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AN EXPERIMENTAL INVESTIGATION OF HYDRODYNAMIC DAMPING DUE TO BAFFLE ARRANGEMENTS IN A RECTANGULAR TANK

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ABSTRACT

The present work is concerned with an experimental study of the hydrodynamic damping provided by using vertical baffles in partially filled rectangular tanks. The damping ratio in a rectangular tank is evaluated for different vertical baffle dimensions, shapes, numbers and arrangements. A test rig for a carrying rectangular tank system is designed and constructed to measure the transient responses in time domain. The baffles are fitted to attenuate the lateral motion of the liquid slosh. Lower and upper mounted vertical baffles of different heights and numbers are tested. Lower mounted vertical baffles with holes of different sizes and numbers are considered. Finally, the effect of a combination between upper, lower and holed vertical baffles on the damping is investigated. The results show that the size and location of the vertical baffles significantly influence the hydrodynamic damping. In general, the damping ratio increases as the lower mounted baffle is close to the liquid free surface and the center of the tank. Increasing the baffle numbers increases the damping ratio. The upper mounted vertical baffles are more suitable for chargeable tank. The twin side upper mounted baffles and centre holed Lower mounted baffle arrangements give a maximum damping ratio.

KEY WORDS

Baffles, Rectangular tank, Slosh

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NOMENCLATURE

A_d total area of holes
A_t tank cross section area (A_t= B H_t)
B tank width
L tank length
B_n number of baffles
d hole diameter
F_r filling ratio (F_r= H/H_t)
H liquid height
H_d hole position (H_d =10 cm)
H_t tank height
H_u upper mounted vertical baffle depth measured from tank ceiling
H_h horizontal baffle depth measured from tank ceiling
H_n number of holes
h lower mounted vertical baffle height
h_h horizontal baffle depth measured from liquid surface
h_u upper mounted vertical baffle depth measured liquid surface
X baffle position relative to the left tank wall (X_1=0.25L, X_2=0.5L)
ζ damping ratio

1. INTRODUCTION

Liquid storage tanks are important components in many mechanical systems and industrial facilities. Liquid sloshing in moving or stationary containers remains of great concern in a wide range of practical problems to aerospace, civil, nuclear engineers, physicists, designers of road and ship tankers and mathematicians, [8-11]. Partially filled tanks are prone to violent sloshing when subjected to external excitations. The large liquid movement creates highly localized impact pressures on tank walls, which may in turn cause structural damage. Furthermore, this impulsive loading may create sufficient moment affects the stability and the integrity of the structure supporting the container, [3, 12, 13 and 14]. Sloshing is not considered a gentle phenomenon even at very small amplitudes. The liquid motion can become highly non-linear, surface slopes can approach infinity and the liquid may encounter the tank top in enclosed tanks, [5].

There are two major problems arising in a computational approach of sloshing; these are:

- The moving boundary conditions at the liquid tank interface.
- The nonlinear motion, if any, of the free surface. The shape and position of the free surface varies with time in a manner not previously known.

Generally, the most effective method to decrease the slosh forces is to reduce the amplitude of the liquid oscillations by increasing the damping applied to the contained liquid. Damping due to liquid viscous action is small, [3] and in many situations introducing baffles is an effective proposition. The baffles may have different designs to divide the liquid bulk mass into different sub-masses or to damp the liquid motion inside the container by using orifices as restrictors, [5]. The magnitude of the impact forces on the container walls depends mainly on the total moving mass of the liquid. Various approaches have been used to predict the effect of baffles and other obstacles in the fluid. Michael and Sundarlingam, [9], developed a hydrodynamic model to estimate the hydrodynamic damping in a rectangular tank by using linearized flow theory. Choun, [4], investigated the effects of a bottom mounted rigid submerged block on the sloshing characteristics of liquid in a rectangular tank by using the linear water wave theory. Biswal et al, [1], adapted a two-dimensional finite element analysis for the sloshing analysis with horizontal rigid baffles using the velocity potential formulation and linear water wave theory. The same authors studied the variation of the natural frequencies of liquid in a liquid-filled cylindrical tank without and with an annular plate as a baffle, [2]. Young et al, [16], has experimentally determined the hydrodynamic pressure on the side wall and tank ceiling for forced harmonic surge excitations. Gedikli and Erguven, [8], et al had studied the effects of baffles on the seismic response of the liquid in a circular cylindrical tank. Younes, [15], carried out an experimental and theoretical investigation for proper selections of viscous liquids in the design of spherical slosh vibration dampers. Ibrahim, [7], studied the damping provided by holed baffles to improve the roll dynamic behavior of cylindrical tank trucks. Hakan, et al, [6], carried out an experimental investigation on rectangular tanks with vertical and horizontal baffles arrangements under pitch oscillations. Evans and Mclever, [5], investigated the effects of a thin vertical baffle on the sloshing frequencies in a rectangular tank using the linearized theory of water waves.The effects of baffles configuration, width, thickness, and location on the damping and frequency of the fundamental anti-symmetric mode of liquid oscillations are to be investigated. Analytical models used in predicting damping are not only tedious but also difficult because of the complexity of boundary conditions and the presence of baffles makes it even tougher, [16].

