

## PRELIMINARY DESIGN OF MONOHULL HIGH-SPEED FERRIES – A MULTIPLE OBJECTIVE OPTIMISATION APPROACH

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**Abstract** High-speed ferries are now widely used for transporting both passengers and passengers and cars. Numerous vessel designs such as catamaran, monohull, hydrofoil, air cushion, surface effect, foil assisted catamaran, and small-waterplane-area twin-hull (SWATH), have been designed to meet these requirements. From the data as published by the Fast Ferry International it can be seen that monohull and Catamaran are by far the most prevalent design solutions used. The efficient structural design of those ferries is very important especially for larger vessels moving at such high speeds. In continuation of a study on the methodology of preliminary design of monohull high-speed ferries [Pal and Peacock, 2001], this is a record of further study of such vessels incorporating structural arrangements for obtaining scantlings with minimum weight satisfying all strength constraints. The structural design is based on the Det Norske Veritas (DNV) rules for classification of high-speed, light craft and naval surface craft. In addition to the aluminium alloys, high strength steels (X-80 steel) are also considered for comparison. The model also addresses design considerations such as resistance and economic analysis, for identification of principal dimensions for a set of owner's requirements. The problem is solved using the compromise decision support problem technique. This technique is a hybrid of both traditional mathematical and goal programming problems which allows the incorporation of multiple conflicting goals and large number of real world constraints. The model has been tested for vessel having a capacity of 500 passengers and 100 cars operating at a service speed of 46 knots.

*Keywords: High-speed ferries, Monohull, Preliminary design*

### INTRODUCTION

High-speed ferries are widely operated to transport passengers, passengers and cars (vehicles) and other cargoes across channels, inter islands, between mainland and islands and other similar waterways. From the data of such vessels built since 1988 published by *Fast Ferry International* it is seen that more than twenty per cent of total ferries built is of monohull type.

The preliminary design stage for new vessels offers the designer a wide range of design alternatives. A quick and reliable methodology to investigate these design alternatives is attractive, as the design process can be complicated and costly for the designer, if poor initial designs are used. With this in mind a mathematical model can be used to help identify 'suitable' preliminary designs for the later stages of design.

Principal design parameters are determined using trends of various relationships between known and unknown design parameters that are obtained using data

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from existing vessels as published by *Fast Ferry International*. The scantlings of the midship section have been calculated using rules of DNV [DNV Rules, July 2000].

To minimise the time required to design such a vessel a need arises to develop a model for assisting the designer to identify principal design parameters at the preliminary design stage. As desirable, the model is evolved for a high-speed mono-hull ferry designed for the minimum total resistance, the minimum lightweight, minimum midship scantling section area and the maximum net present value index for its life of operation.

A concurrent systems engineering approach through the use of a technique known as the Compromise Decision Support Problem Technique is used to find a solution for this problem.

### DECISION-BASED APPROACH TO DESIGN

Decision-based solution is achieved with a holistic systems approach. The philosophical foundation for this is found in the following two basic concepts.

Firstly, the principal role of a designer is to make decisions. Secondly, an appropriate modern approach to designing is one that is based on systems thinking, uses computers as partners in the process of design and includes concurrent engineering design for the life cycle. Some examples of efforts devoted to synthesis and decision support include [Lyon and Mistree, 1985], [Smith, 1992], [Erikstad, 1996], and [Peacock, 1998].

This approach is via the **Decision Support Problem Technique (DSPT)** that is implemented in the software environment, **DSIDES (Decision Support In the Design of Engineering Systems)**. The DSPT and DSIDES are well documented in [Mistree *et al.*, 1991, 1992] and [Reddy *et al.* 1992]. From this philosophical basis, the fundamental **Decision Support Problem (DSP)** construction utilised in this paper is the 'compromise decision' and its description follows.

### The Compromise Decision

The compromise decision requires that the 'right' values (or combination) of design variables be found to describe the best satisficing, [Simon, 1982] system design with respect to constraints and multiple goals.

