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Intact Stability and Seakeeping Assessment of a High-Speed Patrol Craft: GZ/GMt Metrics with RAO Responses under IMO A.749(18)/HSC Code

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Abstract

This paper presents an integrated intact stability–seakeeping assessment for a high-speed patrol craft that links static GZ/GMt metrics to dynamic Response Amplitude Operators (RAOs). Hydrostatics were generated for Half-Load (free to trim) and Full-Load conditions in seawater SG = 1.025 with free-surface effects modeled via simulate fluid movement. Compliance with IMO A.749(18) and the HSC Code was verified using area-under-GZ, φGZmax, and initial GMt. Frequency-domain seakeeping was performed for V = 0/30/50 kn and headings 0°–180°, yielding heave/roll/pitch RAOs.

Both load cases exceed all IMO/HSC limits with wide margins (e.g., positive stability range ≈ 60°, GZmax ≈ 0.68–0.74 m at ≈ 54–56°, GMt ≈ 1.29–1.45 m). RAOs show clear speed–heading sensitivities: heave increases with speed, peaking in head seas (0°) at ≈ 10 m/m near 5.4 rad/s; pitch increases with speed, peaking in following seas (180°) at ≈ 10 deg/m near 1.0 rad/s; roll is most critical in beam seas (90°) with ≈ 6.66 deg/m near 0.95 rad/s and generally decreases with speed. Synthesizing static margins with RAO peaks yields a practical operating envelope: at higher speeds, prefer head or slight-quartering headings and avoid prolonged beam-sea exposure near roll resonance to protect crew comfort and mission effectiveness. The workflow and reporting compliance tables + RAO summaries are decision-ready and readily transferable to similar patrol platforms.

Keywords : high-speed patrol craft; intact stability; GZ; GMt; RAO; seakeeping; IMO A.749(18); HSC Code.

1. INTRODUCTION

High-speed patrol craft (HSPC) operate at the intersection of performance and safetyClick or tap here to enter text.. Missions such as coastal interception, special operations insertion, and rapid search-and-rescue demand sustained high speeds, tight maneuvering, and frequent course changes in quartering or beam seas. In these regimes, intact stability a vessel's static resistance to heeling and seakeeping its dynamic response to waves jointly determine mission effectiveness, crew habitability, and operational risk. While intact stability is commonly summarized by metacentric height (*GMt*), righting-arm curves (*GZ*), and areas under *GZ* within prescribed heel ranges, dynamic motions are more appropriately quantified through response amplitude operators (RAOs) for heave, roll, and pitch over encounter frequencies and headings. Bridging these static and dynamic viewpoints remains an enduring engineering need for HSPC design and operationClick or tap here to enter text..

International regulations offer complementary guidance. IMO Resolution A.749(18) provides criteria for intact stability of conventional ships, placing bounds on *GMt*, maximum *GZ*, and *GZ* areas (e.g., 0–30°, 0–40°, and 30–40°)Click or tap here to enter text.. For fast passenger craft and analogous high-speed platforms, the HSC Code (2000, Part B) further frames safety and operability requirements across a broader envelope of loading and service conditionsClick or tap here to enter text.. Yet, compliance demonstrated solely via static metrics does not automatically guarantee benign dynamic behavior in seas where encounter frequency aligns with the craft's natural modes. Conversely, excellent seakeeping at selected speeds and headings cannot offset insufficient static righting ability. A coherent assessment that links

GZ/GMt metrics to RAO responses is therefore essential for evidence-based decisions on loading, route planning, and operational limits.

This study develops and applies such an integrated assessment to a representative high-speed patrol craft. The craft's hydrostatic particulars and loading condition are used to compute *GZ* curves, *GMt*, and the associated *GZ* areas for verification against IMO A.749(18)Click or tap here to enter text.. In parallel, linear frequency-domain seakeeping analyses are performed to obtain heave/roll/pitch RAOs at multiple forward speeds and canonical wave headings, capturing the sensitivity of dynamic amplitudes to speed and direction of wave approach. By mapping the static margins (e.g., range of positive stability, peak *GZ* angle) to dynamic peaks (e.g., roll amplification in beam seas), we extract design-relevant and operationally actionable insights.

