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Prediction of the launching behaviour of a free-fall lifeboat

SUMMARY

The paper is focussed on determination of the trajectory of the free-fall boat and dynamic forces acting upon its occupants to minimize the risk of an injury.

A software package for predicting the behaviour of the boat during launching has been developed on the basis of the mathematical model of the launching motion.

The simulation procedure, when used in course of design, makes it possible to improve the hull shape and properly position the seats to ensure minimum load exerted upon the occupants. The described procedure was verified in course of model tests and by measurements taken during tests of prototypes.

INTRODUCTION

The risks with conventional lifeboat systems have been substantially reduced by the free-fall concept, which allows the lifeboat to fall freely into the sea. The free fall provides kinetic energy to propel the lifeboat away from the distressed vessel during and after water entry.

The first reference to a free-fall lifeboat was an 1897 patent issued to A.E. Falk [3].

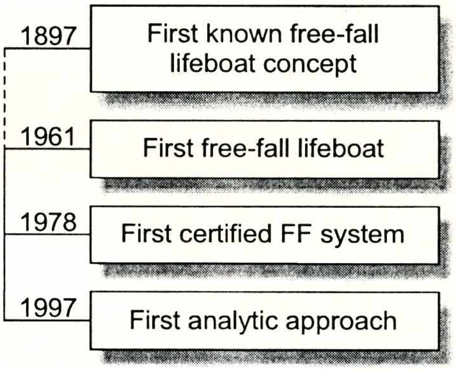

Fig.1. Milestones in the development of FFL

First analytical model of the launching process of FFL was presented by Tasaki [5] and later improved by Nelson [4] who also elaborated a software package to compute launching kinematics and inertial forces.

A procedure is presented below for prediction of the ability of FFL to make successful launching at various initial conditions and for selecting the initial conditions that would allow to increase the launching height and minimize the dynamic load acting upon the lifeboat occupants (Fig.2).

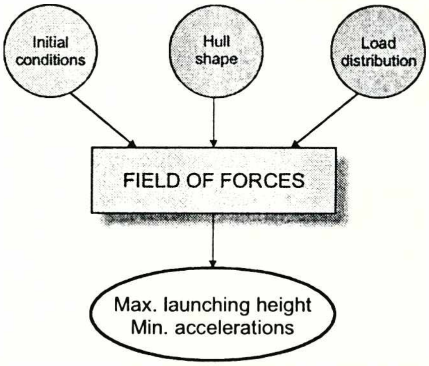

Fig.2. Outline of the procedure for prediction of successful launching of FFL

ANALYTIC MODEL

The below outlined analytic approach to describe the launching motion of the FFL has been developed to provide the designer with a tool to forecast performance of the lifeboat and adjust hull shape and the initial conditions of launching so as to achieve the required launching height at the minimum dynamic load exerted upon the lifeboat occupants.

The launching motion depends mainly on the following parameters of the free-fall system :

- launching height (h)
- ramp length (l) and inclination angle (α)
- coefficient of friction between the sliding rails or rollers and the lifeboat (μ)
- shape of the lifeboat hull
- mass distribution along the lifeboat longitudinal axis, expressed by the mass moment of inertia about the lateral axis (I_{yy}).

The parameters determine the trajectory of the lifeboat and accelerations exerted upon the lifeboat occupants. On the other hand, dynamic response of the occupant's body to the launching acceleration also depends on the position and geometry of the seat and dynamic properties of the human body and elastic outer layer of the seat. The properties are expressed in terms of damping ratio and natural vibration frequency. The values of the two latter parameters recommended for use in the computation, were determined by the IMO [1].

The launching process was idealized for analysis purposes by assumming that :

- ❋ the lifeboat is a rigid body
- ❋ motion of the lifeboat is planar, i.e. lateral displacements of the boat are negligible
- ❋ damping effect of accompanying water and turbulence generated by the entry of the lifeboat into water are neglected.