The emphasis in compromise is on modification and change (e.g., dimensional synthesis) by making appropriate trade-offs based on criteria relevant to the feasibility and performance of the system. Concurrency in the design process is achieved by the simultaneous resolution of coupled decisions.

### PRELIMINARY DESIGN

The design model is formulated as a decision support problem. The model is constructed using the words of *given, find, satisfy, and minimise*. A solution is obtained by minimising the objective function involving the over-achievement and under-achievement (deviation) of goals. This technique was employed to find solutions for specific ship design problems such as a trawler [Pal, 1989], for a hatchcoverless container ship, [Pal *et al.*, 1999], high-speed catamaran ferries [Pal *et al.*, 1999, 2000] and for the structural design of a large hatchcoverless container ship [Chowdhury *et al.*, 2000].

The monohull ferry having chine form is assumed to have two decks. The lower deck is used for stowing cars and the upper deck is for the accommodation of passengers. The hull is constructed of either aluminium alloy or X-80 steel and fitted with diesel engines driving waterjets for propulsion. The overall propulsive coefficient is estimated from the data suggested by Ka Me Wa.

The data required for estimation of design parameters are obtained from the publications of data of fast ferries by *Fast Ferry International*.

### STRUCTURAL DESIGN

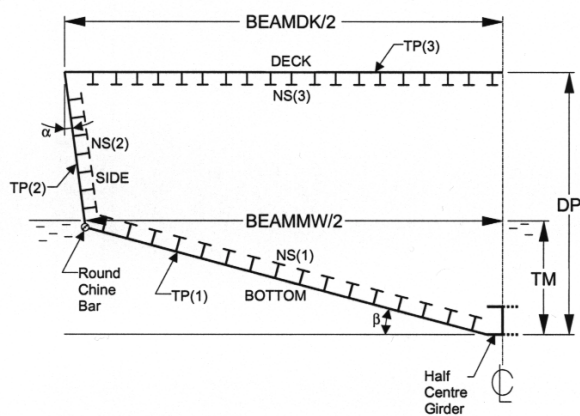
The midship section of the single bottom monohull high-speed ferry is divided into three regions; the bottom shell, side shell, and deck. The deadrise angle  $\beta$  is a design variable, and the angle the side shell makes with a vertical line,  $\alpha$  is calculated from the breadths at the strength deck and that at the load water line together with moulded depth and draught. There are three independent design variables in each of these three regions, namely the plate thickness, size of stiffeners and the number of stiffeners.

The plate thickness and the stiffener size are dictated by the pressure acting in that region. Both sea pressure and slamming pressures are used as required by the rules. However, the number of stiffeners are not directly dependent on the local loads. But there is a basic stiffener spacing defined by the rules which provide the minimum and maximum allowable numbers of stiffeners in a region and these are obeyed.

The local pressure provides the shell plate thickness directly but the size of the stiffeners are given in terms of the section modulus. In this exercise the stiffeners are all assumed to be *tee* cross section and ideally four independent variables are required to define the stiffener size. These are web thickness, web depth, flange thickness and flange width. But for the preliminary design it is considered reasonable to idealize this *tee* section by defining the cross section in terms of a single design variable, which is the web thickness,  $t_w$ . The web depth is thirty times the web thickness,  $t_w$ , the flange thickness 1.5 times  $t_w$  and the flange width 15 times the flange thickness. This process enabled to define the stiffener size by a single design variable,  $t_w$ . Therefore, there are in total 9 independent variables for the midship section.

To make it more realistic a centre girder is placed at the bottom shell (Fig 1). This is a double symmetric I-beam with similar proportion as for the stiffeners and its flange thickness is at least equal to that of the bottom shell. Finally, a solid round rod is placed as chine bar. The diameter of the chine bar and the size of the centre girder are not treated as design variables but any suitable input are possible. Similarly, the frame spacing is also an input data.