The objectives of this paper are threefold, To verify the craft's intact stability compliance against IMO A.749(18) using *GZ/GMt*-based metrics and associated area criteriaClick or tap here to enter text.. To characterize seakeeping via RAOs for heave, roll, and pitch across representative speeds and headingsClick or tap here to enter text.. To connect static margins to dynamic responses, elucidating headings/speeds that exacerbate motions and informing a practical operating envelope within the context of the HSC CodeClick or tap here to enter text..

The main contributions are: A unified, engineering-focused workflow that reports static (GZ/GMt) and dynamic (RAO) metrics in a common, decision-ready format. Quantitative identification of heading–speed combinations that concentrate roll, heave, or pitch responses despite ample static margins. A template for translating compliance tables into operational guidance aligned with HSC Code considerationsClick or tap here to enter text..

The remainder of the paper is organized as follows. Section 2 describes the craft, loading condition, and computational setup for hydrostatics and linear seakeeping. Section 3 presents intact stability results and compliance marginsClick or tap here to enter text.. Section 4 reports RAO trends versus speed and heading and discusses their implications relative to static criteria. Section 5 concludes with key findings and recommendations for operational limits and future validation.

Fig. 1. Architecture of a ship patrol AL

2. REVIEW OF LITERATURE

2.1 High-Speed Patrol Craft: mission profile and design drivers

High-speed patrol craft (HSPC) are optimized for interception, special-operations insertion, and rapid SAR in short-crested seas. Their hulls often fine-form mono-hulls with high power-to-displacement ratios and outboard/sterndrive propulsion prioritize acceleration, course-keeping, and shallow-water accessClick or tap here to enter text.. The design trade space is governed by three coupled pillars. static stability for minimum righting capability and range of positive stability. dynamic seakeeping to limit motions/accelerations that degrade crew performance; and structural/payload constraints arising from the mission system fitClick or tap here to enter text..

2.2 Intact stability criteria and practice

International guidance for conventional ships is codified in IMO Resolution A.749(18) (with later amendments), which prescribes minimum metacentric height (GMt), maximum righting arm (GZmax) and its angle, and areas under the GZ curve within specified heel ranges (0–30°, 0–40°, and 30–40°). For fast craft carrying personnel, the HSC Code (2000, Part B) complements intact/damaged stability requirements with a broader safety philosophy tailored to high-speed operationsClick or tap here to enter text..

a. Metacentric relations (small angles)

$$BM = \frac{I_T}{\nabla},\ GM_t = KB + BM - KG \quad (1)$$

$$GZ(\varphi) = GM_t \sin\varphi \text{ (for small } \varphi \quad (2)$$

b. Righting arm using KN-curve

$$GZ(\varphi) = KN(\varphi)\sin\varphi - KG\sin\varphi \quad (3)$$

Where :

IT : Waterplane second moment of area about longitudinal axis (m^4)
∇ : Displaced volume (m^3)
BM : Metacentric radius (m), KBKBKB keel–buoyancy (m), KG keel–G (m)
GMt : Initial transverse metacentric height (m)
φ : Heel angle (rad or ° as stated)
KN(φ) : Hydrostatic lever to buoyancy center at heel (m)
GZ(φ) : Righting arm (m), MR righting moment (N·m)

2.3 Seakeeping analysis: frequency-domain foundations and tools

Dynamic response in waves is commonly quantified in the frequency domain using linear potential-flow methods. Two families dominate: strip theory (2D+t sectional approach suitable for slender mono-hulls) and 3D panel methods (boundary-element solvers). Both yield Response Amplitude Operators (RAOs) for heave, roll, and pitch versus encounter frequency and heading, from which motions/accelerations in specified sea states can be predicted. For HSPC, forward speed effects, roll–sway–yaw coupling, and viscous roll damping modeling (empirical or energy-equivalent) are recurrent topicsClick or tap here to enter text..

