number (-)
R	Rotor radius (m)	ρ	Fluid density (kg/m^3)	I	Electrical current (A)
g	Gravity (m/s^2)	γ	pitch angle ($^\circ$)	HATT	Horizontal Axis Tidal Turbine
M	Moment of force (N.m)	U_{cv}	Current velocity (cm/s)	V	Voltage
P	Power (W)	ω_{wf}	Wave frequency (Hz)	(S/N)	Signal-to-noise
TSR	Tip Speed Ratios (-)	H	Wave height (m)	ANOM	Analysis of means
D	Rotor diameter (m)	ν	Kinematic viscosity of water (m^2/s)	Re	Reynolds number

1. Introduction

Harnessing the renewable energy of tidal currents can potentially reduce fossil fuel consumption and may offer environmental benefits, with some studies suggesting positive effects such as marine growth and habitat formation on tidal turbine species [1], though definitive conclusions are still under investigation [2]. One of the most prominent conventional devices for extracting energy from tidal currents is the HATTs [3, 4]. Various studies indicate that HATTs are utilized both individually and in arrays, and interactions within tidal turbine

arrays under the influence of current flow are among the most critical topics [5-10]. The optimal performance of tidal turbines depends on physical and geometric variables such as blade geometry, dynamic loadings, water depth, pitch angle, and flow direction. It is also influenced by flow conditions around the HATTs, characterized by combinations of shear velocity profiles, waves, and turbulence levels. The following studies investigate turbulence and shear flows, which have been

prominent topics concerning HATT performance in recent years.

Druault and Germain [11] empirically investigated the effect of upstream turbulent flow alterations using two mounted obstacles in a current-circulating flume tank on the performance of a 1:20 scaled HATT. Their purpose was to examine the turbine's blockage effect in a high Reynolds number turbulent flow and analyze changes in the flow regime. The results indicated that the turbine's blockage parameter has little impact on Reynolds number. Another parameter investigated is the mean axial velocity deficit; when the incoming current flow is uniform, most of the mean axial velocity deficit ($\sim 30\%$) is observed between the hub and obstacles, while at the rotor edge, this value reaches 10%. Magnier et al. [12] experimentally examined the impact of shear flow on HATT blade loading alterations in a flume tank. They employed four different sheared velocity profile panels in upstream incoming current flow and discovered that the phase average of the load and the velocity perceived by the blades, with a certain phase delay, depend on the rotor's rotational velocity and the shear in the incoming current flow caused by turbine induction effects. With four sheared velocity grid arrangements at a current velocity of 1 m/s, the differences in power coefficients ranged between 3% and 7%, with the maximum C_p of 0.45 observed in the absence of the solid plate in the panel. Capone et al. [13] showed that tip-vortex cavitation had little effect on turbine performance but slightly increased noise, while sheet cavitation significantly reduced power and raised noise levels. An upstream support structure caused minor power loss and delayed sheet cavitation without affecting thrust. Mycek et al. [9] investigated the effect of turbulence intensities, 3% and 15%, on a single HATT. The operational range of the HATT TSR for current velocities of 0.4–1 m/s was defined between 3 and 6. The power coefficient at these two turbulence rates increases with increasing current velocity. The minimum increase in C_p at a turbulence intensity of 15% for various current velocities is reported to be 10%, and for all upstream current velocities except the highest (1 m/s), the C_p is below 0.4. However, at 3% turbulence intensity, except for the lowest current velocity (0.4 m/s), the C_p is slightly above 0.4.

Another critical geometric variable in investigating HATT performance is the turbine's stanchion cross sections, including its dimensions, shapes, and distances from the turbine rotor [14, 15]. Shoukat et al. [16] experimentally examined the effects of

stanchion positions on rotor loads of a HATT. Their study on four different distances between the stanchion and rotor at varying current velocities revealed that as the distance decreased, the structural loading on the rotor fluctuated significantly, but had little effect on the mean values of the turbine performance coefficients.

Researchers have recently studied the interactions of HATT arrays under both wave and no-wave conditions in numerous publications. Mike et al. [10] replicated the earlier study [9], this time focusing on the interactions between two axially aligned HATTs. Their findings indicated that the maximum C_p of the downstream HATT decreased by at least 50% at a turbulence rate of 3%, dropping from 0.4 for a single turbine to 0.2. However, if the upstream flow has a higher turbulence rate, the downstream turbine recovers more energy. Watanabe et al. [6] examined the effect of two HATTs positioned at a specified distance in the presence of waves. Experiments were conducted under five different wave conditions and compared to no-wave modes. The power coefficients of the upstream turbine were significantly higher than those of the downstream turbine. The mean power coefficient of both upstream and downstream turbines in wave modes is slightly higher than in no-wave modes. The wave height variations had minimal impact on the mean power coefficients. Additionally, with an increase in wave height and period, the moment of force variations increased. Some studies have reported a slight increase in the mean power coefficient of upstream and downstream turbines under wave conditions compared to no-wave conditions, although this result is not consistent across all literature and depends on specific experimental or environmental factors [3, 17-19].

Extensive studies have also been conducted to evaluate the HATTs in the presence of waves [20]. Draycott et al. [18] carried out an experimental study to assess the impact of irregular waves interacting with tidal currents on turbine loading over a complete tidal cycle. Using a 1:15 scale turbine model, they simulated both following and opposing wave-current scenarios. They found that opposing currents significantly increased wave heights and load fluctuations up to five times greater than current-only cases while mean performance remained stable. Zhang et al. [21] conducted experiments on a 1:60 scale HATT with a rotor diameter of 0.2 m, operating under wave-only, current-only, and combined wave-current conditions. Their findings indicated that both the mean power coefficient (C_p) and its standard deviation peaked at a TSR of 3.5. However, it is

important to note that the optimal TSR for maximum C_p and associated fluctuations is highly dependent on the specific rotor and blade design. Variations in blade geometry, control strategies, and environmental conditions can significantly influence these performance metrics. For instance, other studies have reported different optimal TSR values, underscoring the necessity to consider turbine-specific characteristics when evaluating performance under varying flow conditions [22]. Luznik et al. [23] conducted experiments on a 1:20 scale three-bladed horizontal axis tidal turbine in a large tow tank to investigate the influence of surface waves on turbine performance. The wave conditions were modeled to represent intermediate swells typical of the U.S. eastern seaboard's continental shelf. Their results showed that, while surface waves induced significant cyclic variations in torque, rotational speed, and tip-speed ratio across the wave phase, the average C_p over the wave cycle remained similar to that in steady (no-wave) conditions. These findings suggest that although waves may not always reduce average power output, they introduce considerable unsteady loads that could impact turbine fatigue life and control strategies. This emphasizes the importance of incorporating wave-induced dynamics into the design and deployment of tidal turbines, particularly in shallow or energetic wave environments. Sanchez et al. [24] analyzed a HATT with a 0.9 m diameter in the presence of regular and irregular waves using two control strategies: velocity control and moment of force or torque control. The mean C_p remained consistent regardless of the wave type or control strategy. However, moment control led to a 40% increase in blade root bending moment fluctuations compared to velocity control. Sanchez et al. [25] examined the performance of tidal stream turbines under combined wave-current conditions in a towing tank, using current velocities of 0.5 and 1.0 m/s with waves 0.2–0.4 m high and 2 seconds. They found that while the average C_p was similar to current-only cases, the standard deviation in C_p increased significantly with waves, especially at the lower current speed. This indicates greater power fluctuations due to wave-induced unsteadiness. The variation in C_p also increased with TSR, highlighting interactions between wave frequency and turbine rotation. Torque analysis showed that lower wave heights reduced torque variation by up to 50%, while higher current speeds increased it by 70–80%. These results underscore the importance of considering wave-current effects in turbine design and control to reduce unsteady loading and extend component lifespan. Zang et al.

[26] investigated a HATT under two conditions: no wave and with waves of period (1–2 s) and heights (4.5–8.5 cm) alongside current flows in a recirculating channel. They found that power variations increase when waves are added to currents. Huang et al. [27] conducted a numerical investigation of wave-current interactions on a floating counter-rotating HATT, focusing on how wave-induced motions affect their hydrodynamic coefficients. The results showed that the mean power and thrust coefficients decreased by 9% and 5%, respectively, primarily due to suboptimal rotor operation caused by oscillating inflow. Zhang et al. [28] experimentally studied the effect of waves traveling with the current on a tidal turbine's wake. While mean velocity profiles remained largely unchanged, turbulence intensity increased near the rotor top tip and free surface due to wave orbital motion rather than measurement location. These results highlight the role of waves in amplifying wake unsteadiness, which is important for turbine durability.

The immersion depth is also a significant parameter in evaluating the performance of HATTs.

Lust et al. [29] experimentally studied a two-bladed HATT at two submergence depths (1.3D and 2.25D) in wave and steady flow conditions. While average performance metrics such as power and thrust coefficients were largely unaffected by waves or depth, significant unsteady fluctuations occurred during wave passage, especially near the surface, emphasizing the need for careful depth placement to balance energy output. Dufour et al. [30] experimentally compared the performance of HATTs named Magallanes and Sabella, scaled 1:28 and 1:20, respectively, in wave conditions with an amplitude of 95 mm and a frequency of 0.5 Hz at two immersion depths of -1 m and -0.6 m and current-only cases. They found that power coefficients at an immersion depth of -1 m are higher than at -0.6 m. Concerning Sabella, in current-only conditions, when the immersion depth changes from -1 m to -0.6 m, the maximum power coefficient decreases by about 10%. Conversely, concerning Magallanes, when waves are involved, the maximum power coefficient increased by 10% compared to the current-only case at both immersion depths. Allmark et al. [31] experimentally studied a scaled tidal turbine under irregular waves and shear flow. They found that rotor loading varies with depth and angular position, and that upstream flow structures significantly affect blade loads, especially at lower frequencies.

Few studies have experimentally investigated the impact of flow direction on HATTs in recent years. This may be due to the technical and financial challenges of replicating bi-directional flow in laboratory settings. Research has also focused more on factors such as turbulence, wave-current interactions, rotor pitch variation, and design [32, 33]. Van Ness et al. [34] conducted experimental tests comparing blade pitch and speed control strategies for a horizontal-axis current turbine in time-varying flow. Using a scale model, they showed that pitch control effectively reduced turbine torque and thrust loads compared to both overspeed and underspeed control strategies. This advantage was more pronounced at lower Reynolds numbers, suggesting pitch control may be particularly beneficial for small-scale or low-speed applications. Additionally, the rise of reliable numerical simulations has shifted attention away from physical experiments [35-37]. Wang et al. [38] conducted a comprehensive performance evaluation of China's first megawatt-scale HATT, combining numerical simulations, experimental testing, and sea trials. Their findings showed that the turbine achieved a peak output of 1.442 MW during ebb tide conditions. Performance measured by power and thrust coefficients was consistently higher when the rotor was placed upstream of the supporting stanchion. This improvement is attributed not to the presence of the stanchion itself, but to the absence of upstream flow obstruction, which occurs when the rotor is downstream. The stanchion in the downstream state partially absorbs incoming energy and disrupts the flow, leading to reduced efficiency. Frost et al. [39] investigated the impact of flow direction on a three-bladed HATT performance characteristics with a 0.8 m rotor diameter in a yaw turbine and twisting blade mechanism through 180° rotations numerically. They found that the yaw mechanism, which allows the HATT to face the current flow, is more practical and performs better compared to the twisting mechanism designed to harness bi-directional current flow. Experiments were conducted at three clearance distances (1.8, 2.8, and 3.8 m) from the stanchion to the rotor plane in upstream and downstream flow modes. The immersion depth was fixed, and evaluations were made using experimental and numerical methods. The HATT exhibited better performance in the upstream mode. The results showed that the greater the clearance distance, the better the HATT performance, with the optimal distance being 3.8 m. Thus, there remains a significant gap in experimental research focused on how flow direction influences the performance of HATTs.

Farhoody et al. [40] conducted a comprehensive investigation into the effects of wave-current interactions and pitch angle variations on the performance of a 1:6 scale HATT. Utilizing Froude scaling, the wave-current conditions of the Khoran Strait were modeled for laboratory experiments. The results showed that the HATT achieved optimal performance with wave and no-wave modes at pitch angles of 18.77° and 22.72°, respectively, and the optimal pitch angle range was between 18.77° and 22.77°. The optimal wave number was determined to be 3.43, resulting in a 22.3% increase compared to no-wave cases.

Before Farhoody's study, Alamian et al. [41] experimentally assessed a 100 W horizontal axis tidal turbine (HATT) using towing tank tests under still water conditions. Key parameters such as immersion depth were evaluated, with results showing the highest efficiency near the water surface, achieving a 19–32% performance improvement at zero tip immersion compared to deeper submergence. Complementary to this, Amiri et al. [42] conducted a numerical study on the same HATT to determine the optimal fixed pitch angle using CFD. While previous studies have explored individual performance factors, the novelty of Farhoody's work lies in its comprehensive examination of multiple variables, including the underexplored effect of flow direction.

Despite extensive research on HATT performance under various flow conditions, the influence of flow direction—a critical factor for bi-directional tidal sites—has received remarkably little experimental attention, largely due to the technical and financial challenges of replicating reversing flows in laboratory settings. Previous studies have primarily focused on turbulence, wave-current interactions, and pitch angle variations, but systematic comparisons of upstream versus downstream configurations with realistic wave spectra and controlled pitch adjustments remain scarce. To address this gap, the present study provides the first comprehensive experimental quantification of how flow direction affects the hydrodynamic performance of a 1:6 scale HATT. By extending the earlier work of Farhoody et al. [40] and applying a 180° pitch-angle reversal to enable downstream operation, we systematically evaluate the coupled effects of flow direction, pitch angle, wave number, electrical load, and current velocity using the Taguchi method for efficient experimental design. The key novelty lies in the direct, quantitative comparison of power and moment coefficients between upstream and downstream flows across multiple wave

conditions, revealing that upstream operation yields up to 36.1% higher power coefficient and 18.1% higher moment coefficient. These findings not only fill a critical gap in the literature but also provide actionable design guidelines for yaw-controlled or bidirectional tidal turbine installations, demonstrating that orienting the rotor to face the incoming current (upstream) is essential for maximizing energy extraction and reducing flow-induced losses from nacelle and stanchion interference.

This study is aligned with the previous work of Farhooei et al. [40], with the difference that the HATT is examined and compared in upstream and downstream flow modes. For alteration of flow direction from upstream to downstream position, the optimal pitch angles obtained from the previous work were investigated by adding a 180° adjustment to the rotor pitch angle. In upstream flow, the current first impacts the hub before reaching the rotor blades, while in downstream flow, the current first strikes the nacelle bottom plate and the stanchion before reaching the rotor blades, leading to a notable reduction in power coefficients due to energy loss. The aim of this study is to investigate how variables such as pitch angles, current velocities, flow directions, electrical loads, and wave characteristics with varying heights and periods influence the main hydrodynamic coefficients of the HATT, including power and moment of force. Taguchi's method has been used as a design of experiments method and to evaluate the influence of different variables.

2. Methodology

Experiments were conducted on a 1:6 scale HATT in the towing tank at the Sea-Based Energy Research Group of Babol Noshirvani University of Technology. The towing tank measures 11×3×3 m, with a water depth of 1.85 m. The tank is equipped with two principal mechanical features: a traction system and a wave maker. The traction system uses a 7.5 kW motor to pull the carriage along a 9 m rail at various speeds toward the wave damper, enabling the HATT to operate at different current velocities or under varying TSRs. The wave maker, a flap-type mechanism, generates regular waves with diverse characteristics. To maintain consistent conditions, a wave elimination zone with a porous structure dampens the waves, mitigating the effects of wave reflections and wake flow during wave-current interactions.

The HATT traverses three distinct distance intervals to simulate varying current flow velocities: an initial 1.4 m with increasing velocity, a subsequent 4.4 m with constant velocity, and a final 1.6 m with decreasing velocity until a

complete stop. The starting point, where the turbine begins to move, and the endpoint, where it halts upon hitting the damper, are depicted in Figure 1. Data were recorded, averaged, and analyzed in constant velocity intervals. The wave maker, wave maker control room, carriage traction motor, towing tank dimensions, and the turbine's travel intervals are indicated in Figure 1. Assuming the rotor diameter (1.15 m) and towing speed as the characteristic length and current velocity, respectively, the Reynolds number range ($Re = \frac{U_{cv} \times D}{\nu}$), deduced from the HATT carriage speed, spans from 661,250 to 1,150,000, corresponding to current velocities of 0.575 to 1 m/s.

The HATT was investigated in both upstream and downstream flow directions, with and without wave modes. Figure 2 provides a 3D and 2D side view of the towing tank, showcasing the wave maker, wave damper, wave-current flow direction, and HATT installation positions for both flow directions. In upstream flow, the HATT front hub always faces the incoming current flow before reaching the rotating blades. Conversely, in downstream flow, the incoming current initially strikes the back of the nacelle and stanchion before reaching the blades. The immersion depth of the HATT from the hub center to the water-free surface is fixed at 0.775 m, but the current flow direction varies. Comprehensive design details of the towing tank components, proximity sensor holder, and principles of the wave elimination zone are well studied in a previous paper [40].

