Annexes aux Règles de Classe 2019

Annexe H: Bureau Veritas report **(on the pressure generated by the liquid sloshing in a compartment – Liquid Motion Analysis)**

1. GENERAL

Present Report has been drawn up within BUREAU VERITAS (herein after called BV) Marine Division General Conditions, at the request of *IMOCA* for the benefit of *IMOCA* Class Association.
Following events at sea during which a flooded compartment of an *Open 60* (ft) yacht has lost its watertightness with respect to adjacent compartment, BV was requested by IMOCA to perform a liquid motion analysis in order to evaluate the maximum hydrodynamic forces exerted by this pre-existing water inside compartment on its round shaped doors. The liquid motion analysis assumptions are provided by *IMOCA* such as the compartment and its round shaped doors dimensions, the 3 filling levels to be studied and the deceleration magnitude order to be considered as input motion.
The aim of this report is to present from one hand the liquid motion analysis methodology used to evaluate the hydrodynamic forces acting on the compartment round shaped doors and on the other hand the numerical results for the round shaped doors strength assessment.

2. ASSUMPTIONS

The lost of watertightness of the waterproof compartment is explained due to the weakness of the round shaped doors hinges of the compartment under violent (pre-existing water) water impacts caused by strong decelerations of the *Open 60* (ft) yacht.

2.1. COMPARTMENT DIMENSIONS

The compartment and its round shaped doors dimensions were provided by *IMOCA* ([1]).

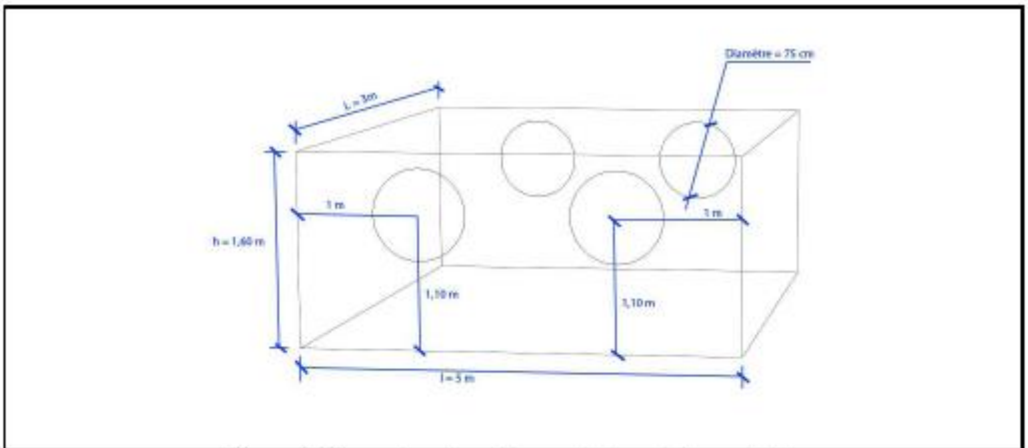

Figure 1: Compartment and its round shaped doors sketch

These dimensions are to be read as follows:
· Length of the compartment = 3.0m
· Breadth of the compartment = 5.0m
· Height of the compartment = 1.6m
· Diameter of the round shaped doors = 0.75m

2.2. FILLING LEVELS TO BE STUDIED

At the request of IMOCA ([1]), 3 fillings levels were studied:

1. h=0.5m
2. h=0.8m
3. h=1.1m

2.3. INPUT MOTIONS

In a first step, at the request of *IMOCA* ([1]), the input motions to be studied were the very strong longitudinal decelerations with 4g as order of magnitude with a duration time of approximately 0.2s ([1]).

In a second step, as the 4g longitudinal deceleration was considered severe with respect to reality, the input motions to be studied were the strong longitudinal decelerations with 1g & 2g as order of magnitude with a duration time of approximately 0.4s & 0.2s respectively ([2]).

3. LIQUID MOTION ANALYSIS

A liquid motion analysis is performed in order to evaluate the maximum hydrodynamic forces exerted by preexisting water inside the above described compartment on its round shaped doors. All the assumptions necessary to perform this liquid motion analysis are given in the previous section 2.

3.1. CFD SOFTWARE USED FOR THE LIQUID MOTION ANALYSIS

The Liquid Motion Analysis has been performed using FLOW3D® ([3]) (Flow Science), CFD software presently used in BV for its large world engineering and scientific applications and tailor-made dedicated procedures. FLOW3D® is CFD software based on Navier-Stokes equations (mass and momentum conservation), Volume of Fluid (VOF) modelling technique and Finite Volume discretization. Each cell of VOF mesh is filled with either liquid or gas and a free surface presence is defined by the corresponding fraction of fluid as the filling rate of cell by the liquid phase.

3.2. MESH OF THE COMPARTMENT

Numerical VOF mesh used for the compartment is uniform. Total number of cells of this optimized mesh is 192,000 cells (respectively 60, 100 & 32 cells for the x, y & z directions) in order to respect both size ratio criteria and accuracy of the numerical solution.
Here below is figured the compartment and its round shaped doors mesh used for the liquid motion analysis.