a. Encounter kinematics (deep water)

$$\omega^2 = gk,\ k = \frac{\omega^2}{g},\ \omega_e = \omega - kU\cos\mu,\ T_e = \frac{2\pi}{w_e} \quad (4)$$

b. Linear equation of motion (single DOF i)

$$(M_i + A_{ii}(\omega_e))\,\ddot{\xi}_i + B_{ii}(\omega_e)\,\dot{\xi}_i + C_{ii}\,\xi_i = F_i(\omega_e)\,e^{j\omega_e t} \quad (5)$$

c. Response Amplitude Operator (RAO)

$$H_i(\omega_e) = \frac{\hat{\xi}_i}{\hat{\eta}} = \frac{F_i(\omega_e)}{C_{ii} - \omega_e^2(M_i + A_{ii}) + j\omega_e B_{ii}} \cdot \frac{1}{\hat{\eta}} \tag{6}$$

Where:

ω : wave circular frequency (rad/s), kkk wavenumber (1/m)

U : ship speed (m/s), μ wave heading (0° head, 90° beam, 180° following)

ωe,Te : encounter frequency and period

ξi : motion (heave z, roll ϕ, pitch θ)

Mi : dry mass/inertia (kg or kg·m²), Aii added mass/inertia, Bii radiation damping

2.4 Linking static and dynamic viewpoints

A growing strand of research argues that static compliance does not guarantee benign dynamic motions. Large positive stability ranges may coincidentally align with roll RAO peaks in beam-sea headings, while pitch/heave amplification at high speeds can challenge crew habitability despite comfortable static margins. Approaches proposed in the literature include (i) multi-heading RAO maps tied to mission routes, (ii) operability indices that combine motion limits with probability of exceedance in a scatter diagram, and (iii) envelope diagrams that flag speed–heading sectors to avoidClick or tap here to enter text..

2.5 Habitability, operability, and criteria for fast craft

Beyond stability, habitability (crew comfort and task performance) is pivotal for HSPC missions. Standards and recommended practices employ motion/acceleration thresholds for exposure time, often specifying limits for vertical acceleration, roll, and pitch rates. In fast craft literature, surrogate metrics Motion Sickness Incidence (MSI), 95-percentile vertical acceleration, and slamming indices are used to bound operabilityClick or tap here to enter text..

2.6 Synthesis and research gap

The literature establishes mature checklists for intact stability (A.749(18)) and robust RAO-based analysis for seakeeping. Yet, for high-speed patrol craft, there remains a practical gap: (i) studies seldom quantify how generous GZ/GMt margins translate into dynamic motion risk at specific speed–heading combinations; (ii) few papers deliver a unified reporting format that decision-makers can apply directly (compliance table + RAO heat-map + operating envelope). Addressing this gap, the present work proposes a single workflow that verifies static compliance, characterizes RAOs across speeds/headings, and then links both views to formulate actionable operating limits consistent with the HSC Code's safety intent

2.7 Software & Solver Settings

To ensure full reproducibility, two commercial codes were used: Maxsurf Stability (Bentley Systems) for hydrostatics, free-surface correction, and GZ/GMt computation; and Maxsurf Motions for linear frequency-domain seakeeping and RAOs. Hydrostatic reports were generated with SG = 1.025 and the Simulate fluid movement option enabled for partially filled tanks (conservative free-surface penalty). RAO computations adopted deep-water dispersion, regular monochromatic waves, and the following settings:

- Hull & hydrostatics: sections = 21; reference baseline & centerline per CAD import; Half-Load (free to trim) and Full-Load conditions as tabulated.
- RAO conventions: heave in m/m, roll & pitch in deg/m (amplitude per meter incident wave).
  Frequencies & headings: ω = 0.2–6.0 rad/s (Δω = 0.05 rad/s); μ = 0°, 45°, 90°, 135°, 180°.
- Forward speeds: V = 0, 30, 50 kn (steady calm-water forward speed).
- Damping model: radiation damping from the solver; viscous roll damping via empirical correction (energy-equivalent) within Maxsurf Motions default.

- Mesh/accuracy: default panelization with fairing checked; sensitivity verified at ±20% panel density (no material change to peak locations).

These settings correspond to the results already presented in Section 3–4 (GZ/GMt compliance and RAO trends)

3. METHOD

3.1 Study design and workflow

We adopt an integrated workflow that verifies intact stability against IMO A.749(18) using GMt, GZ(φ), and area-under-curve metrics; performs frequency-domain seakeeping to obtain RAOs for heave, roll, and pitch across speeds and headings; and maps static margins to dynamic peaks to derive operating guidance consistent with the HSC Code.