2.1. Assembly of HATT Components and Rotor Design

In this study, the cross-sectional shape of the 3-bladed HATT stanchion is rectangular. In addition to the stanchion cross-sectional shape, other physical parameters of the HATT, such as the geometry of the hub and the blade section profile, can influence the HATT's performance characteristics [39, 43]. Detailed HATT design components and additional measurements are presented in Table 1. The blade profile sections were designed using the NACA 63-8xx hydrofoil with Q-blade software. The properties of the HATT blade at different radial sections are based on a previous paper by Farhooei et al. [40]. To adjust the pitch angle, the rear face of the hub is considered as a reference surface; the distance between the hub's rear face and the thickest hydrofoil's trailing edge is called the pitch distance. Figure 3 illustrates how this pitch distance is converted into the pitch angle (γ) in degrees for analysis. The pitch angles used in the experiments were 22.72° for upstream flow and 198.77° and

202.72° for downstream flow. Figure 4 displays the exploded view of the HATT components, all of which are sealed to remain dry underwater. Additionally, two proximity sensors are installed: one inside the nacelle to measure the rotor's rotational velocity and another on the towing tank carriage to measure the linear velocity of the current flow [40].

2.2. Target area and wave characteristics scaling

Current flow velocity and power density are pivotal parameters for determining the ideal location for HATT installation. Based on these criteria, the Persian Gulf and the Oman Sea in southern Iran have outstanding potential for tidal energy [44]. Thorough investigations have identified the Khoran Strait as the target area for HATT installation and wave-current flow characteristic scaling due to its high average power density [8540 (W/m²)] compared to neighboring regions [40, 45]. The depth of the target area must correspond to the turbine's installation depth in laboratory conditions, scaled to 1:6. The Khoran Strait, with a maximum depth of 10 m, meets this requirement. Fig. 5 shows the geographical location of the Khoran Strait as a case study zone [44, 46]. Laboratory experiments were conducted with current flow velocities between 0.5 and 1 m/s, consistent with the flow conditions of the target area [40, 46].

According to Zanos et al. [47], the mean annual wave characteristics in various parts of southern Iran have been compared. The Khoran Strait waves have wave periods and heights of 3.55–1.4 s and 0.45–0.55 m, respectively [40, 47]. The HATT model is scaled 1:6; based on wave scaling relationships (Froude scaling), the corresponding laboratory-scale wave heights and frequencies are between 5–13 cm and 0.567–0.683 Hz, respectively [40, 48, 49]. The 1:6 scale is derived from the ratio of the laboratory turbine's rotor diameter to that of the full-scale prototype. Specifically, the laboratory turbine has a rotor diameter of approximately 1.15 meters, and based on the power coefficient equivalence ($C_{P_{Lab}} = C_{P_{ACTPRO}}$) and the target maximum power output density of 8540 W/m² in the Khoran Strait, the corresponding full-scale prototype rotor diameter is calculated to be approximately 6.9 meters. Therefore, the geometric scale of the laboratory model relative to the prototype is approximately 1:6. This scale is also used in Farhody et al. [40] previous research by Farhody et al. [40], assuming a current flow velocity of 0.5–1.5 m/s. The wave characteristics are summarized in Table 2 using dimensionless numbers called wave numbers (k_d) [40]. According to prior research by Farhody et al. [40], wave number 3.43 has the longest wavelength among all waves.

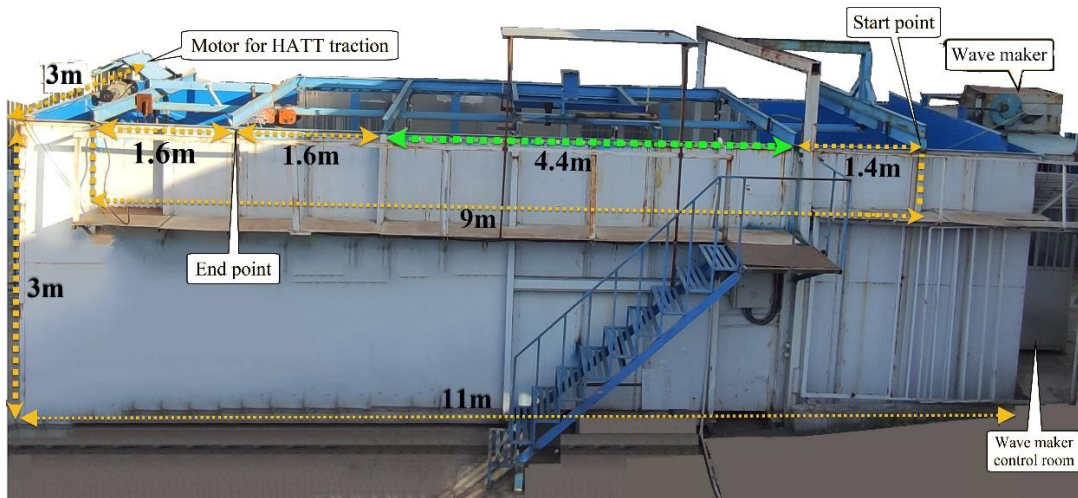
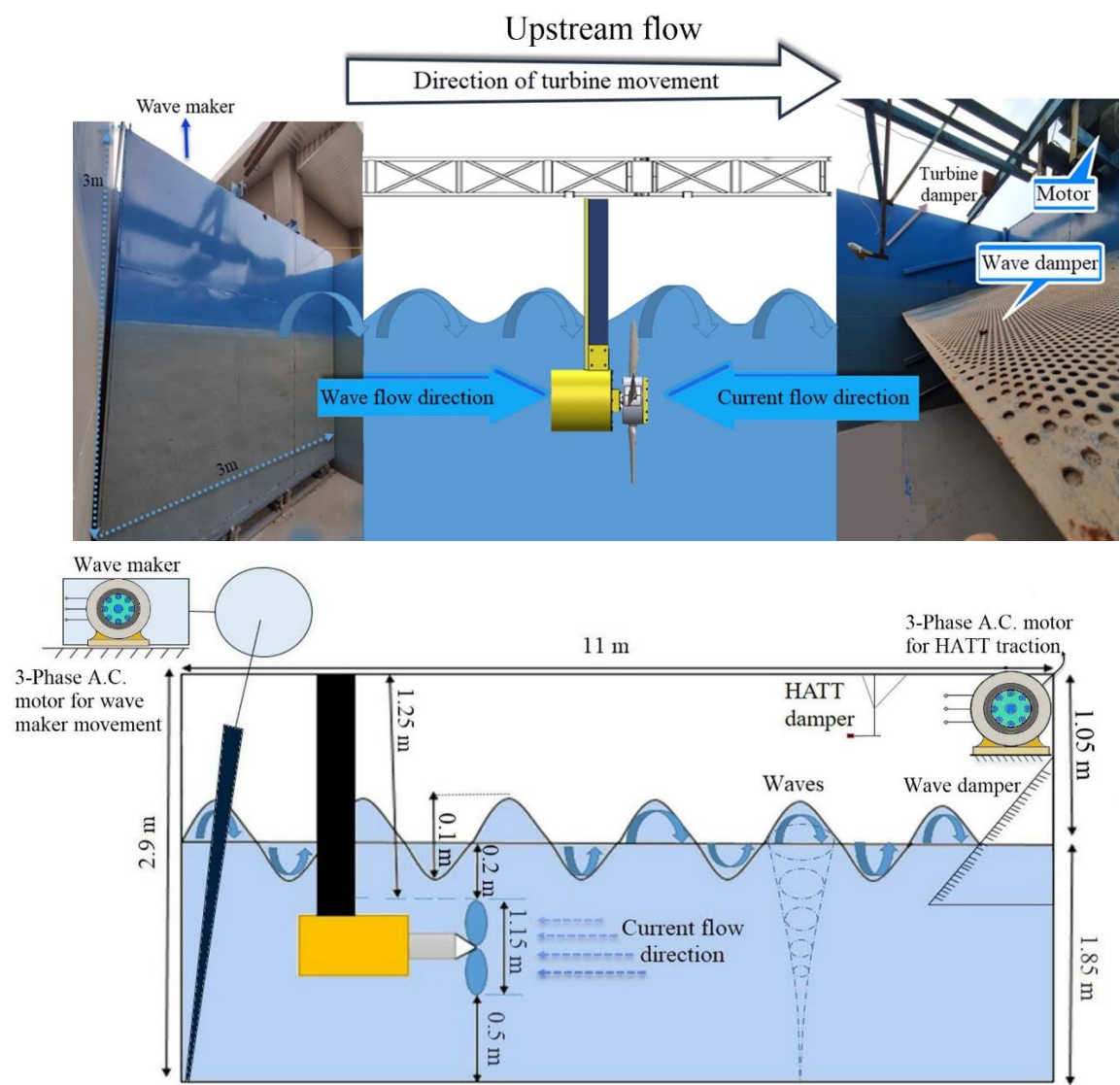
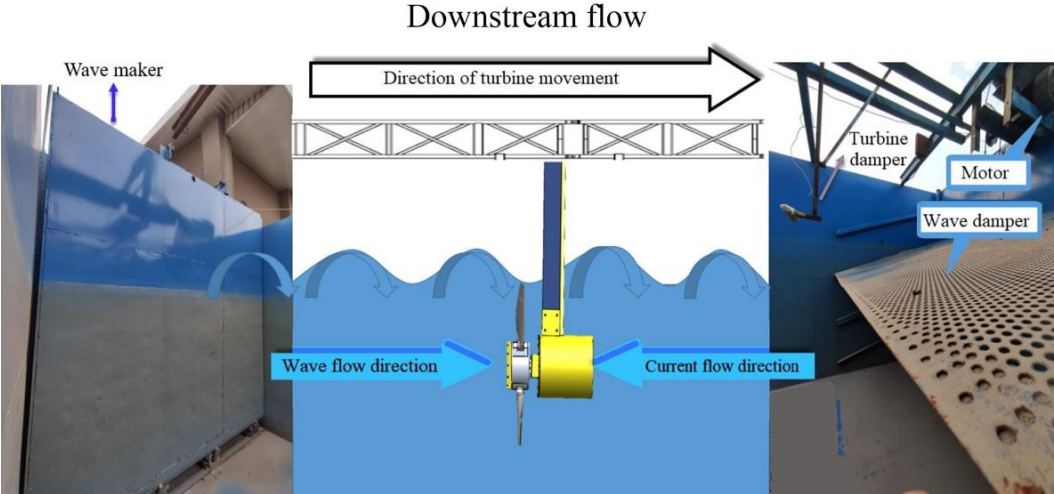


Figure 1. Towing tank dimensions and travel distance interval range of the HATT



(a)



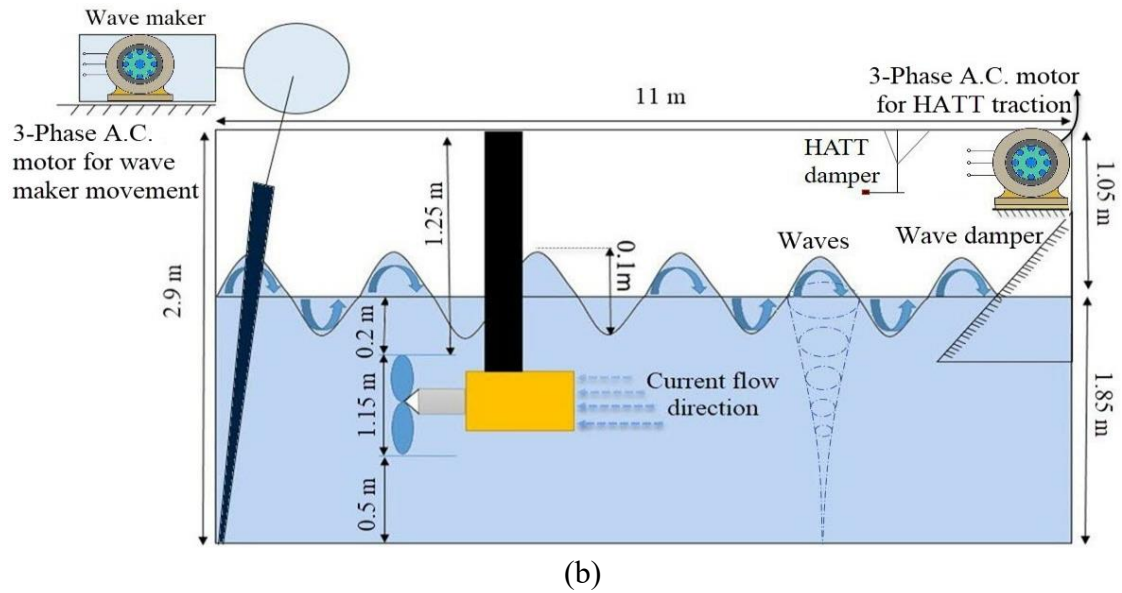


Figure 2. 3D and 2D schematic side view of (a) upstream flow (b) downstream flow with the HATT position and components [40]

Table 1. Description of HATT model components [40]

HATT components	HATT measurements (cm)
Blade length	47
Blade root length	4
Blade root circular diameter	4.5
Hub center from the bottom of circular blade root	10.5
HATT total length (from nacelle rear plate to nose)	51
Nacelle length	32
Nacelle diameter	32
Hub diameter	25
Hub length	12
Rotor diameter	115

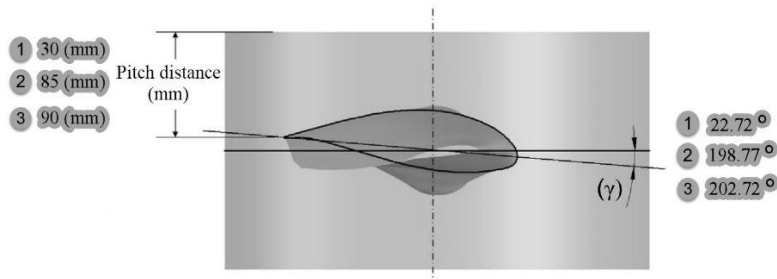


Figure 3. Correlation between pitch distance and pitch angle with their conversions in SolidWorks software [40]

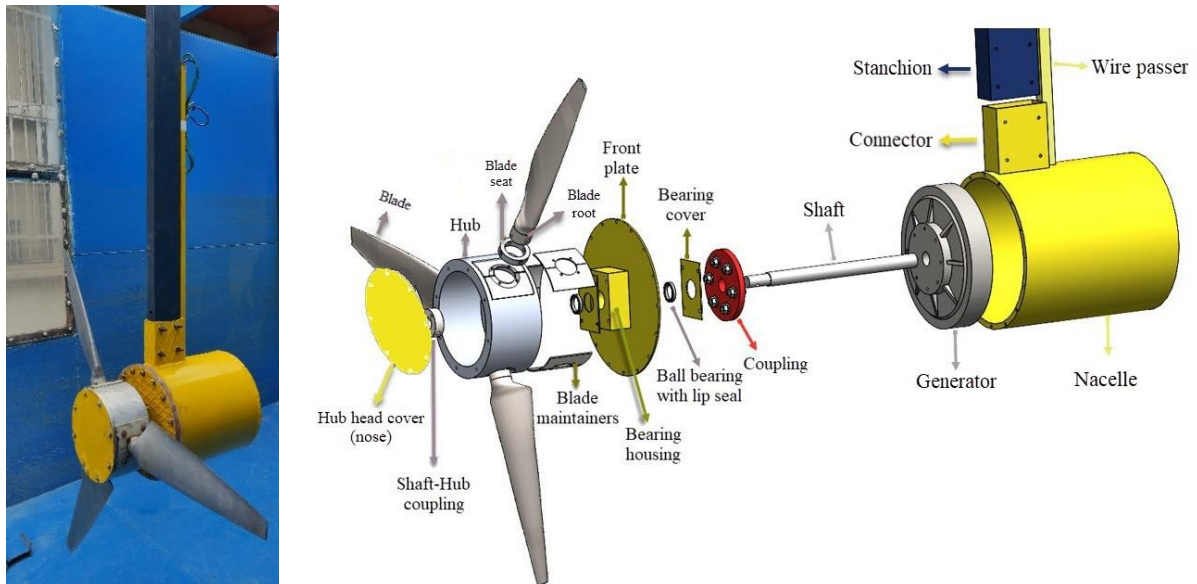


Figure 4. Exploded view of HATT components in SolidWorks and final constructed structure [40]

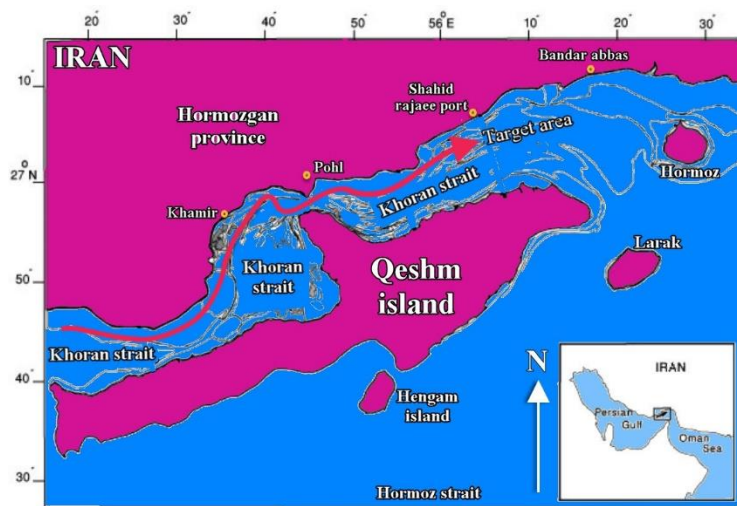


Fig. 5. Geographical location of target area (Khoran Strait) [40]

Table 2. Wave Characteristics [40]

$k_d = \frac{\omega_{\text{wave}}^2 H_{\text{max}}}{g} (\times 10^{-3})$	wave height (cm)	Wave frequency (Hz)
2.37	5	0.683
2.45	7.5	0.576
2.94	9	0.576
3.27	10	0.576
4.49	13	0.583
3.43	10.5	0.576

2.3. Data acquisition system, Calibration and Uncertainty

The electrical circuit diagram for power generation in data acquisition is presented in Figure 6. This circuit features four key outputs: voltage, current, rotor velocity, and current flow velocity. According to Farhody et al. [40], the electrical panel includes several critical components: a

velocimeter, tachometer, rheostat, rectifier (for converting 3-phase AC to DC), voltmeter, ammeter, a battery for panel charging, connectors, and an on/off switch. The panel is mounted above the HATT stanchion, and a camera records the data. The rheostat functions as an alternating electrical load to control rotor velocity, manage voltage-current variations, and enhance HATT

power output. Instantaneous calibration of voltage and current is achieved via the potentiometer screw on the electrical panel, yielding a calibration coefficient of 0.99 [40]. Two proximity sensors (PR12-DP) are used to measure the current flow velocity and the rotor's rotational velocity; the calibration method for these two sensors is preferably described in reference [40]. The calibration coefficients for rotor rotational velocity and current flow velocity are 1.08 and 0.97, respectively [40]. It should be noted that the carriage velocity is actually the current flow velocity. The percentage uncertainty for rotor rotational velocity is 3.5%, and for voltage, current, and current flow velocity, it is up to 2.8% [40]. To ensure system accuracy and responsiveness, each experiment was conducted three times, as verified by the uncertainty analysis [40].

