KEY DESIGN SOLUTIONS AND SPECIFICS OF OPERATION IN HEAVY WEATHER (FLUID MECHANICS APPROACH TO STABILIZATION OF SHIP IN HEAVY SEAS)

Vasily Khramushin, Sakhalin State University,
chairman of Sakhalin Division of the Alexey Krylov Shipbuilders Society. Khram@Mail.ru

ABSTRACT

The diversity of the ship hull and ship architecture design decisions of modern ocean fleets, are the sign existence criterion of the certain reserves for safety storm navigation, which produced by excess of main engines power, as well as possibility of global hydrometeorology accompaniments on all seagoing communication. However, token of real optimization at the ship maritime quality must be uniformity of design decisions only, under which any difference in the hull configuration or general architecture of ship must be explained by navigable requirements or particularly condition of merchant vessel on the sea-line. In the good maritime practice have such determination, which corresponds to the notion of the nice ship, that meaning his nautical quality and ship architecture without unnecessary things.

Keywords: *Ship, pitching, rolling, hull form optimization, trochoidal wave, storm forces and reaction.*

1. INTRODUCTION[1]

The modern shipbuilding does not uniformity of the design decisions for a hull form and common architecture of the ship, that is formally indicative of absence unified engineering approach for fluidmechanics optimization of external power influence for the reason achievements to best ship seaworthiness in stormy condition, and exceedingly dangerous under load impact from steep waves and hurricane winds. Navigation all more relies on prior warning of dangerous sea phenomenas, as a results by newish atmosphere and sea surface monitoring with space satellites. Insufficiently stormy seakeeping imply to unacceptable downtime period of navigation, when all ships waiting for a good weather on the sea, in her self port.

The modern fleet, as a rule, takes fundamental advantage of medieval naves and old-time steamship, expressing to any seagoing ships possess the excess reserve to powers main engines. Reliable functioning of the main engines machines are allows for navigator to actively maneuvers and prevention hard seizure of the ship by storm wave, but if inevitable arising dangerous collision, must be sure to restore the original condition of the sailing: newly and newly achieving for target propulsion, or acceptable course and speed for storm rough minimize. Excess of ship engines power, shall attach effect to increase of fuel expense at voyage on a calm sea. On a stormy sea all ships is decreases a speed ahead, and need to actively using the main engines and helms, which forced works solely for safe

[1] This paper was translated from Russian with computer software and may be difficult to read in English. As the National Committee did not have resources for professional translation of this paper, Russian text was used for peer review and included in the electronic version of the proceedings for further references.

stormy sailing, when hurricane forces make a technical reliability proof for all ship's mechanisms, and examine for navigator of real experience to maritime practices.

2. HULL FORM DEFINE FUTURE AND EFFICIENT OF SHIP NAVIGATION

At present research are reasonable return to glorious experience technical era, when was achieved shipbuilding masterpieces from the geography discovery and far seagoing epoch. Consistent designing for unity ship with ocean nature in the old years was entrusted solely for the experienced captains and the most authoritative seafarers. At this way possible to reveal the main conditions of stormy sailing of the ship; signify recommendations for navigators about course and speed of ship for efficient solving of delivered purpose in any: complex, stormy and ice condition; and, as effect, by similes to reveal new key elements of ship hull and common architecture for future design a new perspective ship.

2.1. Mathematical models of most dangerous storm waves, and their fluidmechanics influences on the surface ship.

The maintenance of stormy seakeeping possible with due regard for fluidmechanics processes in group structures of trochoidal waves and breaking ridges of freak-waves, as obscure marine danger, which noted by Russian and foreigner scientists now.