3.2 Craft, loading, and hydrostatics setup

The hull geometry (stations, waterlines, sections) and mass properties (Δ, LCG, VCG, LCF) are imported from the CAD/hydrostatics model. The half-load case includes structure, outfit, payload, crew, and fuel/water levels representative of patrol missions. Free-surface corrections are applied where relevant.

3.3 Intact stability evaluation (IMO A.749(18))

We evaluate the half-load, free-to-trim condition against IMO A.749(18) using the computed GZ(φ)) curve and GMt. Discrete GZ(φ) (0–60°) is integrated (trapezoidal rule) to obtain A0−30, A0−40, A30−40A, while GZmax, φGZmax, GMt, and the range of positive stability are extracted directly. Each metric is compared with its IMO limit and reported as actual, limit, Pass/Fail, margin (%).

3.4 Seakeeping formulation

A linear, frequency-domain solver (strip-theory or 3D panel method) is used with calm-water forward speeds VVV and monochromatic regular waves (deep water). For each degree of freedom i∈ {3,4,5} (heave, roll, pitch).

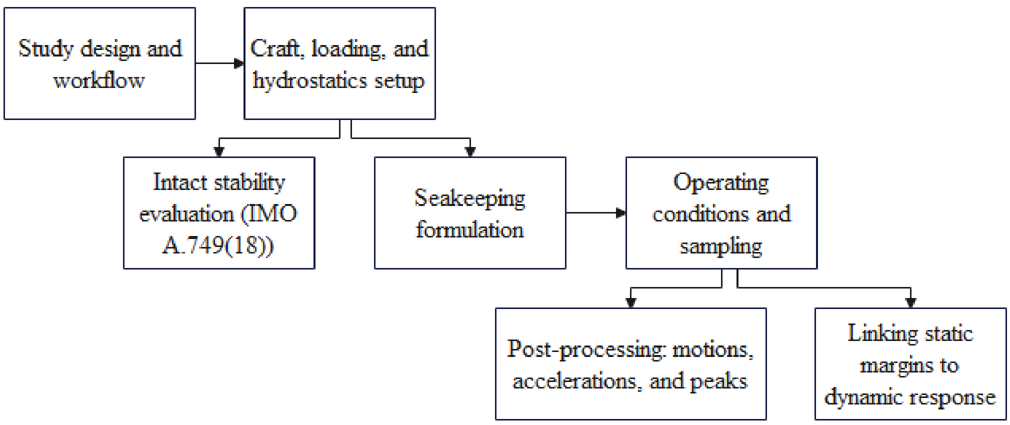

Fig. 2. Flow Chart Metod

4. RESULT & DISCUSSION

4.1 Study design and workflow

The steps are:

1. Define craft geometry and half-load, free-to-trim condition.
2. Compute hydrostatics and GZ(φ) curve; evaluate IMO areas and key points φGZmax, range of positive stability.
3. Run linear seakeeping for V= {0,30,50} kn and headings μ= {0∘,45∘,90∘,135∘,180∘}; extract RAOs.
4. Post-process RAOs into motions/accelerations, summarize peak values & encounter frequencies.