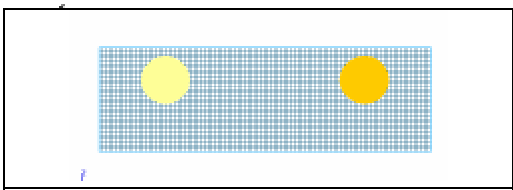
Figure 2: Compartment mesh – front view

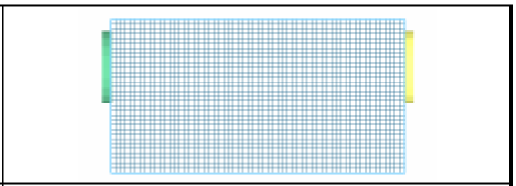
Figure 3: Compartment mesh – side view

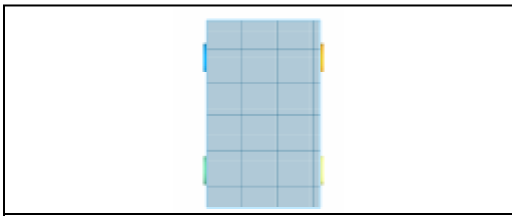
Figure 4: Compartment mesh – top view

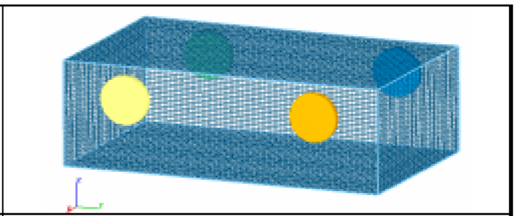
Figure 5: Compartment mesh – 3D view

3.3. INPUT MOTIONS

In a first step, even if longitudinal deceleration with 4g as order of magnitude with only the duration time of approximately 0.2s ([1]) was requested by *IMOCA*, BV decided to run more cases in order to perform a sensitivity analysis on the time duration of this deceleration. Thus for the 3 filling levels h=0.5m, h=0.8m & h=1.1m (requested by *IMOCA*) BV performed 5 calculations corresponding to the following deceleration duration:

· Dt=0.1s, deceleration with 4g as order of magnitude
· Dt=0.2s, deceleration with 4g as order of magnitude (requested by *IMOCA*)
· Dt=0.3s, deceleration with 4g as order of magnitude
· Dt=0.4s, deceleration with 4g as order of magnitude
· Dt=9.9s, deceleration with 4g as order of magnitude (asymptotic case → unrealistic case)

In a second step, as the 4g longitudinal deceleration was considered severe with respect to reality, the input motions to be studied were the strong longitudinal decelerations with 1g & 2g as order of magnitude with a duration time of approximately 0.4s & 0.2s respectively ([2]).

The fluid is at rest at t=0, then at t=0.1s is applied a deceleration with 1g, 2g & 4g as order of magnitude (depending on the case) with the above time durations as figured hereafter.

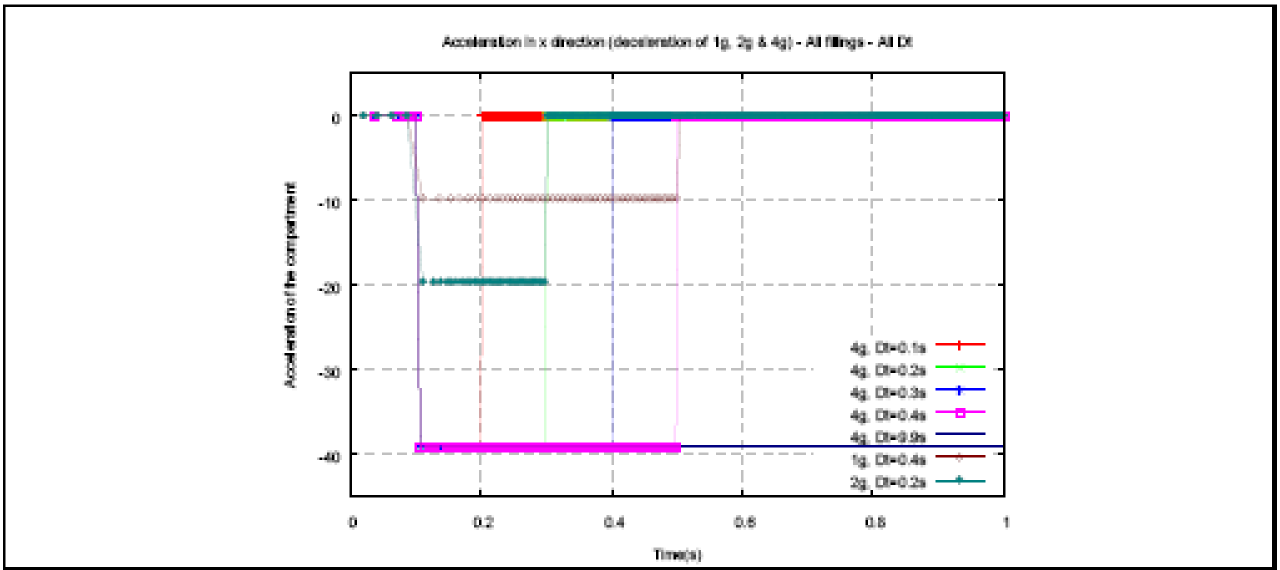

Figure 6: Acceleration of the compartment (deceleration of 4g) for the 5 tested durations

3.4. FILLING HEIGHT H=0.5M

In this section, the filling level h=0.5m is considered.

3.4.1. 4G DECELERATION

As already mentioned (see section 2.3) BV decided to perform a sensitivity analysis on the time duration of the deceleration. Thus for the filling level h=0.5m, BV performed 5 calculations corresponding to the following deceleration duration:

· Dt=0.1s, deceleration with 4g as order of magnitude
· Dt=0.2s, deceleration with 4g as order of magnitude (requested by *IMOCA*)
· Dt=0.3s, deceleration with 4g as order of magnitude
· Dt=0.4s, deceleration with 4g as order of magnitude
· Dt=9.9s, deceleration with 4g as order of magnitude (asymptotic case → unrealistic case)

Hereafter are presented some snapshots of the liquid for the deceleration duration 0.2s (as requested by *IMOCA*) for the first 0.55s of simulation.