In the present study, the damping behavior of the rectangular tank partially filled with liquid is examined experimentally using a scaled prototype model. Different baffles are fitted vertically in the rectangular tank to generate damping potentials against the lateral motion of the liquid. Different baffle shapes, dimensions and arrangements are tested. The damped liquid motion due to both natural characteristics of the liquid and the used baffles is measured experimentally using the logarithmic decrement technique.

2. EXPERIMENTAL AND INSTRUMENTATION SETUP

The test rig used in this investigation is illustrated in Fig. 1 and 2. The supporting frame (1) consists of four I beams (120 x 60 cm^2) tightened by four suspension bars (3) and fixed rigidly on the laboratory floor. A rectangular frame (2) is constructed from welded steel plates (1 x 6 cm) welded to the top ends of the supporting frame. The main vibrating system consists of a wood base 30 cm width and 70 cm length (in the direction of motion) suspended by four steel strips (0.05 x 5 cm^2) and 1.5 m length which provide a guide to control the motion direction. The steel strips are connected to the main frame from one end and to the wood base from the other end through special screw bolts (5) which provide a horizontal adjustment of the wood base. A rigid steel rectangular tank 20 cm width, 30 cm height and 50 cm length is made from steel sheets 1 mm thickness.

The tank has an aluminum C beam (6 x 3 mm^2) at 0.25 and 0.5 and 0.75 from its length. These beams are used as guides to support the baffles made from aluminum sheets 1 mm thickness. Aluminum is used for its light weight so that the variation in the weight for baffled and unbaffled tank can be neglected. The small baffle is 5 cm and the large baffle is 30 cm height. A piezoelectric accelerometer type B&K 4370 with sensitivity ~10 $PC/m.s^{-2}$ and frequency range 0-1000 Hz is mounted on the main structure base as shown in Fig. 2. The charge from the accelerometer is fed to a charge amplifier type B&K 2635, and then transmitted to a digital oscilloscope to acquire the output signals. A 20 cm scale (7) is fixed on the structure base and a pointer (8) is fixed on the supporting frame as shown in Fig.1.

This arrangement is used to measure the initial displacement. Free vibration responses are tested until adjustments are carried out. Final signals are fed to the data acquisition card type LabJack 901 through coaxial cable and then transmitted to a PC computer through usb cable. The LabJak Stream software is used to analyze the digital data and stores it in a data file form.

A digital high pass filter, available in the MATLAB software is used to remove the noise generated from the wiring connections.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Using the logarithmic decrement of the vibrating liquid, free vibration modes [7], the damping ratio ξ is measured.

$$\delta = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$$

Where,

δ the logarithmic decrement, $\delta = \frac{1}{N}\ln\left(\frac{x_i}{x_{i+N}}\right)$

ζ the damping ratio

X_i and X_{i+N} the amplitudes of the main structure at the beginning and end of the cycles,

N is the number of the cycles

The model is designed with a very low structural damping, so that the damping is only a contribution of baffles effect. Different baffles dimensions, shapes, locations and arrangements are tested. A total of 60 tests involving 12 different tank configurations are conducted. Table 1. Summarizes the different cases.

3.1. Effect Of The Lower Mounted Vertical Baffles

The effect of baffle heights (case No. 1) and the filling ratio on the magnitude of the damping ratio ζ is illustrated in Fig. 3. For three liquid height H= 10, 15 and 20cm, the damping ratio is decreasing with high liquid heights due to the increase of the convective liquid mass. The damping ratio is increasing with baffle height for any value of the liquid height. This is due to dissipative forces resulting from the relative motion between the liquid and the baffles installed to suppress the liquid oscillations. These forces are assumed to be proportional to the relative velocity.

The effect of baffles on the damping ratio is gradually increasing when the baffle is moved towards the liquid surface and the maximum effect occurs when the baffle is close to the liquid surface. When the baffle reaches the free surface the effect of the baffle is decreasing because the tank is divided into two small tanks, therefore for each liquid height there is a suitable baffle height.

Figure 4 illustrates the damping ratio for different baffle locations relative to the left tank wall (case No. 1).

The damping ratio for F_r=0.5 and h/H=1 is increasing from ζ=0.008 to ζ = 0.009 when the baffle is moved from X=0.25L to X=0.5 L, the damping ratio is increased by about 15%.