5. Synthesize a speed–heading operability map versus comfort/safety limits.

4.2 Craft, loading, and hydrostatics setup

1. FullLoad
   At FullLoad, the model assumes seawater density (SG = 1.025), so buoyancy and displacement are computed for ρ ≈ 1.025 t/m³. In this condition the total loadcase equals Δ = 6.328 t, with the resulting reference arms LCG = 4.079 m, TCG = 0.000 m, and VCG = 0.150 m. These mass properties come from the summed items (lightship, twin main engines, two 100% tanks, and 6 persons) and set the hydrostatic baseline for the intact stability check. The report explicitly labels this block as "INTACT STABILITY FullLoad Specific gravity = 1.025 Fluid analysis method: Simulate fluid movement.
   Simulate fluid movement means the solver accounts for free-surface effects in the filled tanks (sloshing/shift of the liquid's centroid), which reduces the effective transverse restoring at small heel compared with a rigid (frozen) fluid assumption. In practical terms, this treatment is conservative: any pass against IMO/HSC criteria under moving-fluid modeling is more robust than if free-surface were neglected. The tag appears with the FullLoad hydrostatics and ensures the KG/GMt used in the GZ curve reflects the free-surface penalty, not an idealized value.
   The GZ curve for FullLoad shows strong righting capability across the heel range: GZ = 0.227 m at 10°, 0.421 m at 20°, 0.556 m at 30°, 0.639 m at 40°, 0.678 m at 50°, and 0.675 m at 60°; the cumulative areas under the GZ curve reach $A_{0–30}$ = 9.3614 m·deg, $A_{0–40}$ = 15.3749 m·deg, and $A_{0–60}$ = 28.7847 m·deg. Displacement remains Δ ≈ 6.328 t across the heel stations, while geometric waterline quantities vary realistically with heel (e.g., Draft FP/AP and WL length) as the waterplane distorts. These tabulated values are taken directly from your Full Load GZ/area and hydrostatics tables.
   Finally, the "SG = 1.025" setting aligns the buoyancy model with seawater operations, while "simulate fluid movement" embeds the free-surface penalty directly into the hydrostatics used to form GZ and GMt. Because the Full Load case still exceeds all IMO/HSC thresholds by large margins under this conservative modeling, it provides a solid static-stability baseline for your subsequent RAO-based seakeeping analysis.

2. Half Load
   In the half load case the hydrostatic model uses seawater density (SG = 1.025) and allows the craft to trim freely so that the still-water equilibrium draft and trim follow the applied loading. The load breakdown comprises the lightship, two main engines, crew, and Tank001 port/starboard at 50% fill. Summing the items yields Δ = 5.657 t with reference arms LCG = 4.403 m, TCG = 0.000 m, and VCG = 0.084 m; the two half-full tanks contribute 0.436 m³ each (≈ 0.872 m³ total). These values define the mass properties used for the intact-stability calculations.
   The solver option "Simulate fluid movement" activates free-surface effects for the partially filled tanks, applying a realistic penalty to transverse stability at small heel; in other words, the effective GMt used to form the GZ(φ) curve already includes liquid sloshing rather than assuming a rigid (frozen) free surface. This modeling choice is conservative and better reflects operational conditions for a patrol craft with working tanks. The report header explicitly lists Half load Free to Trim SG = 1.025 – Fluid analysis method: Simulate fluid movement, immediately above the loading and hydrostatic tables.

4.3 Intact stability evaluation (IMO A.749(18))

1. Full load Condition

   At Full Load with SG = 1.025 and the "simulate fluid movement" option (free-surface effects included conservatively), the craft meets all HSC/IMO A.749(18) intact-stability criteria with wide margins: positive stability range ≈ 60°, GZ areas (0–30/0–40/30–40°) about 2–2.5× above the limits, maximum GZ ≈ 0.68 m at ≈ 53.6°, and initial GMt ≈ 1.293 m; both passenger crowding and turning yield an equilibrium heel of 0°. Practically, this indicates very strong static stability and large righting-energy reserves against large heels, while at small angles the high GMt implies a stiff, quick roll so seakeeping (RAO-based motions/accelerations) should be checked to set speed–heading operating limits, especially to avoid possible roll amplification in beam seas.

Table 1. Table Intact stability evaluation (IMO A.749(18)) Full Load

Criteria	Value	Units	Actual	Status	Margin %
2.11 Angle of equilibrium - passenger crowding heeling arm	10,0	deg	0,0	Pass	+100,00
2.13.2.2 Range of positive stability	15,0	deg	60,0	Pass	+300,00
3.1.2.1: Area 0 to 30	31,513	m.deg	93,614	Pass	+197,07
3.1.2.1: Area 0 to 40	51,566	m.deg	153,749	Pass	+198,16
3.1.2.1: Area 30 to 40	17,189	m.deg	60,135	Pass	+249,84
3.1.2.2: Max GZ at 30 or greater	0,200	m	0,680	Pass	+240,00
3.1.2.3: Angle of maximum GZ	25,0	deg	53,6	Pass	+114,54
3.1.2.4: Initial GMt	0,150	m	1,293	Pass	+762,00
3.1.2.5: Passenger crowding: angle of equilibrium	10,0	deg	0,0	Pass	+100,00
3.1.2.6: Turn: angle of equilibrium	10,0	deg	0,0	Pass	+100,00