3. Design of experiments by Taguchi method

According to Farhooody et al. [40], experiments were conducted in upstream flow for five different pitch angles. Optimal performance in wave modes was achieved at a pitch angle of 18.77° , while in no-wave modes, the optimal angle was 22.72° . Thus, the optimal pitch angle range is identified as $[18.77^\circ-22.72^\circ]$. Therefore, by adding 180° to the upstream pitch angles, the optimal downstream flow pitch angles are determined to be between $[198.77^\circ-202.72^\circ]$. The experimental design, utilizing the Taguchi method, was conducted in two segments for upstream and downstream flow. Each segment included wave and no-wave modes. To evaluate the HATT performance, four variables were considered: rheostat resistance and current velocity (each at five levels), pitch angles (at three levels), and wave characteristics of the target area (at six levels). These variables were compared against HATT operational conditions in no-wave modes. The experiments were conducted for three pitch angles: 22.72° , 198.77° , and 202.72° , under wave and no-wave modes, resulting in a total of 220 trials. Incorporating uncertainty analysis and three repetitions for each test, the pre-Taguchi method total trials amount to 660. However, the application of the Taguchi method significantly reduced the required number of experiments to 125. Thus, with three repetitions per test, the final number of trials was streamlined to 375. The flowchart in Figure 7 provides a comprehensive overview of the data acquisition process and the

general stages of conducting the experimental tests. This process is divided into three main parts: system design, parameter design, and Taguchi design results. Tables 3 to Table 8 show the detailed designs of the experiments for upstream and downstream flow [48, 50].

4. Governing equations and dimensional analysis

Dimensional analysis is used to investigate the effect of wave-current interactions on HATT performance. Power (P) and moment of force (M) in Eq. 1 are functions of water density (ρ), current flow velocity (U_{cv}), wave frequency, wave height (ω_{wf}), gravity (g), rotor's angular velocity (ω_{ang}), rotor's swept area (A), and rotor radius (R). The power coefficient (Eq. 2) and moment of force coefficient (Eq. 3) have been obtained using the π -Buckingham method. According to Farhooody et al. [40], the data analysis algorithm available in Minitab software is used to evaluate the mean and average signal-to-noise (S/N) ratios [1, 40].

$$P, M = (\rho, U_{cv}, \omega_{wf}, H, g, \omega_{ang}, A, R) \quad (\text{Eq. 1})$$

$$C_p = f\left(\frac{\omega_{wf}^2 H}{g}, \frac{\omega_{ang} \times R}{U_{cv}}\right) = \frac{P}{\frac{1}{2} \rho A U_{cv}^3} \quad (\text{Eq. 2})$$

$$C_m = f\left(\frac{\omega_{wf}^2 H}{g}, \frac{\omega_{ang} \times R}{U_{cv}}\right) = \frac{M}{\frac{1}{2} \rho A U_{cv}^2 R} \quad (\text{Eq. 3})$$

The power coefficient (C_p) and moment of force coefficient (C_m) are influenced by the dimensionless wave number (k_d) and tip speed ratio. To examine the characteristics of wave-current interactions, the wave number (k_d) is utilized as outlined in Eq. 4 [51].

$$k_d = \frac{\omega_{wf}^2 H}{g} \quad (\text{Eq. 4})$$

The system's output power (P) is determined using Eq. 5 by multiplying the voltage (V) and electric current (I) from the generator, as displayed on the electrical panel screen. The tip speed ratio is defined as the ratio of the axial velocity of the current flow to the tangential velocity of the blade tips, as specified by Eq. 6. Furthermore, the applied moment of force is calculated by dividing the power by the rotor's angular velocity, as outlined in Eq. 7 [52].

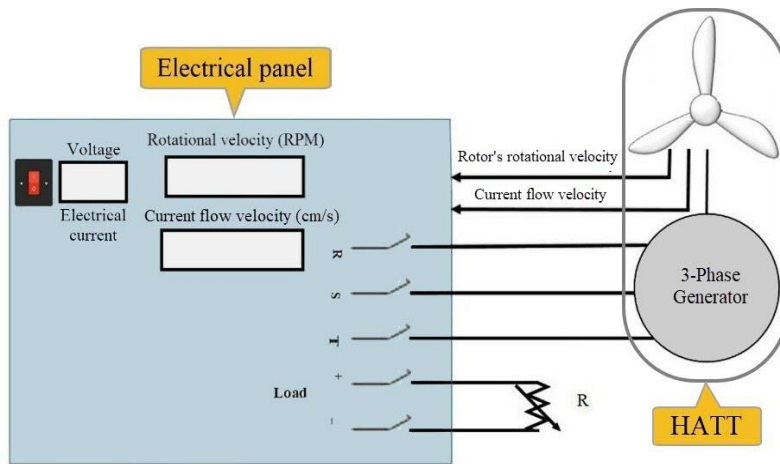


Figure 6. The HATT electrical circuit diagram for data acquisition [40]

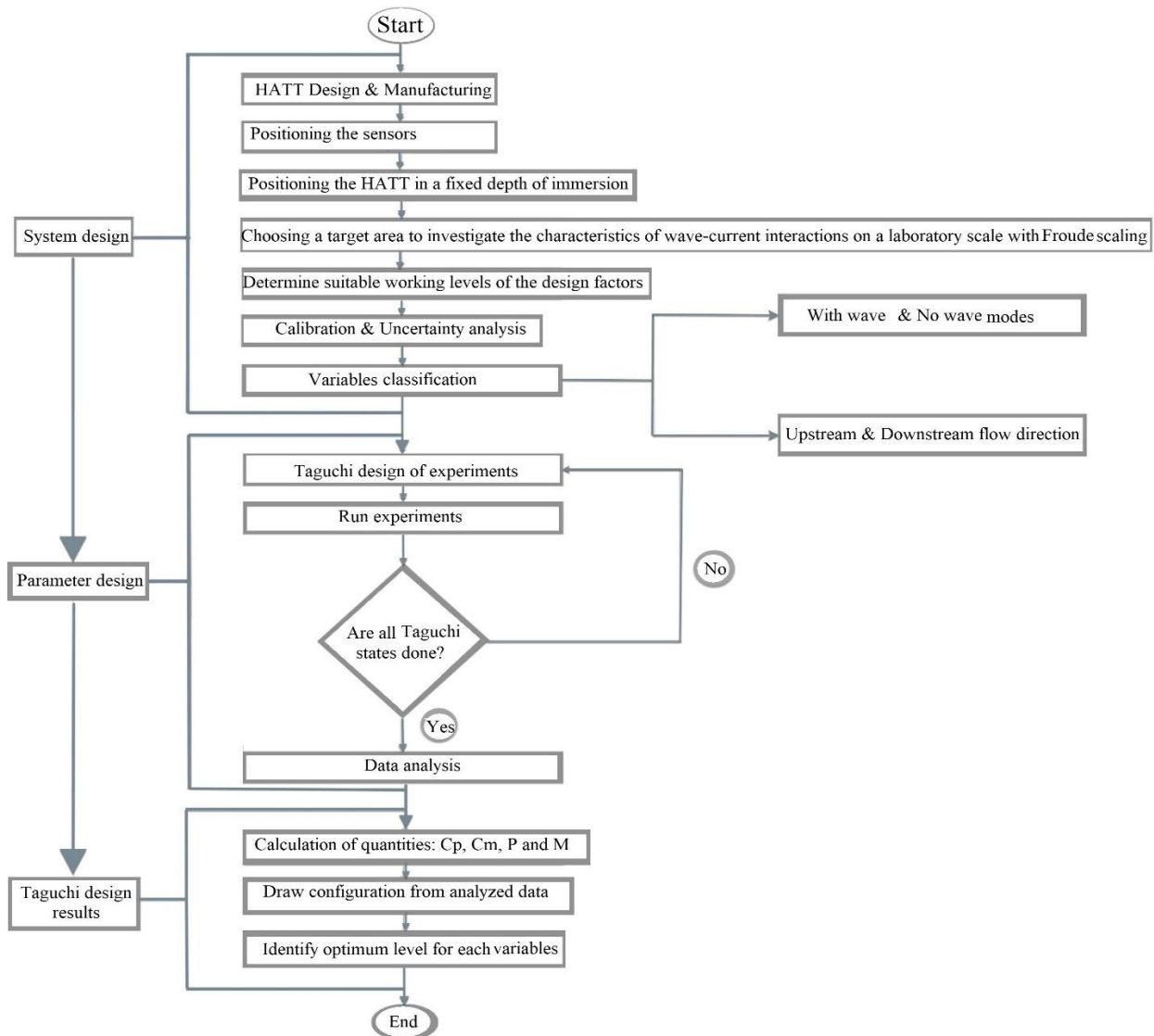


Figure 7. An overview of the data acquisition and analysis procedure flowchart [40]

Table 3. Variables and levels in with wave mode at the pitch angle of 22.72° and rheostat resistance of 20Ω for upstream flow [40]

Variables	Level 1	Level 2	Level 3	Level 3	Level 5
Current velocity (cm/s)	57.50	67.50	77.50	87.5	100
$k_d = \frac{\omega_{\text{wave}}^2 H_{\text{max}}}{g} (\times 10^{-3})$	2.37	2.45	2.94	3.27	3.43

Table 4. Variable and levels in no wave mode at the pitch angle of 22.72° and rheostat resistance of 20 Ω for upstream flow [40]

Variables	Level 1	Level 2	Level 3	Level 3	Level 5
Current velocity (cm/s)	57.50	67.50	77.50	87.5	100

Table 5. Variables and levels for the pitch angle of 198.77° in with wave mode and downstream flow

Variables	Level 1	Level 2	Level 3	Level 3		Level 5
Electrical load (Ω)	10	20	30	40		50
Current velocity (cm/s)	57.50	67.50	77.50	87.5		100
$\mathbf{k_d} = \frac{\omega_{\text{wave}}^2 \mathbf{H_{max}}}{\mathbf{g}} (\times 10^{-3})$	2.37	2.45	2.94	3.27	3.43	4.49

Table 6. Variables and levels for the pitch angle of 198.77° in no wave mode and downstream flow

Variables	Level 1	Level 2	Level 3	Level 3	Level 5
Electrical load (Ω)	10	20	30	40	50
Current velocity (cm/s)	57.50	67.50	77.50	87.5	100

Table 7. Variables and levels for the pitch angle of 202.72° and rheostat resistance of 20 Ω in with wave mode for downstream flow

Variables	Level 1	Level 2	Level 3	Level 3		Level 5
Current velocity (cm/s)	57.50	67.50	77.50	87.5		100
$k_d = \frac{\omega_{\text{wave}}^2 H_{\text{max}}}{g} (\times 10^{-3})$	2.37	2.45	2.94	3.27	3.43	4.49

Table 8. Variables and levels for the pitch angle of 202.72° and rheostat resistance of 20 Ω in no wave mode for downstream flow

Variable	Level 1	Level 2	Level 3	Level 3	Level 5
Current velocity (cm/s)	57.50	67.50	77.50	87.5	100

$$P = V I \quad (\text{Eq. 5})$$

$$\text{TSR} = \frac{\omega_{\text{ang}} \times R}{U_{\text{cv}}} \quad (\text{Eq. 6})$$

$$M = \frac{P}{\omega_{\text{ang}}} \quad (\text{Eq. 7})$$

In this study, the Taguchi method was used as an efficient experimental design strategy to reduce trial numbers and costs while systematically evaluating the effects of key parameters on system performance. To interpret the experimental results, the signal-to-noise (S/N) ratio was calculated, which provides a quantitative measure of system stability and performance quality in the presence of noise or uncontrollable variables. For this investigation, the “larger-the-better” criterion was selected to align with the goal of maximizing output power. The S/N ratio is computed using Eq. 8, where n is the number of repeated measurements under identical conditions, and y_i represents the measured output power in each trial. The index i corresponds to combinations defined by the Taguchi orthogonal array. The Analysis of Means (ANOM) was employed to determine the optimal level of each parameter. This statistical approach

calculates the mean S/N ratio at each level of a factor, thereby highlighting its influence on the performance response. The mean S/N ratio for the i^{th} level of factor l is computed using Eq.9. Here, $M_l^{(i)}$ denotes the mean S/N ratio for the i^{th} level of factor l , and n_{li} represents the number of times that level appears in the experimental matrix [53-55].

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (\text{Eq. 8})$$

$$(M)_{\text{Factor}=l}^{\text{Level}=i} = \frac{1}{n_{li}} \sum_{j=1}^{n_{li}} [(S/N)_{\text{Factor}=l}^{\text{Level}=i}]_j \quad (\text{Eq. 9})$$

5. Results and discussion

The experimental study results are divided into three main sections; in the first section, the results of downstream current flow at a pitch angle of 198.77° are compared under various electrical loads in wave and no-wave modes. The second section follows a similar approach in downstream flow but focuses on a pitch angle of 202.72° and a fixed optimal electrical load for all experiments to study wave-current interactions. In the third section, the results for downstream flow at pitch

angles of 198.77° and 202.72° are compared with each other. Finally, these downstream flow results are compared with upstream flow data from Farhooody et al. [40].

5.1. Downstream flow- pitch angle of 198.77°

Figure 8 (a) and (b) illustrate the power and moment of force coefficients as functions of TSR for various wave characteristics, compared to their respective no-wave modes. The obtained data in this section correspond to Table 5 and Table 6 from the design of experiments section. As observed, the coefficients obtained under wave modes consistently surpass those of the no-wave modes. The curves for wave numbers of 2.37, 2.45, 2.94, 3.27, and 4.49 exhibit a downward trend, meaning that the power and moment of force coefficients decrease as TSR increases. However, the power and moment of force coefficients for the wave number 3.43 exhibit a parabolic trend, indicating the presence of an extremum point in the curve. This anomaly is due to load variations at a specific wavelength, with the wave number 3.43 being significantly longer than the other waves [40]. Table 9 presents the percentage increase of the mean power and moment of force coefficients in the presence of waves compared to no-wave modes for each wave number, along with their maximum achieved extent. The highest increase rate of mean power (6.2%) and moment of force (3.9%) coefficients in wave modes compared to no-wave modes corresponds to the wave number 3.27. The wave number 3.43 is considered an optimal wave number in the studies, with maximum power and moment of force coefficients obtained at a TSR of 6.28, reaching 0.169 and 0.027, respectively. Notably, for wave number 2.94, the power and moment of force coefficients reach their maximum at different TSRs, with this wave number having the longest TSR range of 5.53-7.27.

