The Experimental Investigation of the Impact Absorption Capability of Piston-Cylinder Air-damper Set-up Perforated with Tiny Holes

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Abstract

An air-damper for impact absorption study was designed and fabricated. It had 32 exit holes, each with a diameter of 5/32 inch. The holes were closed using tin rivet and sealed using grease and insulation tape. The numbers of opened exit holes were varied from 0 to 32 with 17 combinations in horizontal and vertical position. There were three classes of load applied and three trials were done for each opened exit holes position. The theoretical impact was solved using the impact equation and found to be higher compared with impact produced with air-damper. The impact produced and the pressure developed inside the air-damper had a direct relationship in which higher impact produced developed higher pressure inside the damper and vice versa, that is, the impact produced was minimum when large amount of applied energy was absorbed by the escaping air. The position of the opened exit holes also affected the amount of impact produced. The analysis of variance (ANOVA) F test at 0.05 level of significance indicated the significant effect of exit holes opening and position.

Keywords: Air damper, impact absorption, analysis of variance

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1 Introduction

Impact is the result when two moving bodies collide or one moving body collides with a static body. Impact absorbers or dampers are used to absorb the kinetic energy induced before collision, through heat dissipation or pressure dissipation to the surroundings. The damper mentioned in this paper used the same principle as the absorber used in automotive suspension. The only difference is, air is used as the damper fluid and the cylinder was perforated with tiny holes which serve as exit ports of the escaping air. During compression, the air escapes to the atmosphere. This escaping air absorbs the kinetic energy induced and carries it to the outside of the damper, thus causing less impact. Veijola and Mattila, (2001), investigated the compact squeezed-film damping model for perforated surfaces. The perforation holes were used to control the damping due to gas and these holes contributed to the lessening of damping effect. Bao, *et al.*, studied the modified Reynolds' equation for squeezed-film air damping of hole-plate. The study was based on the concepts of effective "damping width", damping forces, and damping ratio for rectangular plates, circular plates, and even hole plates with irregular shapes. The purpose of the holes in the plate was to reduce the air damping effect as expected in MEMS devices. Kim, *et al.*, conducted a study on the hydrodynamic force on a plate near the plane wall. The study was focused on the hydrodynamics force on a plate moving in a viscous fluid near the plane wall as a model of a Microelectromechanical System (MEMS). The findings revealed that the damping coefficient for the closed plates, plates or with no holes and plates with 1, 4 and 9 holes of the area ratio 3.4%, 6.8% and 13.6% decreased as the number of holes increased.

The usual method of handling impact problem is by the laws of conservation of energy and conservation of momentum (Barkan, 1964) and (Faires, 1968). If the mass of the spring is negligible and it is assumed that the spring responds elastically, the conservation of energy requires that the kinetic energy be completely transformed to the elastic strain energy (Hamrock, *et al.*, 1999). Then the general relationship is equal to

$$mg(h+\delta_{max}) = \frac{1}{2}F_{max}\delta_{max} = \frac{1}{2}k\delta_{max}^{2}$$

[1]

[A] [B] [C]

Using relationship A and C of equation [1] dynamic deflection can be solved using the equation,

$$\delta = \frac{W}{k} + \frac{W}{k}\left(1 + \frac{2kh}{W}\right)^{1/2}$$

[2]

The impact produced can be solved using the relationship A and B of equation [1],

$$F = 2W\left(\frac{h}{\delta} + 1\right)$$

[3]

2 Theoretical Foundations

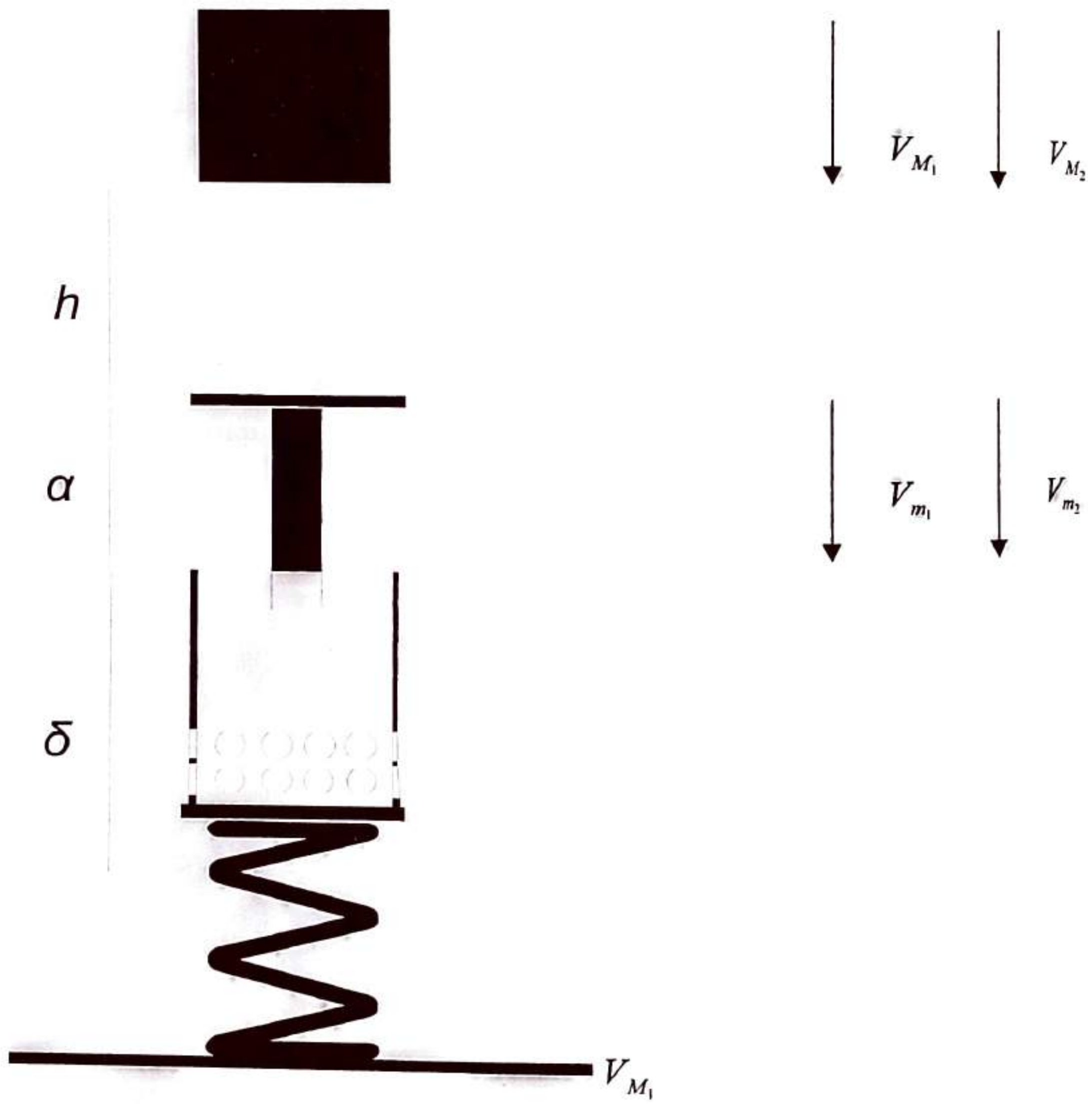


Figure 1. The schematic diagram of spring loaded model with air-damper

Figure 1 shows the schematic diagram of the spring loaded model with air-damper. Using the principle of conservation of energy to analyze figure 1, the applied potential energy is equal to $mg(h+\delta+\alpha)$, where h is the height of the load, δ is the deflection of the spring and α is the deflection of the air-damper at equilibrium position.