The effect of the hole diameter (case No. 2) on damping ratio ζ is illustrated in Fig. 5 for three liquid heights H= 10, 15 and 20 cm. The damping ratio decreases with high liquid heights due to the increase in liquid mass and the relative position between the hole and liquid surface (the hole in the rest liquid regime has no effect).

For small hole diameters, diameter increases the damping ratio until a ceiling value is reached, and finally the damping ratio drops.

In general the damping ratio achieved by this type of baffles is greater than the case of a solid baffle. Referring to Fig. 6, for F_r=2/3, the maximum damping ratio equals 0.03 for a number of holes equal to 15 (case No.3) with a total area equal to 1990 mm^2. To achieve the same damping ratio using one hole, its diameter should equal to 6 cm with an area equal to 2827 mm^2. Therefore, the material removal from the baffle is increasing and the baffle becomes weak. Therefore, several small holes are more effective than one hole with the same area to damp the liquid motion.

3.2. Effect Of The Upper Mounted Vertical Baffles

In Fig. 7 the damping ratios obtained for the tank with a single upper mounted vertical baffle (case No. 4) are shown. The damping ratio increases with the increase of the baffle depth.

This is due to forcing the liquid to flow below down the baffle toward the rest liquid regime. The liquid damping results from the relative velocity between the liquid and the baffle and the relative velocity between the sloshing liquid and the resting liquid (liquid with low velocity). When h_u =0 (the baffle is close to the liquid surface) there is no differences between the baffled and unbaffled responses.

The upper mounted baffle is more effective than the lower mounted baffle for all tested filling ratios due to the effective depth change with the liquid height as shown in, Fig. 8.

3.3. Effect Of Vertical Baffle Arrangements

Referring to Figs. 9 and 10, the damping ratio increases with baffle number for lower and upper mounted baffles. Referring to Fig. 11, the upper mounted baffle is still more effective than the lower mounted baffle for all tested filling ratios The damping ratio achieved by a single hole baffles (case No. 2) is greater four times than the damping ratio obtained when using an upper mounted baffle cases No. 5 and No. 6 as shown in Fig.12.

Figure 13 illustrates the difference between the baffle arrangements in cases (2, 7, 8, 9 and 10). The damping ratio achieved with a single lower mounted baffle with a central hole (case No.2) is greater than the damping ratio obtained in cases (7,9) specially for low filling ratio F_r<0.55. The case No. 8 is the highest effective one for all filling ratios. The damping ratio for this case lies between 0.04 to 0.06. The percentage is greater than the single upper mounted baffle case by 300%, by 48% for the single holed baffle case, by 150% for the multi upper mounted baffles and by 15% for the case No. 10.

4. CONCLUSIONS

The measured damping ratios are summarized in table 2. Study of this table reveals the following conclusions:

Vertical lower mounted baffles located at the center of the tank and closer to the free surface give higher damping than at any other locations.

Upper mounted vertical baffles with depth ratio H_u/H_t=0.83 are more effective in damping the liquid than lower mounted vertical baffles and these are suitable for chargeable tanks, where the liquid height changes during service. Holed vertical baffles with a single hole with relative area A_d/A_t= 0.047 and located just below the liquid free surface are more effective than the other baffle types and they are suitable for semi chargeable tanks and large tank where the sloshing forces are very high. Meanwhile, vertical baffles with several holes give a higher damping ratio than the vertical baffle with a single hole for the same perforated area but it takes more manufacturing cost. Therefore, this type may be suitable for very large and special tanks. For very long tank where extra sloshing forces may be expected the multi baffle arrangements (case No. 8) are recommended. For horizontal baffles, the maximum damping is obtained when the baffle is at the equilibrium surface and mounted on the tank side walls. The maximum damping ratios for the tested conditions are ζ=0.01 and 0.025 for the single and double baffles respectively. Therefore, the horizontal baffles are effective in damping the liquid motion in the taller tanks case, whereas vertical baffles are effective for shallower tanks.