Within Gerstner's theory have a velocity field and geometric shape for gravitational waves upon deep sea, which estimated by parametric description for liquids particles trajectory, moving at Lagrange's (local) coordinates by cycloids with variable radius:

$$x_W = x - a\cdot\sin(x\cdot 2\pi/\lambda)\cdot e^{2\pi\cdot(z+a\cdot\cos(x\cdot 2\pi/\lambda)-a)/\lambda};$$

$$z_W = z + a\cdot\cos(x\cdot 2\pi/\lambda)\cdot e^{2\pi\cdot(z+a\cdot\cos(x\cdot 2\pi/\lambda)-a)/\lambda},$$

where is: x_W, z_W – abscissa and applicata for liquid particles in motion by coordinates: x, z; a – factor of height with theoretical maximum: $A = a\cdot 1{,}134\cdot\lambda/(4\pi)$. Domain of definition for a and x is limited: $0 < a \le 1{,}0$; $z \le 0$.

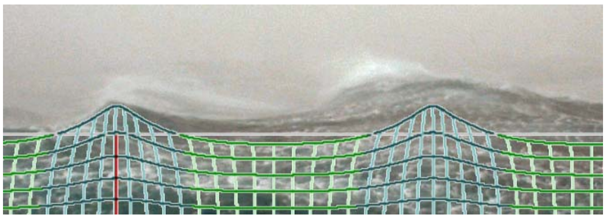

Figure 1.Typical progressive storm waves before crushing its crest on Okhotsk Sea. Angle of slope reach 30°. If wavelength: l=100 m (the period 8 sec), then total height must be 12 m (the tide/low is 9/-3m), and liquid velocity at crest up to 20 knots.

Progressive waves brings the serious danger for unmanned ship, since contradirectional currents at top and trough waves can turn the ship to beam onto the sea, whereupon possible hard blow to ship board and follow drag the body to intensive vertical flow under breaking wave crest.

On deep water trochoidal waves never go by regular progressive waves. After merging to group structures will formed freak-waves, as a central wave of package. This freak-waves doesn't greatly dangerous fluidmechanics influence to ship, because this central waves has really losing self velocities, and reveal itself as standing waves.

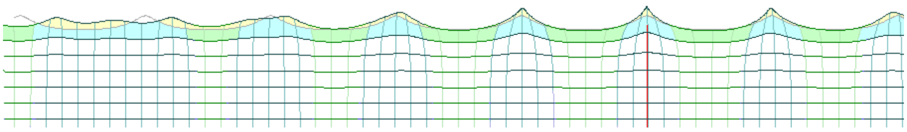

Figure 2. Freak-waves (Ninth billow) is always present in group structure of trochoidal stormy waves, and steepness of slope to 45° (theoretically - 60°).

Empirical synthesis the group structure for trochoidal waves possible as a result of superpositions with counter system of regular waves with phase factor: $x' = -0{,}889 \cdot x$,, and several smaller heights: $a' = a/1{,}286$.

$$x_G = x_W - a' \cdot \sin(x' \cdot 2\pi/\lambda) \cdot e^{2\pi \cdot (z + a' \cdot \cos(x' \cdot 2\pi/\lambda) - a')/\lambda};$$

$$z_G = z_W + a' \cdot \cos(x' \cdot 2\pi/\lambda) \cdot e^{2\pi \cdot (z + a' \cdot \cos(x' \cdot 2\pi/\lambda) - a')/\lambda},$$

where main parameters of trochoidal waves is selected so that: $a = 1{,}0$ and angles of wave slope near crest of progressive waves was reach to 30° , and near freak-waves – reach to 60°.

If freak-wave is a standing wave, but near before and after it is a fast moving and large progressive waves, which can very fast and hard blow on shipboard, and capable to sharp rolling and, hereunder, produce the dangerous conditions of sailing or, another, reduce the force influence of freak-wave to ship.

At practical navigation traditionally used waves models, which contain superpositions of several independent systems of waves: 1) wind waves complies with direction of the wind action, but height of the waves can be at most great; 2) two-three systems of swell waves, being echo earlier passed or remote gale, at length of swell waves is more, than beside of wind waves, but steepness – less. The space model of the storm waves can be forms from package of the group structures, in which length of the wave front that more, than height factor less. This effect corresponds to observed storm waves, where swell front on a sea since elongate and flattening.

