

MITIGATION OF SLOSHING IN AN UPRIGHT CIRCULAR CYLINDRICAL ROCKET PROPELLANT TANK BY A FLOATING BAFFLE

T. Pugazhendhi*, M. Anand*, M. Hemanathan*, S. Shwetaa Raaj*, K. Vijaya Sankaran**, G. Sriram**#,
A. P. Haran* and J.J. Isaac*

Abstract:

During a rocket's ascent phase, sloshing of propellants in its fuel tanks can lead to serious trajectory control problems because the sloshing natural frequencies are close to the controller frequencies and this likely instability is compounded by the large propellant masses involved. Slosh damping devices in the form of fixed ring baffles attached to the propellant tank wall, in a laddered manner, or insertion of longitudinal baffles effectively compartmentalizing the tank and consequently shifting the slosh natural frequencies away have both been attempted. However, both these methods suffer a fall in effectiveness as the propellant levels fall due to fuel consumption leaving some of the baffles dry. It is known that the main sloshing takes place essentially only near the top of the propellant liquid mass. Hence, an appropriate floating baffle has been conceptually developed which would always be effective regardless of the propellant level. A computational and experimental study of sloshing and its corresponding damping by an appropriate floating baffle in an upright circular cylindrical tank is presented.

Introduction:

The influence of slosh dynamics on fluid structure interaction in the propellant tank of an ascending rocket is vital to avoid likely non-controllability and destruction of the total vehicle since the slosh frequencies are fairly close to the flight controller frequency. Mitigation of the deleterious effects of sloshing can be achieved by introducing propellant damping devices in the form of ring baffles or by shifting the fundamental natural frequency through compartmentalizing. However, flexible or rigid wall mounted ring baffles progressively become ineffective as the propellant levels fall due to consumption leaving the rings exposed. There is also an associated weight penalty.

It has been experimentally observed that baffles fitted just below the liquid free surface are very effective in reducing sloshing (Refs 1, 2). Foams have been found to be good candidates for slosh damping but they suffer a key disadvantage-they can be sucked into the rocket chamber (Ref 3).

Hence, it is clear that a floating baffle would be able to provide adequate damping regardless of the propellant level. From symmetry and a damping perspective, the baffle needs to be of a ring type so that vortex shedding and the consequent viscous damping of the sloshing fluid could take place from both the inner and outer edges of the ring. The degree of submersion of the ring and the ring blockage could also play a significant role in providing damping. The configuration of the floating baffle needs to be derived along with its corresponding

Keywords: Sloshing, Propellant tank, Damping, Baffles, CFD.

* PARK College of Engineering and Technology, Coimbatore, Tamil Nadu

** VESRAD Technologies Pvt. Ltd, Kalpakkam, Tamil Nadu

Corresponding author: email; < gsriram@vesrad.in >

damping characteristics. A computational and experimental study of sloshing in an upright cylindrical tank has been carried out in order to evolve a conceptual design and investigate the damping effectiveness of the floating baffle.

Computational:

CFD can be effectively used to provide an accurate description of slosh dynamics. 3D numerical simulations using ANSYS FLUENT 14 were carried out after performing the necessary mesh convergence studies. An unsteady pressure based solver was used along with the "Volume of Fluid" (VOF) model. Air and water (simulated propellant) were specified for the two phases and a realizable $k-\epsilon$ model was employed to capture the turbulent sloshing motion (Figs 1a, 1b).

Experimental:

The corresponding experimental set ups are shown in (Figs 2a, b, c). Table 1 gives details of the ring baffles chosen, all of which had the same blockage relative to the cylinder inner circular area. Since it was surmised that the damping effectiveness of a ring baffle could be essentially due to vortex shedding from its inner and/or outer edges, baffle type 1 was chosen to have vortex shedding from both its inner and outer edges, baffle type 2 only from the outer edge and baffle type 3, essentially only from the inner edge. To provide for propellant drainage, all baffle designs specify some gap between the baffle and the tank wall. By choosing the effective density of the baffle (by appropriate internal weighting), the baffle could be made to float with varying submersion levels. The baffles were constrained by rods to move only in directions parallel to the cylinder wall so as to prevent baffle tilt during the violent sloshing motion (Figs 2b, 2c). Controlled sloshing was initiated by providing an angular impulse to the circular cylindrical tank by a method specially developed for experiments in a academic environment, avoiding the use of an expensive shake table (Figs 2a, 2b) (Ref.4) . The first sloshing natural frequency without a floating annular baffle was determined for various fill fractions (ratio of liquid height to cylinder height). Fig 3 shows that the frequencies (~ 2 Hz) are reasonably constant over the fill fraction range, indicating that a floating baffle could be effective. The analytical prediction was done using a method given by Housner (Ref.5).

Discussions:

From Fig.3, it is seen that there is good agreement between the experiments, computational and analytical predictions showing that the experimental and computational techniques are in order. The corresponding time lapsed views of the sloshing motion without a floating annular baffle are shown in (Figs 4a, 4b) for the experimental and computational studies respectively.

The annular baffles (details shown in Fig.2c and Table 1) were introduced and the modified sloshing motion was studied. The sloshing motion was rapidly damped even with partial submersion (Fig.5). The corresponding time lapsed views (experimental, computational) of the sloshing motion are shown in (Figs 6a, 6b) in the presence of an annular floating baffle. It is surmised that the rapid damping action by a floating annular baffle could be due to

viscous dissipation of annular vortices at both the inner and outer edges of the baffle. Fig.7 shows the expected formation of the vortices at the inner and/or outer edges of the ring baffles. The viscous dissipation of the vortical flow could lead to very effective damping of the sloshing fluid and this is what is seen in practice (Figs 5, 8, 9). The ‘not submerged’ conditions in Figs 9a, 9b refer to case where the baffles were floating on the liquid surface. Fig 8a shows that the (computed) damping is more effective if there is vortex shedding from both the inner and outer edges of the baffle. However, this effect does not clearly show up in the experimental studies – all baffles were very effective dampers (Fig 8b, 9b). The constraining effect of the rods should not be discounted. Figs 8b, 9b for the experimental studies show that the degree of submersion is not significant for damping effectiveness.

Concluding remarks:

The conceptual design of an annular floating baffle has been proposed and shown to be very effective in damping sloshing motion. The configurations which give high damping have been identified.

References:

1. Stephen, DG and Scholl, HP, Effectiveness of flexible and rigid ring baffles for damping liquid oscillations in large-scale cylindrical tanks, NASA TND-3878, 1967.
2. Stephen DG et al., Investigation of the damping of liquids in a right circular cylindrical tank, including the effects of a time variant liquid depth, NASA TND 1367, July 1962.
3. Sauret, A., et al., Damping of liquid sloshing by foam, Physics of Fluids, 27, pp 022103, 2015.
4. Abinesh, R et al., SLOSH dynamics of a liquid in a rectangular tank: Simplified mechanical analogy to oscillation of a liquid in a U-Tube, Proceedings 7th International and 45th National Conference, Fluid Mechanics and Fluid Power (FMFP) Dec 2018, IIT, Bombay.
5. Housner G. W., 'Dynamic pressures on accelerated fluid containers'. Bulletin Seism.Soc. America, Vol.47, No.1, pp.15-35, 1957.

Table.1. Different types of ring baffles and their dimensions.

S.NO	BAFFLE TYPE	OUTER DIAMETER (D _o) mm	INNER DIAMETER (D _i) mm	THICKNESS (B) mm
1	BAFFLE TYPE 1	140	70	15
2	BAFFLE TYPE 2	120	NIL	15
3	BAFFLE TYPE 3	165	110	15