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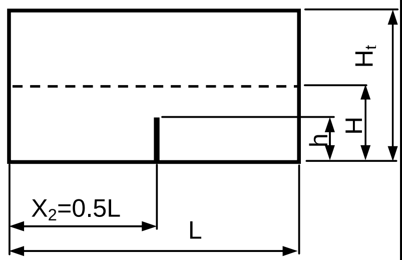
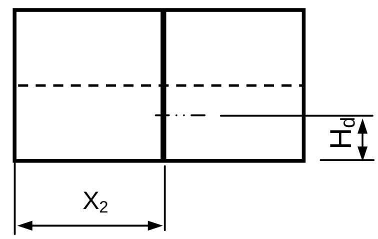
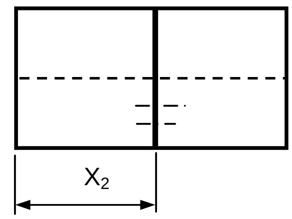
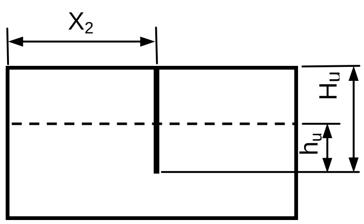
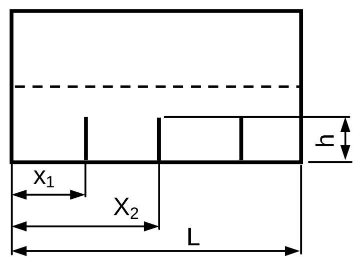
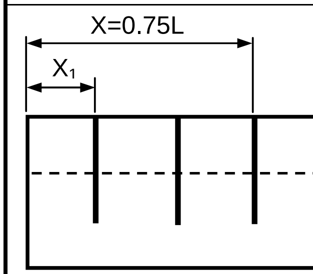
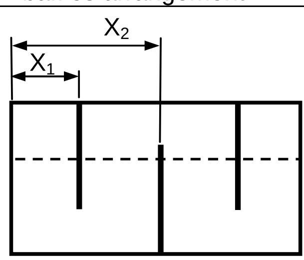
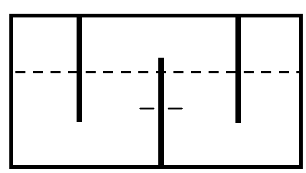
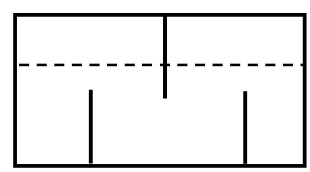
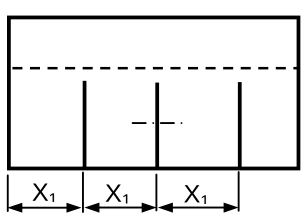
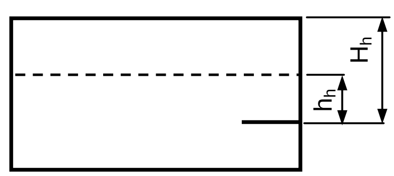
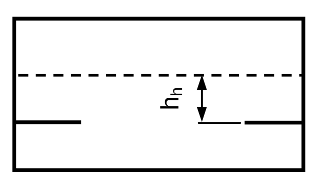
Table 1. Layout of experimental cases

1- Lower mounted vertical baffle	2- vertical baffle with central hole	3- Vertical baffle with several holes
		
4- Upper mounted vertical baffle	5- Several lower mounted vertical baffles	6- Several upper mounted baffles
		
7- Upper and lower mounted baffles arrangement	8- Upper and lower with central hole baffles arrangement	9- Lower and upper baffle arrangements
		
10- Lower baffles arrangement with hole	11- Horizontally mounted single baffle	12- Several horizontally mounted baffles
		

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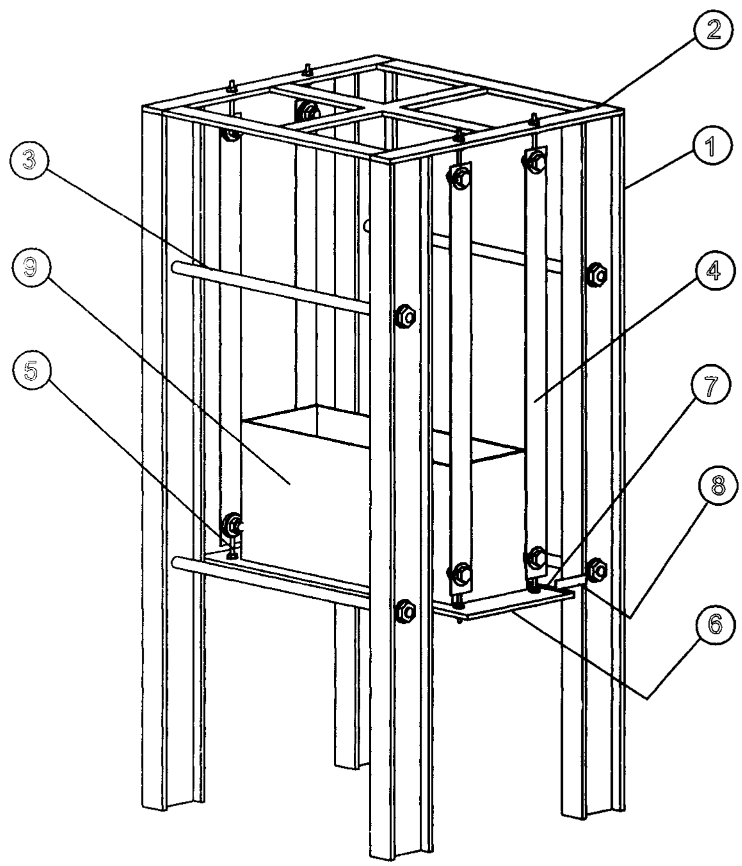