In addition to satisfy the local strength requirements the midship section must also satisfy the hull girder strength requirements, in particular the bending moments in the longitudinal vertical plane. For this purpose, total sagging, total hogging, crest landing and hollow landing moments are computed as per rule; the largest value used to determine the required hull girder section modulus. As a compromise between complexity and practicality plate thicknesses are rounded to half a



**Fig. 1 Midship section**

millimetre. If required, post-optimisation adjustments to the available thicknesses may be done. With regard to the stiffeners the optimum cross-sectional area may be used as a basis for selection from the available rolled section. Both these adjustments will have some effects on the results but these are not expected to be too adverse.

For aluminium construction it is assumed that the plates are of NV-5083 H321/H116 grade alloy and the stiffeners are of NV-6080 T5/T6 grade alloy. For high strength steel NV-550, X-80 steel is considered.

The checking of scantlings against buckling, torsion and shear are not included in the present model.

### MATHEMATICAL MODEL

*Given:*

- A set of owner's requirements:
- Number of passengers, NOP
- Number of Vehicles, NOV
- Service Speed, SPEEDK (knots)
- One way distance in nautical miles
- A set of operation data for estimation of an economic index, NPVI
- Particulars of structural arrangement of midship section

*Find:*

#### (a) System variables

These system variables are chosen as non-dimensional functions of design parameters or the ratio of design parameters and vary between zero and one. The lower and upper limits (defined later) for the variables are selected from the data of recently built vessels. The system variables are shown below:

X(1): A function of length overall which lies between practical lower and upper limits being functions of number of passengers,

$$=(LOA-LOAL)/(LOAH-LOAL) \quad (1)$$

X(2): A function of longitudinal position of centre of buoyancy

$$=(LCB-(-2.0))/-8.0 \quad (2)$$

X(3): A function of length between perpendiculars (LP) to moulded beam ratio; the length between perpendiculars equals length on waterline which is a function of length overall

$$=(LP/BEAMMW-3.33)/2.10 \quad (3)$$

X(4): A function of moulded beam to draught ratio

$$=(BEAMMW/TM-3.75)/3.70 \quad (4)$$

X(5): A function of length between perpendiculars to depth ratio

$$=(LP/DP-4.50)/14.50 \quad (5)$$

X(6): A function of block coefficient

$$=(CB-0.35)/0.10 \quad (6)$$

X(7): A function of maximum section area coefficient

$$=(CM-0.573)/0.247 \quad (7)$$

X(8): A function of passenger seating area per person

$$=(AREAST/NOP-0.80)/0.60 \quad (8)$$

X(9): A function of gross passenger area per seating area

$$=(AREAPG/AREAST-1.3)/0.40 \quad (9)$$

X(10): A function of transom area to maximum section area ratio

$$=(AREATR/AREAMX-0.43)/0.39 \quad (10)$$

X(11): A function of half angle of entrance

$$=(ANGLE-15.0)/13.0 \quad (11)$$

X(12): A function of dead rise angle

$$=(BETA-10.0)/15.0 \quad (12)$$

X(13): A function of waterplane area coefficient

$$=(CWP-0.72)/0.11 \quad (13)$$

X(14): A function of thickness of bottom plating

$$=(TP(1)-8.0)/12.0 \quad (14)$$

X(15): A function of thickness of side plating

$$=(TP(2)-5.0)/10.0 \quad (15)$$

X(16): A function of thickness of deck plating

$$=(TP(3)-5.0)/10.0 \quad (16)$$

X(17): A function of web thickness of bottom stiffeners

$$=(TW(1)-3.0)/7.0 \quad (17)$$

X(18): A function of web thickness of side stiffeners

$$=(TW(2)-2.0)/6.0 \quad (18)$$

X(19): A function of thickness of deck plating

$$=(TW(3)-2.0)/6.0 \quad (19)$$

X(20): A function of number of stiffeners of bottom plating

$$=(NS(1)-NSMIN(1))/(NSMAX(1)-NSMIN(1)) \quad (20)$$

X(21): A function of number of stiffeners of side plating

$$=(NS(2)-NSMIN(2))/(NSMAX(2)-NSMIN(2)) \quad (21)$$

X(22): A function of number of stiffeners of deck plating

$$=(NS(3)-NSMIN(3))/(NSMAX(3)-NSMIN(3)) \quad (22)$$

The upper and lower limits of length overall are estimated as a function of number of passengers based on data of existing vessels. The maximum and minimum number of stiffeners are calculated according to rule requirements.

