An Application of the DOE Methodology in Damage Survivability

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ABSTRACT

This study focuses on the fundamental nature of the flooding process, and attempts to determine the main contributing factors to its evolution. It is performed experimentally by measuring the forces and moments of interest, the water heights inside flooded compartments, and the air pressure inside the double bottoms of the PRR02 - ITTC/SiW passenger Ro-Ro ferry. The controllable factors are: initial draught, damage opening area, time of damage creation, dimensions and locations of flow obstructions inside a large compartment, cross-flooding, air ventilation, and external excitation. The applied Design of Experiments methodology manages to build a model of the transient flooding.

KEYWORDS

Transient and progressive flooding; Ro-Ro passenger ferry; factors; model; Design of experiments.

NOMENCLATURE

CD	Cross Duct
DBA	Double Bottom Aft
DBF	Double Bottom Forward
EB	Engine Block
ER	Engine Room
GM	Metacentric height
GR	Generator Room
IFS	Intermediate Flooding stages
OM	Opening Mechanism
SR	Storage Room
T_Φ	PRR02 natural period

INTRODUCTION

Ro-Ro and Ro-Pax ferries have been growing in size for decades. Despite the global economic downturn, their industry continues to show positive signs. This is evident by the scheduled launch of some humongous new Ro-Pax vessels by 2012 (as the new Stena Line Superferries joining Hook of Holland – Harwich route in May 2010, etc.). The safety of such vessels remains of the utmost importance in their design and operation stages, as accidents of a varying nature (collision, grounding, etc.) can occur. More investigations into these accidents need to be performed based on the available data, and substantial outcomes should be included in the relevant regulations to raise them beyond today's level hoping to prevent maritime accidents' occurrence in the future.

Commercially, Ro-Ro passenger ferries have proven to be successful. This is due to car decks stretching from board to board and from stem to stern, thus reducing the time required for operations onboard. However, it is well known that this characteristic is the main contributor to the sinking of these vessels, as the reserve of buoyancy above the bulkhead deck has completely vanished when the ship shell was damaged (Dand (1989), Spouge (1985)). On the other hand, the geometry of the spaces below the bulkhead deck is also of great importance indeed. When a maritime accident occurs, the geometry and the state of the spaces below the bulkhead deck in such vessels contribute to determining the final state they will reach.

The effect of the intermediate flooding stages (IFS), i.e. transient and progressive, on ships' damaged survivability has been studied based on parametric investigations carried out both experimentally and computationally (Chang and Blume (1998), Chang (1999), Ikeda and Ma (2000)). Generally, these investigations have provided a better understanding of the basic fundamentals of the flooding physics, and have assisted in identifying some parameters which are significant for the assessed phenomena. Besides, when giving some recommendations to reliably assess the IFS, Khaddaj-Mallat et al. (2009) stressed on an actual need to identify the significant factors, their main effects, and the interactions linking them. Therefore, they proposed to apply Design of Experiments methodologies (DOE), in the hopes of meeting this need obviously unreachable by means of parametric investigations.

The paper understudy chiefly aims at shedding lights on the DOE methodology applied in a particular Ocean-Engineering domain, the damage survivability. It also aims to better understand the IFS, determine the factors that govern them, and eventually build a model that could appropriately describe them. Thus, an experimental investigation was carried out in Sept/Oct 2009 using the midsection of the PRR02 - ITTC/SiW passenger Ro-Ro ferry. A detailed description of the experimental set up, as well as first findings relevant to one particular test (and not to any DOE plans) could be respectively found in Khaddaj-Mallat et al. (2010a, 2010b). Thus, this paper is devoted to presenting the guidelines of applying this methodology to perform tests, as well as the first findings, relevant to a DOE plan, the Fractional Factorial Design (FFD). A mathematical model that characterizes the IFS in Ro-Ro Passenger ferries is presented.

EXPERIMENTAL METHODOLOGY

In this chapter, the guidelines for designing the experiment based on DOE approach and for analyzing the results are presented. The experimental quantities and results are presented in model scale.