1- Rigid frame
2- Upper base
3- Suspension bars
4- Steel strips
5- Adjustment screw bolts
6- Wood base
7- Scale
8- Pointer
9- Steel tank

Fig.1. Three dimensional view of the test rig

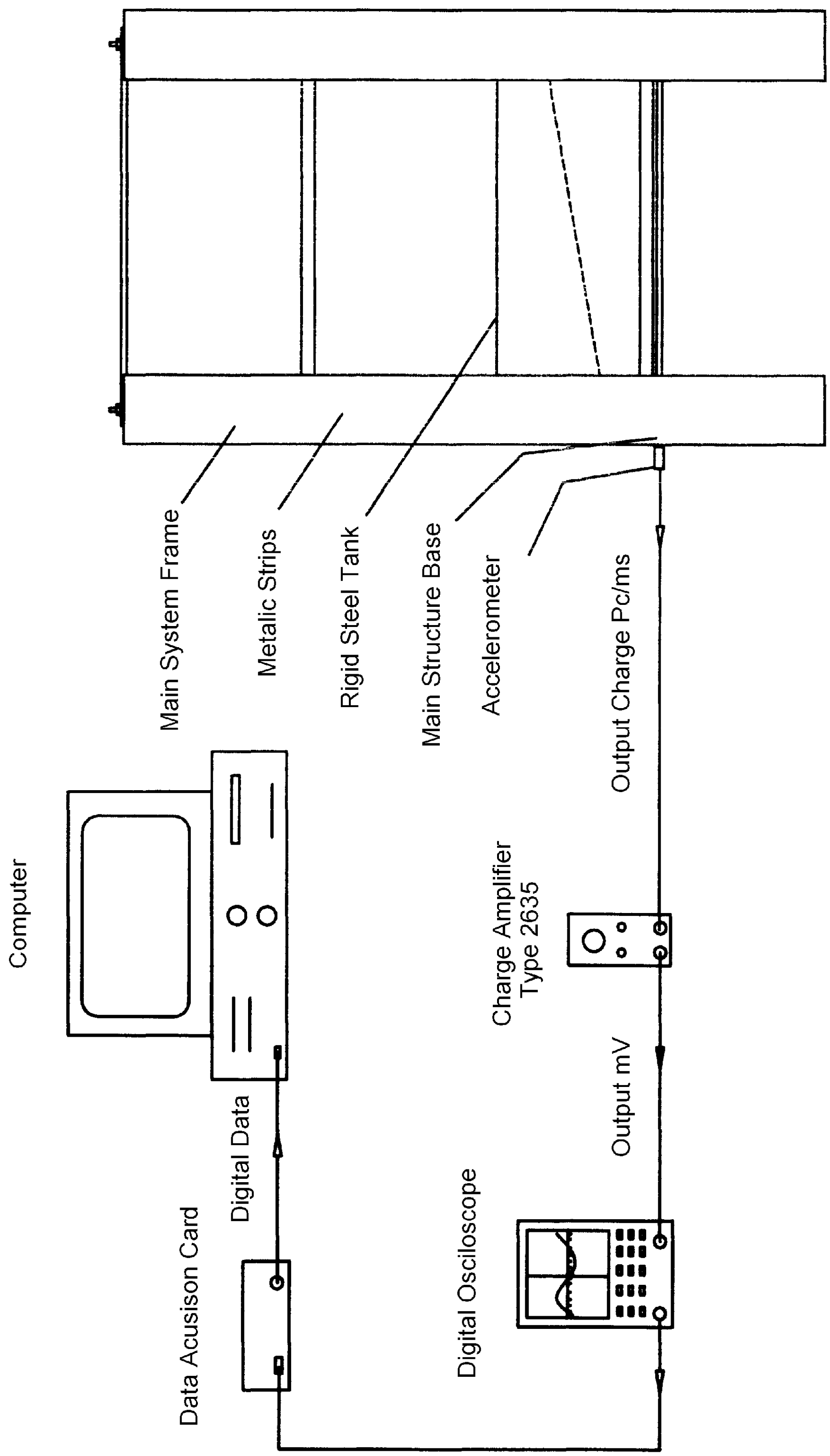

Fig.2. Layout of the test rig and the associated instrumentation

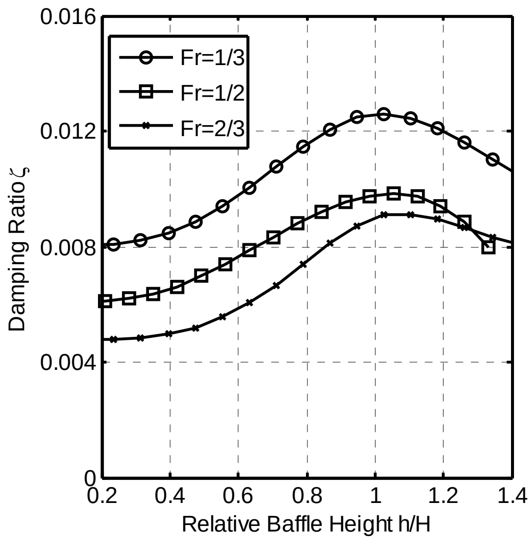

Fig.3. Variation of damping ratio with lower mounted baffle height for different filling ratios (case No. 1)

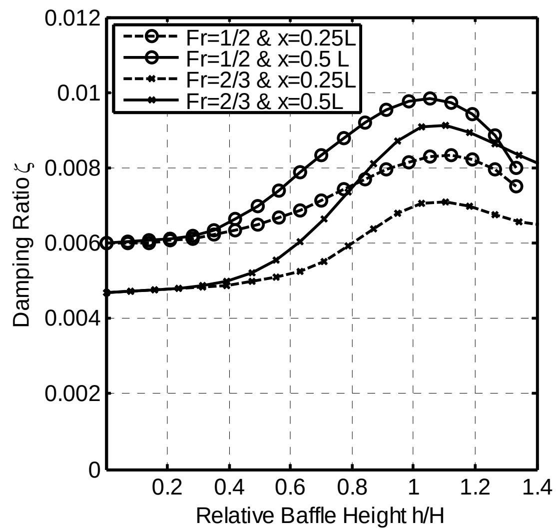