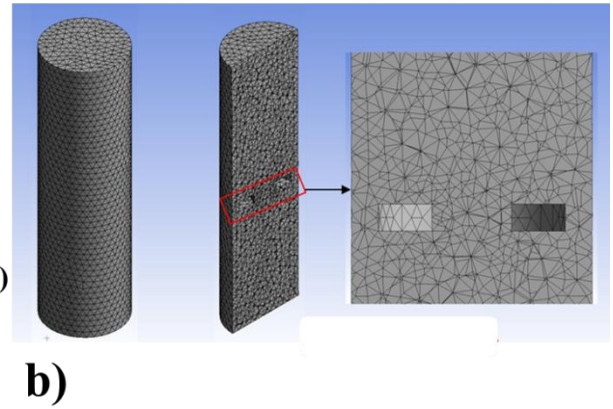
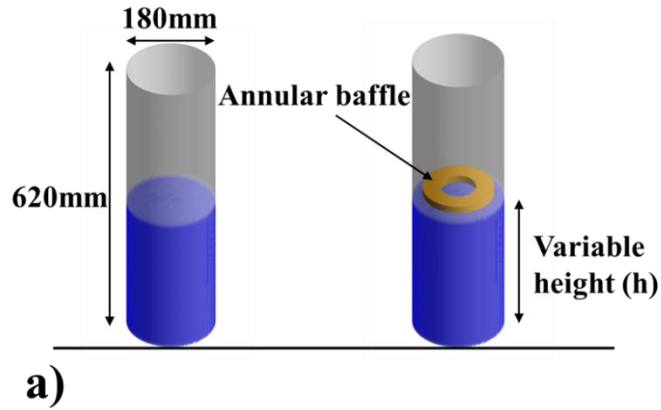


Fig.1a. Computational model of an upright circular cylindrical tank with and without an annular floating baffle.

Fig.1b. Discretization of an upright circular cylindrical tank with and without an annular floating baffle.

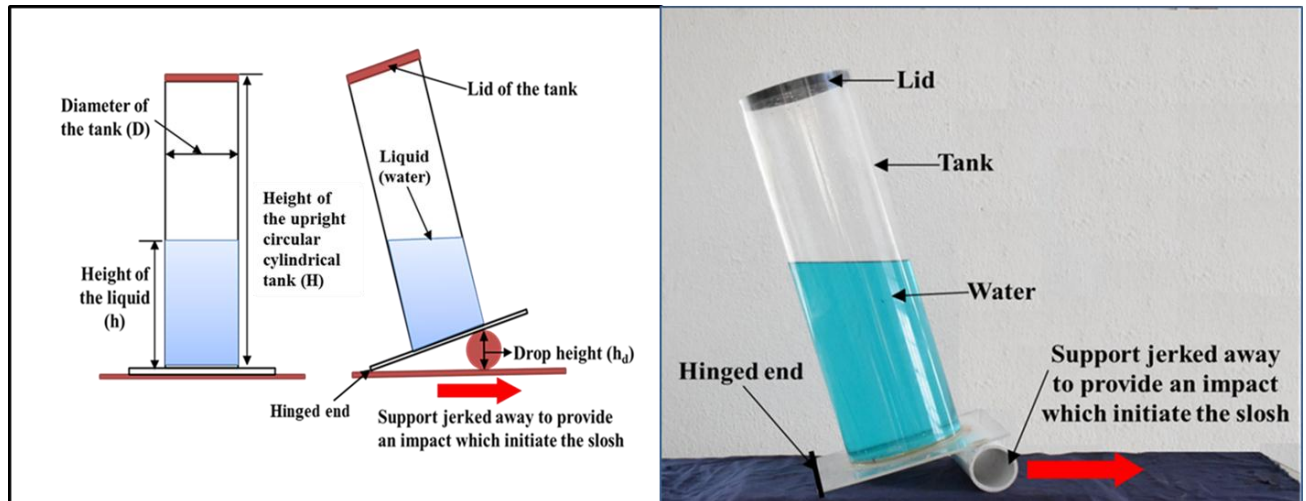
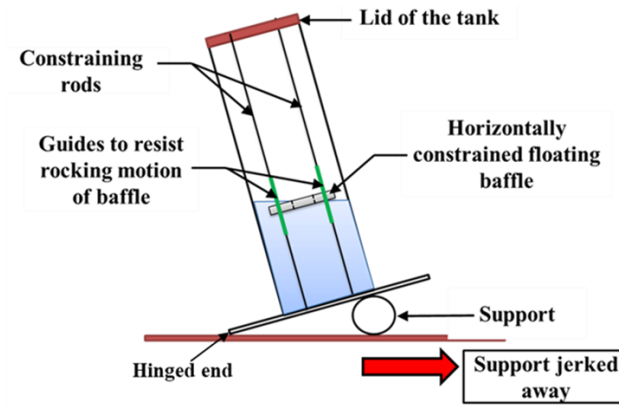
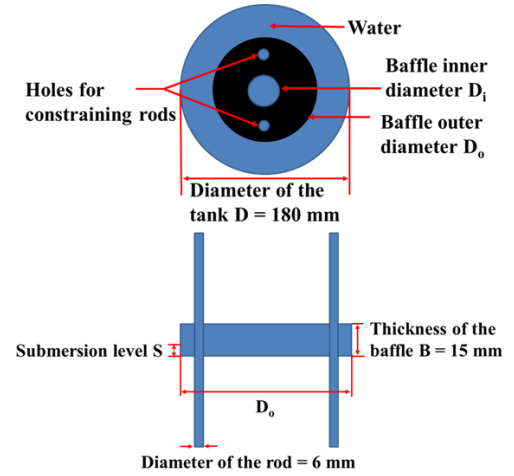