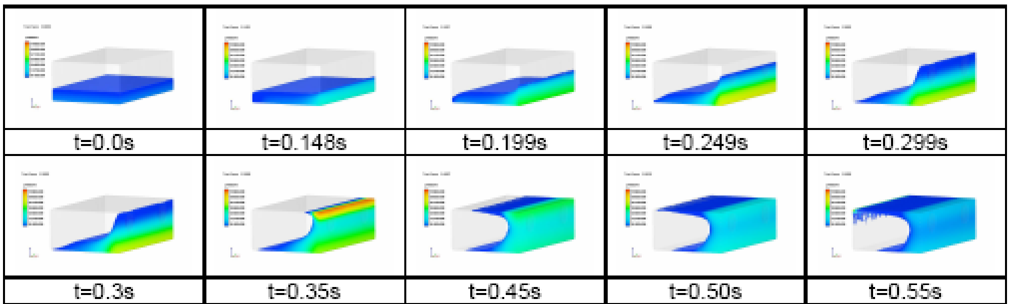

Figure 7: Snapshot of the flow for h=0.5m, Dt=0.2s for t in [0.0s:0.55s]

As we can observe on the snapshots, the flow is quasi 2D. Hence, the forces exerted by the water on the round shaped doors located on the same wall are identical.

The force (as function of the time, see section 2.3) exerted by the water inside the compartment on the most exposed round shaped door during the deceleration is figured below for the 5 different duration times:

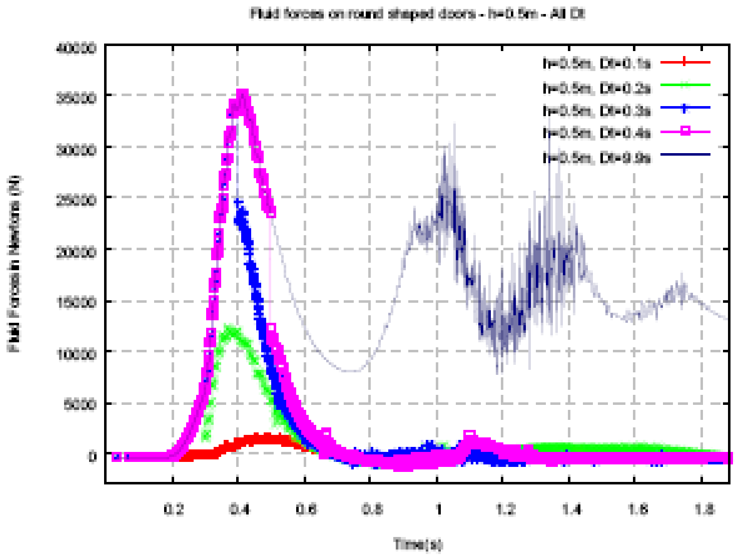

Figure 8: Zoom of the fluid forces exerted on the most exposed round shaped door for h=0.5m

As already mentioned, the fluid force exerted by the water on the round shaped door located on the same wall is identical as this one depicted above (Figure 8).

As we can see, the fluid force increases with the duration of the deceleration till Dt ≈ 0.3s. For deceleration duration times greater than 0.3s (see Dt=0.4s and Dt=9.9s referred here as asymptotic case), **the maximum fluid force exerted by the fluid on the most exposed round shaped door remains identical and equals to 35160 Newtons for h=0.5m.**

For the asymptotic case (long duration for deceleration, Dt=9.9s), the fluid force converges towards a limit which corresponds to the hydrostatic pressure which can be easily calculated by taking into account a modified gravity as follows: $\vec{g}_{eq} = -g\vec{k} + 4g\vec{i}$ where $(\vec{i}, \vec{j}, \vec{k})$ are the unit vectors of the Galilean reference frame.

As the round shaped door surface is equal to 0.442 m² (= $\pi.R^2$), the maximum equivalent pressure acting on the door is equal to:

$$P_{eq} = \frac{F}{S} = \frac{35160}{0.442} \approx 80000\ Pa = 0.8\ bar$$

3.4.2. 1G & 2G DECELERATION

In a second step, as the 4g longitudinal deceleration was considered severe with respect to reality, the input motions to be studied were the strong longitudinal decelerations with 1g & 2g as order of magnitude with a duration time of approximately 0.4s & 0.2s respectively ([2]) as follows:

· Dt=0.4s, deceleration with 1g as order of magnitude (requested by *IMOCA*)

· Dt=0.2s, deceleration with 2g as order of magnitude (requested by *IMOCA*)

Hereafter are presented some snapshots of the liquid for the deceleration duration 0.2s for the first 0.55s of simulation.

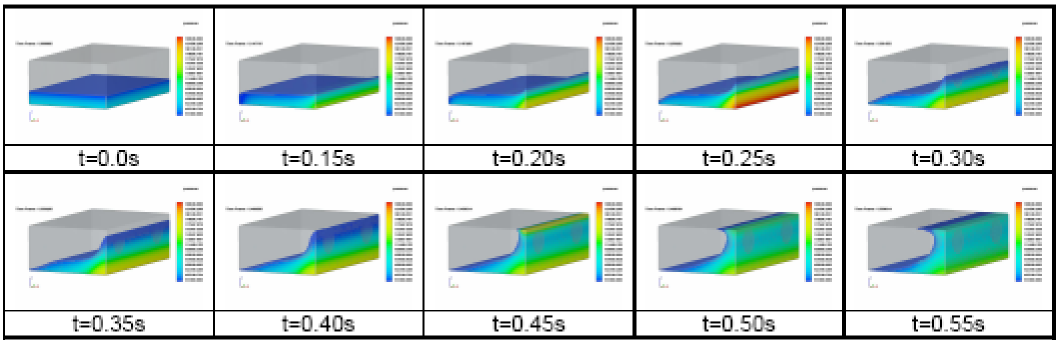

Figure 9: Snapshot of the flow for h=0.5m, Dt=0.2s for t in [0.0s:0.55s]

As we can observe on the snapshots, the flow is quasi 2D. Hence, the forces exerted by the water on the round shaped doors located on the same wall are identical.

