"Mircea cel Batran" Naval Academy Scientific Bulletin, Volume XVIII – 2015 – Issue 1
Published by "Mircea cel Batran" Naval Academy Press, Constanta, Romania // The journal is indexed in:
PROQUEST SciTech Journals, PROQUEST Engineering Journals, PROQUEST Illustrata: Technology, PROQUEST Technology Journals, PROQUEST Military Collection PROQUEST Advanced Technologies & Aerospace

PERFORMANCE ASSESSMENT OF SOLAR THERMAL COLLECTORS IN VARIOUS SEA STATES

Alexandru COTORCEA[1]
Ion VISA[2]
Macedon D. MOLDOVAN[3]
Marian RISTEA[4]
[1] PhD attendee, Transilvania University of Brasov, Romania, alexandru.cotorcea@unitbv.ro
[2] Professor, PhD, Transilvania University of Brasov, Romania
[3] Lecturer, Phd, Transilvania University of Brasov, Romania
[4] Lecturer, Phd, "MirceacelBatran" Naval Academy, Constanta, Romania

Abstract: *In the paper, performance assessment of the flat plate solar thermal collectors installed on the merchant vessels is analyzed. Performance evaluation of the collectors is made by taking into account solar radiance and two significant motions of the vessel: roll and pitch.The amplitude of the roll and pitch angles of a general cargo ship was identified for a degree between 1 and 5 on International Sea and Swell Scale (Douglas scale). For relevance, the height of the waves was considered between 0.1 and 4.0 meters. The simulations of ship motions were carried out using OrcaFlex, a marine dynamics program for static and dynamic analysis of a wide range of offshore systems.Further, considering permanent reorientation of solar collectors due to roll and pitch motions of the ship, a performance assessment is carried out. This is done in order to determine the influence of the roll and pitch motions on the solar collectors performance under the solar radiation quantity that reaches the collectors surface.*
Keywords: *ship, flat plate solar collector, pitch and roll motion, efficiency*

1. Introduction

In the context of current global concerns identifying solutions to improve energy efficiency and reduce greenhouse gas emissions, shipping make small steps towards achieving these goals. Responsible for 3.3% of the global anthropogenicCO_2emissions and a greater share of NOx (37%) and SOx (28%) emissions, shipping is aimingto reduce these emissions through the introduction of emission control areas and additional requirements on newly built marine diesel engines. The base scenarios regarding CO_2 emissions from shipping from 2007 to 2050, modeled by the International Maritime Organization (IMO), indicate an annual increase of CO_2 emissions in the range 1.9–2.7% with the extreme scenarios predicting changes of 5.2% and - 0.8%, respectively. If global emissions of CO_2 are to be stabilized at a level consistent with a 2°C rise in global average temperature by 2050 it is clear that the shipping sector must find ways to stabilize or reduce its emissions; otherwise the projected values will account for 12–18% of all total permissible CO_2 emissions [1].

Moreover, considering that the majority of ships satisfy their electric energy needs by using electrical generators driven by diesel engines (prime movers), it is obvious that the shipping industry is strongly affected by the increase of global fuel prices. In order to reduce the emissions from marine equipment and the hydrocarbon fuel market dependence, a lot of research has been targeted either to the combustion process improvement (fuel chemical treatment, or alternative fuels) or to the efficiency increase of the electrogenerating systems [2].

One of the solutions to increase the energy efficiency of a ship, is the implementation of systems based on renewable sources of energy. Despite their extended use at mainland applications, the solar collectors presence in modern marine technology remains limited, mainly working (in the case of PV systems) as suppliers to small lighthouses, buoys, and chargers for the batteries of small sailing yachts [3].Knowing that onshore collectors are fixed and facing south in most cases, implementation on vessels introduces a number of variables, like position (dependent on the continuous movement) and orientation (dependent on ship's course and sea state). Considering these aspects, it is necessary to determine angles specific to roll and pitch motions of the ship, angles which influence the orientation of collectors to the Sun.

Lack of experimental data on the behavior of vessels for different sea states, requires its simulation using CFD (Computational Fluid Dynamics) techniques. In the last decades, CFD has made remarkable progress. The main impetus to this progress is the increasing industrial demands. As the cost and time required for the computation are much lower than that of model tests, CFD has become an important method in the research of vessel hydrodynamic, and especially a hot issue in seakeeping research [4]. It has been used in practical ship design for predicting the viscous flow around the hull, flow separations, viscous resistance, wake field, appendage alignment, propeller/hull interaction etc. [5]. Inpresent paper, simulations were carried out using OrcaFlex, a marine dynamics program for static and dynamic analysis of a wide range of offshore systems.