Fig.2a. Schematic and experimental setup for an upright circular cylindrical tank without a baffle.



b)

Fig.2b. Schematic of the setup with an annular baffle.



c)

Fig.2c. Schematic of the top and side views of constrained annular baffle floating in water.

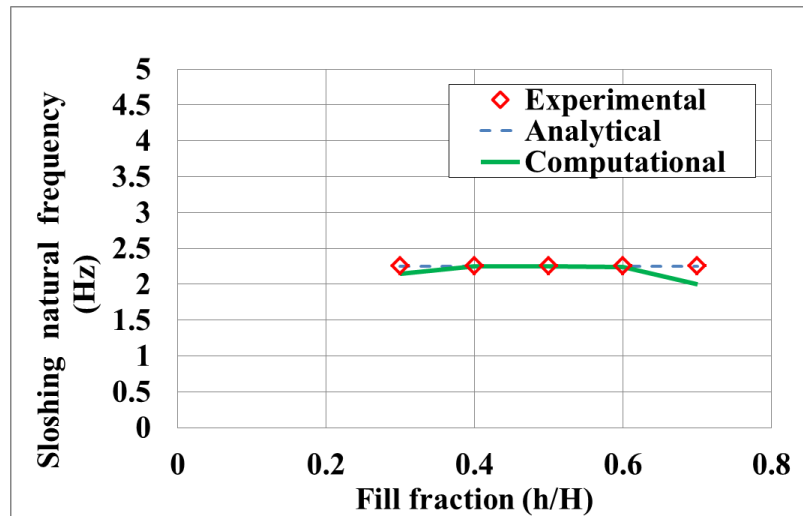
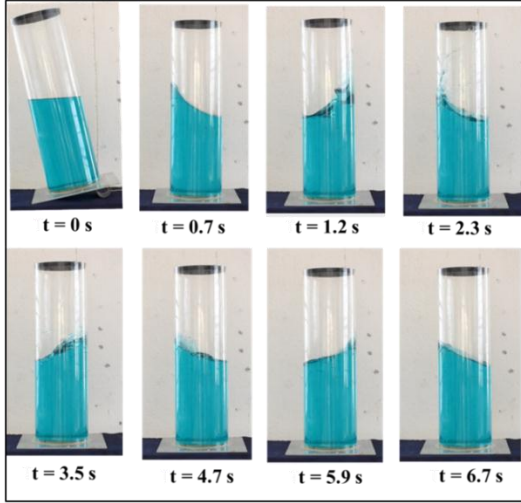
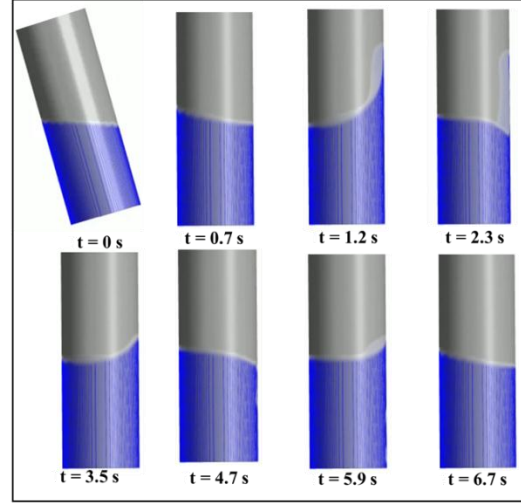