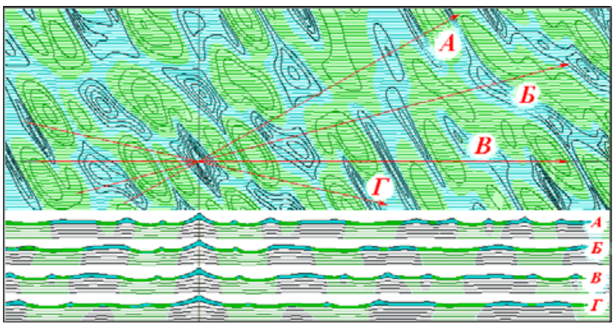

Figure 3. Sea surface with three independent cellular-group structures of wind and swell waves: 1) wind waves: λ=60 m, τ=6,2 s, h=7,2 m, azimuth A=250°; 2) first swell: λ=100 m, τ=8 s, h=6 m, A=210°; 3) second swell: λ=160 m, τ=10 s, h=5 m, A=270°. Sea level isolines and curves of sea profiles draw thru 2 m. The course A lead to headwind, on courses Б, В, Г add +15°, +30° and +45° to port bow. Wave profiles are drawing for noted courses.

At go ahead not less 2-3 freak-waves pass along a ship board, and only hereon possible head-on collision with large wave (provided that helmsmen guides the ship not on each rough). Accepting typical period of the storm waves on Ohotskoye sea equal 8 sec., possible hope that for runaround from hard collision with large wave necessary earliness prediction order 1-1.5 min., that wholly realizable by means of modern computers.

Sea storm sailing is not an catastrophic, for navigator are always allowed greater area with flattening waves, where permissible active maneuvering for active runaround from meeting with specifically large or freak-wave.

However, fluidmechanics condition of sea storm become vastly dangerous, if sea depth is less, then lengths of the storm wave. In this case storm waves save the group structure, but their fronts are extended, that obstructs runaround from a most large waves. Freak-waves already do not behave like standing wave, and capable to inflict the lateral blow to shipboard, practically with extreme phase velocity. At gale on Okhotskoye sea, since typical period of the waves is 8 sec, and blow 12-metre wave at the speed of more than 20 knots, be able threaten for any ship disastrous effects. Exactly such stormy condition for sailing are always availably at near seaside of coast; on anchor positions; and shallow waters, where fisheries continued at whole commercial season.

3. DESTINATION OF SHIP MAINTAIN BY HER SEAWORTHINESS FOR DIFFICULT AND STORMY SAILING

Efficiency or stability of the ship depends of her seagoing conditions, such as total intensity of negative influence at ship hull and superstructures as affected by storm winds and waves. If forces influence of the external ambience great, that ship loses her possibility of the motion to given course, and loses the possibility for active using a self ship mechanism and arms. Several are more simply formulated design conditions for sail on calm weather solely, however in this case it is impossible neglect at stormy seakeeping, at least for maintenance of well-timed possibility for runaround unpredictable dangerous sea phenomenas.

Seagoing on Russia Far East, besides storm and ice condition, is complicated by absence marine ports of refuge, why even coastal communication must to use the fleet with a raised stormy quality.

The marine practice and design requirements for the ship has rare disagree with stormy seakeeping quality, but may be only for exclusively graceless floating platforms, without crew, and without stability guarantees. In real maritime experience have achievement to best seakeeping qualities, and confirm dictums, that "onboard beautiful ship nothing ones spare".

3.1. Storm way on head/follow seas

The custom ships often use stormy course on heading seas, which unique ensuring to safety sailing in hurricane wind and heavy waves. This course ahead are actively used main engines and helms, which constantly subjected to extensive force overloading from intensive stern heaving with pitching of hull processes.

Without special storm sail and floating anchor use, steady of the course on heading seas possible only at maintenance of the minimum moving under main engines, which saved controllability. Pitching and longitudal hull tension on this course can reach of their extreme senses. Than more speed of ship, that more sharp pitching, up to threat slamming and deep burying of bow deck under ridge of waves (Fig.4).