Fig.4. Variation of damping ratio with baffle height for different baffle locations (case No.1)

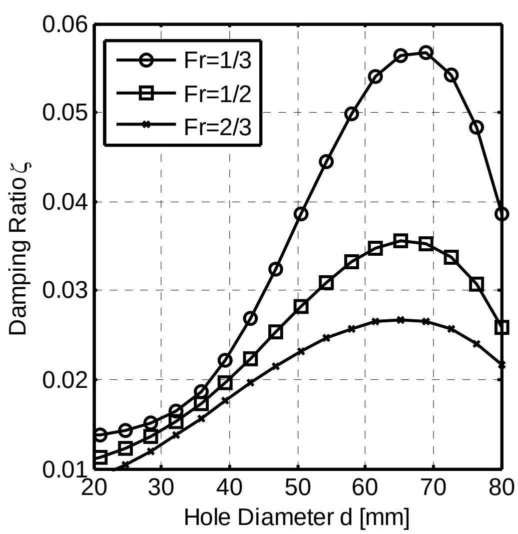

Fig.5. The effect of the hole diameter on damping ratio for different filling ratios (case No.2)

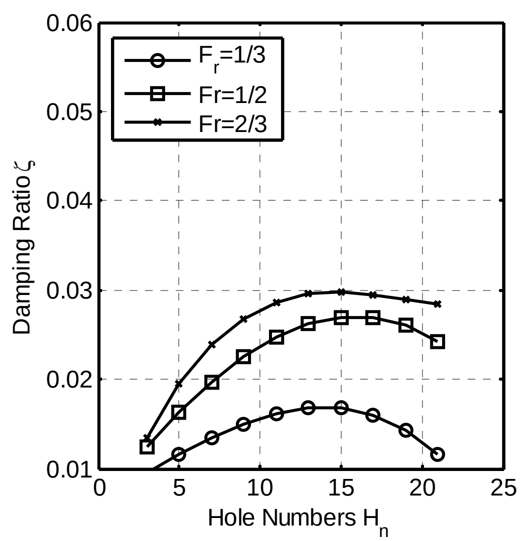

Fig.6. The effect of the hole numbers on damping ratio (case No.3)

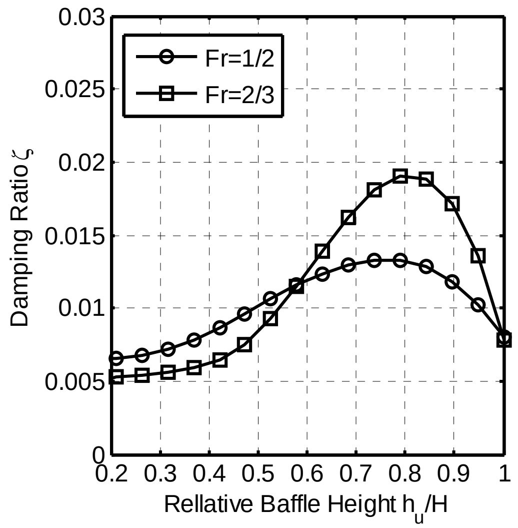

Fig.7. The effect of the upper mounted baffle depths on the damping ratio (case No.4)