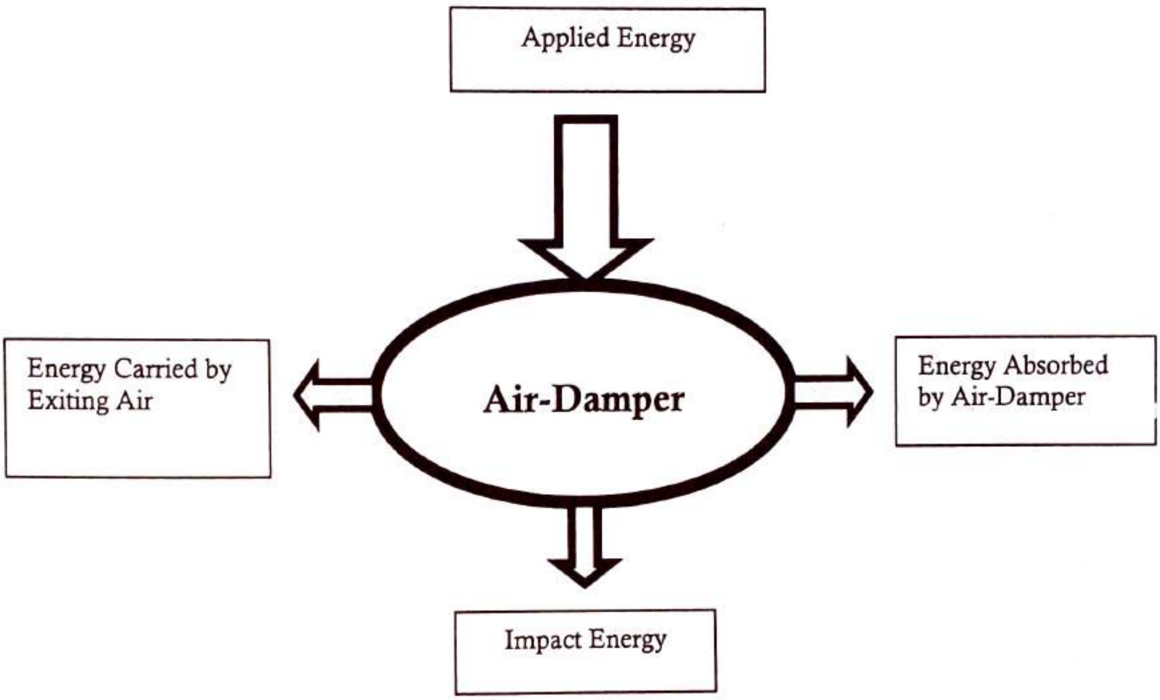


Figure 2. The conservation of energy analysis of the piston-cylinder air-damper

Figure 2 shows the conservation of energy analysis of air-damper which can also be represented using the equation,

$$mg(h+\delta+\alpha)+m_D g(\alpha+\delta)=\frac{1}{2}k\delta^2+\frac{1}{2}PA\alpha+E_{air}$$

[4]

where the first term in the right side of equation [4] is the energy transferred to the body of the damper, and is the impact energy produced; the second term is the energy absorbed by air the damper; and the third term is the energy carried out by the exiting air and dissipated to the atmosphere.

From figure 1, the principle of conservation of energy will also give

$$M(V_{M_1} - V_{M_2}) = m(V_{m_1} - V_{m_2})$$

[5]

Where, $V_{m_1} = 0$ since the damper is at rest before the impact; V_{m_2} is the final velocity of the damper; V_{M_1}, the initial velocity of load applied and V_{M_2} is the final velocity of the load. By equating the potential energy to the kinetic energy, figure 1 will have an equation of,

$$\frac{1}{2} M V_{M_2}^2 = Mgh$$

[6.1]

$$V_{M_2} = \sqrt{2gh}$$

[6.2]

Thereof, the final velocity of the applied load can be determined using equation [6.2] which is totally dependent on height. By using the principle of the coefficient of restitution for the colliding bodies which is applied to figure 1 upon the collision of applied load to the damper system,

$$e = \left(\frac{V_{m_2} - V_{M_2}}{V_{m_1} - V_{M_1}} \right)$$

[7]

The value of the coefficient of restitution (*e*) is totally dependent on the condition of the colliding bodies and if the mass of the damper is smaller compared to the mass of the load applied, the collision will be an inelastic one, meaning that the colliding masses will move in the same direction. Hence, in the present study, it is assumed that the collision is inelastic, as the mass of the load applied is greater than the mass of the air-damper piston. Therefore, the value of e is zero and as such, the coefficient of restitution will not significantly affect the outcome of the experiment. So, equation [7] can be reduced to $V_{m_2} = V_{M_2}$ which, means that the velocity of the applied load is the same as the velocity of the damper piston. Using the above statement, equation [5] can be manipulated to become

$$V_{M_{2_2}} = V_{m_2} = \frac{\frac{M}{m}\sqrt{2gh}}{1+\frac{M}{m}}$$

[8]

This is the velocity of the applied load and the air-damper piston. Using again the principle of energy and momentum as discussed in deriving equation [1], new equation can be manipulated and become

$$\frac{1}{2}(M+m)V_{m_2}^2 = \frac{1}{2}k\delta^2$$

[9.1]

And the deflection of the elastic material or spring as shown in figure 1 will become

$$\delta = V_{m_2}\sqrt{\frac{M+m}{k}}$$

[9.2]

From equation [9.2], the value of δ depends on the impact absorption capability of piston-cylinder. So, every change in the number of tiny open holes in the cylinder causes a change in the deflection of the spring.