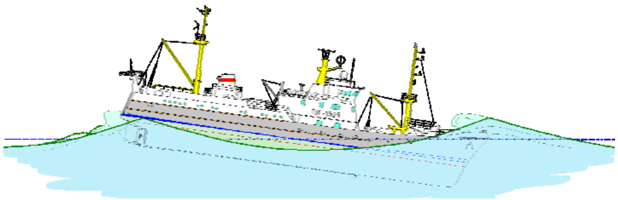

Figure 4. Even at moderate gale the Russian trawler must to cease fisheries, and have wait out bad weather at strongly head seas course.

On course ahead following seas, pitching becomes fluent, but ship gains the possibility for like dolphin porpoising, as a free motion at the speed of stormy wave approach. On follow seas course the ship must keep full speed ahead, because heaving flow after screw propellers have a possibilities to reverse water flow hear helm, that danger for catastrophic steering errors. If there is doubt at steering gear, that duty officer better to leave on stern deck for control screw working, and make sure that fast turbulence flow under screw propellers is not suppressed upon heaving stern on crest of large follow wave. If it condition is fail, what always correspond to lowpower fishing vessels, then after pass wave under stern shoulder, helmsman instead to steady course and get fast yaw circulation to opposite course on beam seas, which are threatens to instant turnover (*broaching effect*).

3.2. Speed ahead on bow/quartering seas

Way on head seas is accompanied with sharp and exhaust pitching. If seaworthiness quality of ship is allow (*are absent boulbous and without spreading bow bilge*) then at storm weather can possible to choose ahead to bow seas. The ship take the propulsion, and commences to trace the lengthened surface of the waves upon wholly moderate rolling.

Figure 5. Inadmissible that overweening speed on bow seas was subjected to the ship. It means that ship design instead of undersea bulbous and spreading bilge, must be use a tumblehome stem with trimming underwater peak, and small volume in bow freeboard.

Operating ship engines ensure steadying to stern overhand for average sea level, that provides general efficiency of the helm and screw propeller functioning, and maintenance to controllability of ship ahead. Impossible obtain hard and operated positioning for sea surfaces of bow and stern simultaneously. At least once, then bow of ship shall be completely free, and allow free yaw and heaving under pitching processes.

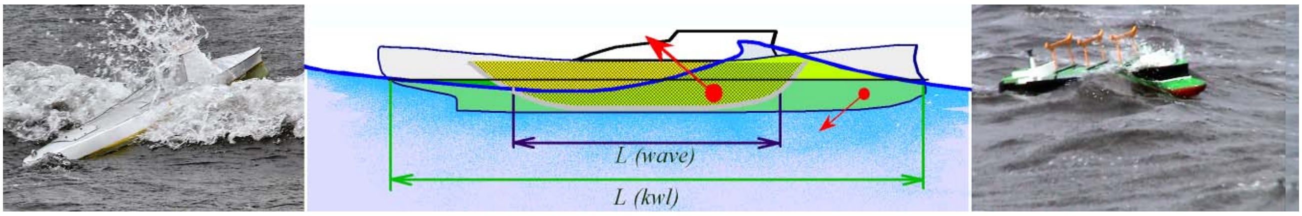

Figure 6. Fluidmechanics of pitching is interpreting by a history notion for wavecreation and wavereaction length of hull: L(wave), outside which, on part of hull length: L(kwl) will fall under hits by progressive trochoidal waves, where bilges and low freeboard will be promote to partial compensation of stormy heaving and pitching.

Stormy way on headquarter seas are very important for runaround from typhoon, or for speed ahead out off cyclone vortex. For this motion have all condition: pitching and rolling become fluent; the speed of ship increases by energy of following waves. However, if underwater lines of hull; freeboard volume; propulsion and steering machines hasn't special stormy optimization, that sailing course on headquarter seas becomes exceedingly dangerous. The ship may somewhat lose speed on windward declivity of backwards first wave, and after sharp turn with seizure by freak-wave, where wide stern overhand and reversed action of helm will bring quick circulation to course on beam seas and strong dangers of the instant turnover under the action forces of two large waves.