The force (as function of the time, see section 2.3) exerted by the water inside the compartment on the most exposed round shaped door during the deceleration is figured below for the 2 cases:

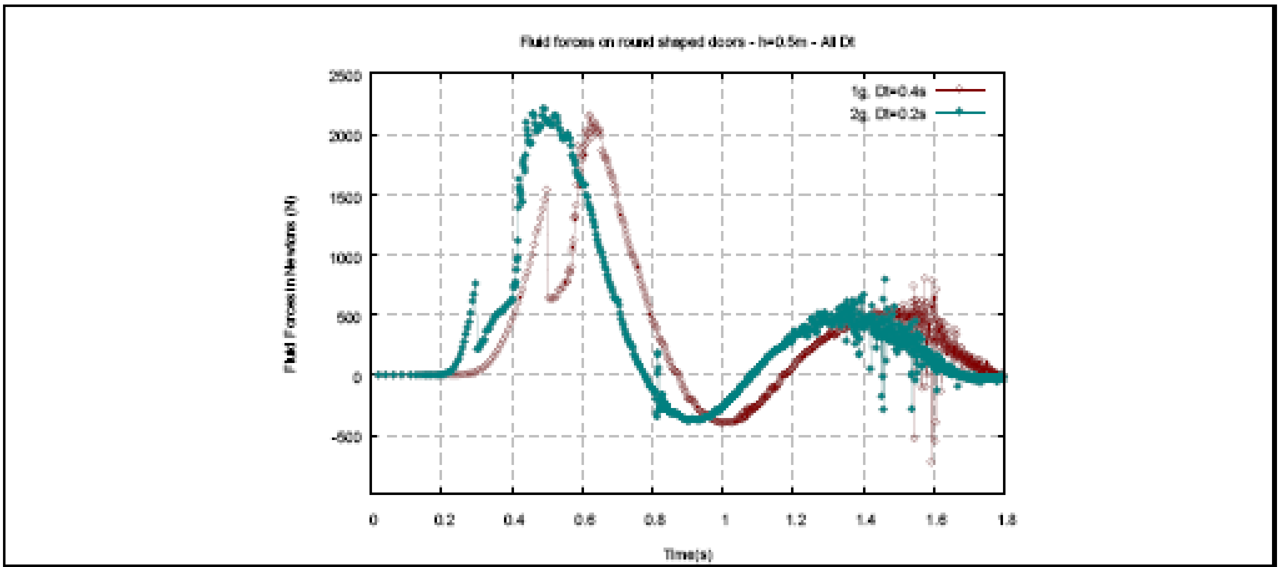

Figure 10: Zoom of the fluid forces exerted on the most exposed round shaped door for h=0.5m

As already mentioned, the fluid force exerted by the water on the round shaped door located on the same wall is identical as this one depicted above (Figure 10).

The maximum fluid force exerted by the fluid on the most exposed round shaped door equals to 2210 Newtons for h=0.5m.

As the round shaped door surface is equal to 0.442 m² (= $\pi.R^2$), the maximum equivalent pressure acting on the door is equal to:

$$P_{eq} = \frac{F}{S} = \frac{2210}{0.442} \approx 5000 \text{ Pa} = 0.05 \text{ bar}$$

3.5. FILLING HEIGHT H=0.8M

In this section, the filling level h=0.8m is considered.

3.5.1. 4G DECELERATION

In this section, the filling level h=0.8m is considered. As already mentioned (see section 2.3) BV decided to perform a sensitivity analysis on the time duration of the deceleration. Thus for the filling level h=0.8m, BV performed 5 calculations corresponding to the following deceleration duration:

· Dt=0.1s, deceleration with 4g as order of magnitude
· Dt=0.2s, deceleration with 4g as order of magnitude (requested by *IMOCA*)
· Dt=0.3s, deceleration with 4g as order of magnitude
· Dt=0.4s, deceleration with 4g as order of magnitude
· Dt=9.9s, deceleration with 4g as order of magnitude (asymptotic case → unrealistic case)

Hereafter are presented some snapshots of the liquid for the deceleration duration 0.2s (as requested by *IMOCA*) for the first 0.55s of simulation.

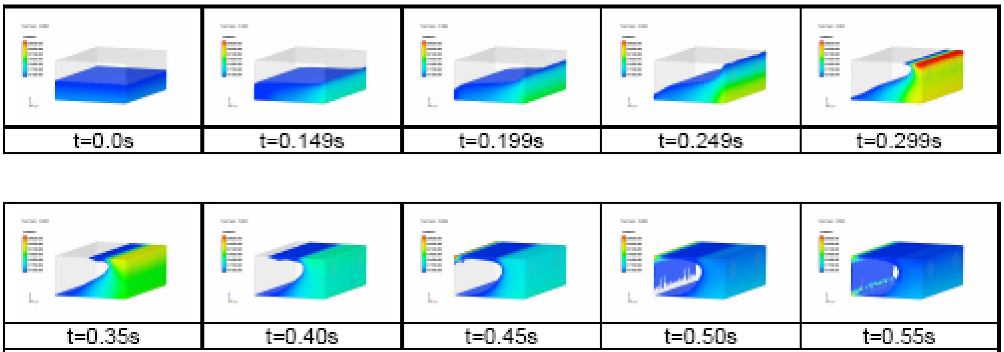

Figure 11: Snapshot of the flow for h=0.8m, Dt=0.2s for t in [0.0s:0.55s]

As we can observe on the snapshots, the flow is quasi 2D. Hence, the forces exerted by the water on the round shaped doors located on the same wall are identical.