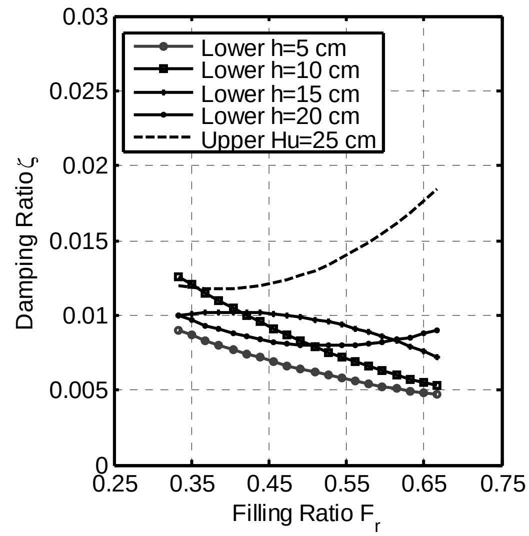

Fig.8. The comparison of the lower mounted and upper mounted baffled cases (cases 1 and 4), B_n=1

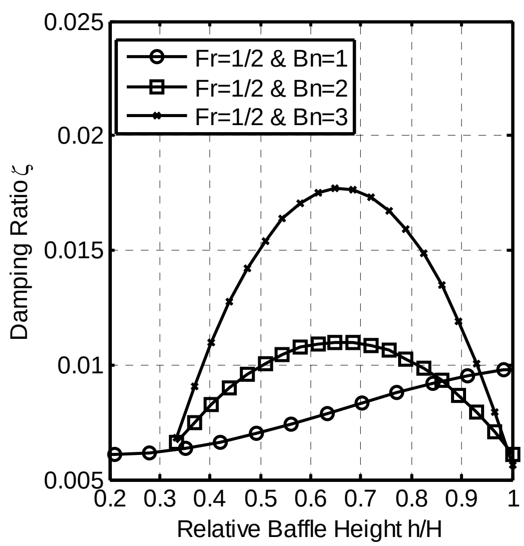

Fig.9. The effect of the lower mounted baffle numbers (case No. 5)

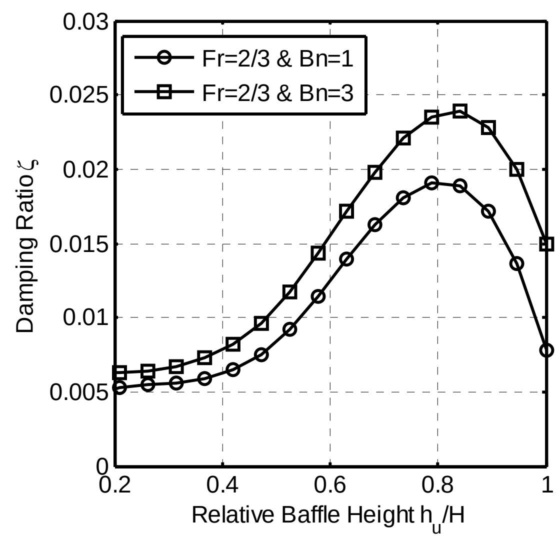

Fig.10. The effect of the upper mounted baffle numbers (case No.6)

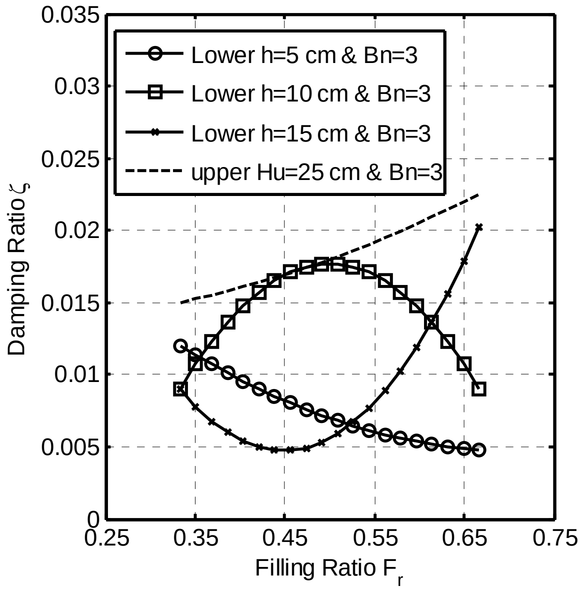

Fig.11. Comparison between the lower mounted and the upper mounted baffled cases (cases 5 and 6), B_n=3

