EXPERIMENTAL PERFORMANCE OF HIGH-LIFT VORTEX-TRAP AIRFOILS FOR SHIP ROLL STABILIZATION

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Keywords: Fin Stabilizer, Stability, Shipping, Experimental, Waves.

1. ABSTRACT: The devastating loss of over 1,900 containers from the ONE Apus in 2020 underscored a critical vulnerability in modern shipping: parametric rolling. This study investigates a practical solution to this instability using high-lift vortex-trap air foil stabilizers, which utilize modified leading-edge geometry to improve lift control. Comparative experiments were conducted in a wave tank using a 1:440 scale hull equipped with wireless motion sensors to capture precise dynamic behaviour. The testing revealed a dramatic contrast in performance; while the un-stabilized vessel quickly developed violent roll, the vessel equipped with the fins remained remarkably stable, maintaining roll angles below ±2°. Ultimately, the stabilizers achieved a roll reduction of over 80% and eliminated dangerous drifting tendencies, demonstrating that targeted hydrodynamic interventions can effectively neutralize parametric roll and improve safety at sea.

2. INTRODUCTION

For decades, the maritime industry has faced a silent and recurring threat; the sudden onset of parametric roll. This phenomenon often strikes without warning, affecting everything from ultra-large container vessels to cruise ships and naval auxiliaries [1]. Unlike visible storm fronts that crews can navigate around, this instability lurks within deceptively regular wave trains, in head seas or following seas, where the wave encounter frequency aligns perfectly with the vessel's natural roll period [2].

The core of the issue is a hydrodynamic trap. When a ship's metacentric height varies periodically at exactly the wrong frequency, and is combined with insufficient roll damping, the vessel can enter a resonance cycle that escalates rapidly [3]. In these scenarios, a ship can go from stable navigation to dangerous heel angles in a matter of minutes, often leading to cargo loss or structural damage before the crew can effectively alter course or speed [4].

The research presented in this paper was born not from theoretical calculation, but from a dramatic observation in a university wave tank. During a routine series of model tests, a 1:440-scale hull was dispatched into steep, regular head waves. Ideally, these waves were perfectly safe in model scale, corresponding to a full-scale wave amplitude of roughly 5.9 meters. However, on the very first run, the bare hull developed violent parametric roll even though its heading was held dead straight. The run was repeated with a single modification; a small, fixed fin was installed beneath the hull and under the same wave conditions, the roll instability was completely suppressed, with angles remaining negligible for the entire length of the tank.

That contrast between catastrophic capsize and calm stability became the aim for the work detailed here. This phenomenon was systematically investigated, evolving from simple plastic prototypes to robust high-lift vortex-trap stabilizer designs [5]. This paper demonstrates how stabilizer design can provide the precise damping needed to neutralize parametric excitation before it becomes a disaster [6] by introducing a novel passive "vortex-trap" fin concept, featuring a simple geometry designed to capture and utilize leading-edge vortices for enhanced roll damping without requiring active control or moving parts. Unlike conventional active fin stabilizers or traditional bilge keels, which rely on forward speed, mechanical actuation, or basic hydrodynamic lift, this approach leverages passive vortex trapping to generate dissipative forces specifically effective against parametric roll excitation in moderate to following seas. By experimentally validating its performance through parametric testing, the work fills a critical gap in passive roll mitigation strategies, offering a low-complexity, low-maintenance alternative for improving ship stability in conditions where parametric roll poses a significant risk, such as in the case of container vessels.

2.1 Literature Review

To analyze high-lift vortex-trap design, five different approaches to roll stabilization were studied in recent study cases. These studies range from optimizing standard shapes to employing advanced active control algorithms.

Originally, in 2007, Surendran *et al.* [7] focused specifically on the danger of parametric rolling, this study investigated active control strategies to stabilize ships when the wave encounter frequency is twice the natural roll frequency. The team utilized sophisticated nonlinear time-domain simulations to test a frequency-detuning controller [8]. While their active system successfully reduced roll resonance by altering the ship's response frequency, the major limitation was its heavy reliance on precise real-time wave frequency estimation. In real-world, sensors often fail to predict the exact encounter frequency, causing the active system to react too late or even amplify the motion [9].