From the principle of fluid mechanics, the relationship of pressure and force at the cylinder is equal to

$$P = \frac{F}{A}$$

[10]

Using the ideal gas law

$$PV = mRT$$

[11]

and the assumption that the process is isothermal due to the very small lapsed time.

$$P_2 = P_1 \frac{V_1}{V_2}$$

[12]

Equation [12] states that to get the higher pressure, the volume of the cylinder must be decreased as much as possible, but in order to decrease the volume of the cylinder, high applied force is needed since pressure is proportional to force, as shown in equation [10]:

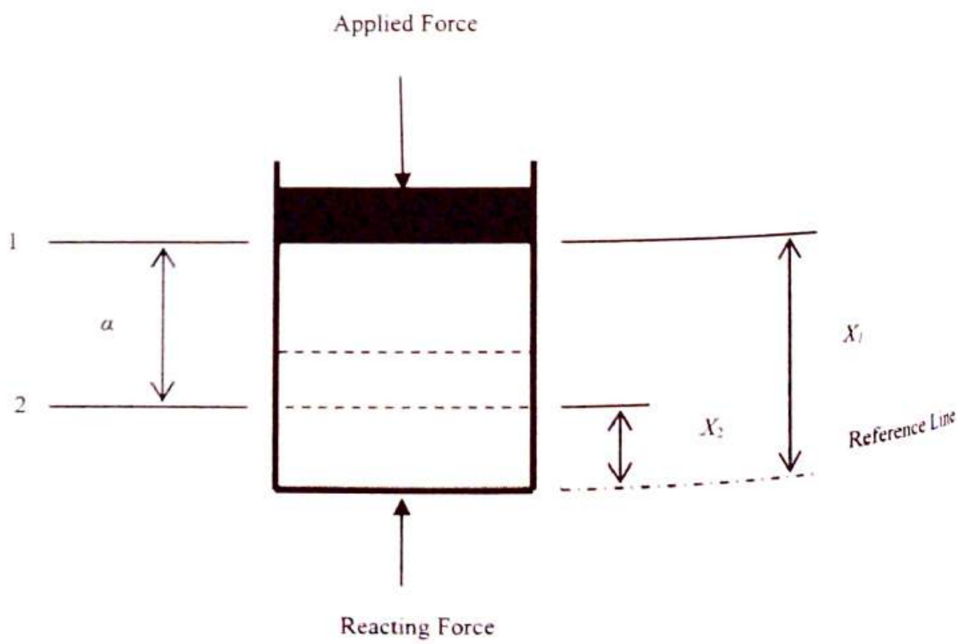


Figure 3. Schematic diagram of air-filled cylinder

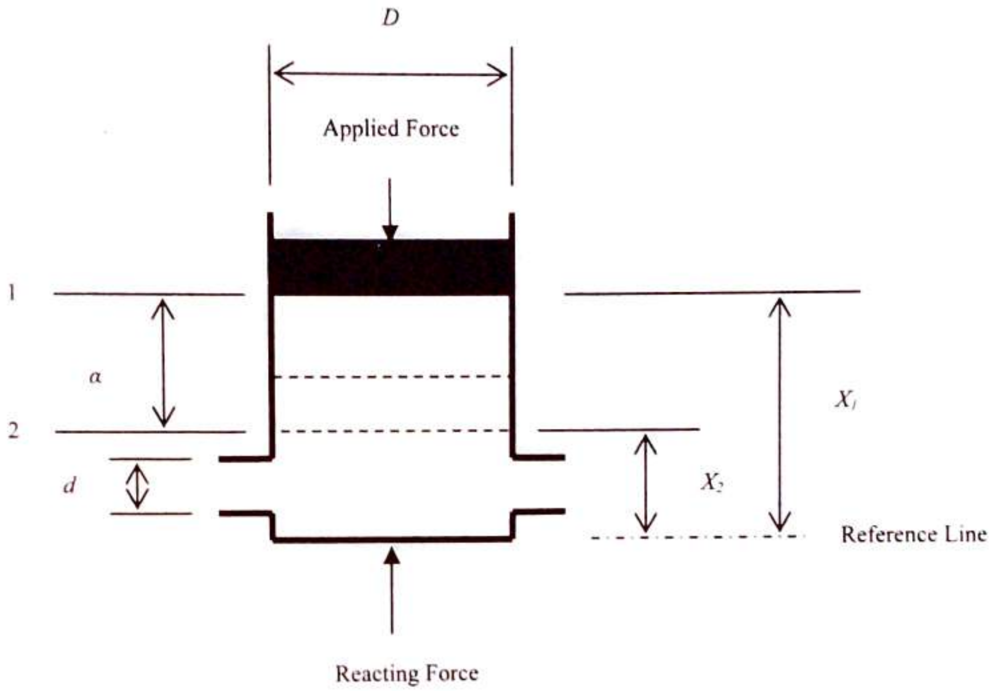


Figure 4. Schematic diagram of air-filled cylinder with holes or exit ports

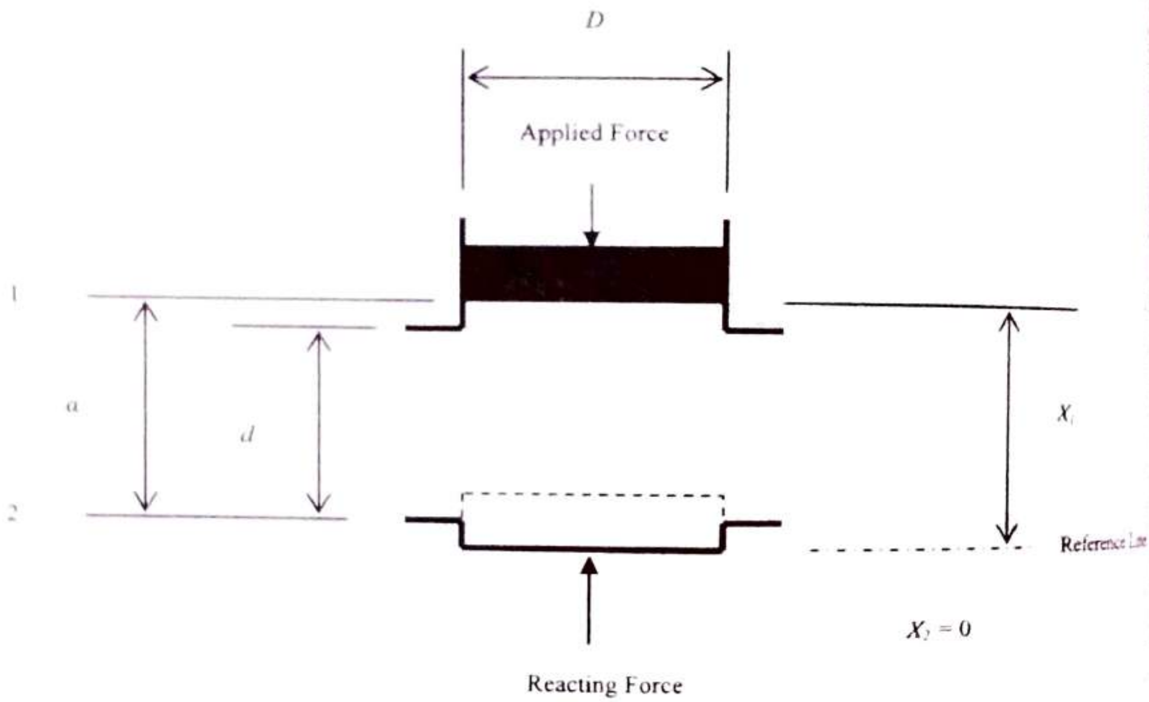


Figure 5. Schematic diagram of air-filled cylinder with very large holes or exit ports