Fig.3. Variation of sloshing natural frequency with fill fraction (circular cylindrical tank partially filled with water) with slosh initiated by an impulse due to a fall of the platform through $h_d = 0.06\text{m}$ (Fig.2a).



a)

Fig.4a. Time lapsed sloshing motion without an annular floating baffle (Experimental; Fill fraction = 0.5).



b)

Fig.4b. Time lapsed sloshing motion without an annular floating baffle (Computational; Fill fraction=0.5).

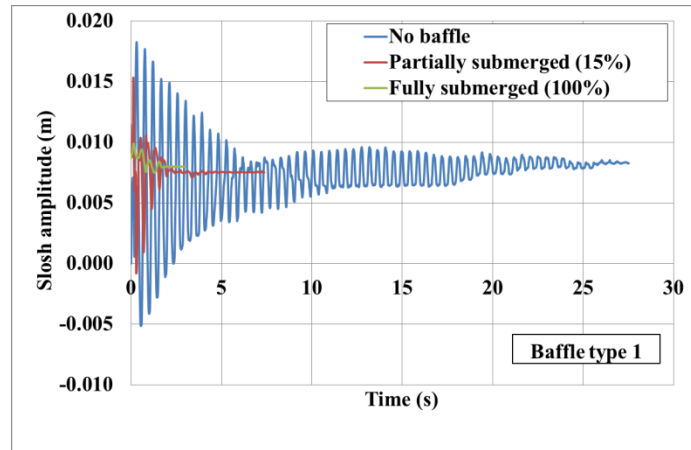
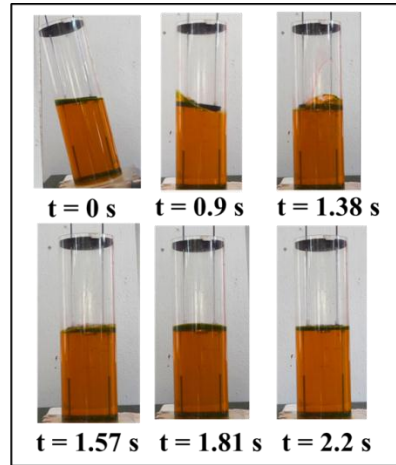
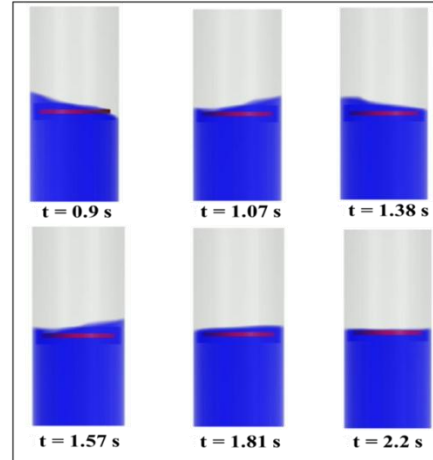


Fig.5. Experimental decay of slosh amplitude in an upright circular cylindrical tank (tank partially filled with water, with and without a constrained annular baffle) with slosh initiated by an impulse due to a fall of the platform through $h_d = 0.06\text{m}$ (Fig.2a).



a)



b)

Fig.6a. Time lapsed sloshing motion with an annular floating baffle (Baffle type 1; Fully submerged; Experimental; Fill fraction = 0.5).