Four phases of FFL motion during launching can be distinguished :

- ★ sliding along the launching ramp
- ★ rotation around the ramp edge
- ★ free fall
- ★ water entry.

The sliding phase of launching begins with release of the boat from its initial position and ends when the gravity centre of the boat passes over the ramp edge.

Then *the rotation phase of motion* starts which lasts until the lifeboat looses contact with the ramp.

The third phase is a free-fall in gravitation field, at constant angular velocity of rotation around y-axis, constant velocity in x-direction and uniformly accelerated vertical motion. It lasts until the hull touches water surface. Then *the last phase of motion, i. e. water entry begins* and lasts until the boat comes to rest in the water.

Three right-handed, orthogonal, Cartesian coordinate systems are used for the analysis: local (x,y,z), global (x_g,z_g) and inertial (ξ,η) [3]. The lifeboat geometry is described in the local coordinate system (Fig.3).

The forces are determined using global coordinate system with the origin at the centre of gravity. Inertial coordinate system is used to define parameters of motion (position, velocity and acceleration). By solving the equations governing each phase of motion, position, velocity and acceleration of the boat are obtained, respectively [4].

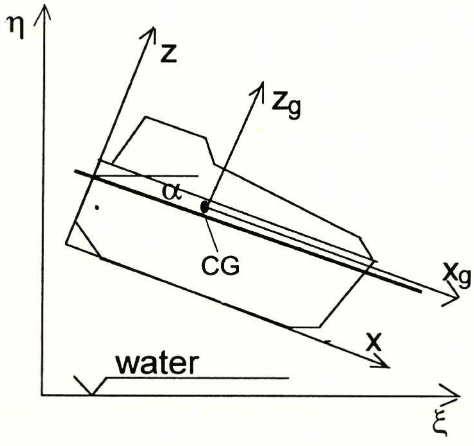

Fig.3. Coordinate systems used in the analytical model

The sliding motion phase is governed by the following equation system :

$$\ddot{\varphi} = 0 \qquad \ddot{x} = a\cos\alpha \qquad \ddot{z} = -a\sin\alpha \tag{1}$$

where : a = g(sinα - μcosα)

The second phase yields the equations :

$$\begin{aligned} m\ddot{x} &= \frac{N}{\cos\rho}\sin(\varphi - \rho) \\ m\ddot{z} &= \frac{N}{\cos\rho}\cos(\varphi - \rho) - Q \\ I_{yy}\ddot{\varphi} &= \frac{N}{\cos\rho}[\Delta x\cos(\varphi - \rho) - \Delta z\sin(\varphi - \rho)] \end{aligned} \tag{2}$$

The third phase :

$$\ddot{\varphi} = 0 \qquad \ddot{x} = 0 \qquad \ddot{z} = -g \tag{3}$$

And the last phase :

$$\begin{aligned} I_{yy}\ddot{\varphi} &= \sum_{j=1}^{n}[F_{xj}r_{zj} - F_{zj}r_{xj}] \\ m\ddot{x} &= \sum_{j=1}^{n}[F_{xj}\cos\varphi + F_{zj}\sin\varphi] \\ m\ddot{z} &= \sum_{j=1}^{n}[-F_{xj}\sin\varphi - F_{zj}\cos\varphi] \end{aligned} \tag{4}$$

First three equation sets have the closed solutions that can be numerically evaluated by using Runge - Kutta method [4].

Equations (4) describe the lifeboat as a 3D rigid body moving in the x-z plane. The finite element procedure was applied to find the numerical solution. The shape of the lifeboat hull was idealized by the network of nodes which form a three-dimensional set of triangular plane elements [4,10]. Position of each node is defined in the local coordinate system.

The inertial characteristics of the lifeboat are described by the mass and mass moment of inertia about y-axis (I_{yy}). The fraction of the mass corresponding to each plate element is proportional to the area of the element. I_{yy} can be either calculated on the basis of the assumed mass distribution at the design stage or determined experimentally by using scale model of the boat [3]. Value of I_{yy} is essential for accuracy of the calculation. In order to compensate the limited information available at the design stage, a tolerance range of I_{yy} is taken in to account while assuming the model parameters and simulation is repeated for different values of I_{yy} .