Therefore, when higher pressure is developed inside the cylinder, higher reaction is also developed because of the reaction effect which causes higher impact. The only way to reduce the build up of higher pressure inside the cylinder is to let air go out to the atmosphere using exit ports or holes. Modifying figure 3 which, includes holes or exit ports, figure 4 stated that the pressure inside the cylinder can be reduced when the exit ports diameters are increased or more exit ports have been done. During the application of load (Applied Force), the piston travels downward compressing the air, since there are holes or exit ports. Some or most of the air goes out. This situation reduces the pressure build-up inside the cylinder which, causes lower impact as discussed above about the relationship of pressure and force. But when the area of exit ports or holes equals to the diameter of the cylinder in which, theoretically no cylinder is present, it is expected that during the application of load, air escapes immediately causing higher impact since the distance a is an additional height of the load. Figure 5 shows the theoretical diagram of the cylinder with very large exit ports.

3 Experimental Works

The over-all experimental set-up frame was fabricated from a 1 inch angle bar with thickness of 1/8 inch as shown in figure 6. The rig has a load handler that was designed to release the load uniformly without tilting. The cylinder liner was perforated with 32 tiny holes which served as exit ports. The diameter of each hole was 5/32 inch with spacing of 20 mm vertical and approximately 22.5 mm horizontal. The distance of the lower level holes from the bottom of the cylinder was 25 mm. The 5/32 inch diameter holes were selected since the smallest tin rivet available was ¼ inch. The purpose of the tin rivet was to close the exit ports since the study varied the opening of the exit ports. The sealant and gasket used in the exit port was the Petron-Multipurpose grease. It was wrapped around with insulation tape for maximum strength to avoid displacement during the build-up of pressure inside the cylinder.

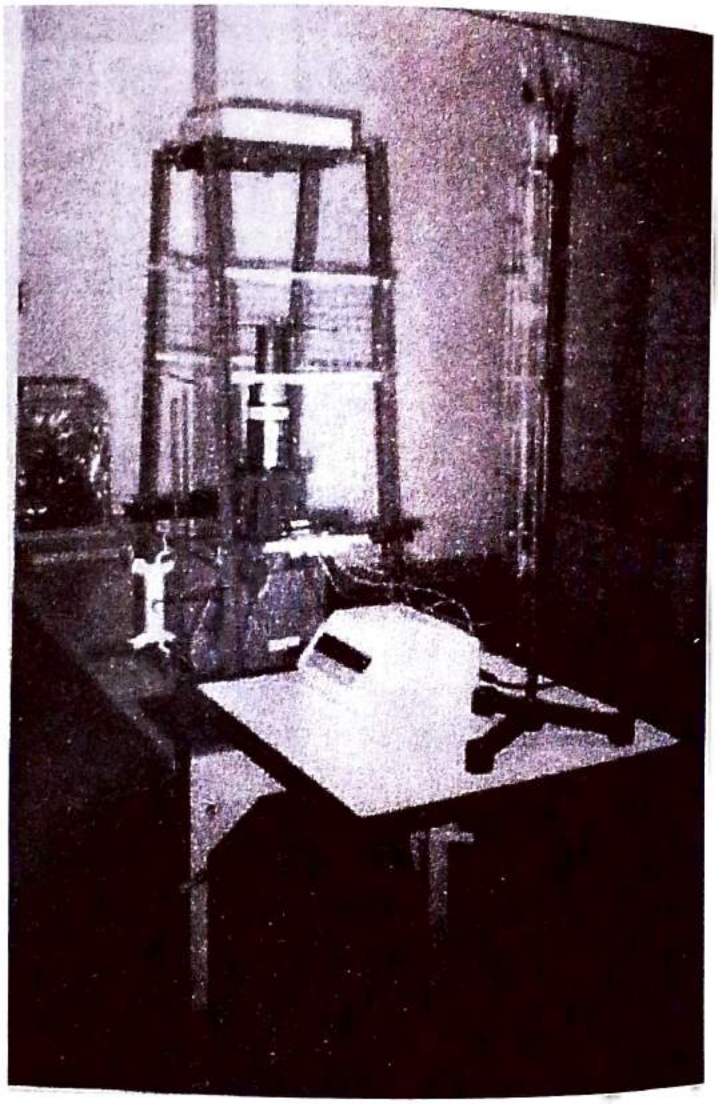


Figure 6. The over-all experimental set-up including the instrumentations

4 Results and Discussions

4.1 Theoretical Impact

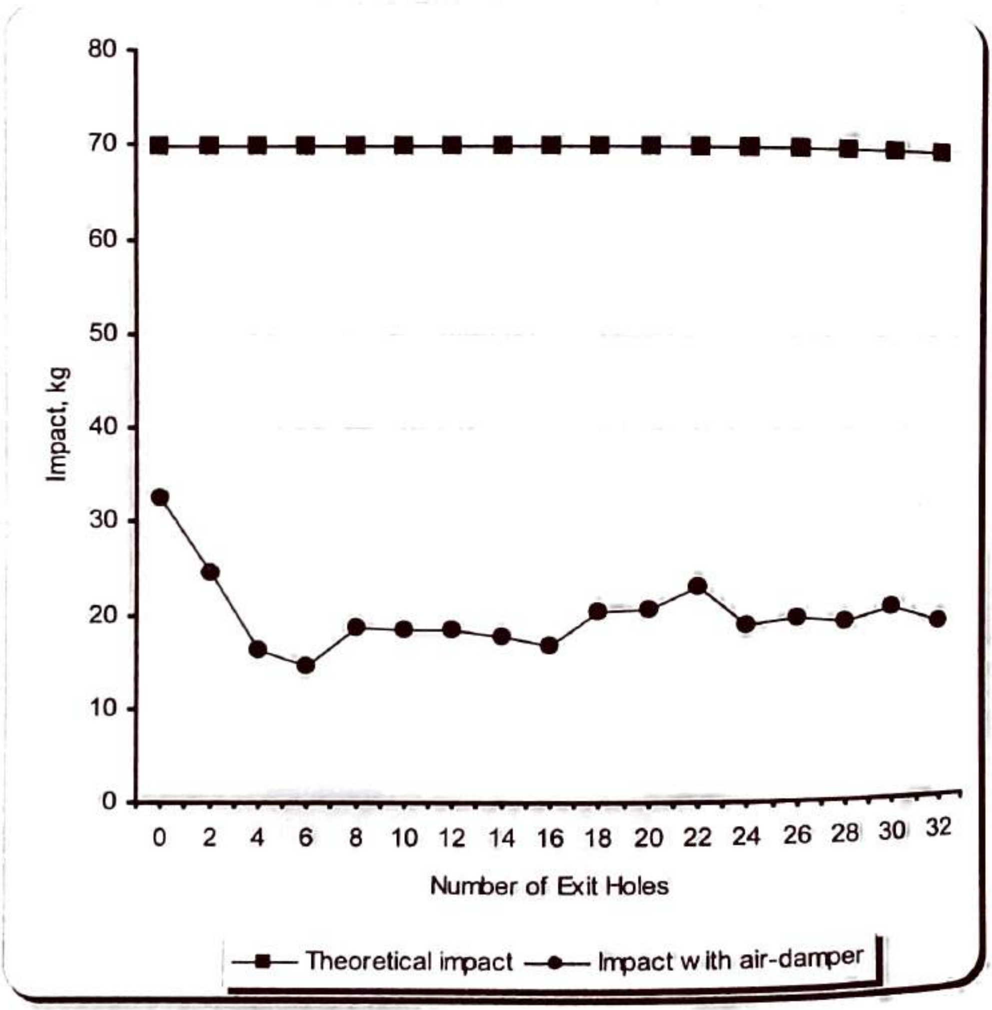
The theoretical impact was obtained using equation [3]. Table 1 shows the result.