Figure 9 (a) and (b) respectively depict the analysis of means (ANOM) and mean of (S/N) ratios of the C_p data obtained from Mini-Tab software, with the horizontal reference line representing the average of the data point values. The ANOM reference data line for Figure 9 (a) is 0.129, while the mean reference data line for the (S/N) ratio is -17.88 in Figure 9 (b). The closer the data points are to the

reference line, the less significant the effect of the corresponding variable. As a result, since the dimensionless wave numbers are near and clustered around the reference line, their impact is minimal compared to the variables of current velocity and electrical load. The current velocity, shown as a diagonal line without breaks, exerts the greatest impact on the HATT, distinguishing it as the most effective variable. The second influential variable, due to a break in its trajectory, is the electrical load. The higher the ANOM responses, (S/N) ratios, or quantity of points are above the reference line, the level of that variable is higher compared to other levels of the same variable. Thus, the C_p is optimized at a wave number of 3.45, an electrical load of 20 (Ω), and a current velocity of 57.5 (cm/s). Evidently, as current velocity increases, the output power also rises, reaching its maximum at a current velocity of 100 (cm/s). However, the power coefficient attains its peak when the current velocity is at its lowest level (Eq. 1). The optimal levels for current velocity (57.5 cm/s), electrical load (20 Ω), and wave number (3.43) enhance the C_p by up to 35%, 31%, and 8.4%, respectively, compared to their lowest levels (100 cm/s, 50 Ω , and 2.37). Table 10 details the precise ANOM responses and (S/N) ratios, with the delta indicating the ranking of variable impacts. The table presents the ANOM response and means (S/N) ratios of the data.

Figure 10 (a) and (b) display the power and moment of force coefficients in relation to the two dimensionless quantities, wave number and tip speed ratio, for a pitch angle of 198.77° . As observed, the power and moment of force coefficients increase as the tip speed ratio decreases. The maximum power and moment of force coefficients generally occur when the tip speed ratio is below 6.4, and the dimensionless wave number is less than 4. Overall, this chart indicates that each wave number may be optimal under a specific tip speed ratio.

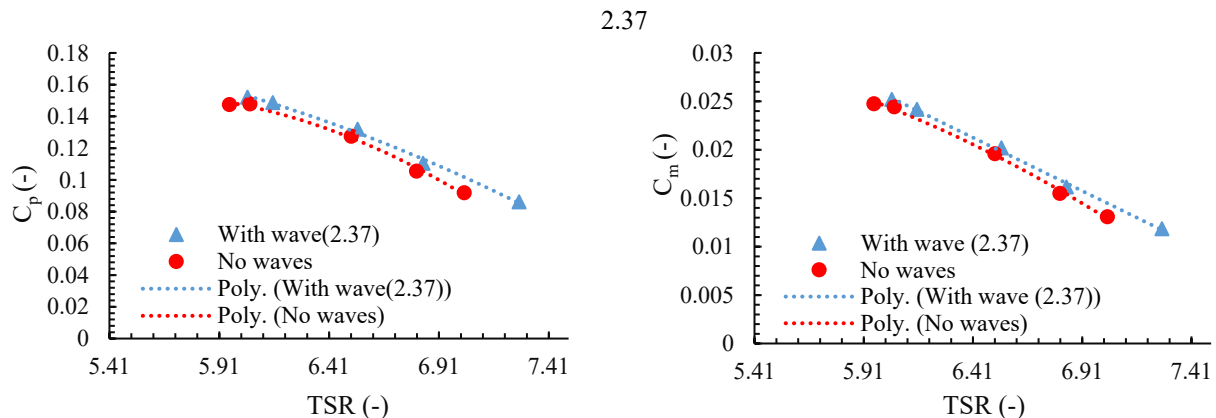
Figure 11 (a) and (b) illustrate how the power and moment of force coefficients vary with tip speed ratios and electrical loads in the absence of waves. Both coefficients increase as the tip speed ratio decreases, while the moment of force coefficient rises with an increase in the applied electrical load.

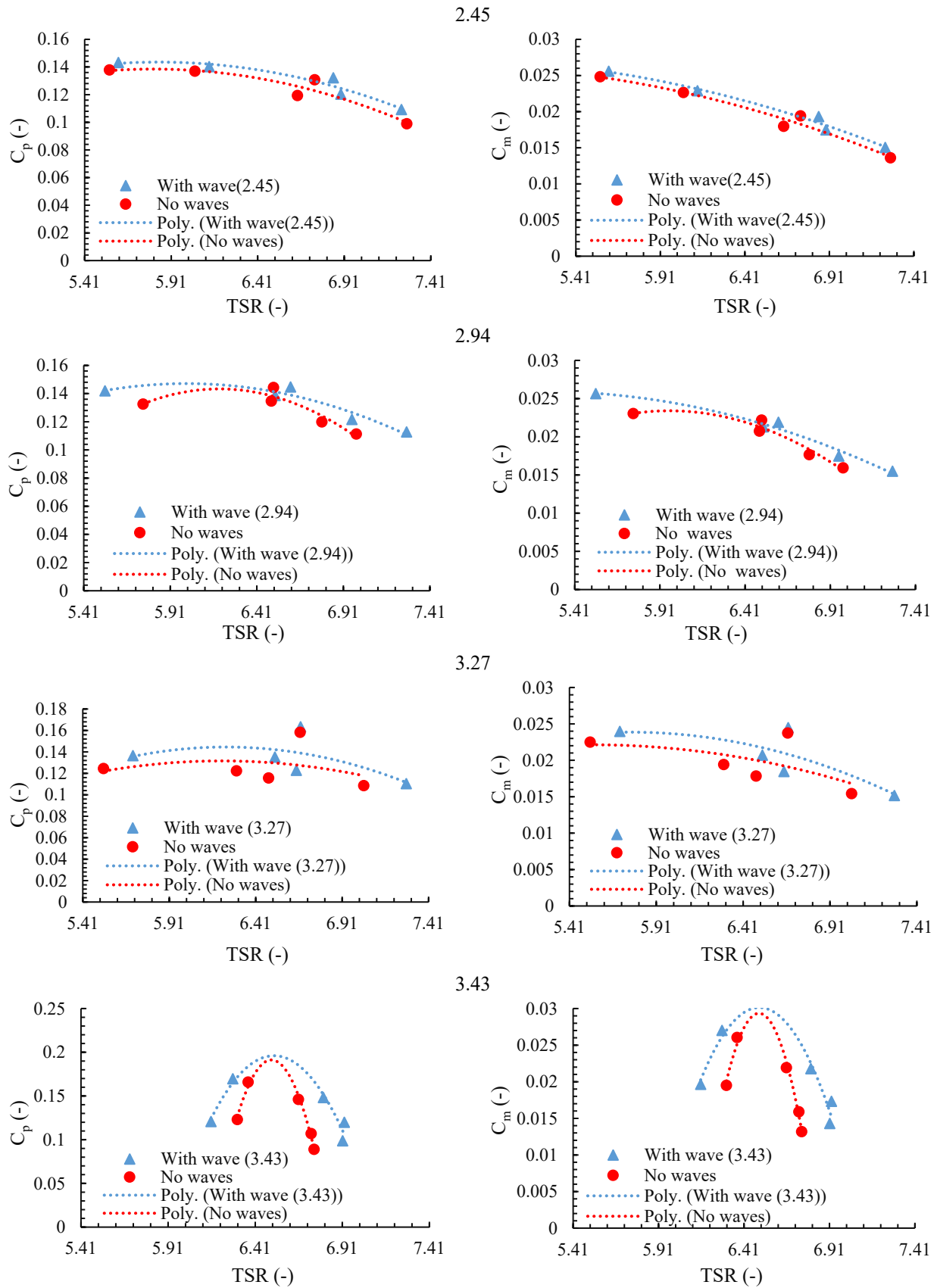
This indicates that the blades endure significant moment of force, but the power coefficient contour peaks at an electrical load ranging from 20 to 30 Ω . Figure 12 (a), (b), and (c) illustrate the effects of wave number on power coefficients, moment of force coefficients, and tip speed ratios as functions of electrical load, respectively. Both power and moment of force coefficients can be optimized across all wave numbers with electrical loads below 35 Ω , whereas the tip speed ratio is optimized with electrical loads above 35 Ω . The power and moment of force coefficients exhibit similar behaviors, with only minor differences in their contours. The tip speed ratio increases with higher electrical loads at a specific wave number but remains relatively constant across all wave numbers for a fixed electrical load. This indicates that electrical load has a more significant impact on HATT performance than wave number.

Figure 13 (a) and (b) show the TSR as a function of current velocity and electrical load for with-wave and no-wave modes, respectively. The behavior in both graphs is similar; however, the areas affected by the TSR are more extensive in red color under with-wave modes than no-wave modes. At a constant current velocity, the tip speed ratio increases with rising electrical load, but it remains nearly constant with changing current velocity at a fixed electrical load. This indicates that the current flow velocity has a more significant impact on turbine performance than electrical load. According to the results from Figure 12 (c) and Figure 13, the effects of current velocity, electrical load, and waves on HATT performance are ranked from most to least significant.

Figure 14 (a) and (b) show the power and moment of force coefficients as functions of TSR for in the

presence of waves at a pitch angle of 198.77° , respectively. The wave number 3.43 is identified as the optimal wave number, where power and moment of force coefficients are expected to reach 0.2 and 0.03, respectively. At the optimal wave number ($k_d = 3.43$), the amplitude of the aggregated curve causes the maximum predicted power coefficient. The highest values for C_p and C_m are observed at a wave number of 3.43 and TSR of 6.28, with values of 0.169 and 0.027. Conversely, the lowest coefficients occur at a wave number of 2.37 and TSR of 7.27, with C_p and C_m values of 0.086 and 0.0118, respectively. The influence of waves on power and moment of force coefficients, based on curve fitting for each test, follows the order: $3.43 \geq 4.49 \geq 3.27 \geq 2.94 \geq 2.45 \geq 2.37$, indicating the HATT best performance. This ranking is derived from the peak power and moment of force coefficients and their corresponding polynomial curve fits.





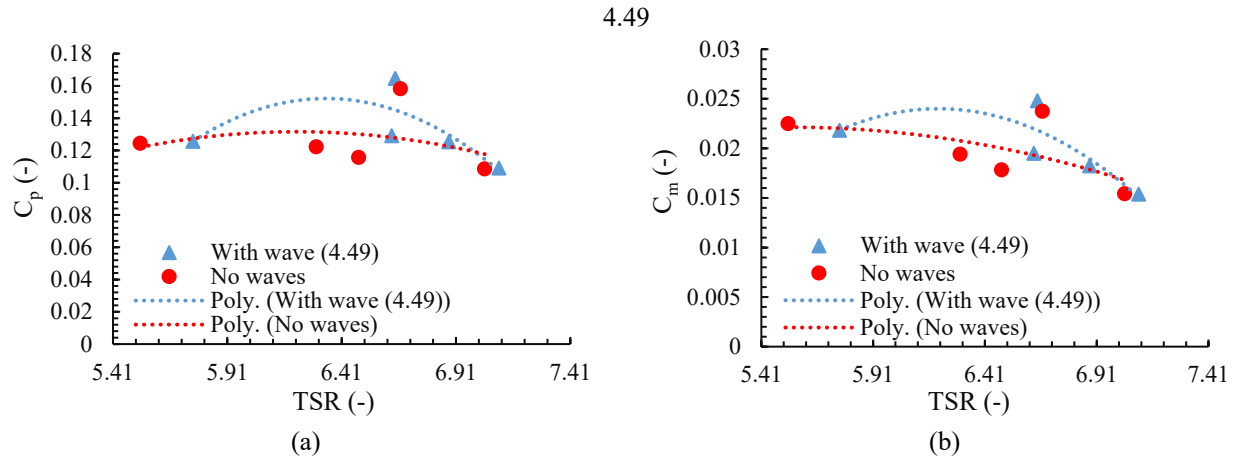
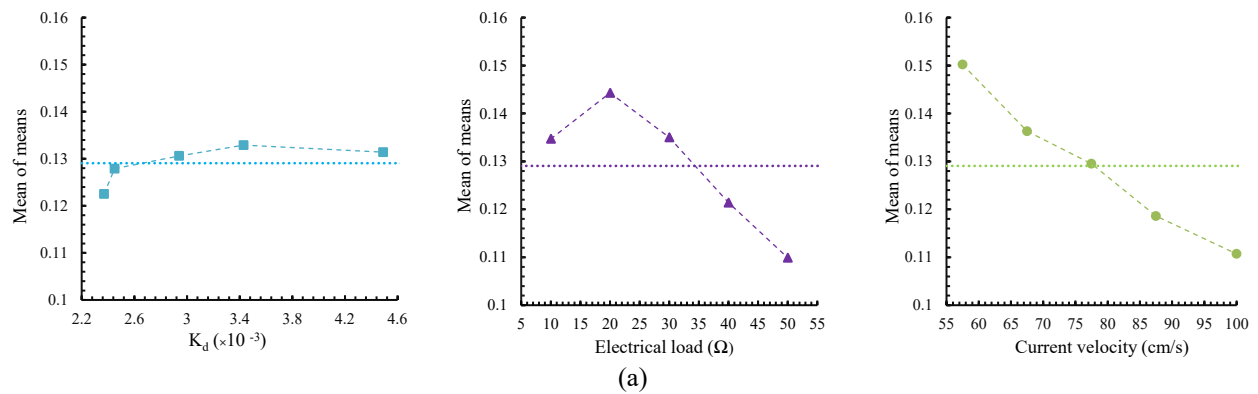
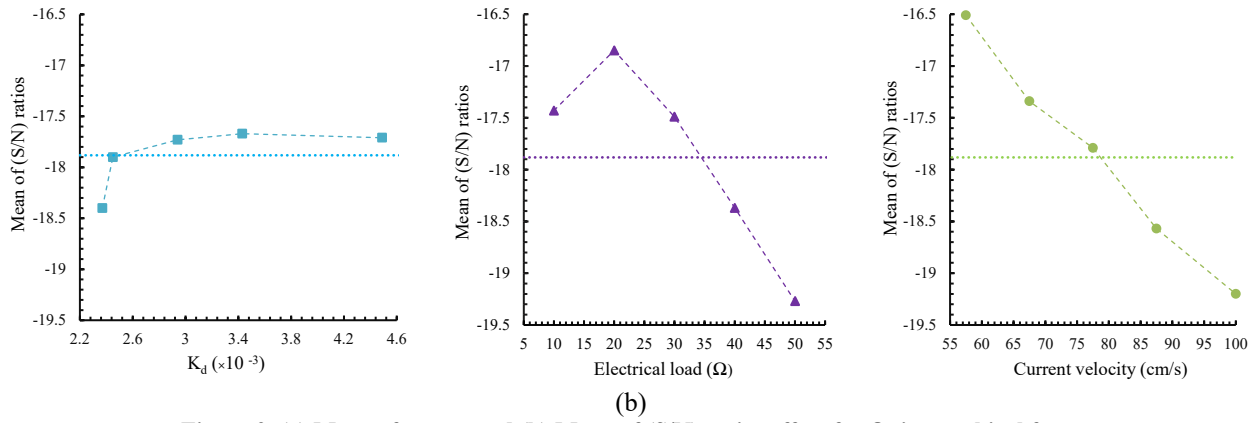


Figure 8. (a) Power coefficient and (b) Moment of force coefficient as a function of TSR for different wave numbers compared to no waves mode

Table 9. Comparison of HATT Performance coefficients in different wave characteristics at a pitch angle of 198.77°

$k_d (\times 10^{-3})$	The percentage increase in the mean power coefficients compared to the no-wave modes	The percentage increase in the mean moment of force coefficients compared to the no-wave modes	$C_{p_{max}}$	$C_{m_{max}}$	$TSR_{at C_{p_{max}} \text{ and } C_{m_{max}}}$	TSR range
2.37	1.5	0.2	0.152 (± 0.01 4)	0.025 (± 0.00 2)	6.03 (± 0.27)	6.03-7.27
2.45	3.4	1.9	0.143 (± 0.01 3)	0.025 (± 0.00 2)	5.60 (± 0.25)	5.6-7.24
2.94	2.6	2.3	0.144 (± 0.01 3)	0.025 (± 0.00 2)	$C_p=6.60 /$ $C_m=5.53$	5.53-7.27
3.27	6.2	3.9	0.162 (± 0.01 5)	0.024 (± 0.00 2)	6.66 (± 0.30)	5.69-7.28
3.43	4.2	3.7	0.169 (± 0.01 6)	0.027 (± 0.00 2)	6.28 (± 0.28)	6.15-6.91
4.49	4.01	0.8	0.164 (± 0.01 5)	0.024 (± 0.00 2)	6.64 (± 0.30)	5.75-7.09





(b)
Figure 9. (a) Mean of means and (b) Mean of (S/N) ratios effect for C_p in graphical form

Table 10. The variable levels response for C_p of HATT performance

Response Table for Means, Larger is better (a)				Response Table for Signal to Noise Ratios (b)			
Level	K_d	Electrical load (Ω)	current velocity (cm/s)	Level	K_d	Electrical load (Ω)	current velocity (cm/s)
1	0.1225	0.1347	0.1502	1	-18.40	-17.43	-16.51
2	0.1279	0.1443	0.1363	2	-17.90	-16.85	-17.34
3	0.1306	0.1350	0.1295	3	-17.73	-17.49	-17.79
4	0.1329	0.1214	0.1186	4	-17.67	-18.37	-18.57
5	0.1314	0.1099	0.1107	5	-17.71	-19.27	-19.20
Delta	0.0104	0.0344	0.0394	Delta	0.73	2.42	2.68
Rank	3	2	1	Rank	3	2	1