Fig.6b. Time lapsed sloshing motion with an annular floating baffle (Baffle type 1; Fully submerged; Computational; Fill fraction = 0.5).

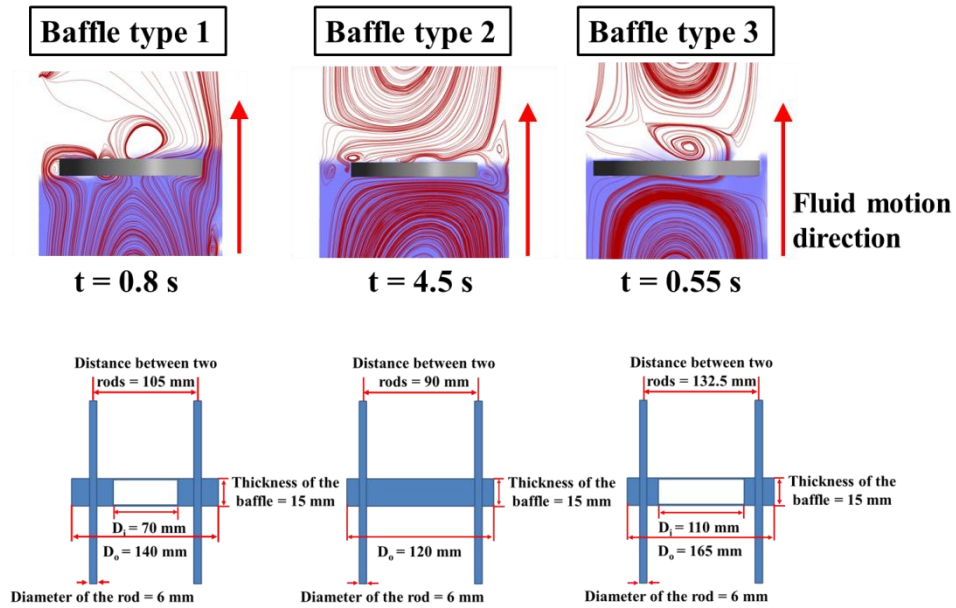


Fig.7. Computed streamlines of the flow past different types of baffles under fully submerged conditions.

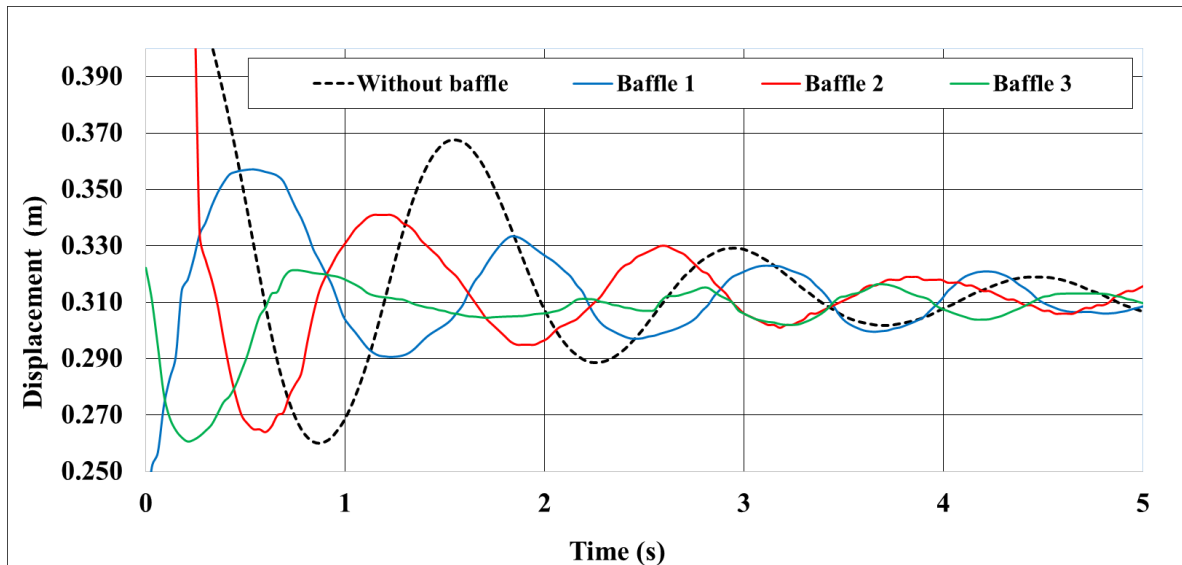


Fig.8a. Comparison of three different types of baffles in fully submerged condition (Computational).