Table 1. The theoretical impact without air-damper.

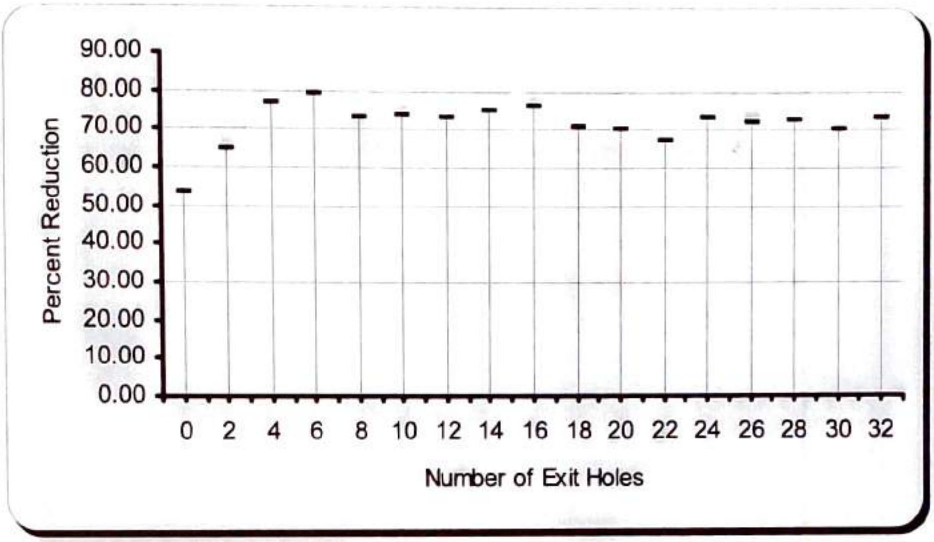
Load, (kg)	Height h, (m)	Deflection δ, (m)	Impact Effect, (kg)
1.0	0.326	0.01459	48.61
1.5	0.326	0.01803	60.09
2.0	0.326	0.02098	69.92
2.5	0.326	0.02362	78.70
3.0	0.326	0.02603	86.73

4.2 Impact with Air-Damper

The impact effect with air-damper as energy absorber at 2.0 kg, 2.5 kg and 3.0 kg for a given number of exit holes are shown in figures 7 to 9.

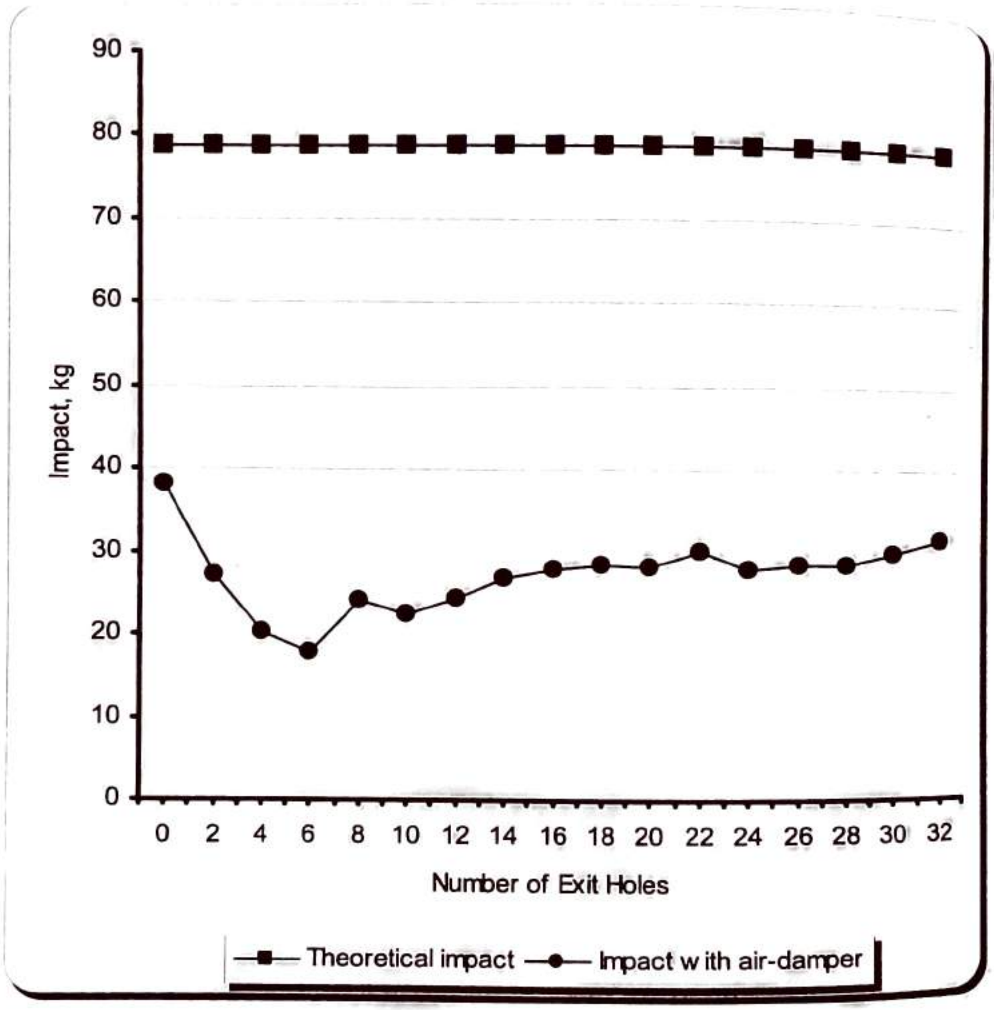

80
70
60
50
40
30
20
10
0
Impact, kg
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Number of Exit Holes
Theoretical impact
Impact with air-damper