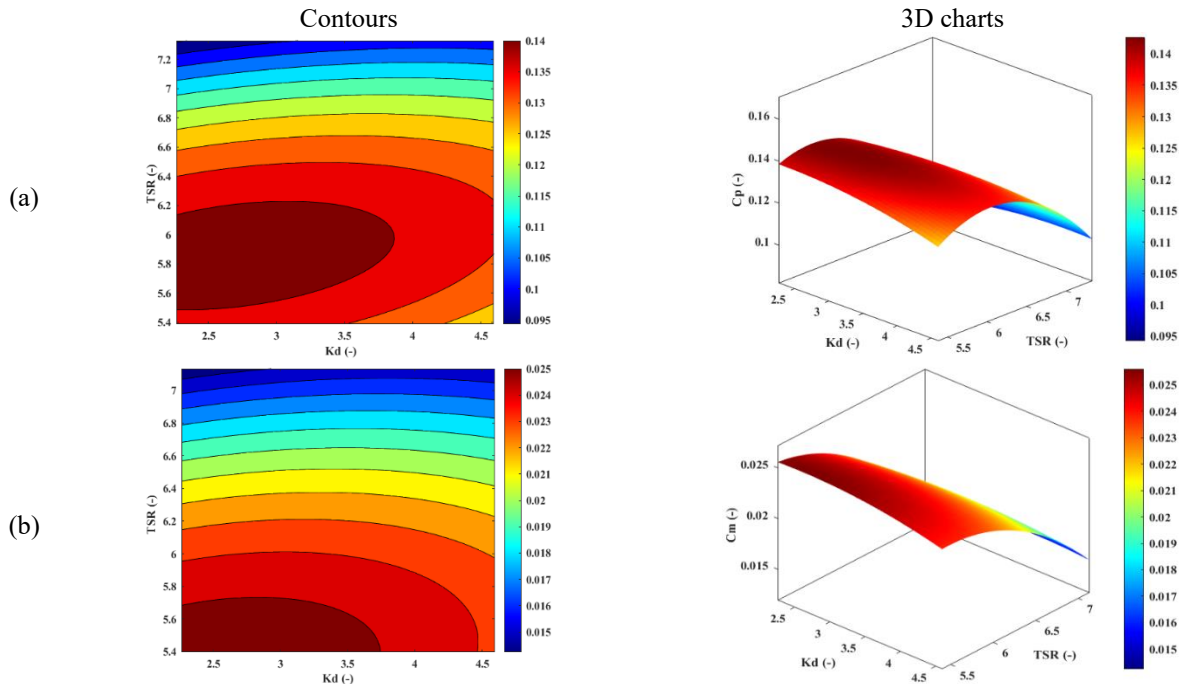


Figure 10. Contours and 3D charts of (a) C_p and (b) C_m in terms of TSR in different wave numbers

Contours

3D charts

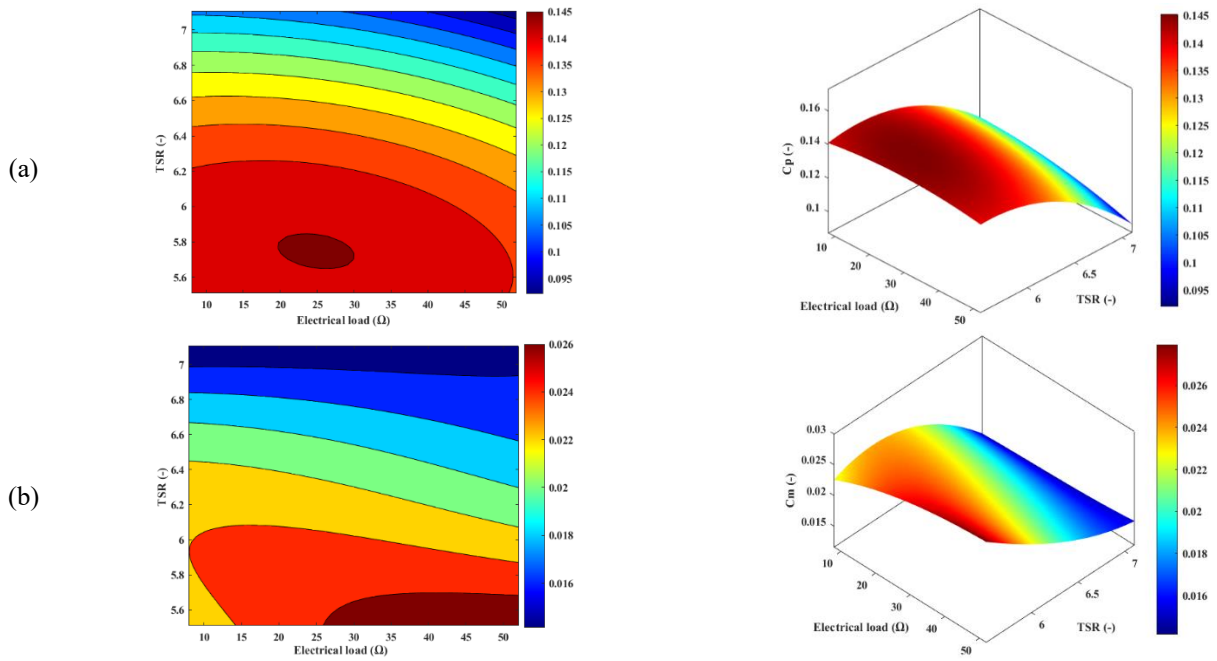


Figure 11. Contours and 3D charts of (a) C_p and (b) C_m in terms of TSR and varying electrical loads for no wave modes

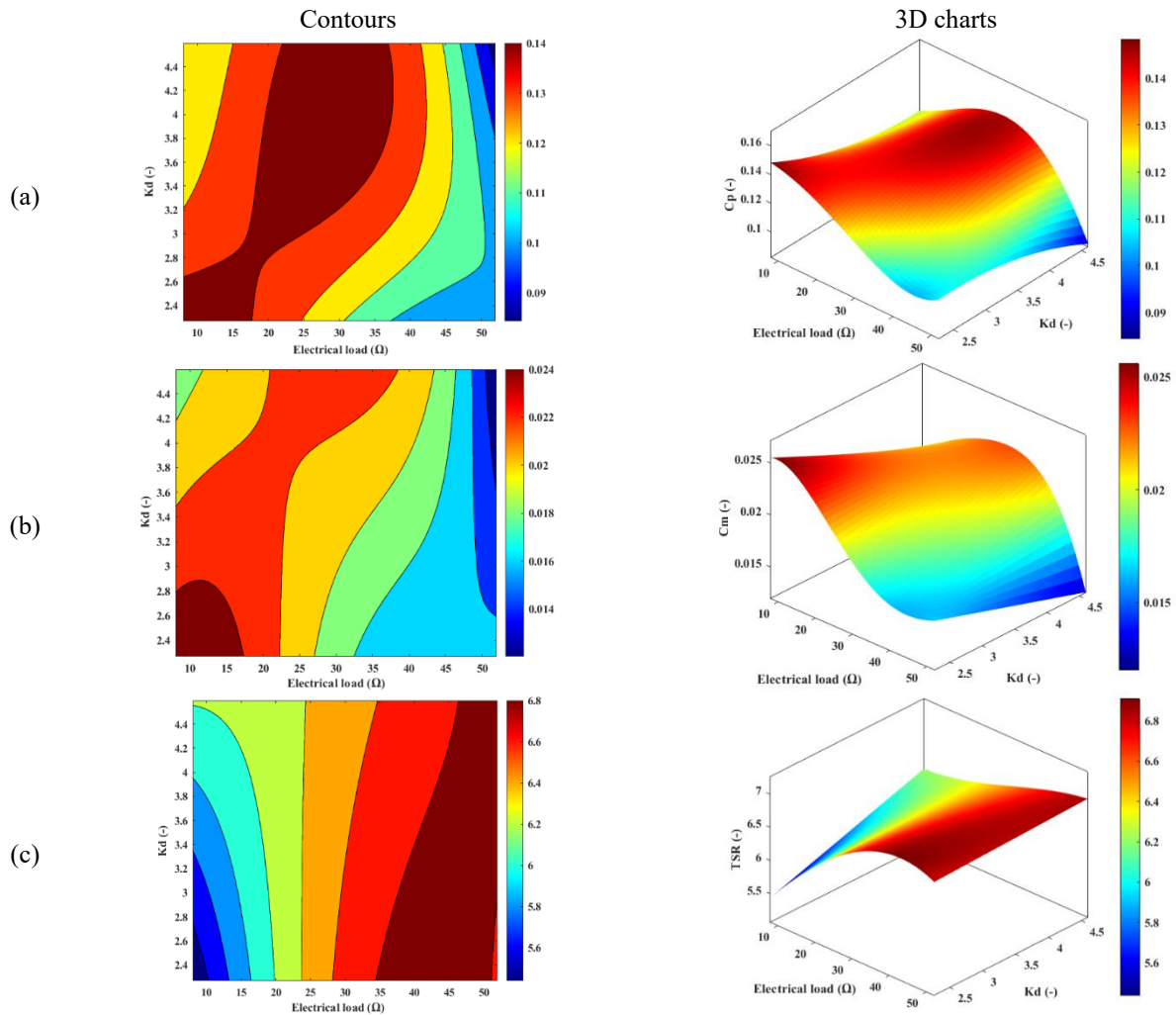


Figure 12. Contours and 3D charts of (a) C_p and (b) C_m , and (c) TSR in terms of different wave numbers and electrical loads

Contours

3D charts

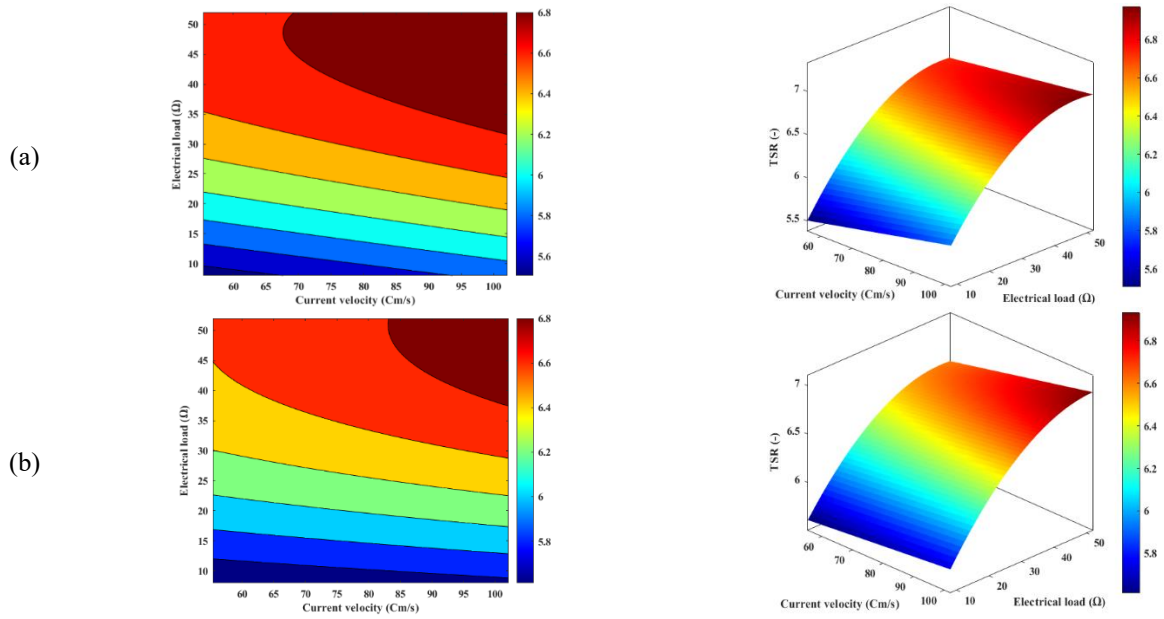


Figure 13. Contours and 3D charts of TSR (a) with wave, and (b) no wave modes in terms of different electrical loads and varying current velocities

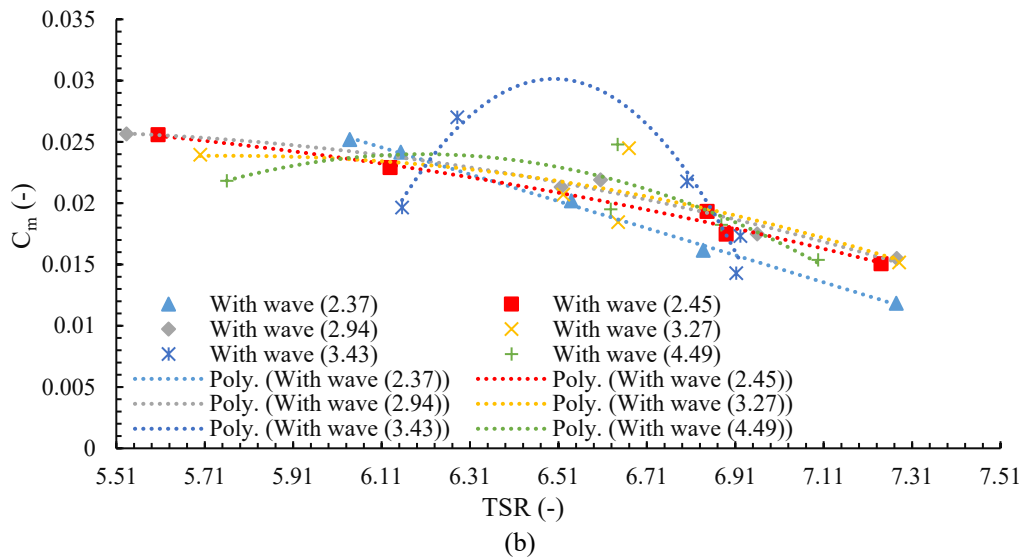
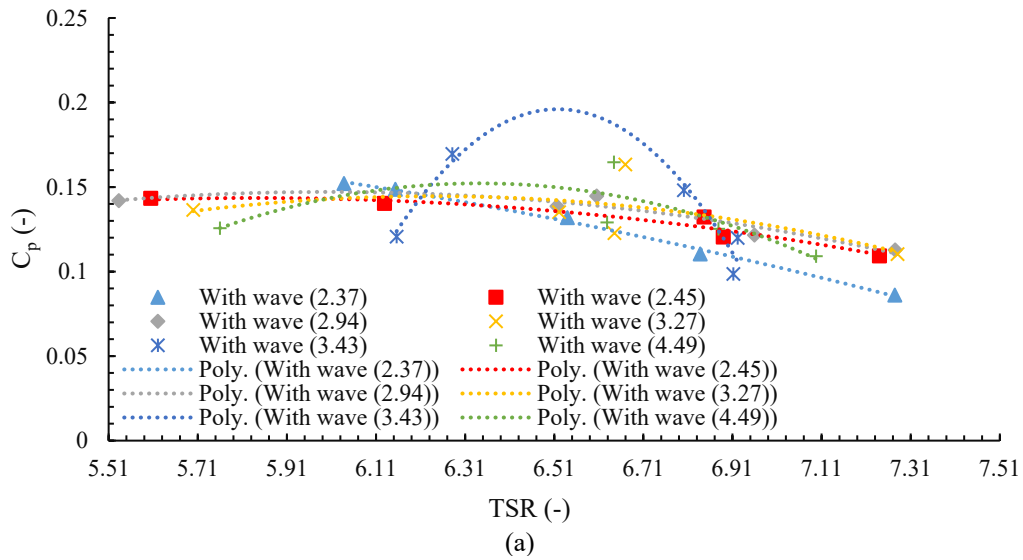
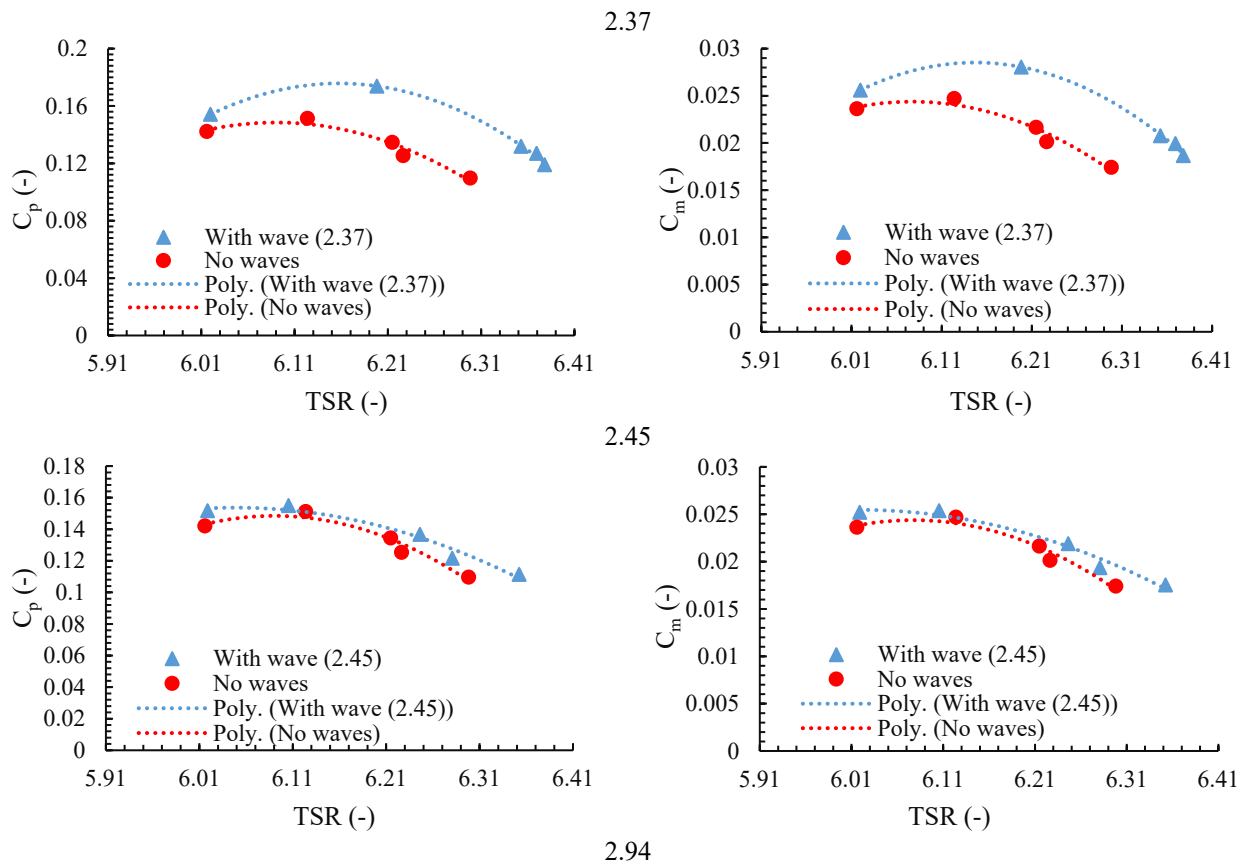