$$LOAL = (NOP-44.616)/10.269$$

$$LOAH = (NOP-12.154)/3.892$$

From the above mentioned system variables, necessary design parameters may easily be calculated.

**(b) Deviation variables**

Deviation variables are used to evaluate the under-achievement and the over-achievement of minimisation of total resistance, lightship weight, hull girder midship section area, maximisation of net present value index of operation for the life goals, and equalisation of displacement and weight. There are ten deviation variables that are shown with the goal constraints.

*Satisfy:*

Constraints (must be satisfied for a feasible solution)

**(a) System constraints**

Twenty-seven inequality constraints are formulated as greater than or equal to 0.0. Four constraints are due to scope of resistance estimation; two are due to deck area requirements, one for freeboard, one for initial metacentric height, three for motions, and two for displacement and weight. Twelve are for thickness of plate and web and number of stiffeners. One is for depth and other is for deadrise angle. Due to shortage of space, the details of constraints are not shown.

**(b) Bounds on normalised system variables:**

$$X(1), X(2), \dots, X(22) \geq 0.0 \quad (23-44)$$

$$X(1), X(2), \dots, X(22) \leq 1.0 \quad (45-66)$$

**(c) Goals (as much as possible):**

Goal constraints:

$$TRRES D/RES D - d_1^- + d_1^+ = 1.0 \quad (67)$$

$$TRWLT/WLT - d_2^- + d_2^+ = 1.0 \quad (68)$$

$$NPVI/TRNPVI + d_3^- - d_3^+ = 1.0 \quad (69)$$

$$DISPLT/WEIGHT + d_4^- - d_4^+ = 1.0 \quad (70)$$

$$TRHGSA/HGSA - d_5^- + d_5^+ = 1.0 \quad (71)$$

Where,

$d_i^-$ , with  $i = 1, 2, 3, 4, 5$  are under-achieved deviation variables, and  $d_i^+$ , with  $i = 1, 2, 3, 4, 5$  are over-achieved deviation variables. The deviation variables represent the over- and under-achievement of the goals. The target values for minimisation goals are chosen as the lowest expected value and that for maximisation goals are as the highest expected values.

*Minimise:*

The objective function

The general Archimedean formulation of the objective function (a function of deviation variables) is:

$$Z(d_i^-, d_i^+) = [P_1(d_1^- + d_1^+) + P_2(d_2^- + d_2^+) + P_3(d_3^- + d_3^+) + P_5(d_5^- + d_5^+)] \quad (72)$$

where,  $P_1, \dots, P_5$  are priority levels for each deviation.

**EVALUATION OF CONSTRAINTS**

The resistance estimation is made using the regression equations developed by [Savitsky and Brown, 1976] for

vessels operating below a volume Froude Number of 1.8 and by [Lahtiharju, *et al*, 1991] for round bilge form and chine form vessels operating in a range of volume

Froude Number between 1.8 and 3.3. The mass items are estimated as suggested by [Karayannis, *et al*, 1999]. The motion characteristics are evaluated using the equations in [Lamb, 1969]. Structural scantlings are evaluated from the [DNV rules, July 2000].

**ECONOMIC ANALYSIS**

The economic analysis model is developed for an operation over a period of ten years. The cost of the vessel is estimated by the method as suggested by [Karayannis, *et al*, 1999]. A brief description of the analysis is shown in [Pal, *et al*, 2001].