(a)



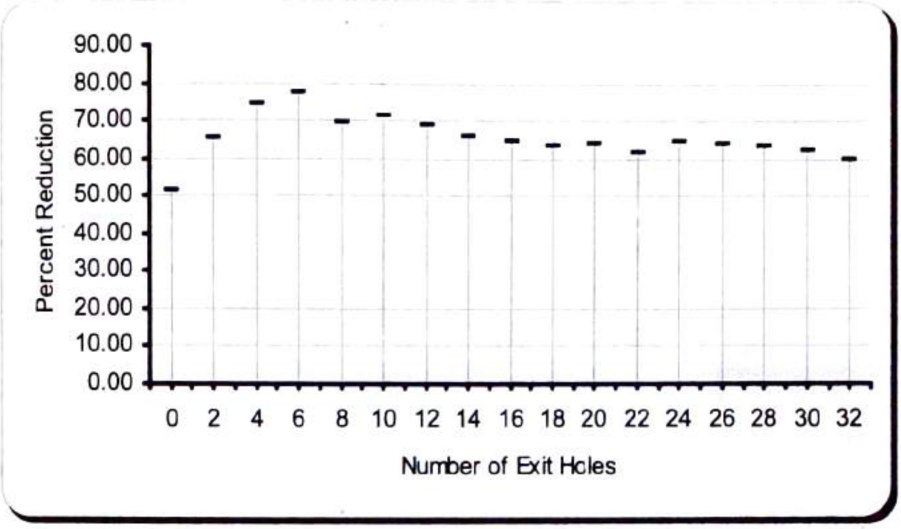
(b)

Figure 7. Impact effect at 2.0 kg loading (a) Comparison of impact with and without damper; (b) Percent reduction of impact with air-damper



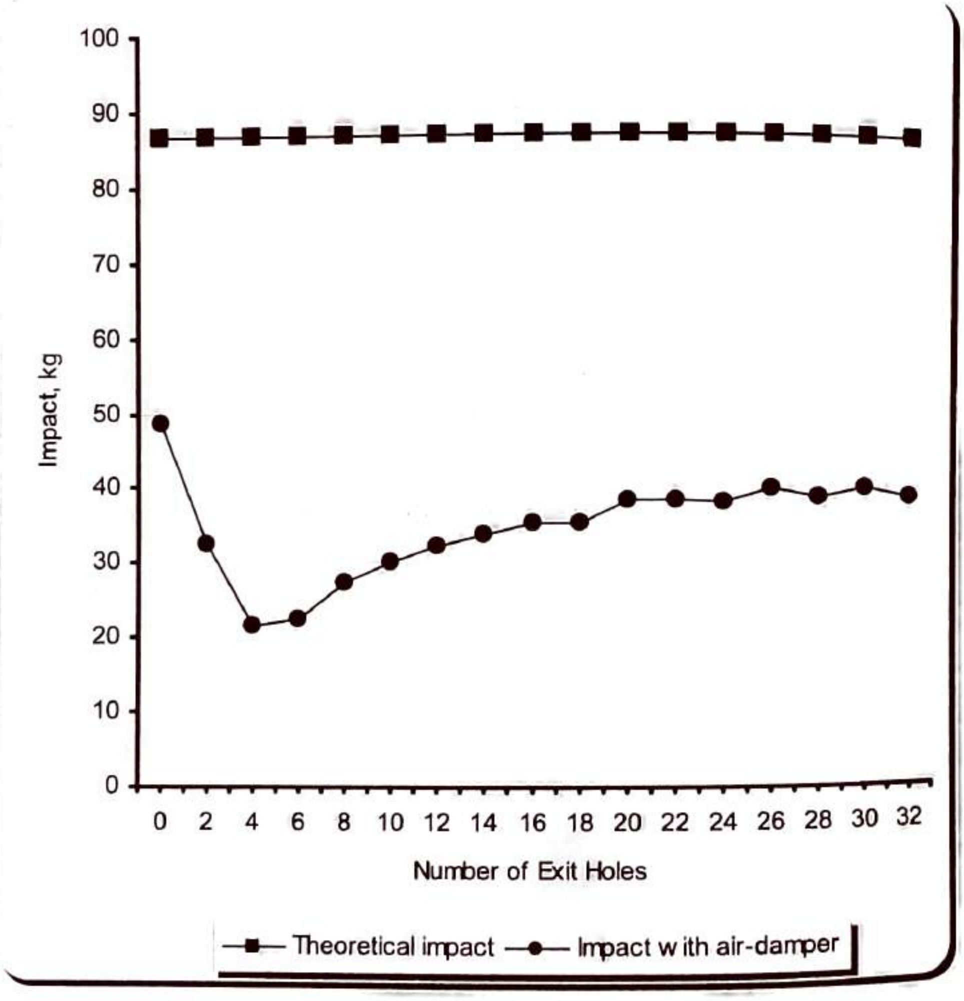
Impact, kg
90
80
70
60
50
40
30
20
10
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Number of Exit Holes
Theoretical impact
Impact with air-damper

(a)

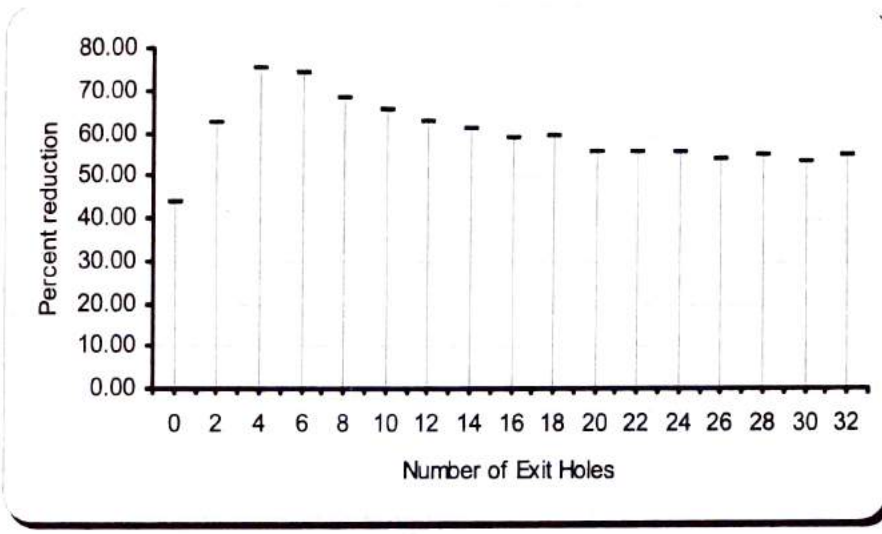


(b)

Figure 8. Impact effect at 2.5 kg loading (a) Comparison of impact with and without damper; (b) Percent reduction of impact with air-damper


100
90
80
70
60
50
40
30
20
10
0
Impact, kg
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Number of Exit Holes
Theoretical impact
Impact with air-damper

(a)



(b)

Figure 9. Impact effect at 3.0 kg loading (a) Comparison of impact with and without damper; (b) Percent reduction of impact with air-damper

For 2.0 kg, 2.5 kg and 3.0 kg loading as shown in figures 7 to 9 using two-way analysis of variance (ANOVA) F test at 0.05 level of significance the obtained p-value is equal to 1.41E-81which is less than the specified α of 0.05, then this statistical results show that the opening of exit holes affected the amount of impact produced.