Figure 14. Comparison of (a) C_p and (b) C_m in terms of TSR for with wave modes at a pitch angle of 198.77° **5.2. Downstream flow- pitch angle of 202.72°**

Figure 15 (a) and (b) illustrate the power and moment of force coefficients in relation to the tip speed ratio for a pitch angle of 202.72° and a resistive electrical load of $20\ \Omega$. The obtained data in this section correspond to Table 7 and Table 8 from the experimental design of experiments section. The curve fitted to the experimental data forms a second-degree parabola, with values under wave states consistently exceeding those observed in no-wave modes. As observed, the influence of waves expands the TSR range to $[6.01-6.37]$, compared to $[6.01-6.29]$ in the absence of waves. The maximum and minimum points for power and moment of force coefficients occur at current velocities of 57.5 cm/s and 100 cm/s , respectively, as also indicated by ANOM (Figure 9). Table 11

shows the percentage increase of the mean power and moment of force coefficients with wave modes compared to similar no-wave-mode tests for each wave number, along with their maximum extent. The results pertain to a pitch angle of 202.72° and optimal electrical load of $20\ \Omega$. The highest percentage increase in the mean power coefficients (6.50%) and moment of force coefficients (5.10%) compared to no wave states corresponds to $k_d = 2.37$. The maximum C_p (0.179) and C_m (0.028) values are achieved at $k_d = 3.43$ and $\text{TSR} = 6.19$. The TSR range for different wave numbers across five current flow velocities ranges from 6.01 to 6.37. The influence of waves on the HATT performance follows the order of $3.43 \geq 4.49 \geq 2.37 \geq 2.94 \geq 2.45$, based on the highest power coefficient obtained to the lowest.



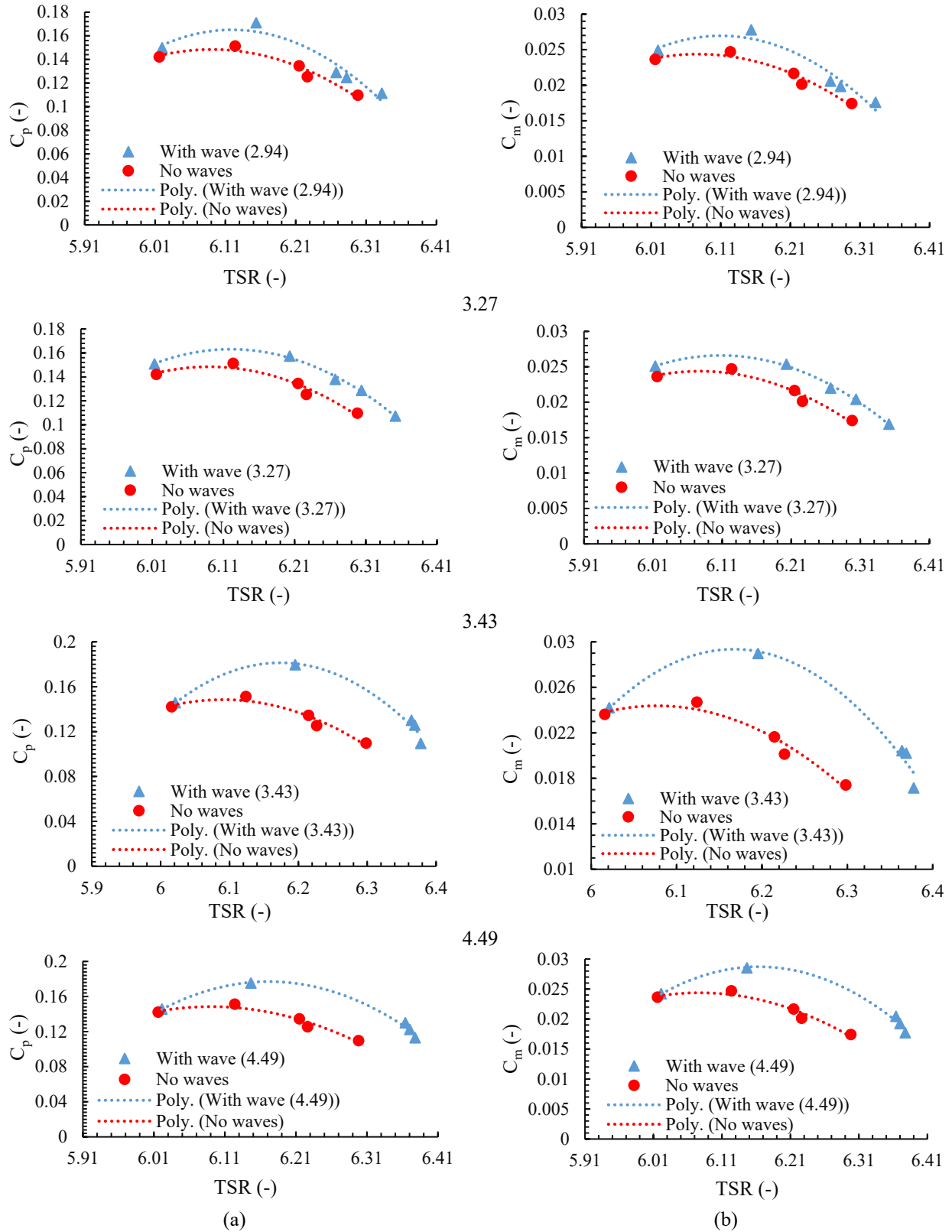


Figure 15. (a) C_p and (b) C_m as a function of TSR for different wave numbers compared to no waves mode at pitch of 202.72° and optimal electrical load

Table 11. Comparison of HATT Performance coefficients in different wave characteristics at a pitch angle of 202.72° and optimal electrical load

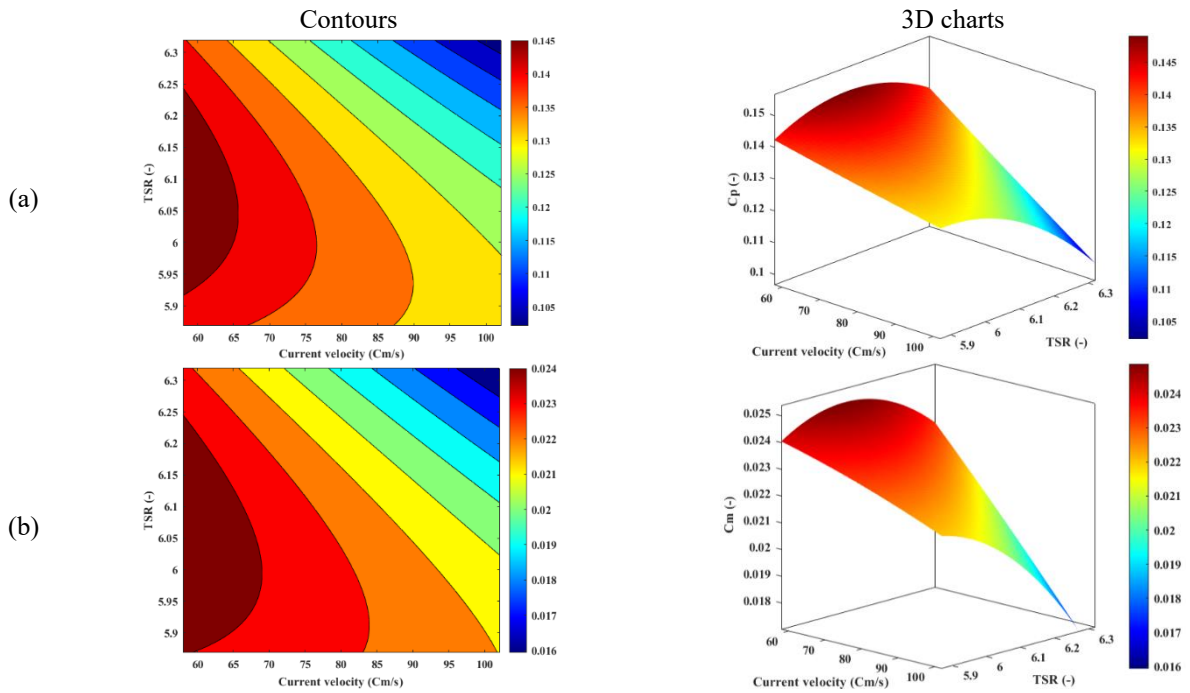
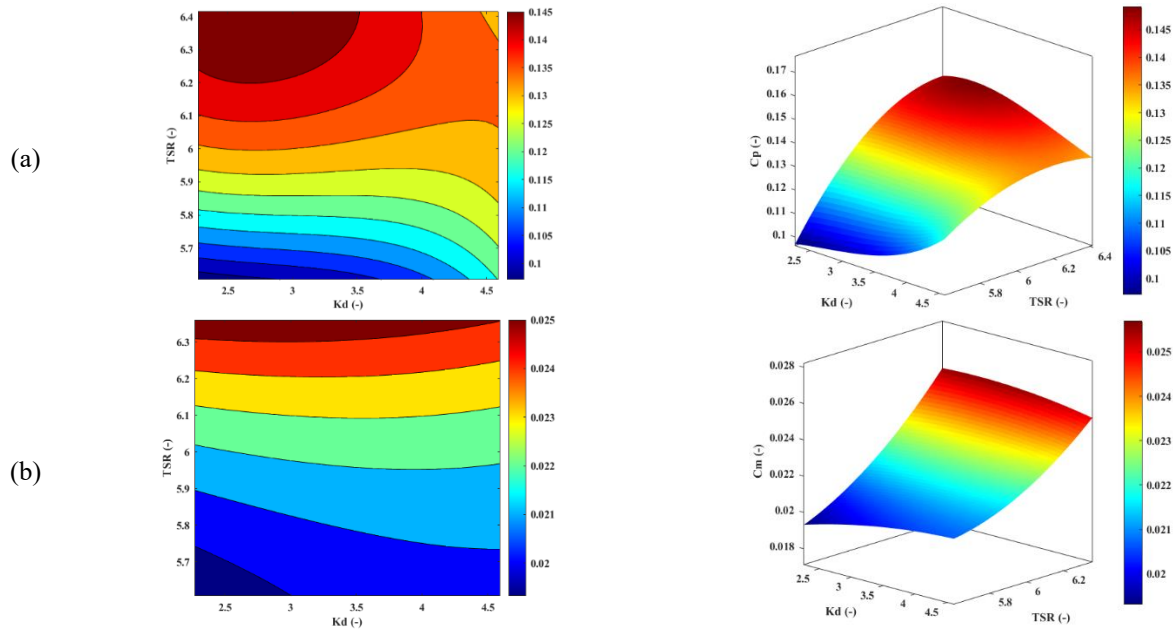
$k_d (\times 10^{-3})$	The percentage increase in the mean power coefficients compared to the no-wave modes	The percentage increase in the mean moment of force coefficients compared to the no-wave modes	$C_{p_{max}}$	$C_{m_{max}}$	TSR _{at $C_{p_{max}}$ and $C_{m_{max}}$}	TSR range
2.37	6.5	5.10	0.173 (± 0.016)	0.028 (± 0.002)	6.19 (± 0.28)	6.01-7.37
2.45	2.09	1.77	0.154 (± 0.014)	0.025 (± 0.002)	6.10 (± 0.27)	6.01-6.35
2.94	3.40	2.90	0.171 (± 0.016)	0.027 (± 0.002)	6.15 (± 0.28)	6.01-6.33
3.27	2.90	2.10	0.157 (± 0.015)	0.025 (± 0.002)	6.20 (± 0.28)	6.01-6.35
3.43	4.20	3.20	0.179 (± 0.017)	0.028 (± 0.002)	6.19 (± 0.28)	6.02-6.37
4.49	3.60	2.40	0.175 (± 0.016)	0.028 (± 0.002)	6.14 (± 0.28)	6.02-6.37

Figure 16 (a) and (b) display the contour and 3D plots of power and moment of force coefficients as functions of TSR for various wave numbers at a pitch angle of 202.72° and optimal electrical load. The power coefficient curve exhibits a parabolic shape with a downward concavity as the wave number increases. Maximum power coefficients typically occur for wave numbers below 3.5 and tip speed ratios above 6.2. The power coefficient increases with the tip speed ratio and decreases with the wave number. In Figure 16 (b), the fitted moment of force coefficient curve has an upward concavity, indicating that the moment of force coefficient increases with the tip speed ratio. For a constant wave number, the moment of force coefficient rises with the tip speed ratio, but for a constant tip speed ratio, the wave number remains nearly unchanged, highlighting the greater influence of the tip speed ratio compared to the wave number. Figure 17 (a) and (b) depict the power and moment of force coefficients as functions of the tip speed ratio and current velocity in no-wave conditions for a pitch angle of 202.72°, respectively. The power and moment of force coefficients peak as the current velocity decreases.

Contours

The maximum values for these coefficients are observed within the tip speed ratio range of 5.9 to 6.25 and for current velocities below 77.5 cm/s. The behavior of the power and moment of force coefficient curves, with respect to the tip speed ratio and current velocity, shows a downward concave trend. Figure 18 (a) and (b) illustrate the power and moment of force coefficients as functions of the tip speed ratio for various dimensionless wave numbers at a pitch angle of 202.72°, respectively. The fitted curves for wave numbers 3.43, 4.49, and 2.37 exhibit similar behavior and are positioned above the other waves (2.94, 2.45, and 3.27). The impact of the waves on the C_p and C_m , according to the fitted curve for each experiment, follows the order: $3.43 \geq 4.49 \geq 2.37 \geq 2.94 \geq 3.27 \geq 2.45$. Wave number 2.37 shows behavior approaching optimal performance, aligning closely with the optimal wave number ($k_d = 3.43$). The maximum power and moment of force coefficients of the turbine at a pitch angle of 202.72° and wave number 2.37 increase by 14% and 11%, respectively, compared to the same wave at a pitch angle of 198.77° in Figure 14.