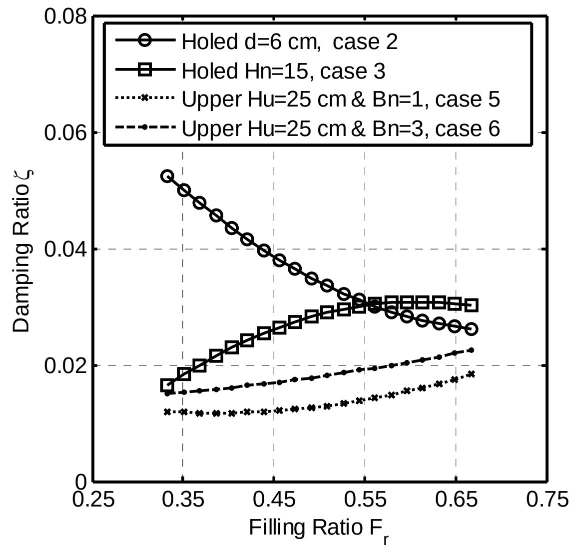

Fig.12. Comparison between holed and upper mounted baffle cases (cases 2,3,5 and 6)

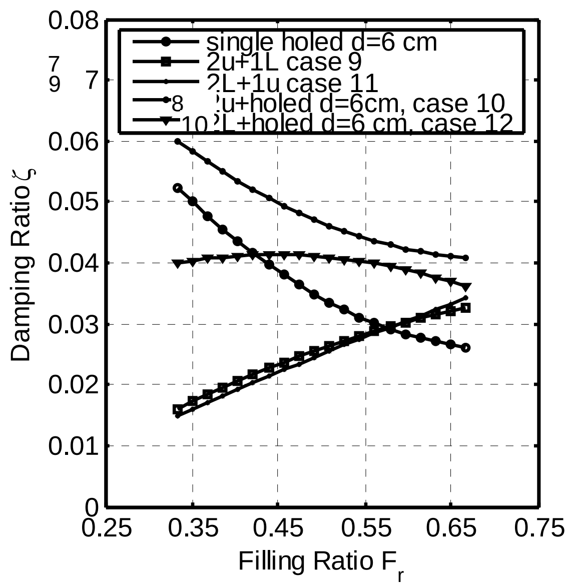

Fig.13. Comparison between holed, upper and lower mounted baffle arrangements (cases 2,7,8,9,10)

Table 2, Summary of experimental damping ratios for different vertical baffle arrangements

Cases	Parameter		Damping ratio $F_r=1/3$	Damping ratio $F_r=1/2$	Damping ratio $F_r=2/3$
Lower mounted baffles, case No. 1	h/H_t	1/6	0.009	0.0063	0.0047
		1/3	0.0126	0.008	0.0053
		1/2	0.01	0.00974	0.0072
		2/3	0.01	0.008	0.009
		1	0.01	0.008	0.0078
Vertical baffles with central hole, case No. 2	A_h/A_t	0.0052	0.01	0.012	0.009
		0.021	0.023	0.02	0.018
		0.047	0.05	0.034	0.026
		0.084	0.038	0.026	0.02
Vertical baffle with several holes case No. 3	A_h/A_t	0.0066	0.009	0.014	0.013
		0.019	0.015	0.02	0.022
		0.033	0.016	0.028	0.03
		0.046	0.015	0.027	0.026
Upper mounted vertical single baffle, case No. 4	h/H_t	1/6	0.012	0.007	0.0048
		1/3	0.009	0.0177	0.009
		1/2	0.009	0.0056	0.02
Upper mounted vertical baffles, case No. 5	H_u/H_t	0.5	0.0079	0.006	0.0054
		0.66	0.0079	0.0074	0.008
		0.83	0.012	0.0128	0.018
		1	0.01	0.008	0.0078
Case No. 6	$H_u/H_t=0.83$		0.015	0.018	0.0225
Case No. 7	$h=H_u= 0.5$		0.016	0.026	.03
Case No. 8	$h=H_u = 0.5$		0.06	.046	.041
Case No. 9	$h = H_u= 0.5$		0.015	0.025	0.034
Case No. 10	$A_h/A_t=0.047$		0.04	0.041	.036
Horizontally mounted baffles, cases No. 11, 12	H_h/H_t	1/3, $B_n=1$	0.007	.005	0.01
		1/2, $B_n=1$	0.007	0.01	0.004
		1/2, $B_n=2$	0.007	0.025	0.004