Based on the results presented in figures 7 to 9 and compared to the results shown in table 1, the use of air-damper perforated with tiny holes could reduce the impact significantly.

4.3 The Relationship of Pressure and Impact

Figures 10 to 12 show that for higher impact effect, the pressure of the air inside the air-damper was also higher.

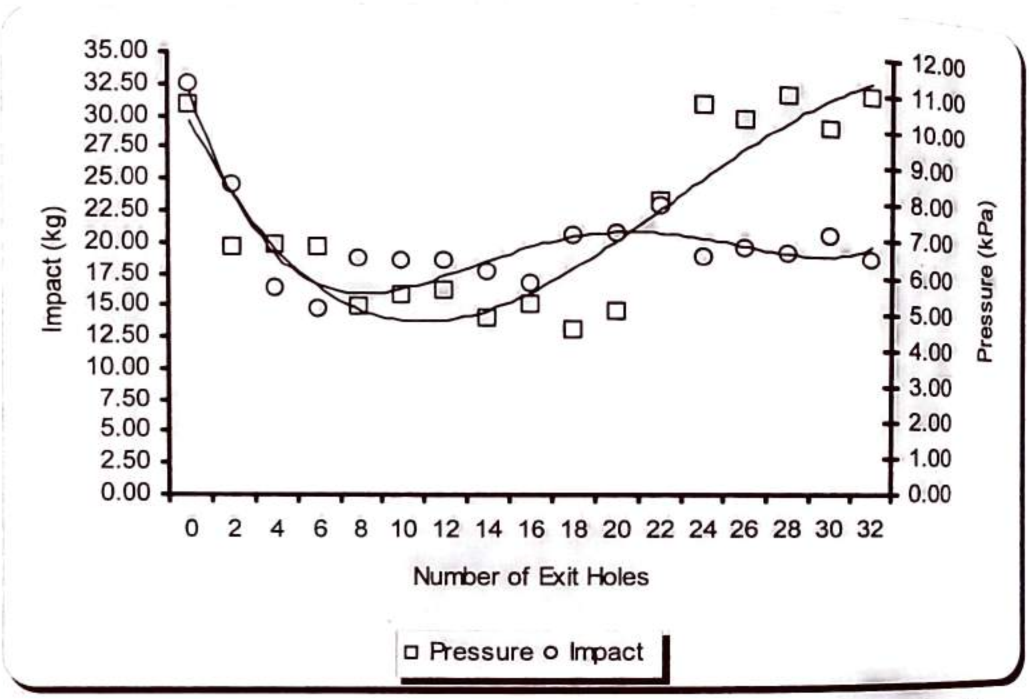


Figure 10. The pressure-impact relationship at 2.0 kg loading

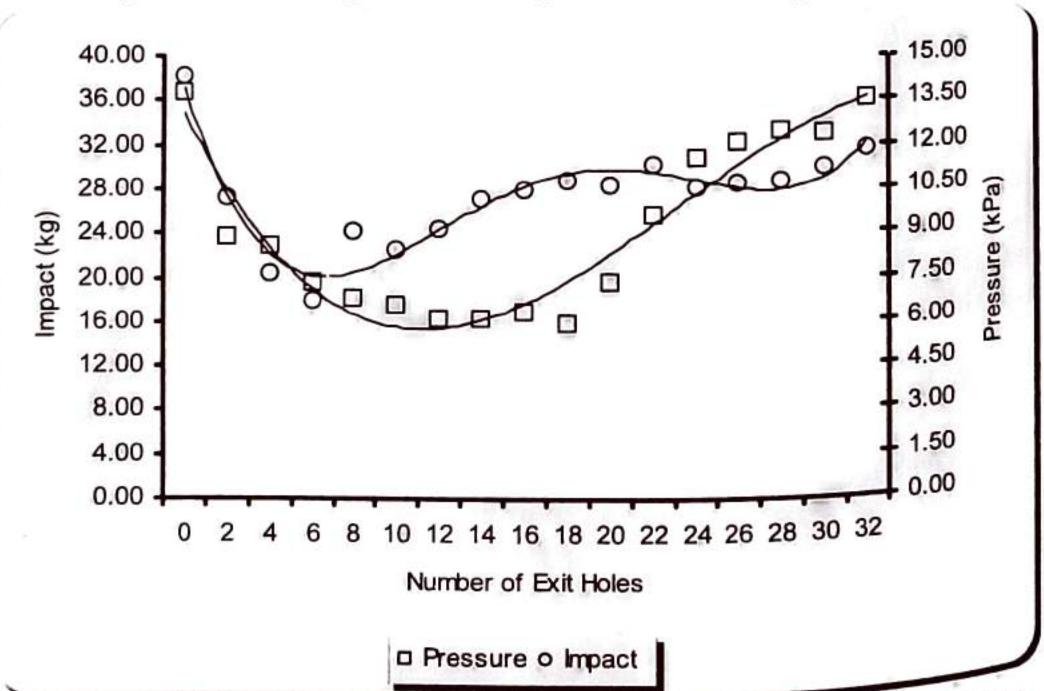


Figure 11. The pressure-impact relationship at 2.5 kg loading

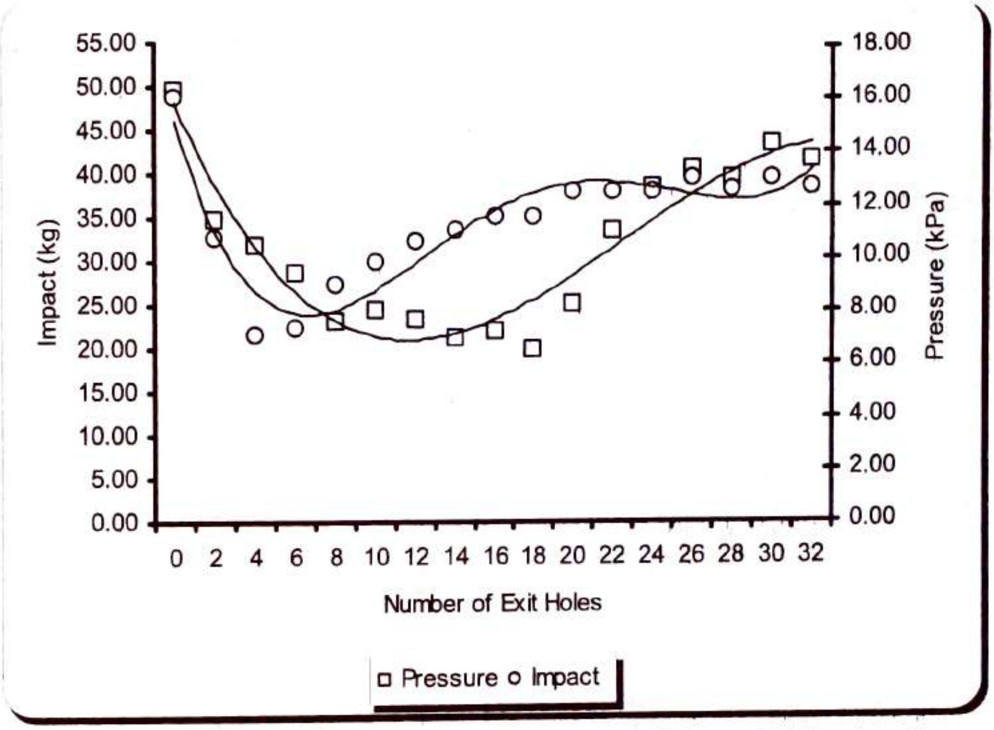


Figure 12. The pressure-impact relationship at 3.0 kg loading

Figures 10 to 12 shows that the relationship of pressure developed inside the cylinder and the impact had an agreement as discussed in theoretical foundations.

4.4 The Dissipation of Applied Energy

The applied energy was distributed to the air-damper specially to the spring which, measured the amount of impact effect and to the energy carried by escaping air. Figures 13 to 15 represent equation [4] using the data obtained from the experiment. The applied energy was distributed to energy absorbed by air-damper, lost