3.3. Emergency sailing or course ahead on beam seas

On the ship upper decks will arise a minimal water flow, if her sailing on deep sea, and kept the course or have a freely sailing on beam seas. This promotes by very high transverse stability; by the symmetry of hull form comparatively midship frame; by presence high raked stem and spreading freeboard in extremity and middle part of hull. If ship be capable to keep a full speed ahead, that special requirements to stern lines can't presented until the shipboard capable to reflect whole energy stormy waves.

Hydrodynamics of such sail is explained by ship ability to keep upper deck on parallel plane for local surfaces and sloping of storm waves. Operational on beam seas course are quite applicable to boat or small vessel with open decks. Such condition of stormy sailing absolutely not acceptance for large ships, because sharp rolling with large amplitude in rate of the stormy waves, will become to unbearable live condition foe crew, and can't ensure of hull strength sufficient.

And very importance for seakeeping researches result, what even this complicated experience on beam seas of stormy sailing doesn't appear design and operating contradiction for common minimization of forces influence of stormy waves to the ship hull (*Figure 7*). If ship have a small static stability estimation, and period of self rolling of the ship well over period of the storm waves, that amplitude of rolling will noticeably decrease, but only storm waves began to free gush over upper decks. Last means creation a new fluidmechanics effect, which can using for decrease of stormy force influences on shipboard, or even for complete compensation of the ship rolling.

Figure 7. Maritime experiment with optimized hull form for model of ship on stormy sailing under intensive influence from breaking waves on shallow water.

4. KEY DECISION FOR ACHIEVEMENT STORMY SEAKEEPING: EFFICIENCY AND SAFETY NAVIGATION

Source researching for the optimal hull form of ship is performed by using the theoretical integral of John Henry Mitchell (1898). Physical and geometric interpreting which allows to reveal intercoupling between ship waves creation under great speed moving of ship on calm sea, and power influence to ship hull from intensive sea waves, including for waves with discrete stormy characteristics. In Michell's fluidmechanics discovery where are fully mathematical tools and physical principles for contradictory designing and experimental optimization of ship hull form, against distribution of fluidmechanics forces along ship hull, which defined solely geometric particularity of ship lines.

$$A(\lambda)=\frac{M}{\lambda}\cdot\left|\int_{\Omega} q(x_0,y_0)\cdot e^{k\cdot(-z_0+i\omega_0)} д\Omega_0\right|$$

$$R_x=-\frac{\pi}{2}\cdot\rho V_0^2\int_{Л}^{0} A^2(\lambda)\cdot\frac{д\lambda}{\lambda\cdot M^3\sqrt{M^2-1}}$$

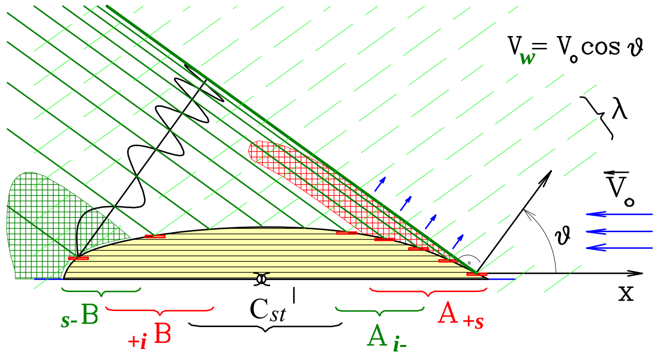

Figure 8. Waveformation process as reflection of progressive waves from shipboard. The Michell's integrals produce to physical measurement function as: A(λ) – height of ship waves; $M=\sqrt{Л/\lambda}$ - ratio of maximal Λ and axial λ wave lengths; $\omega_0=x_0/M+y_0\cdot\sqrt{M^2-1}/M$ - wave frequency; $k=2\cdot\pi/\lambda$.