The software package worked out by the author on the basis of the aforesaid procedure comprises data generation sequence including 3D animation helpful in reviewing the idealized shape of the lifeboat prior to initializing computation. By using the animation module it is possible to observe rotational motion after water entry that is of paramount importance for safety of the passengers.

The computed accelerations are oriented in accordance with the inertial coordinate system.

„Inertial" accelerations acting at the seat supports should be determined in order to determine accelerations acting upon the seat support. This can be achieved by transforming the computed accelerations to the coordinate system bound to the seat.

Then the Dynamic Response Index (DRI) is computed to evaluate the response of the human body to inertial forces induced during lifeboat launching [1].

$$DRI = \sqrt{\left[\left(\frac{d_x}{\delta_x}\right)^2 + \left(\frac{d_y}{\delta_y}\right)^2 + \left(\frac{d_z}{\delta_z}\right)^2\right]} \tag{5}$$

By executing the computation procedure for various initial conditions and different shape descriptions the most suitable launching conditions and optimum lifeboat shape can be determined for a given launching arrangement position on board a ship.

In order to verify the procedure, a number of models were analyzed based on the series of free-fall lifeboats built by the USTKA Shipyard. The simulation results were compared with the observations recorded during the launching tests as well as with the measurement results.

The following example illustrates the considered procedure.

Tab.1. *Lifeboat data and launching conditions*

Mass * [kg]	4900
Number of occupants	18
CG position x_c/z_c [m]	2.70/1.05
Mass moment of inertia I_{yy} [kgm^2]	5200±10%
Launching height h [m]	10 and 12m
Ramp length/boat lengt ratio	1.2
Ramp inclination angle [^{o}]	30
Coefficient of friction between the ramp and lifeboat	0.05

** Loaded and equipped, all supplies onboard*

The lifeboat hull was idealized by a mesh of 384 triangular plane elements (Fig.4).

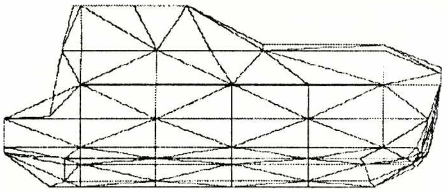

Fig.4. *Idealization scheme of the free-fall lifeboat shape*

Fig.5 indicates computed trajectories of the centre-of-gravity at the launching height of 10 and 12 m. To demonstrate whether the lifeboat is able to make positive headway from the mothership, its position and velocity should be computed at a certain distance from the water entry point.

In course of simulation, the position after time passage of 10 s (x_{10}) and velocity in x-direction (v_{x10}) were determined as follows : at the launching height of 10 m : x_{10}= 26 m and v_{x10}= 0.8 m/s; and at 12 m : x_{10}= 29.5 m and v_{x10}= 1.1 m/s.

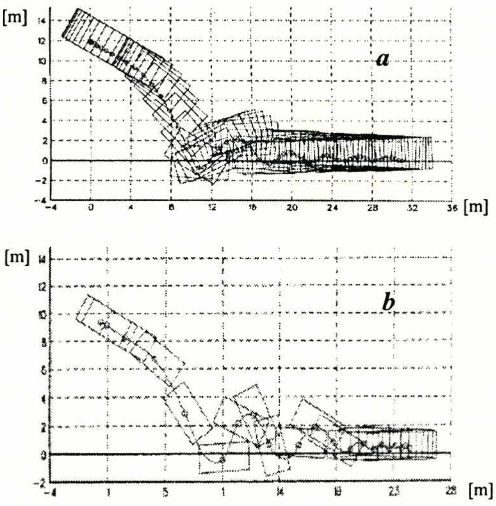

Fig.5. *Examples of launching trajectories -the vertical position of the centre of gravity [m] plotted against the horizontal distance [m] :*
a) *the lifeboat makes positive headway and the rotation remains within allowable limits,* ***b)*** *the rotation exceeds the safety limits*

The simulated trajectory allows to analize the motion of the lifeboat under study after water entry and to decide if the lifeboat parameters were properly selected.