The force (as function of the time, see section 2.3) exerted by the water inside the compartment on the most exposed round shaped door during the deceleration is figured below for the 5 different duration times:

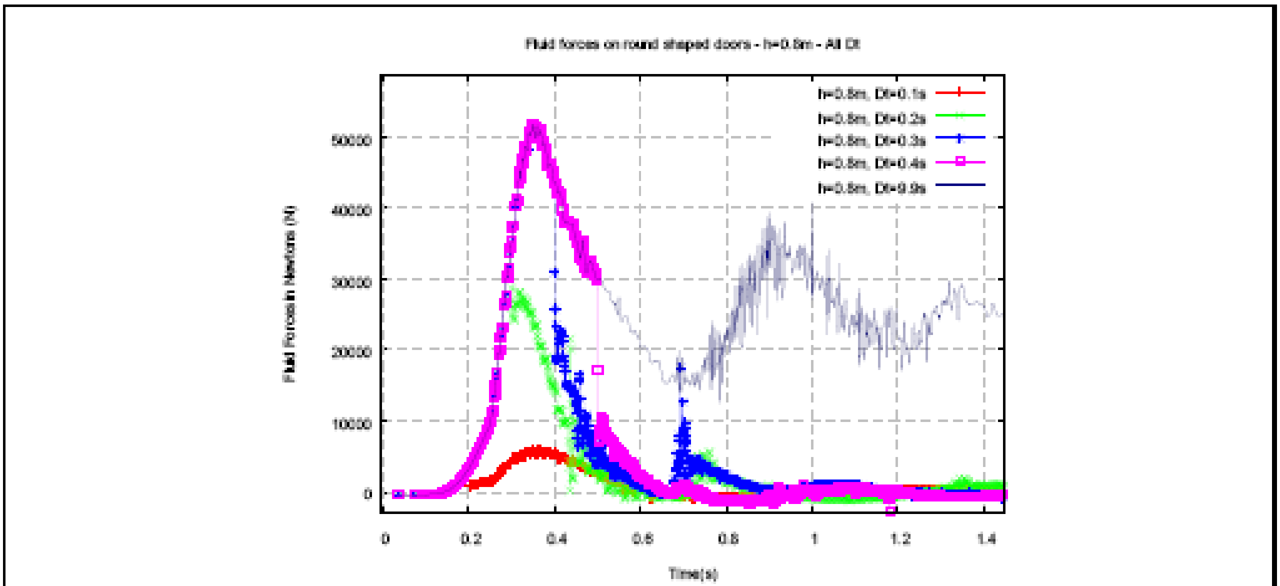

Figure 12: Zoom of the fluid forces exerted on the most exposed round shaped door for h=0.8m

As already mentioned, the fluid force exerted by the water on the round shaped door located on the same wall is identical as this one depicted above (Figure 12).

As we can see, the fluid force increases with the duration of the deceleration till Dt between 0.2s and 0.3s. For deceleration duration times greater than 0.3s (see Dt=0.4s and Dt=9.9s referred here as asymptotic case), **the maximum fluid force exerted by the fluid on the most exposed round shaped door remains identical and equals to 51800 Newtons for h=0.8m.**

As already mentioned, for the asymptotic case (long duration for deceleration, Dt=9.9s), the fluid force converges towards a limit which corresponds to the hydrostatic pressure which can be easily calculated by

$\vec{g}_{eq} = -g\vec{k} + 4g\vec{i}$ $\quad (\vec{i}, \vec{j}, \vec{k})$

taking into account a modified gravity as follows where are the unit vectors of the Galilean reference frame.

As the round shaped door surface is equal to 0.442 m² (= $\pi.R^2$), the maximum equivalent pressure acting on the door is equal to:

$$P_{eq} = \frac{F}{S} = \frac{51800}{0.442} \approx 118000 \text{ Pa} = 1.18 \text{ bar}$$

3.5.2. 1G & 2G DECELERATION

In a second step, as the 4g longitudinal deceleration was considered severe with respect to reality, the input motions to be studied were the strong longitudinal decelerations with 1g & 2g as order of magnitude with a duration time of approximately 0.4s & 0.2s respectively ([2]) as follows:

· Dt=0.4s, deceleration with 1g as order of magnitude (requested by *IMOCA*)
· Dt=0.2s, deceleration with 2g as order of magnitude (requested by *IMOCA*)

Hereafter are presented some snapshots of the liquid for the deceleration duration 0.4s for the first 0.55s of simulation.

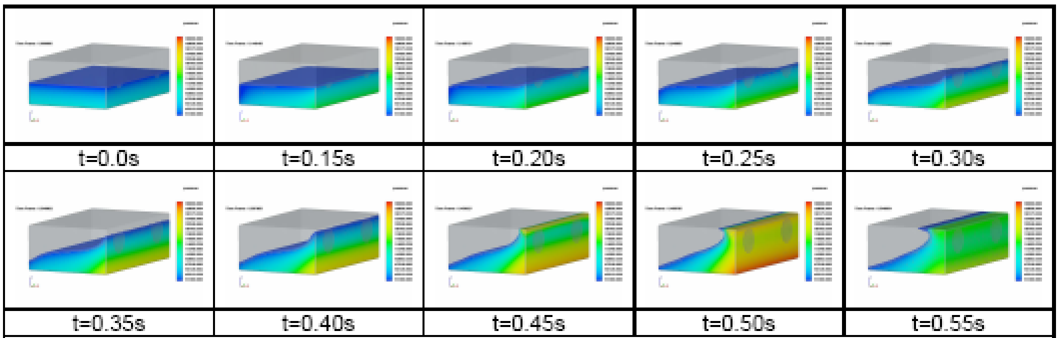

Figure 13: Snapshot of the flow for h=0.8m, Dt=0.1s for t in [0.0s:0.55s]

As we can observe on the snapshots, the flow is quasi 2D. Hence, the forces exerted by the water on the round shaped doors located on the same wall are identical.