Further, a methodology forestimation of received energy at collector's surface is presented, with respect to ship behavior on different sea states.

2. Methodology for estimation of received energy at collector's surface

In order to determine the quantity of energy received by a solar collector mounted on a ship, it is firstly necessary to know how ship behave on different sea state. General description of the motions of a ship include surge, sway, heave, roll, pitch and yaw (Figure 1). In practical applications, this six-degree-of-freedom (6DOF) model is often reduced to a simpler one who's DOF is less than six [6]. One of the fundamental requirements in ship design is ensuing stability against capsizing. In this regard, the most critical degree of freedom is roll [7]. In this paper, only roll and pitch motions are taken into account.

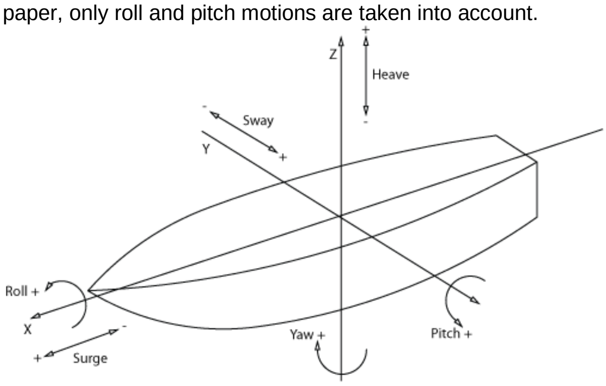


Figure 1 Ship motions on sea
(Source: http://www.shipmotion.se)

During simulations, sea degree was computed according to the Douglas Sea Scale, also called the "International Sea and Swell Scale", a scale which measures the height of the waves and alsothe swell of the sea. Its main purpose is to estimate the roughness of the sea for navigation. The scale is very simple to follow and is expressed in one of 10 degrees. In table 1 state of the sea is presented, considering wave's height and description of sea surface.

"Mircea cel Batran" Naval Academy Scientific Bulletin, Volume XVIII – 2015 – Issue 1
Published by "Mircea cel Batran" Naval Academy Press, Constanta, Romania // The journal is indexed in:
PROQUEST SciTech Journals, PROQUEST Engineering Journals, PROQUEST Illustrata: Technology, PROQUEST Technology Journals, PROQUEST Military Collection PROQUEST Advanced Technologies & Aerospace

Table 1 State of the sea (Douglas scale)

Sea degree	**Wave height** $[m]$	**Description**
0	No wave	Calm (glassy)
1	0 – 0.1	Calm (rippled)
2	0.1 – 0.5	Smooth
3	0.5 – 1.25	Slight
4	1.25 – 2.5	Moderate
5	2.5 – 4.0	Rough
6	4.0 – 6.0	Very rough
7	6.0 – 9.0	High
8	9.0 – 14.0	Very high
9	Over 14	Phenomenal

During simulations, mean directions of wave acting on the ship are changed from 0° to 180° (0° is aft, 180° is bow direction) at 45° intervals(Figure 2).

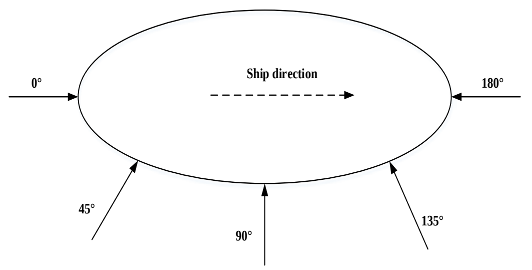


Figure 2 Wave direction toward ship

Lack of information and data regarding solar radiation available on sea, have imposed estimation of direct solar radiation (denoted B) available at the Earth's surface under clear sky by use of a model [8, 9], described by equation (1):

$$B = B_0 \cdot exp\left(-\frac{T_L}{0{,}9+9{,}4\cdot sin\alpha}\right)[W/m^2] \tag{1}$$

where extraterrestrial radiation B_0 is determined with the following formula:

$$B_0 = 1367 \cdot [1 + 0{,}0334 \cdot \cos(0{,}9856° \cdot N - 2{,}72°)][W/m^2] \tag{2}$$