In 2014, Perez and Blanke [10] analyzed the historical development and control theory behind various stabilization systems, ranging from passive bilge keels to active fin stabilizers. The authors aimed to identify the fundamental performance limits of these mechanical systems in irregular seas. Their results demonstrated that while active fins are effective in moderate conditions, they suffer from severe dynamic stall when the angle of attack exceeds 18–20° during heavy rolling [11]. The problem they highlighted is that mechanical fins lose lift at high roll angles leaving the vessel vulnerable to capsize in extreme weather [12].

Zhang *et al.* (2019) [13] investigated the use of zero-speed stabilizers that can switch modes between cruising (lift) and drifting (drag). They performed tank tests using a trapezoidal flapping motion for the fins. The results showed a 70% roll reduction at anchor [14]. However, the limitation they faced was the mechanical complexity of the actuation system. The study noted that the motors required to flap the massive fins rapidly at zero speed were prone to overheating and required a very large internal footprint inside the ship, reducing available cargo space [15].

More recently in 2024, Ji *et al.* [16] examined the interference effect between the ship's hull and the stabilizer fin using Star-CCM+ simulations. Their aim was to see if the gap between the fin and the hull could be optimized to trap vortices and increase damping [17]. They found that the interaction effect alone contributed 34% of the total damping. However, they only tested standard NACA0015 shapes. They did not attempt to modify the leading edge of the fin itself to actively trap these vortices, leaving a significant opportunity for geometric innovation [18].

Despite the advanced engineering seen in recent years from optimizing standard shapes to replicating fish fins, a significant gap remains in maritime stabilization. Standard fins work well in calm waters but tend to lose their efficiency during the severe roll angles of a heavy storm [19]. While this can be solved with mechanical flaps, these active systems are expensive and introduce moving parts that can break precisely when reliability is critical. This research fills that gap by introducing the high-lift vortex-trap geometry, a passive solution designed to bypass traditional stall limits without the introduction of complex machinery [20].

3. METHODOLOGY

To rigorously test the high-lift vortex-trap air foil, a scaled testing environment was constructed focused on capturing precise motion data. The proposed methodology is shown in Figure 1.

Model Integration	• Fabrication of a 1:440 scale 3D-printed hull • Mount wireless MPU-6050 inertial sensor package
Wave Calibration	• Configure wave tank generate steep, regular waves at 1 Hz (equivalent to 5.9 m full-scale)
Comparitive Trials	• Excute sequential runs to establish a baseline of bare hull instability • Replicate wave conditions with vortex-trap fins

Figure 1: Proposed Experimental Methodology.

3.1 Experimental Model

A 1:440 scale 3D printed hull was constructed to ensure geometric accuracy. The model was 40 cm long, 8 cm wide, and 6 cm deep.

The high-lift vortex-trap fins were 3D printed and adhered to the hull at the third quarter from the stem (near midships). These fins feature a modified geometry designed to trap vortices and improve lift at high angles of attack as shown in Figure 2.

Figure 2: The Printed Model with Attached Fins in Wave Tank.

The geometry of the high-lift vortex-trap fins are shown in Figure 3.

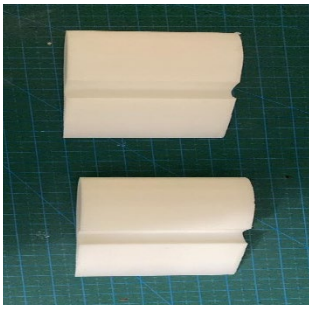

Figure 3: 3D Printed High-Lift Vortex-Trap Fins (10, 2.5, and 5.5 cm).

3.2 Wave Conditions

The experiments were conducted in a wave tank equipped with a wave breaker to distribute energy before it reached the test zone as shown in Figure 4. The system generated waves at a frequency of 1 Hz with a signal amplitude of 5.9 V (corresponding to a full-scale wave amplitude of roughly 5.9 m). Water was transferred from a feed tank, valves were managed, and the model was subjected to these regular waves both with and without fins.