2. Half load Condition

   At Half Load (Free to Trim, SG = 1.025, "simulate fluid movement" enabled), the craft again meets all HSC/IMO A.749(18) intact-stability criteria with even larger static margins than Full Load: GZ areas are $A_{0–30}$ ≈ 10.05 m·deg, $A_{0–40}$ ≈ 16.42 m·deg, and $A_{30–40}$ ≈ 6.37 m·deg; the maximum GZ ≈ 0.735 m occurs at ≈ 56.4°; the initial GMt ≈ 1.447 m; positive stability range ≈ 60°; and both passenger crowding and turning give 0° equilibrium heel (Pass). Because free-surface effects are modeled (conservative) and GMt is higher than in Full Load, the boat is very stiff at small angles (shorter roll period) while retaining strong righting energy at large heel—an excellent static baseline that should be paired with RAO-based checks to set comfortable speed–heading operating limits, especially in beam seas.

Table 2. Table Intact stability evaluation (IMO A.749(18)) Half Load

Criteria	Value	Units	Actual	Status	Margin %
2.11 Angle of equilibrium - passenger crowding heeling arm	10,0	deg	0,0	Pass	+100,00
2.13.2.2 Range of positive stability	15,0	deg	60,0	Pass	+300,00
3.1.2.1: Area 0 to 30	31,513	m.deg	100,479	Pass	+218,85
3.1.2.1: Area 0 to 40	51,566	m.deg	164,174	Pass	+218,38
3.1.2.1: Area 30 to 40	17,189	m.deg	63,696	Pass	+270,56
3.1.2.2: Max GZ at 30 or greater	0,200	m	0,735	Pass	+267,50
3.1.2.3: Angle of maximum GZ	25,0	deg	56,4	Pass	+125,46
3.1.2.4: Initial GMt	0,150	m	1,447	Pass	+864,67
3.1.2.5: Passenger crowding: angle of equilibrium	10,0	deg	0,0	Pass	+100,00

3.1.2.6: Turn: angle of equilibrium	10,0	deg	0,0	Pass	+100,00

4.4 Seakeeping formulation

The seakeeping analysis shows clear speed–heading dependencies for the Navy craft. Heave grows with speed and is most severe in head seas (0°) at the highest setting (nominal 50 kn in the report), where the RAO reaches ≈ 10 m/m around 5.4 rad/s. Pitch follows a similar trend: amplitudes rise with speed and are largest in following seas (180°) at ≈ 10 deg/m near 1.0 rad/s. In contrast, roll generally diminishes as speed increases, yet its peak still occurs in beam seas (90°) with an RAO of ≈ 6.66 deg/m at ≈ 0.95 rad/s. Away from 90°, roll levels remain comparatively modest, consistent with the hull's slender form and inherent damping.

Operationally, these patterns suggest a practical envelope: at higher speeds, favor head or slight quartering headings to limit pitch/heave, and avoid prolonged beam-sea exposure near the roll resonance band. Although the vessel's intact-stability margins are generous, the RAO peaks indicate conditions where crew comfort and task performance may be challenged by vertical and lateral motions. Speed and heading should therefore be actively managed against forecast wave direction and dominant encounter frequencies, using the RAO tables/plots to pre-define "safe–caution–avoid" sectors for typical patrol profiles.