Physical-geometric interpretation of fluid dynamic processes at Michell's integral will present a particular mechanism for external sea wave reflection with shipboard reaction, which run up with slanting angles: ϑ , within the range of lengths: $\lambda\in[\,0\div\Lambda=2{\cdot}\pi{\cdot}V_0^2/g]$, where: Λ - a length of the maximal transverse ship's wave, corresponding to speed of ship V_0. In computation is taken that on hull extremity a ship's waves can't come off from shipboard, and wave processes are changed by shock summation with short waves amplitudes, and according wave transformation near of bow surface, in the form of simple liquids source.

At particular case, for analysis of origin rolling momentum of forces and ship lines optimizing, may be simulating hull transverse wave's flow under ship bottom, and search special form of hull, which make possibilities for minimal deformation of free sea waves, in their transmitting processes across ship hull. This condition accords to minimal wave forces reaction, and may be reasonable for large stormy waves influence also.

4.1. Variant of ship hull without rolling

Invention application RU-2007133623 from 07.09.2007.

Intensive rolling of ship on any courses ahead on stormy seas may be excepting, if make a tumblehome board of the order 10-20 degrees (*Fig. 9*) in middle part of shipboard. Maximal slope of board make enough only on waterline level, where is a point of inflection on frame section contour under negative surface curvature at shipboard. It allows to take special fluidmechanics particularities of a large stormy waves, always having trochoidal nature since sharing liquid particles with motion over cyclonical trajectory, where are maximal speed on peak of wave crest.

Progressive storm waves have a slow in down part, when it nearer to tumblehome shipboard surface. It produce the particularity fluidmechanics condition, under which all liquid flow of wave to rushes under bilge and bottom of the ship, which draught of hull must be approximately a half of ship hull width. This intensive wave's stream brings about redistribution of hydrodynamics' pressures, why, with provision for ship drift, replaced the critical point in field velocity currents to leeward board of ship, than is party compensated of hydrostatic moment of forces to windward list on sloping surface of the storm wave. Hangover of wave stream flow under bottom of ship, required also to forming viscosity forces on the board keels, since otherwise this keels produce a disadvantage list momentum of forces under the drift motion action.

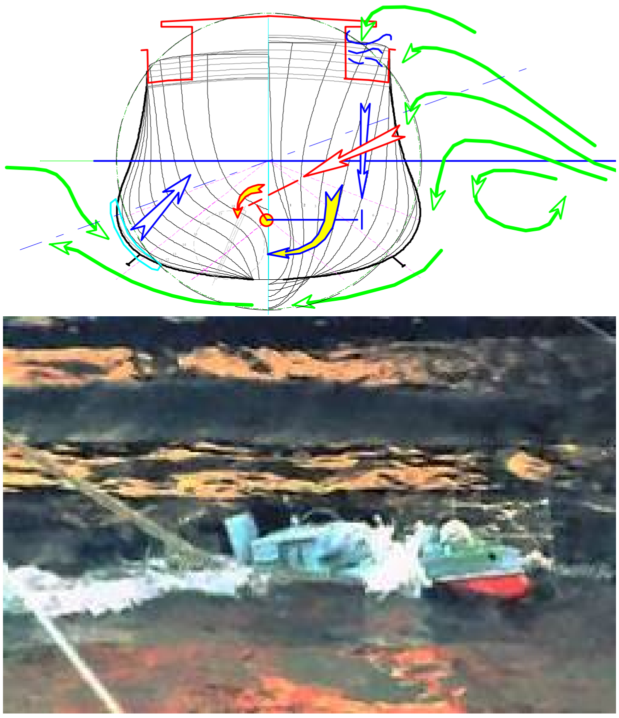

Figure 9. Total vectors of power mutually compensate all lists momentum into hydrodynamics field of trochoidal stormy waves (the up scheme). On the down photo present a frame of video from seakeeping experiments into towing tank of the Komsomolsk-on-Amur state technical university. At video frame was fixed a waves tipping over the upper deck of ship, which not caused list to opposite starboard of floating model.

Ship hull with concave frame contours on the design waterline level, have a striking expressed acquisition by the S-shaped static stability diagram, that allows safely to reduce initial metacentre for the reason increasing of the rolling time period, without commonly reduction of the criterion for dynamic stability of the ship in stormy sailing condition as a whole.