Recognition of and statement of the problem

Physically, the first phase of flooding that occurs after an abrupt damage creation, i.e. the transient phase, is dependent on the flooding process and the procedure of water accumulation inside internal compartments itself related to water ingress / egress through the damage hole. This phase is influenced by hosts of factors we aim to quantify their trends. Thus, two distinct tests in calm water using the ship midsection are performed as a first step:

- Flooding experiments in which the model is kept fixed. These tests are performed to a) assess the influence of the investigated factors on hydrodynamic efforts exerted on the model during the IFS, b) better understand the behavior of both implicated fluids, i.e. water and air.
- Forced oscillation tests performed for realistic combinations between the six degrees of freedom. These tests allow us to quantify the influence of external excitations on the measured quantities and sloshing.

A brief description of the experimental set up

The tested body is a 1/38.25 scaled model of the PRR02 midsection. Its main dimensions and general arrangements are given in Table 1, and Figure 1, respectively.

Table 1: Model main dimensions.

Feature	Value
Length, L(m)	26.71
Beam, B(m)	25.00
Draft, T(m)	6.40
Car deck above baseline (m)	9.10
PRR02 Length, L_{pp}(m)	174.80

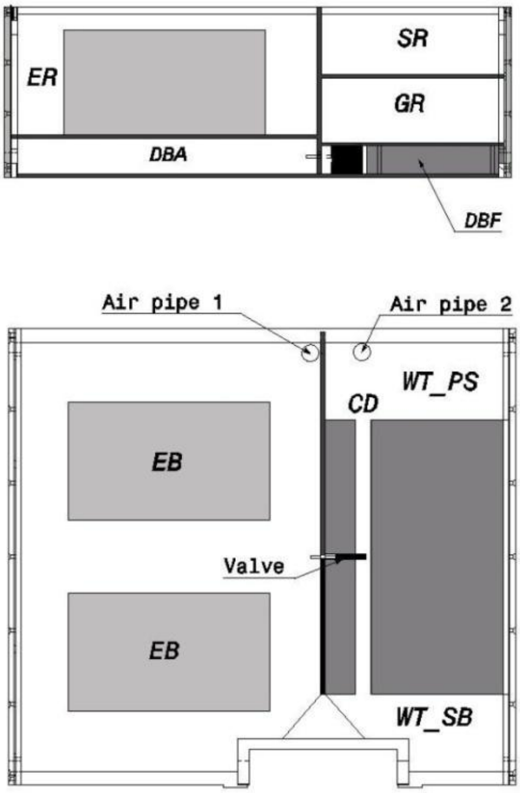

Figure 1: Model general arrangements.

In the DBF, a CD connects the two wings double bottom tanks. A valve is mounted at the midpart of the CD. It is either opened (On) or closed (Off) during the experiments. Moreover, two air pipes are included in the model, to reproduce air pressure fluctuations expected in full-scale ship.

The flooded compartments are chosen according to the worst SOLAS 90 damage scenario. The damage characteristics are as follows.

- A rectangular shape in side, reproducing the real bilge shape. Two damage areas pertaining to different types of accidents are tested. To do so, the vertical extent of the damages is varied while keeping its longitudinal one constant.
- Isosceles-triangles notches in all decks penetrating to the B/5 lines are performed, reproducing the damage that would be created by the striking vessel's bow. Because of the hull bilge part and the opening door, the performed notch has the shape shown in Figure 1.

The damage OM comprises a vertical door that appropriately fits with the hull shape. An electrical motor, mounted on the deck along with a rope-pulley system, opens the door and lets it run on rails up alongside the hull and over the deck.

Thus, the experimental set up that we believe it appropriately enables meeting the drawn objectives, mainly relies on the use of a 6-DOF-motion platform "Hexapod" settled upside down, as well as a custom-made 6-DOF dynamometer attached to its movable plate. It is shown in Figure 2.