Tab.2. *Maximum launching acceleration components a_x and a_z at x =5.0 m, z = 0.8 m for different launching heights (simulation results)*

	Acceleration [g]				
h [m]	10	12	14	16	18
a_x	-5.05*	-5.94	-6.61	-7.93	-9.01
a_z	8.21	9.12	9.31	12.23	12.94

** The average duration at the half-peak level was 0.04±0.01 s*

Fig. 6 to 8 indicate the influence of mass distribution and launching initial conditions on the distance travelled by the lifeboat after water entry.

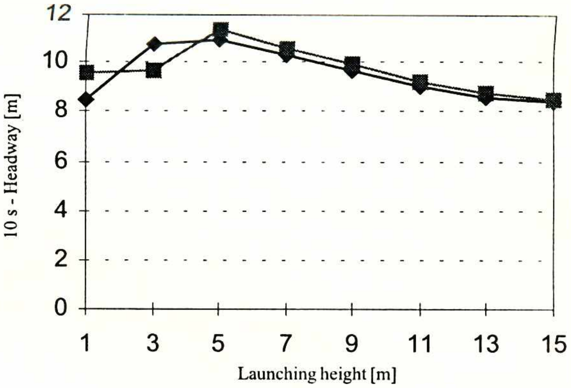

Fig.6. *Headway of the lifeboat at different values of the launching height*

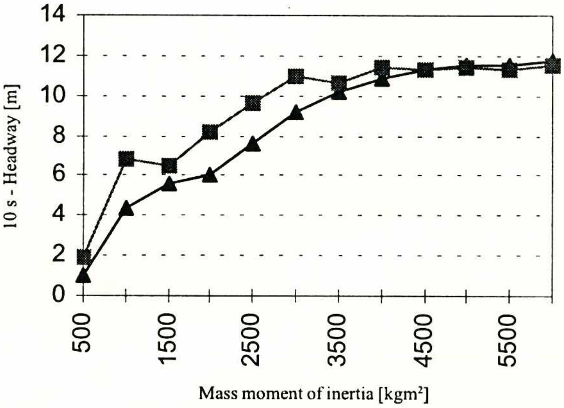

Fig.7. *Relationship between mass moment of inertia and the headway*

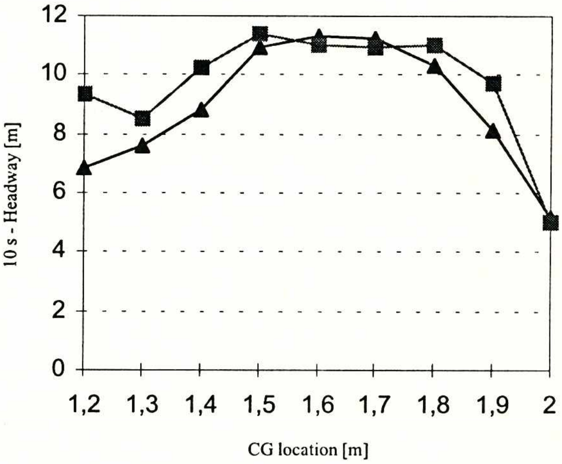

Fig.8. *Headway plotted against CG location*

Marks „▲" and „■" in Fig.6 to 8 correspond to two different hull shapes. The relationships shown in the figures were obtained for the scale model of FFL. Analysis of the simulation results leads to the conclusion that location of the centre of gravity is crucial for the lifeboat behaviour.

CG at the position too much shifted to the bow may cause unwanted rotational motion of the lifeboat, which adds a substantial component to the acceleration acting on the lifeboat occupants. On the other hand, CG located too close to the stern causes decreasing the headway.