The force (as function of the time, see section 2.3) exerted by the water inside the compartment on the most exposed round shaped door during the deceleration is figured below for the 2 cases:

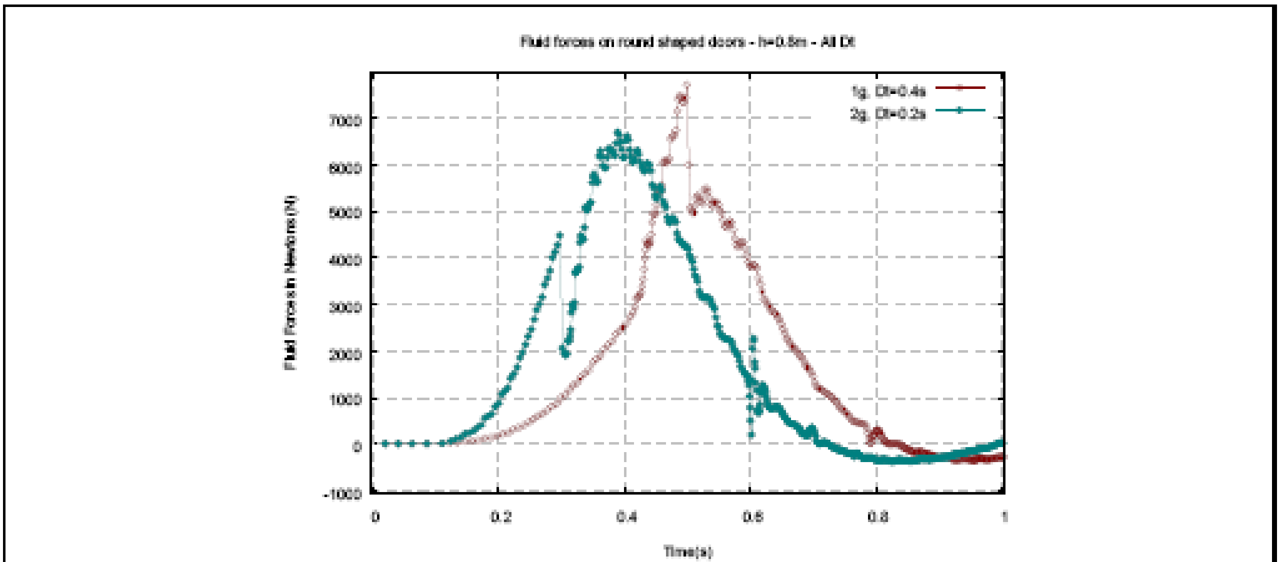

Figure 14: Zoom of the fluid forces exerted on the most exposed round shaped door for h=0.8m

The maximum fluid force exerted by the fluid on the most exposed round shaped door equals to 7700Newtons for h=0.8m.

As the round shaped door surface is equal to 0.442 m² (= $\pi.R^2$), the maximum equivalent pressure acting on the door is equal to:

$$P_{eq} = \frac{F}{S} = \frac{7700}{0.442} \approx 17420 \text{ Pa} = 0.17 \text{ bar}$$

3.6. FILLING HEIGHT H=1.1M

In this section, the filling level h=1.1m is considered.

3.6.1. 4G DECELERATION

In this section, the filling level h=1.1m is considered. As already mentioned (see section 2.3) BV decided to perform a sensitivity analysis on the time duration of the deceleration. Thus for the filling level h=1.1m, BVperformed 5 calculations corresponding to the following deceleration duration:

· Dt=0.1s, deceleration with 4g as order of magnitude
· Dt=0.2s, deceleration with 4g as order of magnitude (requested by *IMOCA*)
· Dt=0.3s, deceleration with 4g as order of magnitude
· Dt=0.4s, deceleration with 4g as order of magnitude
· Dt=9.9s, deceleration with 4g as order of magnitude (asymptotic case → unrealistic case)

Hereafter are presented some snapshots of the liquid for the deceleration duration 0.2s (as requested by *IMOCA*) for the first 0.55s of simulation.

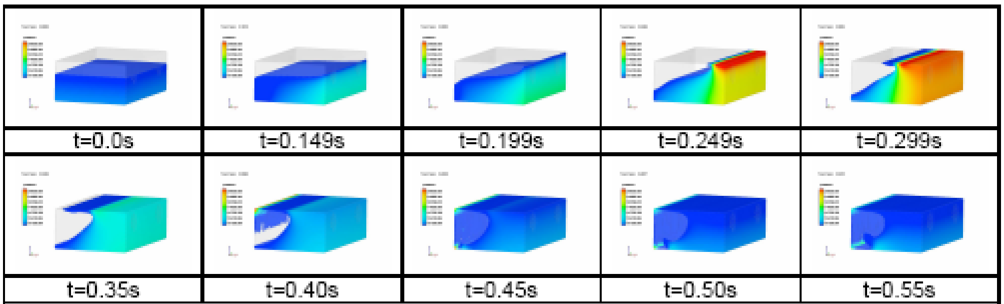

Figure 15: Snapshot of the flow for h=1.1m, Dt=0.2s for t in [0.0s:0.55s]

As we can observe on the snapshots, the flow is quasi 2D. Hence, the forces exerted by the water on the round shaped doors located on the same wall are identical.