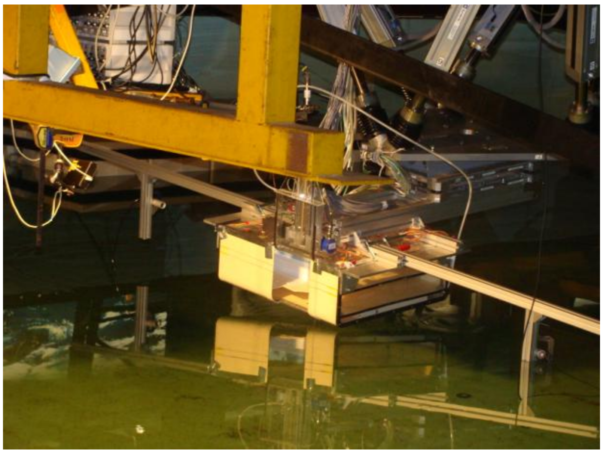

Figure 2: The experimental set up when drying the model.

The measured quantities are:

- The hydrodynamic efforts on the body kept fixed and under forced-oscillations.
- The water heights in several locations inside every flooded compartment.
- The air pressures in compartments of interest (the DBs).

In addition, a set of video cameras is used to visualize the physical conditions and both water and air behaviors. A sampling frequency of 1 kHz is used to capture expected peaks in the behaviors of all measured quantities.

Why DOE Methodology?

DOE offers several key advantages over the traditional one-variable-at-a-time approach. It allows for the evaluation of the statistical significance of individual process parameters, as well as the interaction between factors. Another major advantage of the DOE approach is that it requires only a small set of experiments and thus helps to reduce costs. It is hoped that DOE lets us develop a mathematical model able to predict how input variables interact to create output ones (responses and criteria) in the event of flooding. Detailed accounts of how to design DOE experiments can be found, for example, in Schimmerling et al. (1998) and Ryan (2006).

Choice of factors, levels, and ranges

IFS are dependent upon a fair number of factors related to the event of damage creation, the initial ship hydrostatic and the environmental conditions.

The selection of controllable factors and their levels is a demanding and intricate task, since the DOE plan performance is directly attached to the data used to train it. To do so, a number of discussions involving experienced individuals such as Mr. Paul Schimmerling of Renault, France, took place and valuable advice was provided on the reliability of the experimentation strategy.

Thus, we first screen initial heel and trim, as their influence on the IFS is relatively small. Besides, GM is not considered in the current experiment, as the experimental set up is conceived to measure hydrodynamic efforts. Thus, the design factors for this study, as well as their selected levels are determined and presented in Tables 2 and 3. It is worth to mention that this study deals with a large number of factors influencing the IFS; GM is the sole factor influencing these stages that is not taken into account.

Table 2: List of the variables affecting the IFS.

Variables of control	Symbol	Dimension
Initial draught	A	L [m]
Damage opening's area	B	L^2 [m^2]
Valve status	C	-
Air ventilation level	D	-
ER's permeability μ	E	-
Transversal distance between the centerline and the EB	F	L [m]
Time of damage creation	G	T [s]
Motion amplitude of the midsection hull	H	L [m]

Table 3: List of the controllable factors' levels.

Factor	Level 1	Level 2
A	LC_1 $A_1 = 0.167$	LC_2 $A_2 = 0.140$
B	Small damage $B_1 = 0.00946$	Large damage $B_2 = 0.04730$
C	$C_1 = 1$; Opened valve $C_1 = 0$; Closed valve	$C_2 = 0$; Opened valve $C_2 = 1$; Closed valve
D	Fully ventilated $D_1 = 0.146$	Partially ventilated $D_2 = 0.058$
E	70% ER Permeability $E_1 = 0.70$	85% ER Permeability $E_2 = 0.85$
F	EBs 21.8cm far from the centerline $F_1 = 0.218$	EBs at the centerline $F_2 = 0$
G	Instantaneous damage opening $G_1 = 0$	Damage created in $4T_{\Phi}/3$ $G_2 = 3.45$
H	No external excitation $H_1 = 0$	Combined Heave & Roll Forced-Oscillation $H_2 = 0.0298$

Selection of the response variable

After conducting tests to assess the repeatability and the reproducibility of our experiment, we find that the experimental uncertainty is relatively small (<3.5%) and that our measurement system is reliable. Therefore, based on the quantities we measured, we have determined the following response variables.