PASSENGER SAFETY FACTOR

The domain of the input data for the launch prediction is limited by the space required for passengers, mass of the passengers and their seats, space and mass of the on board equipment and the buoyancy panels necessary to maintain stability of the lifeboat.

On the other hand, the manufacturers are usually reluctant when it comes to any change of the lifeboat hull shape, because it would require expensive changes of the production facilities. For these reasons, the lifeboat hull shape and mass distribution can be changed within a very limited range only.

The launching initial conditions, i.e. launching height, length of the ramp and its inclination angle could also be altered in a limited range. First of all, the lower limit of the launching height is determined by the customer' demand. The length and inclination of the ramp have to be selected in accordance with the space limit at the stern of the mother vessel.

The conclusion is that inertial forces acting upon the lifeboat can be controlled only in a narrow range and hence the passenger safety on board a free-fall lifeboat can be influenced mainly by DRI value.

In terms of the lifeboat design, the rest position of each seat should be determined according to the condition of minimum DRI value. The relationship between seat rest position and DRI depends on shape of the lifeboat and location of the seat in the boat. Therefore the simulation results do not offer any general solution. The simulation procedure should be repeated with various data sets and verified experimentally, to achieve an optimized solution.

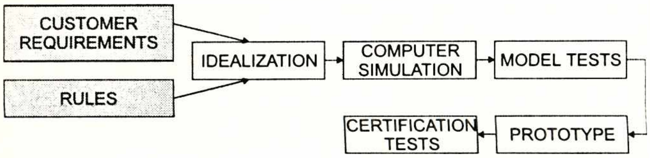

Fig.9. Scheme of the free-fall lifeboat creating process

CLOSING REMARKS

- The method of FFL behaviour prediction outlined in this paper, verified by a number of experiments carried out on isomorphic models and prototypes, demonstrated fair accordance with experimental results in both launching trajectory and level of accelerations.
- The launching height of the tested lifeboats all built by the USTKA Shipyard, ranged from 10 to 20 m, and the number of occupants was between 18 and 42.
- The computer simulation supported by the necessary experimental evaluation of such parameters as the coefficient of friction between the lifeboat and launching ramp and mass moment of inertia of the lifeboat can provide the sufficient amount of information to carry out the design process with minimum margin of uncertainty.
- Some of the simulation results indicated that it is necessary to use different positions for the seat resting in the front and after part of the lifeboat and different one of the helmsman's seat. Implementation of this conclusion led to substantial decrease of the DRI, which also allowed to extend the range of launching height for some of the lifeboats.
- In course of further study the problem of evacuation of wounded and disabled persons will be investigated.

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Appraised by Lech Rowiński, Assoc.Prof.,D.Sc.

NOMENCLATURE

a - acceleration in the Ist phase of motion
CG - centre of gravity
d_x, d_y, d_z - components of Dynamic Response
DRI - Dynamic Response Index
FFL - free-fall lifeboat
F_x - hydrostatic force
F_z - hydrodynamic force
g - gravity acceleration
h - launching height
I_{yy} - mass moment of inertia
j - number of the finite element
l - ramp length
m - mass of the boat
n - number of the elements
N - normal reaction of the ramp
Q - weight of the boat
r_{xj}, r_{zj} - position of the centroid of the j finite element
x, y, z - coordinates in the local system
$\ddot{x}, \ddot{y}, \ddot{z}$ - acceleration components in the local coordinate system
x_g, z_g - coordinates in the global system
α - ramp inclination angle
$\delta_x, \delta_y, \delta_z$ - allowable values of Dynamic Response components
$\Delta x, \Delta z$ - center-of-gravity displacement
μ - coefficient of friction between launch rails and the boat
ξ, η - coordinates in the inertial system
ρ - friction angle
φ - angle of rotation during free fall
$\ddot{\varphi}$ - free fall angular acceleration of the boat

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