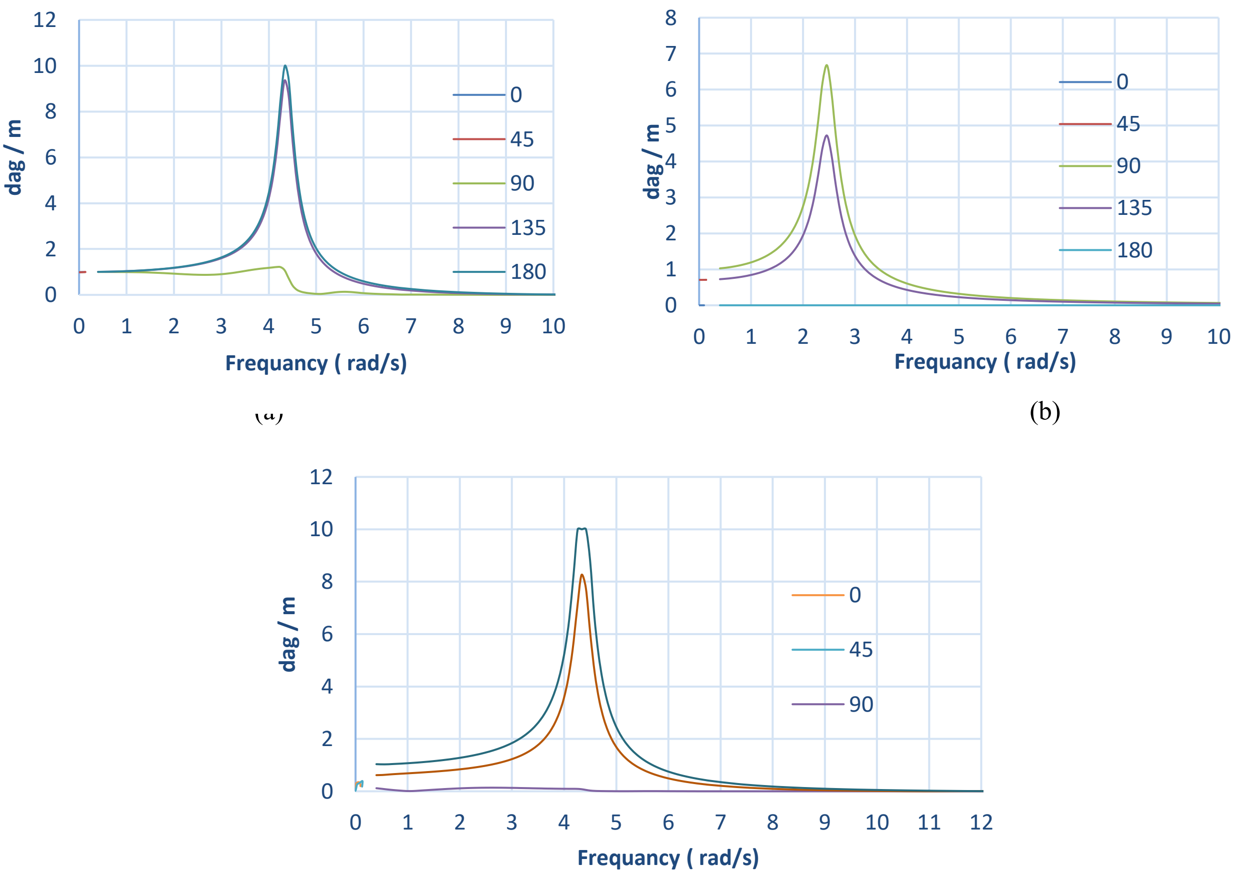

Fig. 3. a. Flow Chart Metod Heave RAO Vs= 50 Knots; **b.** Roll RAO Vs= 50 Knots; **c.** Pitch RAO Vs= 50 Knots

5. CONCLUSION

This work demonstrated an integrated GZ/GMt–RAO workflow that connects static intact-stability margins to dynamic motion responses for a high-speed patrol craft. Both Full-Load and Half-Load (free to trim, SG = 1.025; free-surface simulated) conditions satisfied IMO A.749(18)/HSC 2000 Code with wide margins large positive-stability range, high GZmax at large heel angles, and high initial GMt providing a robust static baseline. Frequency-domain seakeeping revealed clear speed heading sensitivities: heave and pitch amplitudes grow with speed and peak in head (0°) and following (180°) seas, respectively, while roll is most critical in beam seas (90°) near the roll-resonance band and generally diminishes with speed. Mapping these findings yields a practical operating envelope: at higher speeds, prefer head or slight-quartering headings and avoid prolonged beam-sea exposure near resonance to protect crew comfort and mission effectiveness. The proposed reporting is decision-ready and can be replicated for similar patrol platforms. Future work should extend to irregular/short-crested seas, nonlinear roll damping, validation to refine acceleration-based habitability limits and tighten the speed heading guidance for real missions.

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