- For F_x, F_y, M_x, F_z, and M_y: The maximum amplitude, the time to reach it with respect to the start of the damage creation, the amplitude after the IFS end, the amplitude when the door movement ceases, and the slope during the event of damage creation (only for F_z and M_y).

- The flooding rates and the discharge coefficients through the damage opening.
- For air pressures in DBA and DBF: the peak and its correspondent time of occurrence, the values at the end of the door movement and after the IFS end.
- For water heights measured by means of twenty probes: the peak, time to reach it, and the slope during the water accumulation.

These quantities (89 outputs) are evaluated for each test providing a thorough account of data to analyze. The analysis will determine the response variables and the design factors that best characterize the IFS.

Choice of experimental design

A fractional factorial design (FFD) is used to design the experiments to minimize the runs. With eight factors, the quarter-fractional two-level factorial design (2^{8-2}) requires a combination of 64 experimental tests. The 64 run combinations for the 2^{8-2} design are shown in Table 4.The design is a Resolution IV design following Q_2 strategy, which means that all main effects and two-factor interactions can be estimated without ambiguity (Schimmerling et al. (1998)).

Table 4: FFD data sheet.

Std. order	A	B	C	D	E	F	G	H
1	1	1	1	1	1	1	2	2
2	2	1	1	1	1	1	1	1
3	1	2	1	1	1	1	1	1
4	2	2	1	1	1	1	2	2
5	1	1	2	1	1	1	1	2
6	2	1	2	1	1	1	2	1
7	1	2	2	1	1	1	2	1
8	2	2	2	1	1	1	1	2
9	1	1	1	2	1	1	1	2
10	2	1	1	2	1	1	2	1
11	1	2	1	2	1	1	2	1
12	2	2	1	2	1	1	1	2
13	1	1	2	2	1	1	2	2
14	2	1	2	2	1	1	1	1
15	1	2	2	2	1	1	1	1
16	2	2	2	2	1	1	2	2
17	1	1	1	1	2	1	2	1
18	2	1	1	1	2	1	1	2
19	1	2	1	1	2	1	1	2
20	2	2	1	1	2	1	2	1
21	1	1	2	1	2	1	1	1
22	2	1	2	1	2	1	2	2
23	1	2	2	1	2	1	2	2
24	2	2	2	1	2	1	1	1
25	1	1	1	2	2	1	1	1
26	2	1	1	2	2	1	2	2
27	1	2	1	2	2	1	2	2
28	2	2	1	2	2	1	1	1
29	1	1	2	2	2	1	2	1
30	2	1	2	2	2	1	1	2
31	1	2	2	2	2	1	1	2
32	2	2	2	2	2	1	2	1
33	1	1	1	1	1	2	2	1
34	2	1	1	1	1	2	1	2
35	1	2	1	1	1	2	1	2
36	2	2	1	1	1	2	2	1
37	1	1	2	1	1	2	1	1
38	2	1	2	1	1	2	2	2
39	1	2	2	1	1	2	2	2
40	2	2	2	1	1	2	1	1
41	1	1	1	2	1	2	1	1
42	2	1	1	2	1	2	2	2
43	1	2	1	2	1	2	2	2
44	2	2	1	2	1	2	1	1
45	1	1	2	2	1	2	2	1
46	2	1	2	2	1	2	1	2
47	1	2	2	2	1	2	1	2
48	2	2	2	2	1	2	2	1
49	1	1	1	1	2	2	2	2
50	2	1	1	1	2	2	1	1
51	1	2	1	1	2	2	1	1
52	2	2	1	1	2	2	2	2
53	1	1	2	1	2	2	1	2
54	2	1	2	1	2	2	2	1
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56	2	2	2	1	2	2	1	2
57	1	1	1	2	2	2	1	2
58	2	1	1	2	2	2	2	1
59	1	2	1	2	2	2	2	1
60	2	2	1	2	2	2	1	2
61	1	1	2	2	2	2	2	2
62	2	1	2	2	2	2	1	1
63	1	2	2	2	2	2	1	1
64	2	2	2	2	2	2	2	2

Statistical analysis of the data

After performing the FFD experimental runs, the obtainable data is analyzed to build a model for every output. Each of the 89 responses (Y) can be written as the summation of its mean effect, that of all the 8 controllable factors (each factor is considered individually), and those of second-order interactions (see Eq. (1)). Relevant coefficients are to be evaluated according to Schimmerling et al. (1998).