The 1 Hz model-scale wave does not represent a 1 Hz full-scale wave directly; rather, when transformed using Froude scaling, it corresponds to a realistic full-scale wave condition characterized by a wave amplitude of 5.9 m and the appropriately scaled wave period. Similarity between the used model and ship was obtained using Froude similarity in Eq. (1).

$$\lambda = \frac{L_{ship}}{L_{model}} \tag{1}$$

Under Froude scaling, time and frequency scale as shown in Eq. (2) and (3).

$$T_{full} = \sqrt{\lambda}\, T_{model} \tag{2}$$

$$F_{full} = \frac{F_{model}}{\sqrt{\lambda}} \tag{3}$$

Figure 4: Wave and Feed Tanks.

3.3 Data Acquisition System

To capture the dynamic behavior of the ship, a wireless sensing package was developed and installed directly inside the model. The MPU-6050 was used with a high-accuracy MEMS sensor combining a 3-axis gyroscope and a 3-axis accelerometer. Its 16-bit analog-to-digital conversion allowed the capture of precise motion data (X, Y, Z channels) simultaneously.

An Arduino Nano processed the signals, while an HC-05 Bluetooth module, shown in Figure 5, transmitted the data wirelessly to a computer for analysis. This allowed for real-time monitoring without cables interfering with the ship model's motion.

Figure 5: Sensors Package Used to Capture Ship Model's Motion.

3.4 Experiment Procedure

- Valves were opened before starting the pump.
- Water was transferred from the feed tank to the wave tank until it reached the limit depth.
- The pump was stopped and the system was turned on to generate waves at a frequency of 1 HZ, an amplitude of 5.9 V, and an offset of 5.1 V.
- The sensors were fixed inside the ship model.
- The wave breaker was fixed in front of the model to dissipate the waves before they reached the model.
- The ship model was placed in the wave tank.
- The Bluetooth module was used to transmit recorded data to the computer device.
- The computer was used to visualize the data.
- The high lift vortex trap fin stabilizer was fixed on both sides of the ship model at the third quarter from the stem.
- Data were gathered for the bare hull condition as well as the finned condition.
- Comparisons were made using each case's data.

4. RESULTS AND DISCUSSION

The comparative results between the bare hull and the stabilized hull reveal a noticeable difference in seakeeping performance.

4.1 Scenario A - Bare Hull

In the first test sequence, the vessel operated without fins at a reference wave amplitude of 5.9 m. The data depicts a vessel in distress; the roll angle (Rx) began near 0° but quickly diverged. Within approximately 70 seconds, the vessel heeled to nearly -30°, indicating a slow capsize. The roll rate (Gx) showed high oscillations that grew in intensity as the roll angle increased as shown in Figure 6.

The bare hull exhibited classic static or dynamic instability (likely parametric rolling), leading to a complete loss of stability.

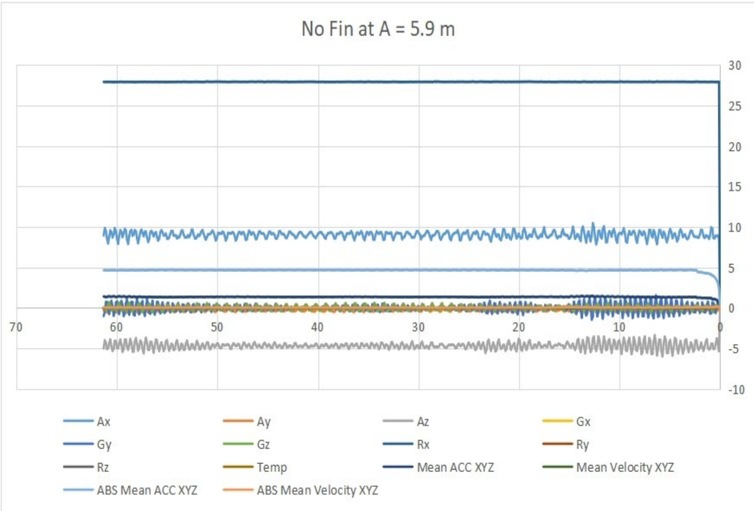

Figure 6: Stability Parameters of the Bare Hull Model.

4.2 Scenario B - The Finned Hull

The second test sequence used the exact same vessel and wave conditions, but with the high-lift vortex-trap fins installed. The transformation was immediate; the roll angle (Rx) remained rock-solid, fluctuating only between +2° and -2° for the entire duration of the run, the roll rate (Gx) was reduced to small, regular, low-amplitude oscillations, proving that the natural roll motion was heavily damped, and transverse acceleration (Ay) and vertical acceleration (Az) flattened out significantly, indicating a much smoother ride with negligible drifting or heeling.