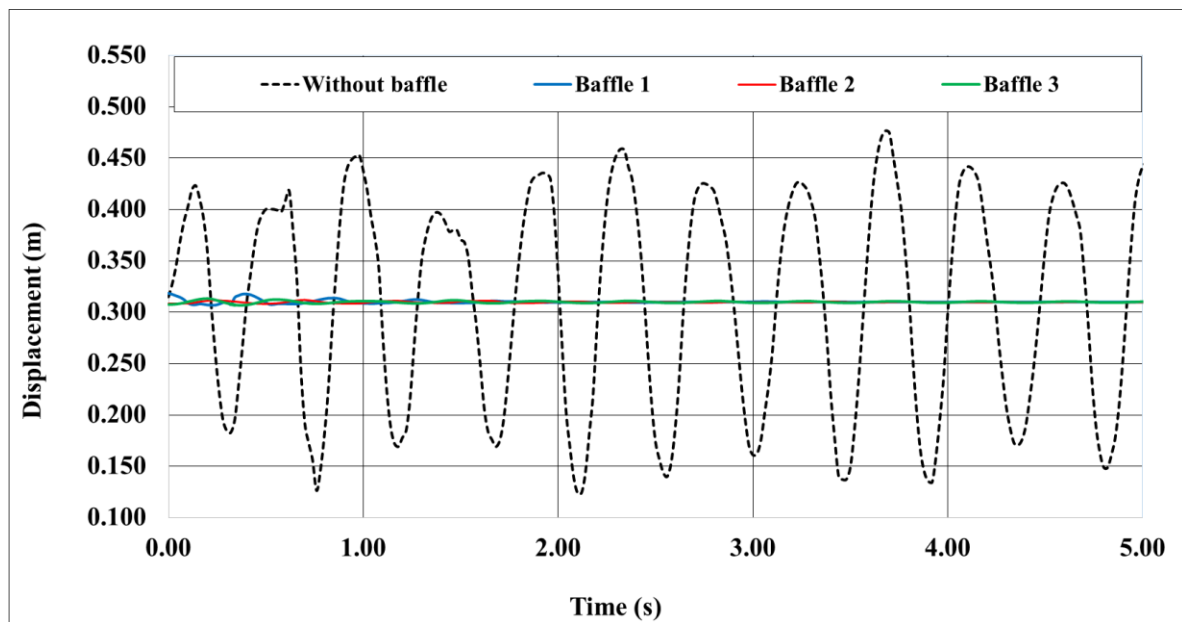


Fig.8b. Comparison of three different types of baffles in fully submerged condition (Experimental).