$Y = I +$

$[a_1\ a_2].A + [b_1\ b_2].B + [c_1\ c_2].C +$
$[d_1\ d_2].D + [e_1\ e_2].E + [f_1\ f_2].F +$

$[g_1\ g_2].G + [h_1\ h_2].H +$

$$B^TM_{BA}A + C^TM_{CA}A + D^TM_{DA}A + E^TM_{EA}A + F^TM_{FA}A + G^TM_{GA}A + H^TM_{HA}A +$$
$$C^TM_{CB}B + D^TM_{DB}B + E^TM_{EB}B + F^TM_{FB}B + G^TM_{GB}B + H^TM_{HB}B + \quad (1)$$
$$D^TM_{DC}C + E^TM_{EC}C + F^TM_{FC}C + G^TM_{GC}C + H^TM_{HC}C +$$
$$E^TM_{ED}D + F^TM_{FD}D + G^TM_{GD}D + H^TM_{HD}D +$$
$$F^TM_{FE}E + G^TM_{GE}E + H^TM_{HE}E + G^TM_{GF}F + H^TM_{HF}F +$$
$$H^TM_{HG}G$$

Where:

- X^T designates X transpose matrix,
- $A = [A_1\ A_2]^T \ldots H = [H_1\ H_2]^T$ represent the input variables (see Table 3),
- I represents the response's mean effect,
- $[a_1\ a_2] \ldots [h_1\ h_2]$ are the coefficients to evaluate that represent the individual effect of each factor, and
- $M_{BA} = [(ba)_{11}\ (ba)_{12};\ (ba)_{21}\ (ba)_{22}] \ldots M_{HG} = [(hg)_{11}\ (hg)_{12};\ (hg)_{21}\ (hg)_{22}]$ are the coefficients to evaluate that represent second-order interactions.

Eq. (1) helps determine to which extent each of the input factors affects any selected response. Thus, with fixing a criterion, we are able to determine which factors are significant for the selected responses, and; therefore, for the physical phenomenon.

Determining Eq. (1)'s coefficients (I, $(a_1,a_2)\ldots(h_1,h_2),(ba)_{11}\ldots(hg)_{11}$) is useful to evaluate Eq. (2)'s coefficients (α_0, $\alpha_1 \ldots \alpha_8$, $\alpha_{12} \ldots \alpha_{78}$).

$$Y = \alpha_0$$
$$+ \alpha_1x_1 + \alpha_2x_2 + \alpha_3x_3 + \alpha_4x_4 + \alpha_5x_5 + \alpha_6x_6 + \alpha_7x_7 + \alpha_8x_8$$
$$+ \alpha_{12}x_1x_2 + \alpha_{13}x_1x_3 + \alpha_{14}x_1x_4 + \alpha_{15}x_1x_5 + \alpha_{16}x_1x_6 + \alpha_{17}x_1x_7 + \alpha_{18}x_1x_8$$
$$+ \alpha_{23}x_2x_3 + \alpha_{24}x_2x_4 + \alpha_{25}x_2x_5 + \alpha_{26}x_2x_6 + \alpha_{27}x_2x_7 + \alpha_{28}x_2x_8$$
$$+ \alpha_{34}x_3x_4 + \alpha_{35}x_3x_5 + \alpha_{36}x_3x_6 + \alpha_{37}x_3x_7 + \alpha_{38}x_3x_8 \quad (2)$$
$$+ \alpha_{45}x_4x_5 + \alpha_{46}x_4x_6 + \alpha_{47}x_4x_7 + \alpha_{48}x_4x_8$$
$$+ \alpha_{56}x_5x_6 + \alpha_{57}x_5x_7 + \alpha_{58}x_5x_8$$
$$+ \alpha_{67}x_6x_7 + \alpha_{68}x_6x_8$$
$$+ \alpha_{78}x_7x_8$$

Eq. (2) provides a general modeling of the output variables, as it enables evaluating any response (Y) for any values ($x_1 \ldots x_8$) of any input variables (selected within their ranges of variations).