**RESULTS**

The model is tested for a set of owner's requirements, ie, number of passengers (500), number of vehicles (100), one way distance (230 nautical miles), and service speed (46 knots) as well as a set of necessary operating data for the assessment of economic index, for vessels with chine form only.

The summary results for a speed of 46 knots for both constructions are shown in Table 1

**DISCUSSION**

Comparing the values shown in Table 1, it is seen that the aluminium alloy hull has a lower displacement leading to lower resistance and installed power. The calculated values of length, beam, block coefficient, prismatic coefficient, half angle of entrance, longitudinal position of centre of buoyancy appear to be independent of hull construction materials. The draught is increased for the steel construction as the displacement increases. It is seen that the high speed ferry construction is economical to operate with hull construction of aluminium alloy when compared with the steel construction. The required fare per person and per vehicle are much higher for the operation of vessel with steel construction to be viable under the assumed condition of economic analysis.

**CONCLUSION**

The model developed in this study is suitable for preliminary design of mono-hull ferries transporting passengers and cars. Many issues can be investigated, using the model presented and by extending this approach into other relevant domains. Once one has something, the awareness of what he does not have increases. Effective computer-based design synthesis, efficient rapid prototyping and design simulation have been demonstrated in this model.

**Table-1: Summary results of chine form hull constructed of aluminium alloy and steel, speed: 46 knots, passengers: 500; vehicles: 100; one way distance: 230 nautical miles; crew:12; and number of jet units: 4, Diesel machinery**

		Aluminium alloy	X-80 Steel
Speed	kn	46	46
Overall Propulsive Coefficient		0.77	0.77
Volume Froude Number		2.38	2.28
Length Overall	m	94.18	93.10
Length Between Perpendiculars	m	82.03	81.08
Length on Waterline	m	82.03	81.08
Draught (mean)	m	2.31	3.05
Draught at Transom	m	1.85	2.44
Depth	m	7.09	5.28
Height of C.G. Above keel	m	6.03	4.48
Beam (maximum) on Waterline	m	15.21	15.36
Beam (maximum) on Deck	m	15.97	16.13
Half-angle of Entrance	degrees	15.01	15.04
Deadrise Angle	degrees	16.85	20.60
Block Coefficient		0.35	0.36
Prismatic Coefficient		0.60	0.61
Longitudinal Position of Centre of Buoyancy from Midship % of LL		-3.94	-6.50
Displacement	tonnes	1044.46	1401.09
Weight	tonnes	1043.45	1392.63
Weight Lightship	tonnes	840.56	1164.02
Deadweight	tonnes	202.89	228.61
Resistance	kN	995.07	1570.19
Effective Power	mW	243.54	37.16
Installed Power	mW	41.24	65.08
Acquisition Cost of Ship	mA\$	36.11	44.61
Net Present Value	mA\$	4.68	18.44
Net Present Value Index		0.13	0.41
Fare per Person	A\$	120	182
Fare per Vehicle	A\$	130	190
Midship scantling cross section area.	sq cm	3583	3194
Required midship section modulus	cu cm	667804	341663
Calculated midship section modulus	cu cm	732645	371325
Bottom shell plate thickness	mm	9.00	8.50
Side shell plate thickness	mm	5.50	8.50
Car deck plate thickness	mm	7.00	6.50
Bottom shell stiffeners web thickness	mm	3.5	3.50
Side shell stiffeners web thickness	mm	2.50	3.00
Car deck stiffeners web thickness	mm	2.46	3.00
Number of stiffeners in the bottom shell		21	12
Number of stiffeners in the side shell		13	3
Number of stiffeners in the car deck		21	12
Frame spacing	m	1.20	1.80
Diameter of chine bar	mm	20.00	12.00

## FUTURE WORK

The extension of the model may be made to include other aspects of the design of such vessels. Once one has a model such as this, it will be possible to include global structural analysis, detailed seakeeping analysis, propulsion system design analysis modules and further goals minimising the hull weight, motion sickness and maximising the propulsive coefficient. It is recommended that further development be driven by industrial involvement.

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