The force (as function of the time, see section 2.3) exerted by the water inside the compartment on the most exposed round shaped door during the deceleration is figured below for the 5 different duration times:

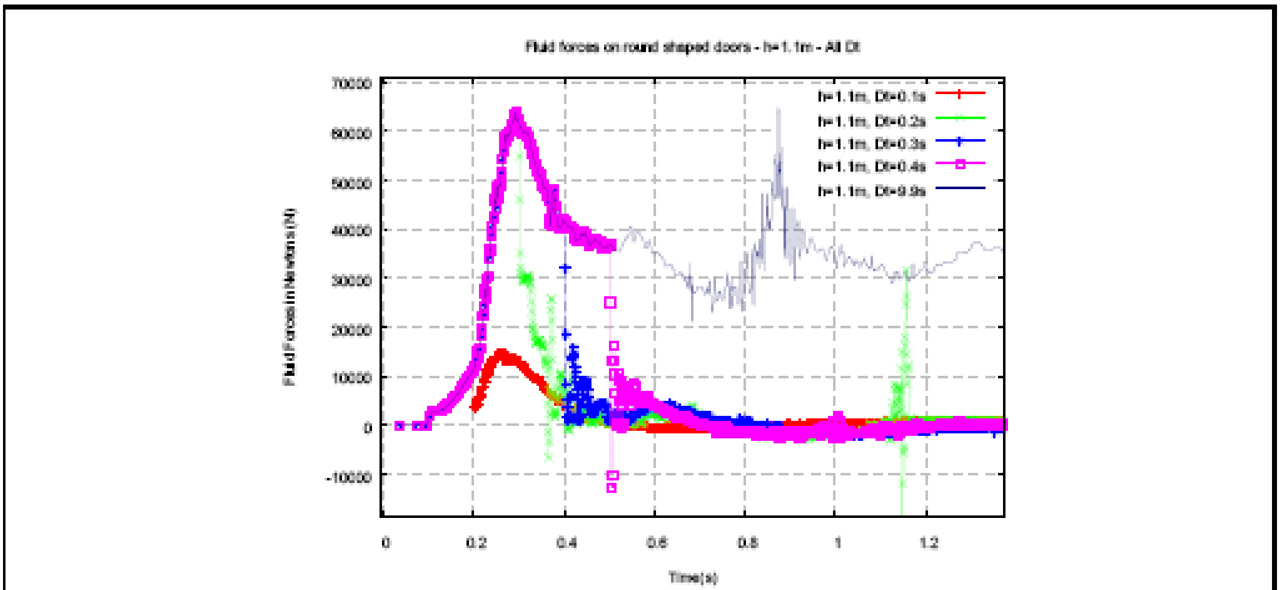

Figure 16: Zoom of the fluid forces exerted on the most exposed round shaped door for h=1.1m

As already mentioned, the fluid force exerted by the water on the round shaped door located on the same wall is identical as this one depicted above (Figure 12).

As we can see, the fluid force increases with the duration of the deceleration till Dt ≈0.2s. For deceleration duration times greater than 0.2s (see Dt=0.3s, 0.4s and Dt=9.9s referred here as asymptotic case), **the maximum**

fluid force exerted by the fluid on the most exposed round shaped door remains identical and equals to 63680 Newtons for h=1.1m.

As already mentioned, for the asymptotic case (long duration for deceleration, Dt=9.9s), the fluid force converges towards a limit which corresponds to the hydrostatic pressure which can be easily calculated by taking into account a modified gravity as follows $\vec{g_{eq}} = -g\vec{k} + 4g\vec{i}$ where $(\vec{i}, \vec{j}, \vec{k})$ are the unit vectors of the Galilean reference frame.

As the round shaped door surface is equal to 0.442 m² (= $\pi . R^2$), the maximum equivalent pressure acting on the door is equal to:

$$P_{eq} = \frac{F}{S} = \frac{63680}{0.442} \approx 144100 \text{ Pa} = 1.44 \text{ bar}$$

3.6.2. 1G & 2G DECELERATION

In a second step, as the 4g longitudinal deceleration was considered severe with respect to reality, the input motions to be studied were the strong longitudinal decelerations with 1g & 2g as order of magnitude with a duration time of approximâtely 0.4s & 0.2s respectively ([2]) as follows:

· Dt=0.4s, deceleration with 1g as order of magnitude (requested by *IMOCA*)
· Dt=0.2s, deceleration with 2g as order of magnitude (requested by *IMOCA*)

Hereafter are presented some snapshots of the liquid for the deceleration duration 0.2s for the first 0.55s of simulation.

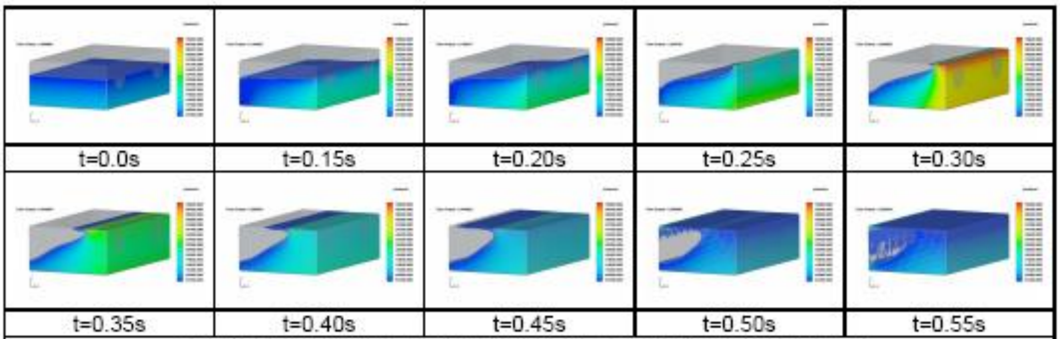

Figure 17: Snapshot of the flow for h=1.1m, Dt=0.2s for t in [0.0s:0.55s]

As we can observe on the snapshots, the flow is quasi 2D. Hence, the forces exerted by the water on the round shaped doors located on the same wall are identical.