3D charts



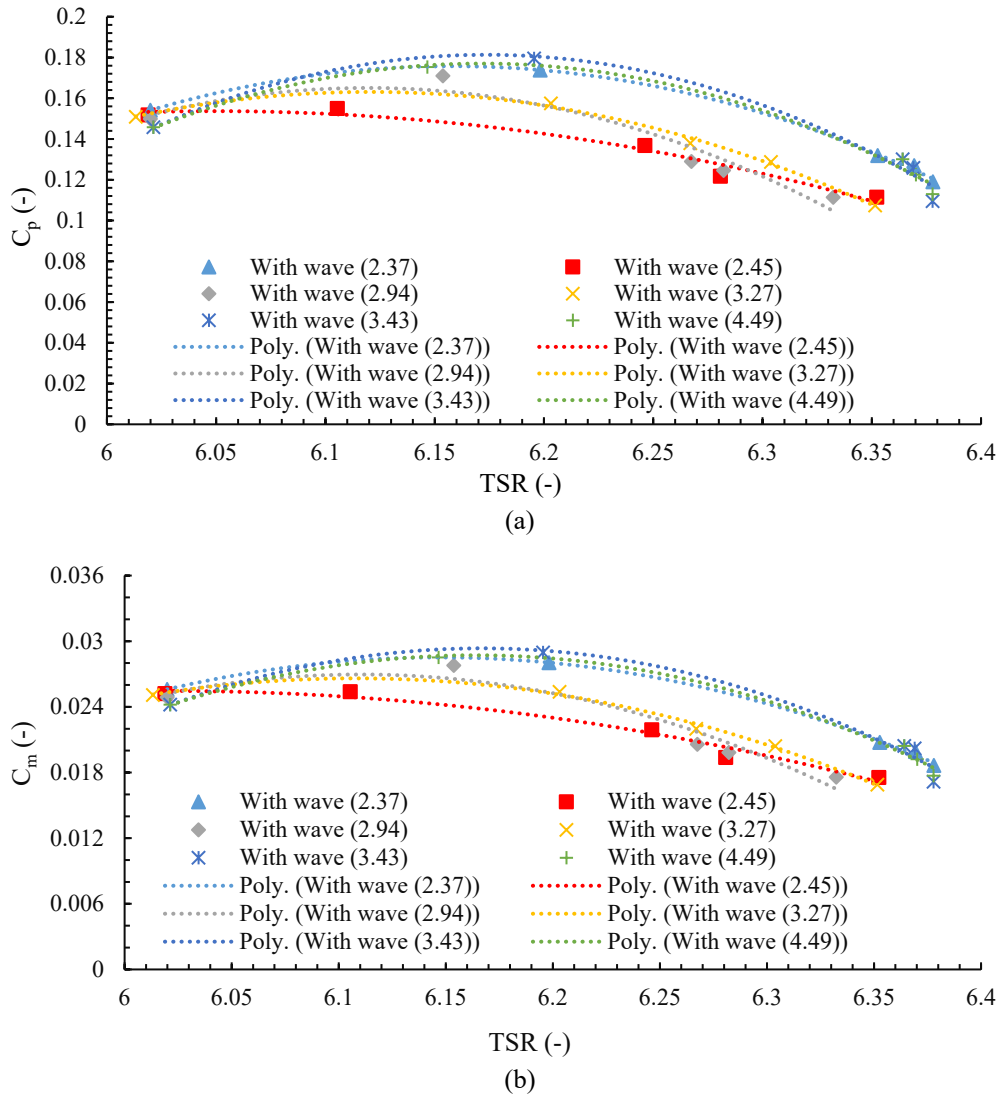


Figure 18. Comparison of (a) C_p and (b) C_m in terms of TSR for with wave modes at a pitch angle of 202.72° and optimal electrical load

5.3. The comparison of HATT performance in downstream flow pitch angles

Figure 19 (a) and (b) show the generated power at pitch angles of 202.72° and 198.77° . The results are obtained with and without wave modes at 20Ω electrical load resistance, respectively. According to Figure 19, the mean data of with and without wave modes for the pitch angle of 198.77° increase by a maximum of 20% and 6.3%, respectively, compared to the pitch of attack of 202.72° . In downstream flow, whether with or without waves, the HATT performance is consistently optimized at the pitch angle of 198.77° . However, in upstream flow, performance is optimized at the pitch angle of 22.72° without waves and 18.77° with waves [40]. This variation occurs because, in the upstream

flow, the current flow regime is initially split by the hub, establishing a regular flow regime in front of the rotating blade. Conversely, in downstream flow, the current first impacts the back of the HATT and the stanchion before reaching the rotating blade, creating a turbulent rotating flow regime. This explains why there is one optimal pitch angle from the two investigated pitch angles in both with-wave and no-wave modes for downstream flow. The output power has a direct relationship with carriage traction velocity, increasing as the current flow velocity increases. In the with waves mode, with the increase of the current flow velocity, the distance between the two curves widens upward, and the wave effect in these pitch angles shows itself more by enhancing the HATT performance. Conversely, in no wave

modes, the fitting curves have a closer behavior together.

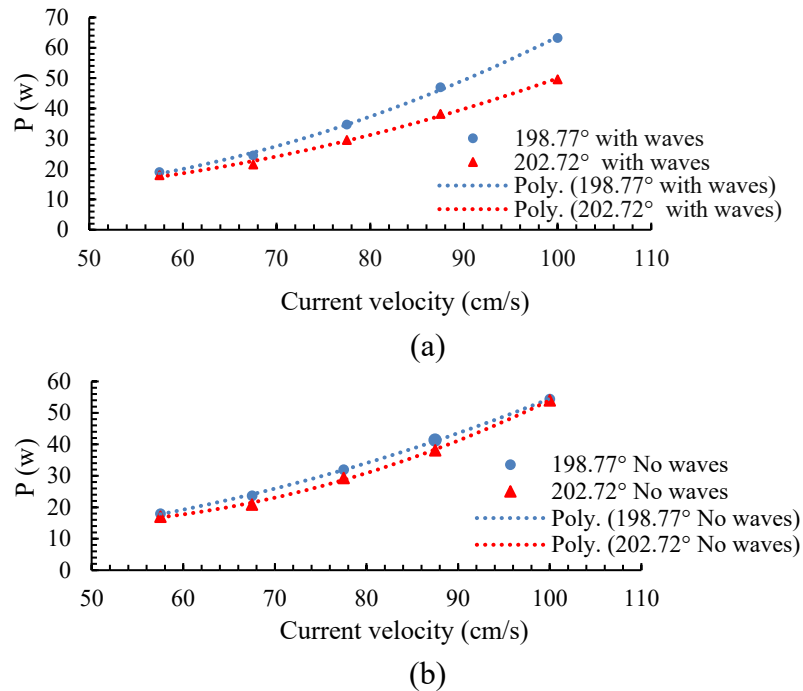


Figure 19. Comparison of downstream flow pitch angles (202.72° and 198.77°) for (a) with waves and (b) no waves state

5.3.1. The comparison of upstream and downstream flow in wave modes

The upstream flow was examined at pitch angles of 13.01°, 26.79°, 22.72°, 18.77°, and 14.91° [40]. If pitch angles are tested solely by changing the flow direction under downstream conditions, the power output will be zero because of the blade profile's shape. To prevent this zero-power output, the turbine blade profile must be rotated by up to 180° along with the change in flow direction. In this section, the upstream flow at a pitch angle of 22.72° from reference [40] (Table 3) is compared with the downstream flow at a pitch angle of 202.72° (Table 7). Figure 20 (a) and (b) show the power and moment of force coefficients against the tip speed ratio for the pitch angle of 22.72° in upstream flow and its complementary pitch angle of 202.72° in downstream flow for each wave number. The power and moment coefficients at a pitch angle of 22.72° generally occur at higher tip speed ratios and are shifted to the right compared to those at an angle of attack of 202.72°, indicating higher values. This increase is attributed to the rotor's higher rotational velocity (ω_R) at a constant flow velocity at the pitch angle of 22.72°. Comparing the power and moment of force coefficients in upstream and downstream

conditions reveals that the fitted curve for the 22.72° pitch angle typically lies above the pitch angle of 202.72°. Figure 21 shows the rotor's rotational velocity against current velocity for pitch angles of 22.72° and 202.72° under the influence of different wave numbers. The resulting graphs display linear and increasing behavior. As observed, the rotor's rotational velocity at the pitch angle of 22.72° is consistently higher than at 202.72° at a similar constant velocity. This shift results in power and moment of force coefficients occurring at higher tip speed ratios.

In conclusion, comparing upstream and downstream flows reveals that if the HATT can rotate around its axis to always face the flow directly, initially hitting the hub and blades, the HATT will achieve optimal performance. This fixed pitch angle for maximum HATT performance is 18.77°. Table 12 presents the percentage increase in the mean HATT performance coefficients, such as power coefficient, moment of force coefficient, tip speed ratio, and rotor's rotational velocity, for a pitch angle of 22.72° compared to a pitch angle of 202.72°, for each wave number individually. According to Table 12, the highest increase in the power coefficient for a pitch angle of 22.72° is observed for wave number 2.94, the highest

increase in the moment of force coefficient for wave number 3.27, and the highest increases in the tip speed ratio and rotor's rotational velocity for

wave number 3.43, showing increases of 36.1%, 18.1%, 16%, and 17.4%, respectively, compared to the pitch angle of 202.72°.

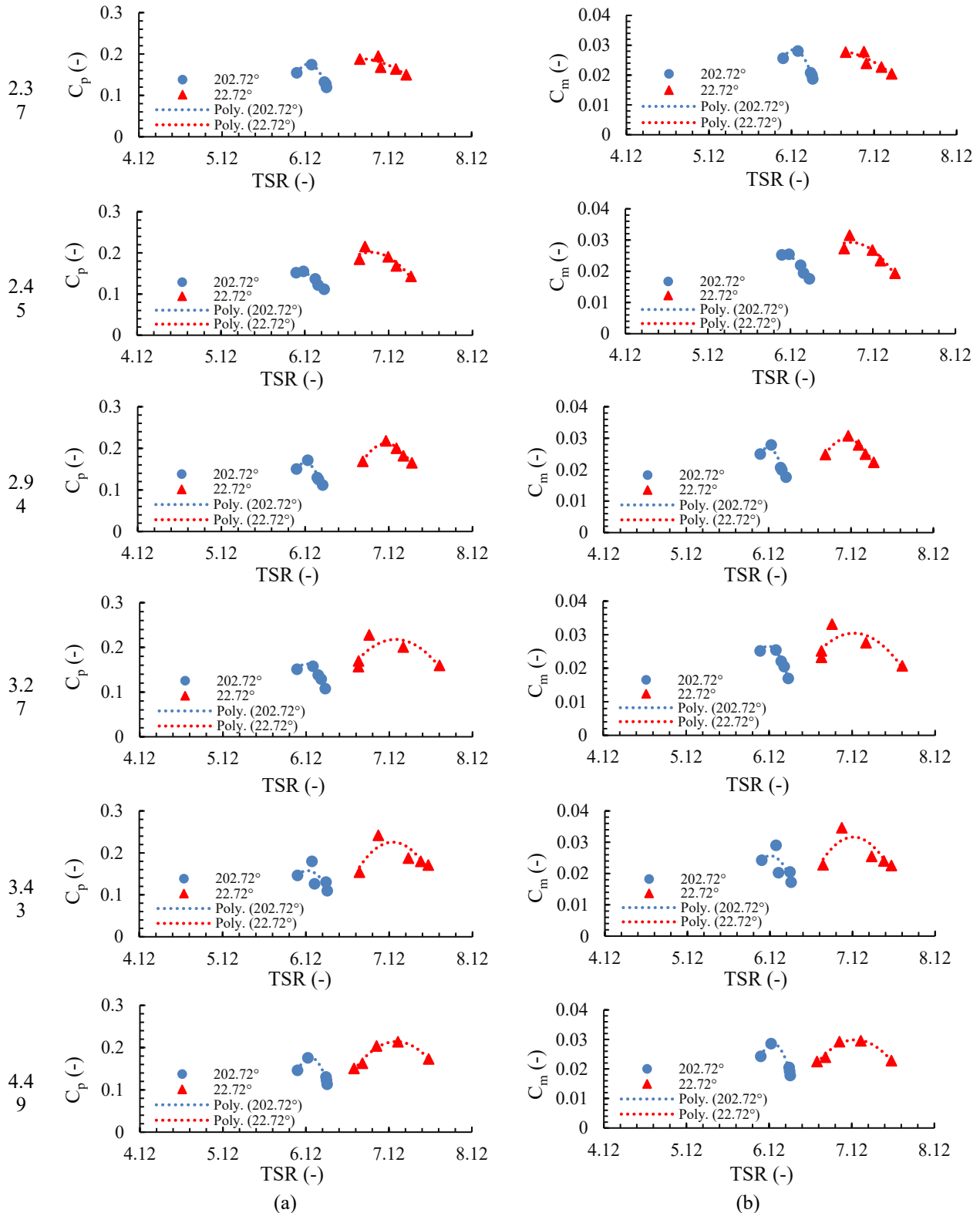


Figure 20. (a) C_p and (b) C_m as a function of TSR for pitch angles of 22.72° (upstream flow) and 202.72° (downstream flow) in the impact of wave current interactions

Table 12 compares the maximum values of HATT Performance coefficients at pitch angles of 22.72°

and 202.72° for different wave numbers. The maximum power coefficient of the HATT at a pitch

angle of 22.72° is always higher than at a pitch angle of 202.72° . The highest power and moment of force coefficients for the optimal wave number 3.43 are 0.241 and 0.034 for a pitch angle of 22.72° , and 0.179 and 0.028 for a pitch angle of

202.72° , respectively. The maximum rotor's rotational velocities recorded are 126 and 103 RPM for pitch angles of 22.72° and 202.72° , respectively.

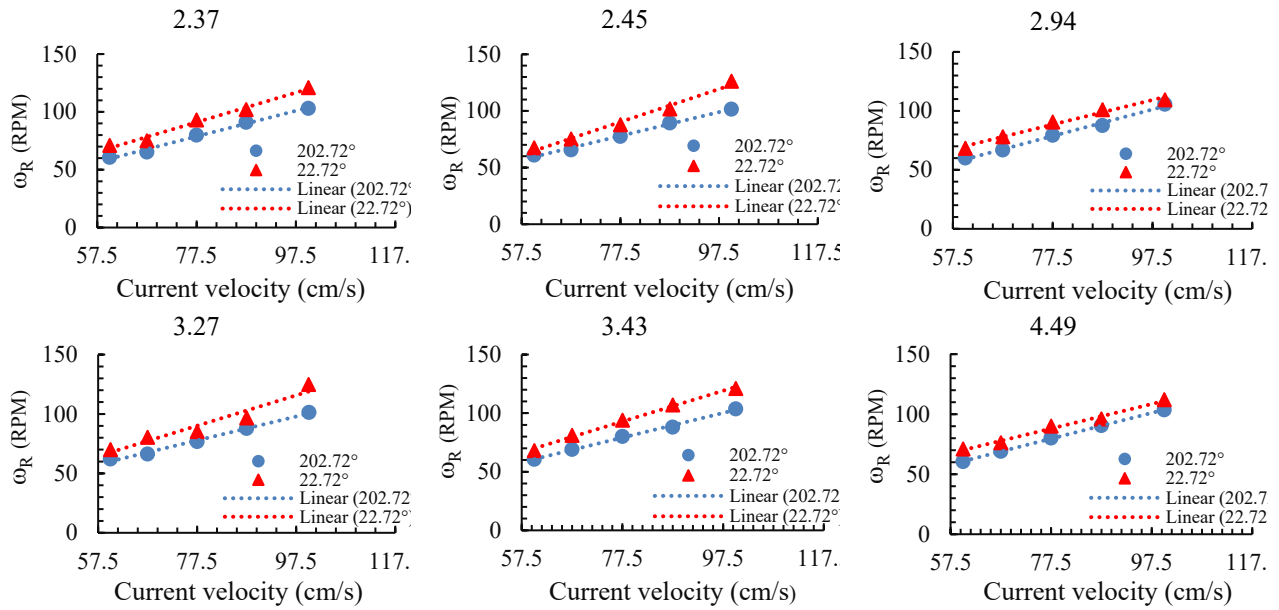


Figure 21. Rotor's rotational velocity against current velocity for pitch angles of 22.72° (upstream flow) and 202.72° (downstream flow) in the impact of wave current interactions

Table 12. The comparison of percentage increase in the mean HATT Performance coefficients for the pitch angle of 22.72° compared to 202.72° in different wave characteristics

$k_d (\times 10^{-3})$	$C_p (-)$	$C_m (-)$	TSR (-)	ω_R (RPM)
2.37	22.30	8.45	12.80	15.50
2.45	33.30	17.30	13.90	16
2.94	36.10	17.90	15.20	12
3.27	34.10	18.10	13.60	16
3.43	35.50	16.70	16	17.40
4.49	31.70	16.20	12.8	10.30

Table 13. Comparison of the maximum values of HATT Performance coefficients for pitch angles of 22.72° and 202.72° in different wave characteristics

$k_d (\times 10^{-3})$	Pitch angle ($^\circ$)	$C_{p_{max}}$ (-)	$C_{m_{max}}$ (-)	TSR_{max} (-)	ω_{R-max} (RPM)
2.37	22.72	0.194 (± 0.018)	0.027 (± 0.002)	6.99 (± 0.31)	121 (± 4)
	202.72	0.173 (± 0.016)	0.028 (± 0.002)	6.19 (± 0.28)	103 (± 4)
2.45	22.72	0.215 (± 0.020)	0.031 (± 0.002)	6.83 (± 0.31)	126 (± 4)
	202.72	0.154 (± 0.014)	0.025 (± 0.002)	6.10 (± 0.27)	101 (± 4)
2.94	22.72	0.217 (± 0.020)	0.031 (± 0.002)	7.08 (± 0.32)	110 (± 4)
	202.72	0.171 (± 0.016)	0.028 (± 0.002)	6.15 (± 0.28)	105 (± 4)
3.27	22.72	0.227 (± 0.021)	0.033 (± 0.003)	6.87 (± 0.31)	125 (± 4)
	202.72	0.157 (± 0.015)	0.025 (± 0.002)	6.20 (± 0.28)	101 (± 4)
3.43	22.72	0.241 (± 0.022)	0.034 (± 0.003)	6.98 (± 0.31)	121 (± 4)
	202.72	0.179 (± 0.017)	0.028 (± 0.002)	6.29 (± 0.28)	103 (± 4)
4.49	22.72	0.213 (± 0.020)	0.030 (± 0.002)	7.23 (± 0.33)	112 (± 4)
	202.72	0.175 (± 0.016)	0.029 (± 0.002)	6.14 (± 0.28)	103 (± 4)

5.3.2. The comparison of upstream and downstream flow in no wave modes

Figure 22 (a) and (b) show the power and moment of force coefficients versus the tip speed ratio for

the no-wave condition. The mean power coefficients for the upstream flow (22.72°) occur at higher tip speed ratios compared to the downstream flow (202.72°). The maximum power and moment of force coefficients for a pitch angle of 22.72° are

0.197 and 0.028, respectively, occurring at a tip speed ratio of 7.02. For the pitch angle of 202.72° , the maximum power and moment of force coefficients are 0.151 and 0.0246, respectively, occurring at a tip speed ratio of 6.12. Figure 22 (c) shows the generator output power versus the carriage traction speed or current velocity. The highest power in the no-wave condition is 73 (W) for the upstream flow at a pitch angle of 22.72° , and 54 (W) for the downstream flow at a pitch angle of 202.72° . Figure 22 (d) illustrates the moment of force applied to the HATT blades versus the

current velocity. The highest moment of force in the no wave condition is 5.8 (N.m) for the upstream flow at a pitch angle of 22.72° , and 5 (N.m) for the downstream flow at a pitch angle of 202.72° . The power and moment of force curves versus current velocity are upward trending, but the power and moment of force coefficients have extremum points, indicating a second-order nonlinear parabolic curve. The rotor's rotational velocity curve versus current velocity is linearly increasing (Figure 22 (e)).