Variable parameters involved in the model are: sunrays elevation angle α (dependent on solar time t_s), day number N and turbidity (Linke) factor T_L of considered location. Through turbidity factor T_L there are estimated losses of solar radiation while crossing atmospheric layer in clear sky conditions (cloudless). Losses are caused by and dependent on the concentration of particulate matter, air mass, temperature, degree of pollution and humidity. Linke factor takes values between 1 (for theoretically pure atmosphere) and 8 (for polluted atmosphere). Elevation angle α is modeled by:

$$\alpha = sin^{-1}(cos\delta \cdot cos\omega \cdot cos\varphi + sin\delta \cdot sin\varphi) \tag{3}$$

Here δ is declination, ω is hour angle and φ represent latitude. Equatorial orientation angles, ω and δ, derive form the following relations:

$$\omega = 15^{\circ}(12 - t_s) \tag{4}$$

$$\delta = 23{,}45° \cdot sin\frac{360°(N-80)}{365} \tag{5}$$

Direct solar radiation (denoted B^*) receivedin a certain plan, whose normal forms with solar beam an incidence angle ν, is modeled by Lambert's law:

$$B^* = B \cdot cos\nu \tag{6}$$

and

$$\nu = cos^{-1}(cos\alpha \cdot cos\alpha^* \cdot \cos(\psi - \psi^*) + sin\alpha \cdot sin\alpha^*) \tag{7}$$

whereψ is the angle between sun beam projection and south direction in horizontal plane of observer (it is 0 for collectors facing south), α^* and ψ^* are azimuthal orientation angles of normal to collector's surface. Azimuthal angle ψ is expressed by the following equation:

$$\psi = sgn\omega \cdot cos^{-1}\left(\frac{cos\delta \cdot cos\omega \cdot sin\varphi - sin\delta \cdot cos\varphi}{cos\alpha}\right) \tag{8}$$

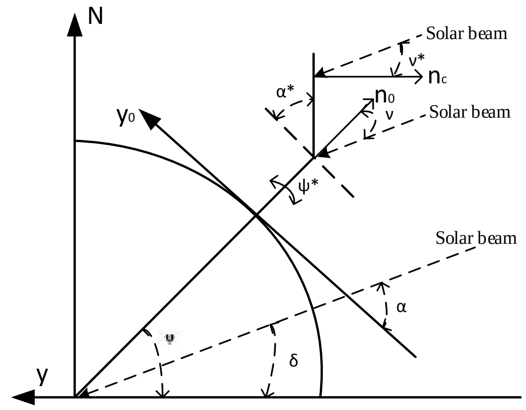


Figure 3 Representation of angles relative to Earth surface and observer position

Determination of the total energy available is based on the equation:

$$E = \sum_{t_s=1}^{t_s=n} E_B \, [Wh/m^2]$$

where $E_B = (B_n + B_{n-1}) \cdot (t_n - t_{n-1})[Wh/m^2]$

Similarly, total energy received in the collector plane is determined according to:

$$E^* = \sum_{t_s=1}^{t_s=n} E_{B^*} \, [Wh/m^2]$$

where $E_{B^*} = (B_n^* + B_{n-1}^*) \cdot (t_n - t_{n-1})[Wh/m^2]$

In the following section, it is analyzed the energy gain at collector surface considering the case of an 8700 dwt general cargo and two tilt angles.

3. Case study: Energy gain at collector surface arranged on an 8700 dwt general cargo in different sea state

Vessel used as a model in simulations is intended for general cargo, bulk cargo, equipment, containers and timber (in warehouses or on the deck). Main dimensions and general characteristics of the ship are presented in table 2.

Table 2 Main dimensions and characteristics of the ship

Length overall	$L_{max} = 130.86\,m$
Beam	$B_{max} = 17.70\,m$
Draught	$T_{max} = 8.10\,m$
Displacement (full load)	$\Delta = 12350\ tons$
Total carrying capacity	8700 dwt
Maximum speed	$V_{max} = 15\,kn$
Cruising speed	$V = 10\,kn$

Results from simulationsmade in OrcaFlex are shown in table 3 (for roll angles) and table 4 (for pitch angles).

Table 3 Roll angles for different sea state and wave direction

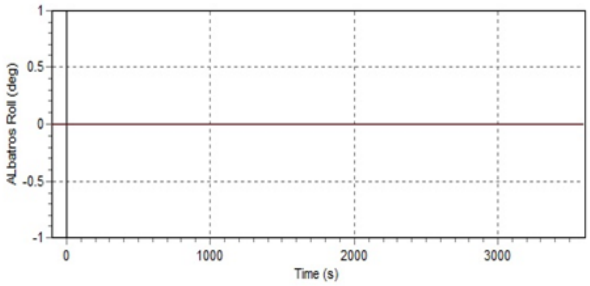
Sea state	**Wave direction**				
	0°	**45°**	**90°**	**135°**	**180°**
1	0.00°	0.15°	0.33°	0.15°	0.00°
2	0.00°	0.75°	1.66°	0.76°	0.00°
3	0.00°	1.87°	4.16°	1.9°	0.00°
4	0.00°	3.75°	8.32°	3.8°	0.00°
5	0.00°	5.99°	13.31°	6.07°	0.00°