The force (as function of the time, see section 2.3) exerted by the water inside the compartment on the most exposed round shaped door during the deceleration is figured below for the 2 cases:

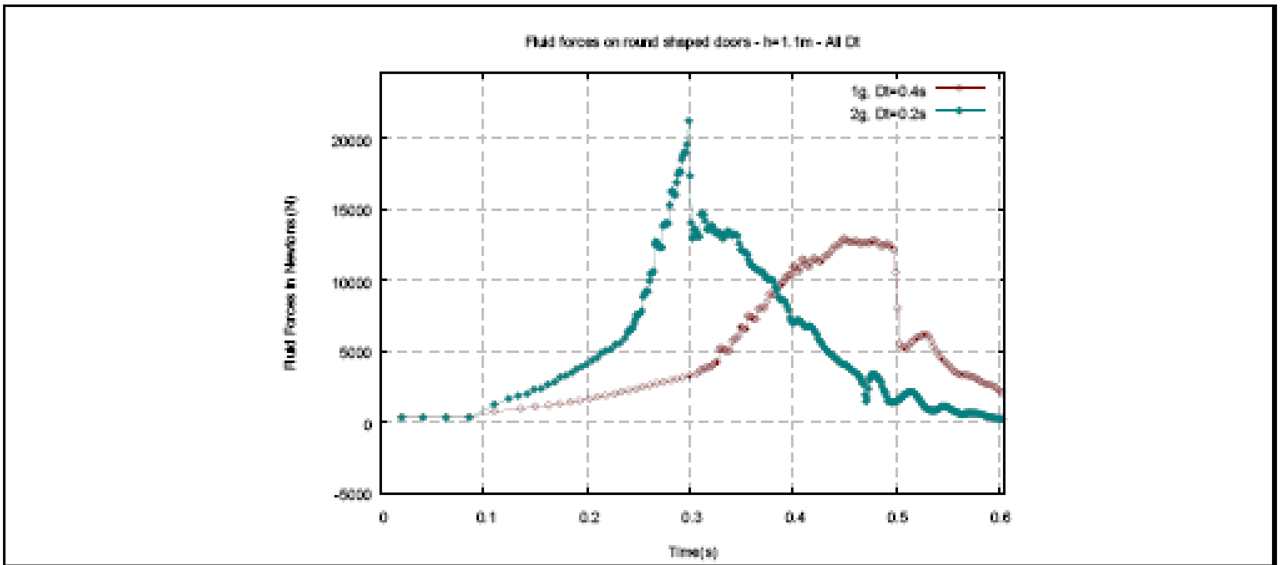

Figure 18: Zoom of the fluid forces exerted on the most exposed round shaped door for h=1.1m

The maximum fluid force exerted by the fluid on the most exposed round shaped door remains identical and equals to 21200 Newtons for h=1.1m.

As the round shaped door surface is equal to 0.442 m2 (= $\pi.R^2$), the maximum equivalent pressure acting on the door is equal to:

$$P_{eq} = \frac{F}{S} = \frac{21200}{0.442} \approx 50000 \text{ Pa} = 0.5 \text{ bar}$$

3.7. MAXIMUM FORCE ON THE TRANSVERSE WALL

As shown on the figure 15, the maximum force exerted by the fluid on the compartment's transverse wall is equal to:

$F_{max} = p_{eq} * S = 1.3 * 101300 * 5 * 1.6 = 1053520$ *(Newtons)*

This maximum fluid force (exerted by the fluid on the compartment's transverse wall) is obtained for the fluid height h=1.1m, a 4g longitudinal deceleration and for Dt=0.2s. It corresponds to a uniform pressure acting on the compartment's transverse wall equal to 1.3 bars.

3.8. RESULTS SYNTHESIS

Putting together all the results obtained for h=0.5m, 0.8m and 1.1m (see sections 3.4, 3.5 & 3.6), the maximum fluid forces obtained on the most exposed round shaped door are summed up in the following table:

Force in Newtons (N)	h=0.5m	h=0.8m	h=1.1m
4g, Dt=0.1s	1 515	5862	14 800
4g, Dt=0.2s	12 346	34 654	63 680
4g, Dt=0.3s	34 270	51 800	63 680
4g, Dt=0.4s	35159	51 800	63 680
4g, Dt=9.9s	35159	51 800	63 680
1g, Dt=0.4s	2 155	7 696	12 906
2g, Dt=0.2s	2 211	6 686	21 200

So the maximum force fluid force obtained on the most exposed round shaped door is equal to 63800 Newtons obtained for h=1.1m, a 4g longitudinal deceleration and for a deceleration time Dt=0.2s.

For 1g & 2g longitudinal decelerations, the maximum force fluid force obtained on the most exposed round shaped door is equal to 21200 Newtons obtained for h=1.1m and for a deceleration time Dt=0.2s.

4. CONCLUSION

The maximum force fluid force obtained on the most exposed round shaped door is equal to 63800 Newtons obtained for h=1.1m, a 4g longitudinal deceleration and for a deceleration time Dt=0.2s. It corresponds to a uniform pressure acting on this round shaped door equal to 1.44 bars.

For 1g & 2g longitudinal decelerations, the maximum force fluid force obtained on the most exposed round shaped door is equal to 21200 Newtons obtained for h=1.1m, a 2g longitudinal deceleration and for a deceleration time Dt=0.2s.

The maximum force exerted by the fluid on the compartment's transverse wall is equal to 1050000 Newtons for a fluid height equal to h=1.1m and for Dt=0.2s. It corresponds to a uniform pressure acting on the compartment's transverse wall equal to 1.3 bars.

REFERENCES

DOCUMENTS:

[1] “Cahier des charges de calculs de pression d’eau dans un compartiment de bateau *IMOCA* ”, *IMOCA* email sent to BV on the 22 February 2010.
[2] “*IMOCA* Sloshing”, *IMOCA* e-mail sent to BV on the 18 March 2010.

SOFTWARE:

[3] FLOW3D®, v.9.4 (Flow Science)