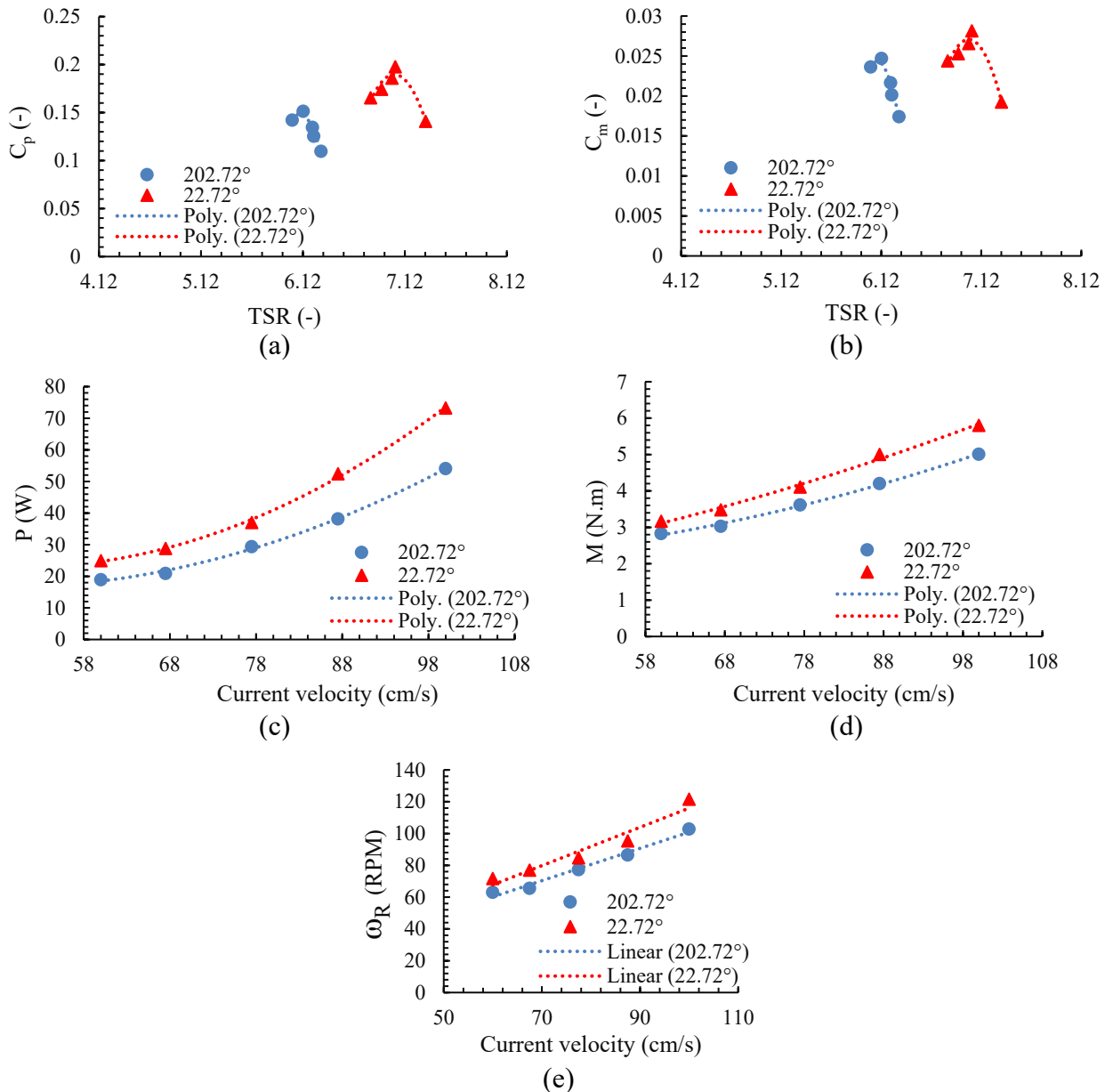


Figure 22. (a) Power coefficient versus TSR (b) moment of force coefficient versus TSR (c) Power versus current flow velocity (d) moment of force versus current flow velocity (e) rotor's rotational velocity versus current flow velocity for no wave modes

The maximum rotational velocity of the rotor is 121 RPM at a pitch angle of 22.72° , and 102 RPM at a pitch angle of 202.72° . The HATT with a pitch angle of 22.72° performs better, generating more electricity as the rotor's rotational velocity increases.

Table 14 illustrates the percentage increase in the mean HATT performance coefficients for the pitch angle of 22.72° compared to 202.72° in no-wave modes.

Table 14. The comparison of percentage increase in the mean HATT Performance coefficients for the pitch angle of 22.72° compared to 202.72° in no wave modes

M (N.m)	P (w) (-)	C _p (-)	C _m (-)	TSR (-)	ω_R (RPM)
15.44	34.19	30.40	15.03	13.40	13.99

5.4. Integration with Previous Studies and

Implications for Bidirectional Flow Turbine

Design

The findings of this study not only confirm but also substantially extend the limited body of knowledge on the effect of flow direction on HATT performance. The observed 30–36% increase in power coefficient for upstream operation compared to downstream operation (at identical pitch angles) aligns qualitatively with the numerical predictions of Frost et al. [39], who reported that yaw--controlled turbines outperformed twisting--blade mechanisms in bidirectional flows. However, while Frost et al. focused primarily on clearance distance and employed numerical methods, the present study provides the first experimental quantification of this difference under realistic wave--current interactions, including six distinct wave numbers and a systematic pitch--angle sweep using Taguchi design. This adds a critical layer of physical evidence that was previously missing.

Wang et al. [38] also reported higher power and thrust coefficients when the rotor was placed upstream of the supporting stanchion in their megawatt--scale sea trials. They attributed this improvement to the absence of upstream flow obstruction. Our results strongly corroborate this interpretation: in downstream flow, the nacelle and stanchion create a turbulent wake that partially absorbs incoming kinetic energy before it reaches the blades, leading to reduced C_p and C_m values across all wave numbers. Moreover, our study quantifies this penalty with unprecedented

detail—showing that the penalty is wave--dependent, with the smallest reduction (22.3% in C_p) occurring at wave number 2.37 and the largest (36.1%) at wave number 2.94. This wave--dependent behavior has not been reported previously and suggests that the severity of flow--direction losses is modulated by wave characteristics.

A particularly noteworthy finding is that in downstream flow, a single pitch angle (198.77°) was optimal for both wave and no--wave conditions, whereas in upstream flow, two distinct optimal pitch angles were identified (22.72° for no--wave, 18.77° for with--wave) in our earlier work [40]. This discrepancy arises because downstream flow first impacts the back of the nacelle, generating a turbulent and non-uniform flow regime that reaches the blades. Such turbulence appears to dominate the blade -wake interaction, reducing the turbine's sensitivity to small pitch--angle variations. This observation has practical implications: for bidirectional sites where the turbine must operate in both flow directions, pitch--angle optimization becomes more complex for upstream operation but simpler for downstream operation—yet downstream operation is inherently less efficient.

Implications for Bidirectional Flow Turbine Design:

The results of this study offer several actionable design guidelines for tidal turbines intended for bidirectional flow environments (e.g., estuaries, straits with reversing tides):

- **Prefer Yaw--Based Active Alignment:** The substantial 30–36% increase in C_p in upstream flow strongly supports the use of

an active yaw mechanism that rotates the turbine to always face the incoming current. While this adds mechanical complexity and cost, the energy gain far outweighs the penalty of fixed downstream operation, especially in high--resource sites. This aligns with the conclusion of Frost et al. [39] but is now supported by robust experimental evidence under wave--current interactions.

- **Optimize Nacelle and Stanchion Geometry:** Since the performance loss in downstream flow originates from upstream obstruction by the nacelle and stanchion, designers should consider streamlined nacelle profiles, reduced frontal area, or even novel support structures that minimize wake generation. Our data show that the penalty is wave--dependent, with the highest penalty at intermediate wave numbers ($k_d \approx 2.94\text{--}3.27$), suggesting that structural optimization should be tailored to the dominant wave climate of the deployment site.
- **Consider Pitch--Angle Strategies for Each Flow Direction:** For bidirectional turbines without yaw capability (i.e., fixed orientation), the optimal pitch angle may need to be a compromise between the two flow directions. Our results indicate that downstream operation at 198.77° yields better performance than 202.72° under all wave conditions, providing a clear preferred setting for the downstream phase. For upstream operation, if the turbine must also operate downstream, a pitch angle near 22.72° may be acceptable for both directions, albeit with reduced performance in upstream with--wave conditions (where 18.77° would be optimal). This trade-off must be evaluated against site--specific current duration and energy capture goals.
- **Array Layout Considerations:** In multi-turbine arrays, downstream turbines are already subject to wake losses from upstream turbines [9, 10]. If, in addition, individual turbines face downstream flow (relative to their own orientation), the combined losses could be catastrophic.

Therefore, for array design in bidirectional sites, yaw control becomes even more critical to ensure that each turbine operates in upstream mode relative to the local flow direction, reducing cumulative wake effects and improving overall farm efficiency.

- **Economic Implications:** The 30--36% performance gain from upstream operation translates directly into increased annual energy yield (AEP) and improved levelized cost of energy (LCOE). For a commercial--scale turbine, this could represent hundreds of MWh per year. The additional cost of a yaw system (including bearings, actuators, and control electronics) is typically less than 5--10% of the total turbine cost, making it highly cost--effective given the performance uplift. Our experimental data provide the quantitative basis for such techno-economic assessments, which were previously based only on numerical estimates.
- In summary, by critically integrating our experimental findings with prior numerical and field studies, this work establishes that flow direction is a first--order design parameter for HATTs in tidal environments. The results challenge the common assumption that bidirectional flows can be passively accommodated with fixed turbine orientations. Instead, they advocate for active yaw control and streamlined support structures as essential features for maximizing energy capture and ensuring economic viability in bidirectional tidal sites. Future research should investigate the fatigue loading and dynamic response of yaw--controlled turbines under rapidly reversing flows to fully validate these design recommendations.

Conclusion

This paper presents an experimental investigation into the effects of flow direction, pitch angle, and wave characteristics on HATT performance under various electrical loads and current velocities, using a 1:6 model. The wave

characteristics were scaled using the Froude method, with the Khoran Strait serving as the target area. Due to the high number of experiments required by the one-factor-at-a-time approach, the Taguchi method was employed to optimize the experimental design by reducing cost and time. The study's key findings are summarized in two main sections:

Downstream Flow Analysis

- The optimal wave number for various electrical loads, with a pitch angle of 198.77° , was found to be 3.43, yielding maximum power and moment of force coefficients of 0.169 and 0.027 at a tip speed ratio of 6.28. However, the highest increases in power and moment of force coefficients were observed for wave number 3.27, with mean increases of 6.2% and 3.9% compared to the no-wave modes.
- The highest increases in power and moment of force coefficients at a pitch angle of 202.72° and a $20\ \Omega$ electrical load were for wave number 2.37, with increases of 6.5% and 5.1% compared to the no-wave modes. The optimal wave number of 3.43 yielded maximum power and moment of force coefficients of 0.179 and 0.028 at a tip speed ratio of 6.19.
- Comparing the mean power output at pitch angles of 202.72° and 198.77° in downstream flow shows that the pitch angle of 198.77° yields 20% and 6.3% higher efficiency with and without wave modes, respectively, compared to the pitch angle of 202.72° .
- The pitch angle of 198.77° is optimal for both with and without waves in downstream flow. This is because the incoming flow first impacts the back of the HATT before reaching the blade, creating turbulence and wake flow by altering the flow regime.
- A comprehensive parametric analysis reveals that when the HATT blade pitch angle is 198.77° , different electrical loads result in varying TSRs range. However, with a fixed $20\ \Omega$ electrical load and a pitch angle of 202.72° , the TSRs range remains relatively constant.

- The 3D analysis results for pitch angles of 198.77° and 202.72° reveal that the maximum values of each output variable and their corresponding coefficients, including power, moment of force, and tip speed ratio, can vary depending on the wave numbers and applied electrical loads.
- The analysis of wave-current interactions and no-wave modes shows that increasing the applied electrical load at a constant current flow velocity or wave number increases the tip speed ratio, following a concave-down curve.
- Typically, the performance of the converter improves with increasing wave height. The wave number 3.43 is considered optimal for both angles of 198.77° and 202.72° , and the optimal electrical load of $20\ \Omega$ is used as the reference in these conditions.
- The maximum power coefficient of the HATT at a wave number of 2.37 and a pitch angle of 202.72° increases by 14% compared to the same wave number at a pitch angle of 198.77° .
- The influence of waves on the pitch angles of 198.77° and 202.72° follows the order: $3.43 \geq 4.49 \geq 3.27 \geq 2.94 \geq 2.45 \geq 2.37$ and $3.43 \geq 4.49 \geq 2.37 \geq 2.94 \geq 3.27 \geq 2.44$, respectively.
- Optimal current velocity, electrical load, and wave number (57.5 cm/s, $20\ \Omega$, and 3.43) at a pitch angle of 198.77° result in power coefficient increases of 35%, 31%, and 8.4%, respectively, compared to their similar variables minimum level values.
- Analysis of the impact of variables on turbine performance indicates that current velocity has the most significant impact, followed by electrical load and waves, respectively.

Upstream and Downstream Flow Comparison

In this section, with the electrical load resistance set to its optimal value of $20\ \Omega$, the upstream flow at a pitch angle of 22.72° was compared to the downstream flow at a 180°

adjusted pitch angle of 202.72° . The key findings are as follows:

- If upstream flow pitch angles are tested under downstream flow conditions without a 180° reversal, or vice versa, the power output will be zero due to the blade's shape.
- Waves were analyzed as dimensionless parameters separately. The average power and moment of force coefficients for upstream flow at the pitch angle of 22.72° are consistently higher than downstream flow with a pitch angle of 202.72° , due to the different initial interactions of wave-current flow with the turbine's geometry.
- The highest increases in power coefficient for a pitch angle of 22.72° are observed for $k_d = 2.94$, the highest increases in moment of force coefficient for $k_d = 3.27$, and the highest increases in tip speed ratio and rotor's rotational velocity for $k_d = 3.43$, with increases of 36.1%, 18.1%, 16%, and 17.4%, respectively, compared to the pitch angle of 202.72° .
- The HATT performance coefficient curves, indicating C_p and C_m , are second-order nonlinear parabolas that initially rise and then fall after the extremum point. The ω_R versus current velocity increases linearly, meaning ω_R increases as the carriage velocity increases.
- Analysis shows that C_p and C_m at a fixed 20 Ω electrical load are higher for a pitch angle of 22.72° than for 202.72° . The maximum C_p and C_m and ω_R for a pitch angle of 22.72° are 73 (W), 5.8 (N·m), and 121 (RPM), respectively, compared to 54 (W), 5 (N·m), and 102 (RPM) for a pitch angle of 202.72° .
- Comparing upstream and downstream flows suggests that if the flow direction is always upstream and a yaw mechanism is used for HATT stanchion design, the HATT achieves the highest efficiency for harnessing bidirectional flows.

In summary, this study demonstrates that HATT performance can be significantly influenced by flow direction, pitch angle, and wave characteristics. Optimal configurations

and conditions can lead to substantial improvements in power generation and turbine efficiency.

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