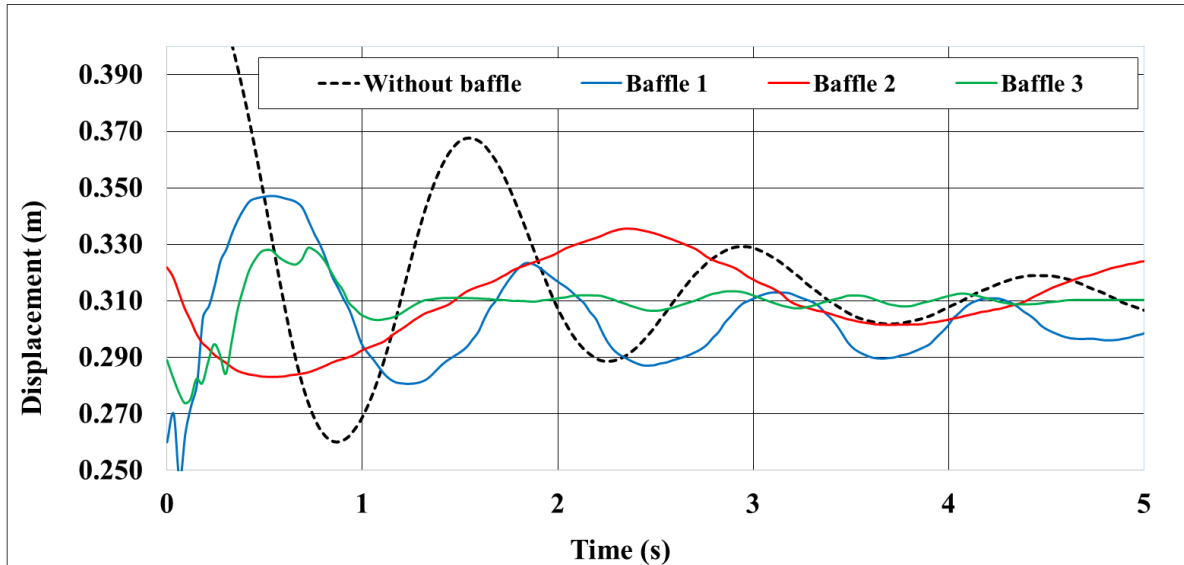


Fig.9a. Comparison of three different types of baffles in 'not submerged' condition (Computational).

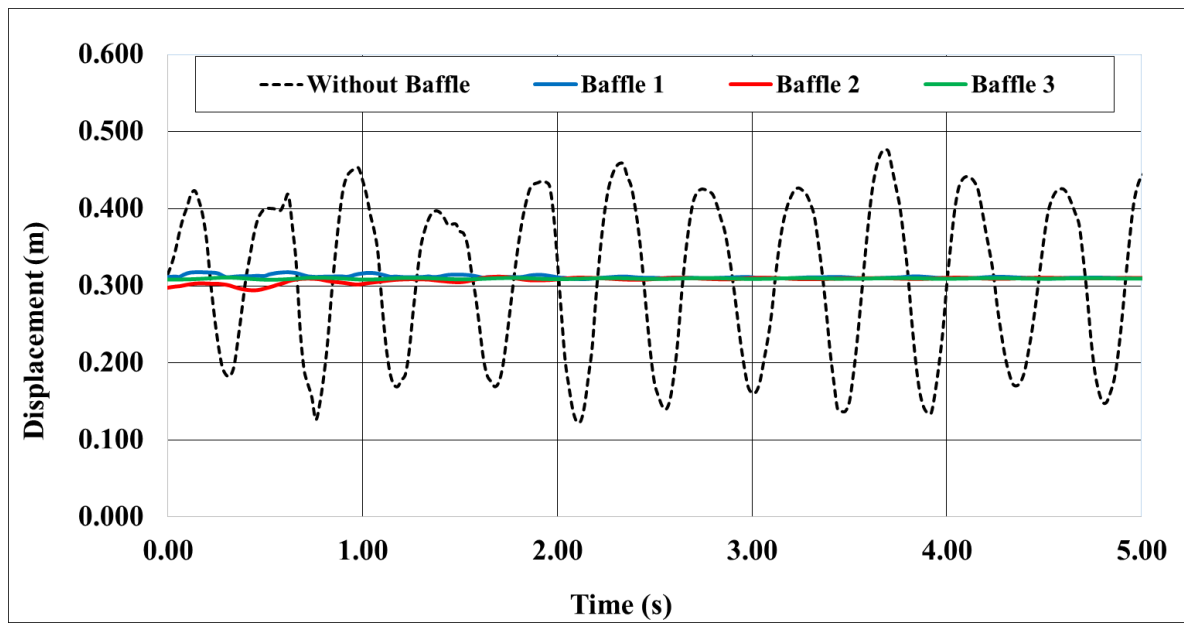


Fig.9b. Comparison of three different types of baffles in 'not submerged' condition (Experimental).