Experimental investigation for the stormy ship seaworthiness with remote control models was executed on regular waves in towing tank (*Figure* 9) and under fresh wind on Okhotskoye sea open surface. All testing got a fully confirm design decisions for decreasing of the ship rolling, when approached right result both: on fast speed ahead; and on emergency sailing without moving.

Video with seaworthiness experiments for the special remote control models are published on: http://www.youtube.com/Khramushin.
Titles of clips is: «Ship with small rolling on heavy waves in towing tank» (01:40); and «Historical Ship on Hurricane Storm Waves» (06:35).

4.2. Ship with small pitching at full speed ahead on stormy seas

Invention application RU-2007133625 from 07.09.2007.

For exception of intensive pitching need to using backwards stem and small freeboard volume in bow of ship hull. Formally this promotes hydrostatic effects for reduction of heaving forces on a fast motion sea surface under heavy storm condition. Pitching stabilizations for ship at fast speed ahead must be approach by using special vortices form of underwater bow bilges of hull, which forming by a gliding twisted surface for influx liquid from up waves flow, and redirecting it under bow bilge of the hull, which occur strongly in place of the forming first ship's breaking wave crest (*Figure 6*).

Vertical heaving not so heavily reflects on surging and losing of speed ahead of ship, and as a whole, she not so is heavily reflected on the conditions of habitability inward of ship hull and superstructures.

Full pitching avoidance is very important achievements (*Figure* 10), and special optimizing design for ship without pitching will capable additional seakeeping qualities also:

- maintain the high speed of ship at storm weather condition;
- following any course on large stormy waves;
- useful reduce a space-flooding on upper decks;
- completely excluded a burying bow deck of ship under large and freak-wave;
- avoid the dangerous capture of the ship by large wave ridges;
- reduce the accelerations inward of ship hull; perfect safety and reliability of the shipment fastening.

Figure 10. Almost fully transformation pitching to heaving of ship was reached in this design of a small remote control vehicle with flapping wing propulsion. Experimental test was confirmed propulsive quality and small pitching of ship on intensive waves sailing.

Video from experimental searches publish in the same place on YouTube:
«China ship from Marco Polo with Flapping Wing Propulsion.» (02:20), and «China-1275 from Marco Polo's Map with Ship on Pacific Ocean» (02:25).

Design for optimal hull form may be founded on special computational experiment for analyze of series results with simplest form or next elements of ship hull form. More important problem for computational researches is: 1) decreasing or full excluding a trim difference of ship at her full speed ahead; 2) minimizing ship waves radiation for full range of ship speed, including over critical speed of sailing on calm water, in which produced ship waves with comparable length for external sea stormy waves. In physical experiments is confirmed that specified numerical minimization for trim difference, after significant reducing a pitching of ship on a real stormy waves.

In the event of loss way, the hull stabilization effect disappears, and ship newly regain wholly appreciable pitching. Enhanced stormy seakeeping can reached high propulsion and small pitching at full speed ahead on rough seas. This qualities accept to use special lines of hull form under stern afterrake, that ensured particular condition for helm and screw propeller. In this case, emergencies and loss way will be aggravated by dangerous amplification of the storm wave's power influence to stern extremity of the ship.

However, exactly intensive vertical heaving of stern afterrake under blow of stormy waves is effective actuation of passive flapping propulsor, as which can using the active wings stabilizer for pitching and rolling.

4.3. Active wing stabilizer for pitching and rolling – emergency stormy propulsor

Invention application RU-2008116649 from 04.25.2008.

At stormy condition stabilized by direction water flow to liquids near ship hull, going speed ahead, there is under stern afterrake only, directly after operating screw propellers. Exactly here (Figure 11) possible to obtain of the most power for active stabilization of the list and trim difference of ship, including at the calm weather on the sharp circulation.