Table 4 Pitch angles for different sea state and wave direction

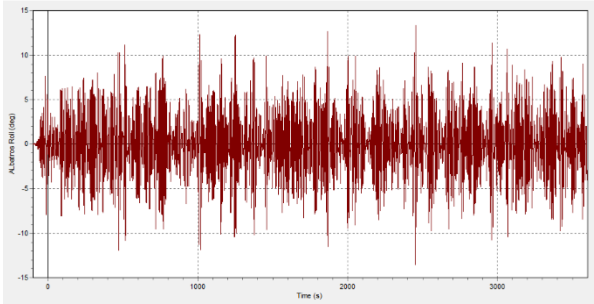
Sea state	**Wave direction**				
	0°	**45°**	**90°**	**135°**	**180°**
1	0.12°	0.12°	0.02°	0.10°	0.13°
2	0.60°	0.60°	0.08°	0.50°	0.66°
3	1.48°	1.52°	0.20°	1.25°	1.64°

4	2.95°	3.04°	0.40°	2.50°	3.28°
5	4.72°	4.86°	0.65°	4.00°	5.25°

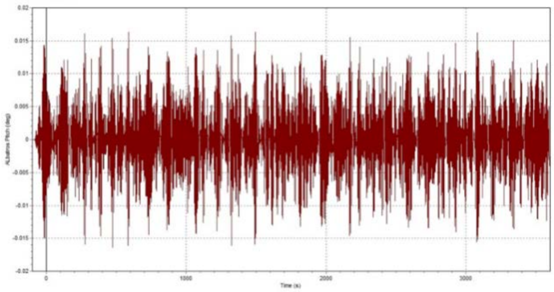
Sea state 1 correspond to a wave height of 0.1 m, sea state 2 to 0.5 m, sea state 3 to 1.25 m, sea state 4 to 2.5 m and sea state 5 to 4.0 m. In figure 4 are presented representative graphical results from simulation, results corresponding to minimum and maximum angles for roll and pitch movements.



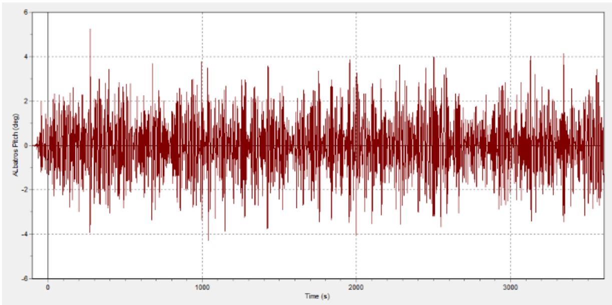
Roll – sea state 1 – wave direction 0°



Roll – sea state 5 – wave direction 90°



Pitch – sea state 1 – wave direction 90°



Pitch – sea state 5 – wave direction 180°

Figure 4Representative illustrations from simulation

As can be observed, roll angles are zero for all sea states and a wave direction of 0° and 180°, and minimum for all wave directions corresponding to sea states 1 and 2. The maximum roll angle (13.31°) is specific to sea state 5 and wave direction of 90°. On the other hand, pitch angles aren't very high, maximum of 5.25° being obtained for a sea state 5 and 180° wave direction (opposed to vessel heading).

To determine direct solar radiation on collectors surface, the following assumptions were considered:

a. Simulation were made for a N=172, which is summer solstice in northern hemisphere;
b. Latitude is 43°N;
c. Period of time analyzed is one hour, at tenths of a second intervals;
d. Linke factor was taken 4, value specific to humid and warm air;
e. Solar collector tilt is$\alpha^* = 90°$(ie horizontally) and $\alpha^* = 62°$, optimum angle for the day considered at this latitude [10]

Further, roll and pitch movements of the shipare influencing angle of incidence vas follows:

- If the direction of vessel is straight to north, a positive value of pitch (corresponding to bow) is subtracted from angle $\alpha^*$and, vice-versa, a negative value is added to α^*; in this case, roll has no influence;
- If the direction of vessel is straight to east, pitch is considered as in the previous case, while roll is acting the same on observer azimuthal angle ψ^*; also ψ^* is taken 90°.