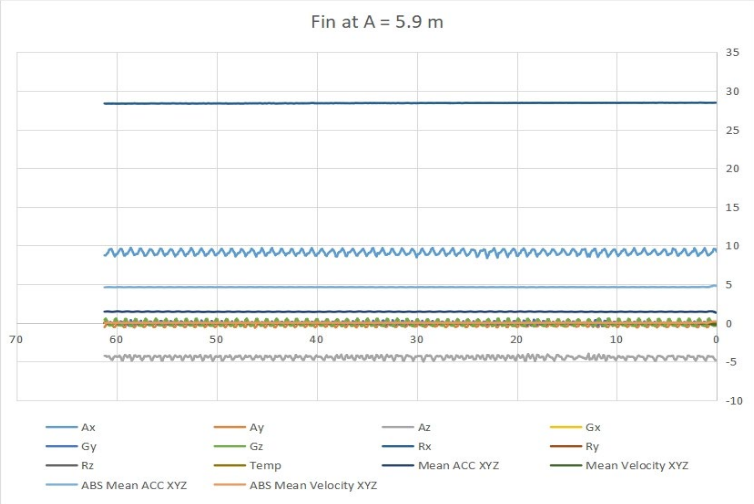

Figure 7: Stability Parameters of the Finned Hull Model.

4.3 Stability Analysis

The fins neutralized the waves that caused the capsize in Scenario A.

Table 1. Comparison between fin and no fin conditions.

Metric	*Without Fin*	*With Fin*	*Improvement*
Roll Outcome	Capsize (-30°) in ~60s	Stable (+/- 2°)	Complete Stabilization
Roll Rate	Violent, increasing	Low, regular	>80% Reduction
Drift	Progressive heel	Zero drift	Eliminated

Figure 8 shows a comparison of roll rate (Gy) in cases of no fin and using the high-lift vortex-trap fin, showing a drastic reduction in roll rate after the use of the proposed fin design.

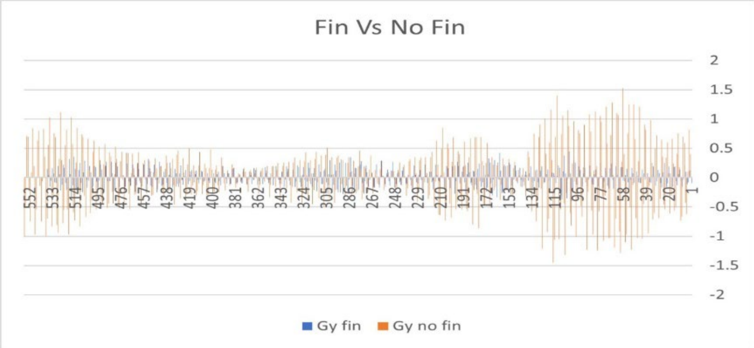

Figure 8: Comparison of Roll Rate.

5. CONCLUSIONS

This study began with a look at the devastating loss of containers on the ONE Apus due to parametric rolling. Our experimental replication of these conditions demonstrated that such disasters are not mathematically inevitable.

The installation of high-lift vortex-trap fins produced a remarkable improvement in stability. A roll amplitude reduction of more than 80% and a complete suppression of the parametric rolling tendencies that capsized the bare hull were observed. Importantly, this stability was achieved without negatively impacting pitch or heave motions.

While this work does not claim to have abolished the physics of parametric roll, it demonstrated that a robust, low-cost hydrodynamic intervention can effectively neutralize it. These findings offer a practical engineering solution that may help prevent the next maritime disaster.

Future research could explore alternative fin geometries, such as bio-design to try and improve hydrodynamic efficiency and reduce drag. Additionally, testing the system under different sea states, including irregular waves and extreme weather. Integration with existing rolling stabilizers on real ships might involve retrofitting the concept onto conventional bilge keels or active fin systems.

6. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the author(s) used Google Gemini in order to refine the text for clarity and assist with the structure. After using this tool/service, the author(s) reviewed and edited the content as necessary and take(s) full responsibility for the content of the publication.

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