At event of loss way, the stern extremity of ship gets the significant vertical heaving fluctuations under influence of the storm waves, it's stipulated of wide waterlines and large freeboard volume above stern afterrake, which made for ensuring intact boundary stream to helm and screw propellers. Such heaving is a necessary condition for operate of free-springy wings as a passive flapping wings propulsor, which are actuated at the most dangerous sailing on stormy seas after main engines stopped. Passive flapping propulsor does not require additional power or controlling influence on wing device, and free-springy rotation (backlash) of wheels at angle to ±30° will simultaneously insure the ship at shock influence to board of ship from stormy waves, that is important for the active stabilization of heaving at full speed ahead.

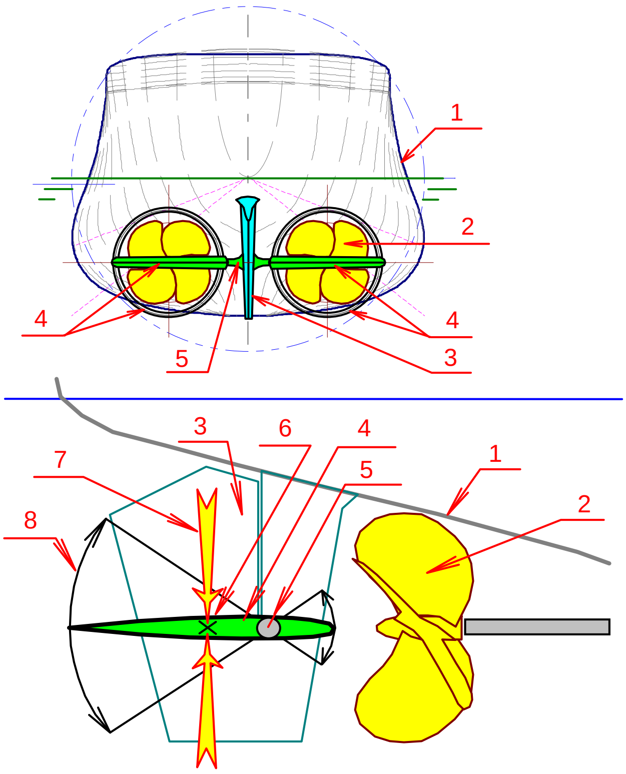

Figure 11. Helm (3) and screw propeller (2) complex with level wings of active list and trim stabilizers (4), which in event at loss a way to self operate as stormy emergency flapping propulsor. 1 – afterrake hull of ship; 4 – wing may be set on wheel to ruderpost; 5 – level balanced wheel is set in stream flow after screw propeller, and allows free-springy rotate at the angle order±30°; 6 – centre of wing flat area, to which is total power (7) at heaving of afterrake; 8 – angle of free-springy rotation of planes of the wing.

4. CONCLUSION REMARKS

Analytical and experimental studies of stormy seakeeping of ships and vessels of the different purpose has a results of the key concepts for contradictory designing of ship architecture and lines of hull, further to propulsions, fluidity rolling and pitching and safety sailing on heavy storm seas.

Seakeeping experiments for special remote control models of seagoing ships with telemetric measuring system on regular waves in towing tank of Komsomolsk-on-Amur state technical university, and following proving their under wind on open sea at seasides of Sakhalin isl., was confirm a fully satisfactory nautical qualities for all optimized ship models.

The complete determination of design solving will offer new technical decisions to active stabilization of the residual rolling and pitching ship at speed ahead. As it supposes of maritime experience, the draft a wing stabilizers as well emergency stormy propulsors, what became a development of contradictory designing principles for shipbuilding and marine seagoing.

5. ACKNOWLEDGEMENTS

This ship designing researches is initiated as government order from Main management of shipbuilders, and follow of present state by means of enlightening grant from oil company "Sakhalin energy", which perform by Sakhalin division of Russian geographical society.

The special gratitude author expresses for S.Antonenko and V.Bugaev (*ship theory and design division of Fareast State Technical university*), as well as N.Mytnyk and N.Taranukha (*shipbuilding division of Komsomolsk-on-Amur State Technical University*) - as true coauthors all new shipbuilding decisions.

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