The evaluation of Eq. (1)'s coefficients for all the responses provides insight into the responses that best affect the physical phenomenon, i.e, the ship behavior during the IFS. Thus, among the 89 outputs, the following responses are found significant: the maximal amplitude of the Vertical Force Fz (Y_7), the time to reach Y_7 (Y_{10}), the slope of Fz during the door vertical movement (Y_{11}), the maximal amplitude of the roll moment My (Y_{15}), the time to reach Y_{15} (Y_{18}), the slope of My during the door vertical movement (Y_{19}), the time needed for each water height probe to reach its maximum for the first time, the maximum flow rate (Y_{88}), and the time to reach Y_{88} (Y_{89}).

Then, a general analysis based on FFD results is conducted to refine the model, i.e. determine the factors and interactions which effectively contribute to every response judged significant. It is found that (B, H, A, G) are the most affecting factors; then (E, F) come with a relatively less influence. C and D factors show a relatively very little influence that allows us neglect them, as well as their interactions from the model showed in Eq. (2). Moreover, the interactions between A and F, on one hand, and between B and E, on the other hand, could be neglected. Some out-of-FFD-plan tests are conducted and their results serve in validating the refined model.

Thus, the model characterizing the IFS can be written as follows.

$$Y = \alpha_0'$$
$$+ \alpha_1'.\ x_1 + \alpha_2'.\ x_2 + \alpha_5'.\ x_5 + \alpha_6'.\ x_6$$
$$+ \alpha_7'.\ x_7 + \alpha_8'.\ x_8$$

$$+ \alpha_{12}'.\ x_1x_2 + \alpha_{15}'.\ x_1x_5 + \alpha_{17}'.\ x_1x_7 + \alpha_{18}'.\ x_1x_8 + \alpha_{26}'.\ x_2x_6 + \alpha_{27}'.\ x_2x_7 + \alpha_{28}'.\ x_2x_8 + \alpha_{56}'.\ x_5x_6 + \alpha_{57}'.\ x_5x_7 + \alpha_{58}'.\ x_5x_8 + \alpha_{67}'.\ x_6x_7 + \alpha_{68}'.\ x_6x_8 + \alpha_{78}'.\ x_7x_8 \quad (3)$$

CONCLUSIONS

An experimental study is conducted to assess the transient and progressive flooding phases in the PRR02 Ro-Ro Passenger Ferry. The Design of Experiments methodology serves to plan the tests, conduct the experiments, and analyze the data. A Fractional Factorial Design is used as it allows us to determine the significant factors, as well as their interactions without ambiguity. It is worth to mention that ensuring both water and air tightness, changing some factors' levels between tests, and selecting the factors' levels and their variations' ranges are the most challenging tasks in preparing the experiments, conducting the tests, and designing the DOE plan, respectively. It is found that the IFS are mainly affected by the damage opening area, the external excitation (due to the environment and the accident), the initial draught, and the time of damage creation. A model is first built then successfully refined. It must be noted that the main objective of presenting this paper in the ISSW is to investigate and demonstrate the applicability, weaknesses and strengths of using DOE approaches in developing design formulae in the damage survivability domain. However, the authors would indicate that this study treats one particular ship, the metacentric height is not considered, and the results are based on a campaign planned as a first step in the DOE approach. These particularities clarify the perspective for further research in this domain. At last and not least, more detailed, illustrated, and further findings would be presented in the workshop, in the hope that fruitful discussions take place aiming to improve our common understanding of the damage survivability.

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