All assumptions are made for a collector faced south initially in the longitudinal section of the ship. In table 5, the amount of energy at collector surface is presented, for three eloquent cases. For the first case, sea state 1 and wave direction 0°, the roll is zero and pitch is insignificant. Second case, sea state 5 and wave direction 45°, correspond to an important pitch angle. Finally, the third case, sea state 5 and wave direction 90°, was taken into account the worst situation, which is described by the higher roll angle.

Table 5 Amount of energy at collector surface

Sea state	Wave direction	Ship direction / collector orientation			
		North/horizontal	North/optimum	East/horizontal	East/optimum
1	0°	825.04	865.37	824.91	728.17
5	45°	829.65	863.04	824.57	718.28
5	90°	825.78	865.03	824.85	719.91

For comparison, without considering roll and pitch motions, in horizontal plane is obtained an amount of energy of$824.91\ Wh/m^2$ for both north and east direction of the ship. For collector tilted with optimum angle, it will result an amount of $865.43\ Wh/m^2$ for a ship headed north and of$728.35\ Wh/m^2$ for a ship headed east.

Based on the results from table 5, following aspects can be identified:

- the amount of energy is almost the same, no matter sea state, ship heading or direction of the waves toward ship, for horizontal collector;higher values are influenced by pitch angle, but the gain is under 1% compared to situation without roll and pitch movements;
- when the collector is tilted with optimum angle, there will be an additional 33- 40$Wh/m^2$when the ship is heading north (which represent 4-5%); on the other hand, when the ship is heading east there will be a decrease of energy between 96 and 106 Wh/m^2 (11-13%).

As final remarks, it can be stated that wave height and ship movements are not influencing the amount of energy collected. Also, it is recommended that for any other orientation than south (because of vessel heading), solar collector should be horizontally arranged.

Conclusions

A performance assessment of solar collectors in various sea state has been performed. Further work will focus on developing the methodology presented and will take into account real sky conditions.
Energy issue,a topic increasingly important every day, should be reconsidered even for shipping industry. Solutions must be identified in order to compel with emissions and energy efficiencyregulations.
The idea of implementing systems based on renewable energy onboard merchant ship isn’t quite a novelty, but lack of onsite data (regarding solar potential, tidal power, etc.) and lack of interest of shipownersfor this kind of technology, makes the job even harder. This happens because there are no policies to encourage investments in this area, at least for newly built ships.
Acknowledgments: This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the project number POSDRU/159/1.5/S/134378.". Authors also thanks Marine Offshore Consultants for providing the access to OrcaFlex software.

Bibliography

[1] Alexandru Cotorcea and Ion Visa, *Study of adaptability of solar thermal systems on merchant vessels*, Proceedings of the Conference for Sustainable Energy (CSE), 2014
[2] Kyritsis, A., Papanikolaou, N., Prousalidis, J., &Loupis, M., *Incorporating commercial inverters in the low voltage network of ships for energy saving applications*.
[3] IoannisKobougias,Emmanuel Tatakis, and John Prousalidis,*PV Systems Installed in Marine Vessels: Technologies and Specifications*, Advances in Power Electronics, volume 2013
[4] Yang Bo, Wang Zuo-chao, Wu Ming, *Numerical simulation of Naval ship’s roll damping based on CFD*, Procedia Engineering 37 (2012) 14-18
[5] Zhang, Z., Liu, H., Zhu, S. & Zhao, F. (2006), *Application of CFD in ship engineering design practice and ship hydrodynamics*. In Conference of Global Chinese Scholars on Hydrodynamics, 11-14 July, Shanghai. Journal of Hydrodynamics, 18 (3, Supplement 1), 315-322.
[6] M.A. Hinostroza, Weilin Luo, C. GuedesSoares, *Robust fin control for ship roll stabilization based on L2-gain design*, Ocean Engineering 94 (2015) 126-131
[7] Giovanni Malara, Pol D. Spanos, Felice Arena, *Maximum roll angle estimation of a ship in confused sea waves via a quasi-deterministic approach*, Probabilistic Engineering Mechanics 35 (2014) 75-81
[8] Meliss, M., *Regenerative energie-quellenpraktikum*, Springer, 1997
[9] Vătășescu M., Moldovan M., Burduhos B., *Limkages for solar tracking*, Transilvania University of Brasov, 2011 (in romanian)
[10] CameliaStanciu, DorinStanciu, *Optimum tilt angle for plat collectors all over the world – A declination dependence formula and comparisons of three solar radiation models*, Energy Conversion and Management 81 (2014) 133-143