energy carried by escaping air and the impact. From the figures 13 to 15, the lost energy carried by the escaping air was higher in the regions between zero holes and when all the holes were opened. The energy absorbed by the damper increased as the number of the holes increased. From the graphs, as the energy absorbed by the escaping air increases, the impact decreases. The amount of applied energy absorbed by the air-damper had small effect on the reduction of the impact as represented in the graphs. The major absorber of the applied energy was the escaping air; however as the amount of escaping air increases and is almost freely flowing from the damper to the outside, the impact increases significantly.

At zero holes, the deflection of the piston assembly of the air-damper was minimum since the air inside could not escape, became pressurized, opposing the applied load and resulted to higher impact. At maximum opening of holes, (thirty two holes), the

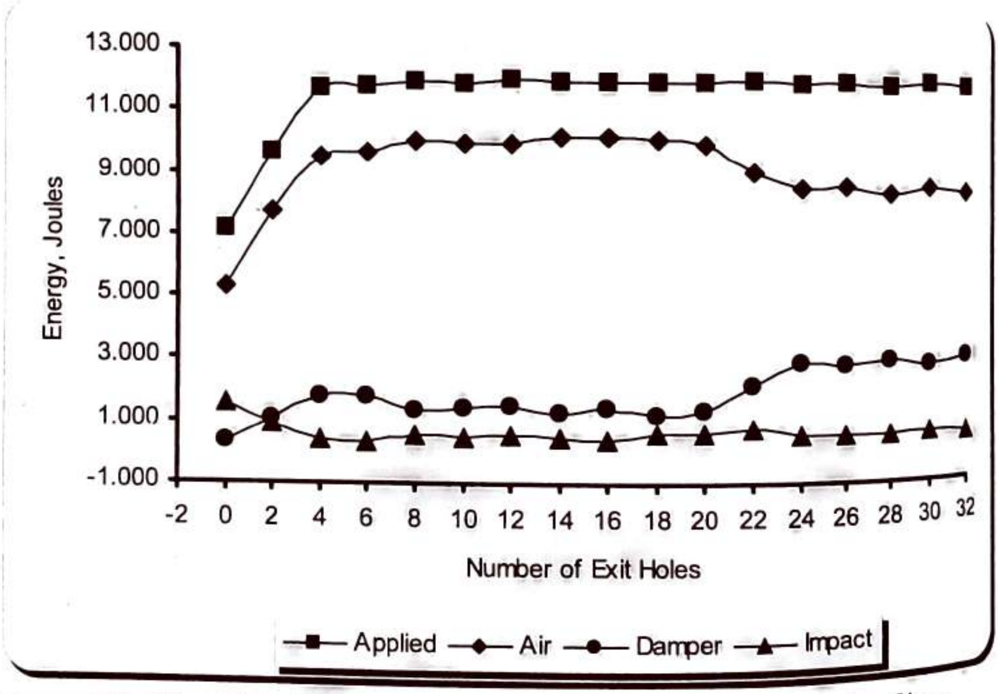


Figure 13. The distribution of applied energy at 2.0 kg loading

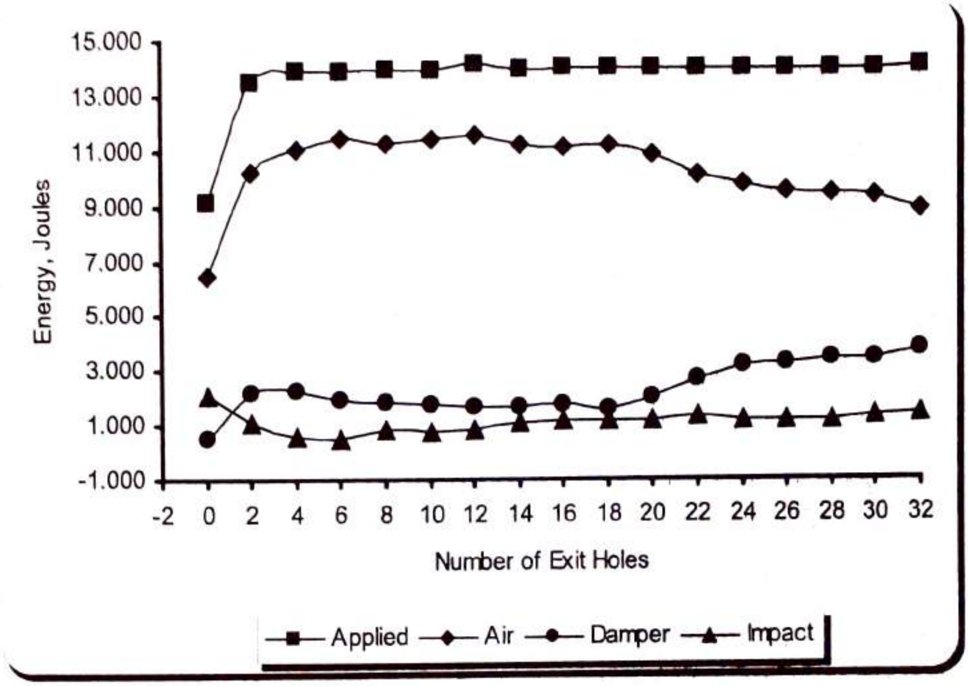


Figure 14. The distribution of applied energy at 2.5 kg loading

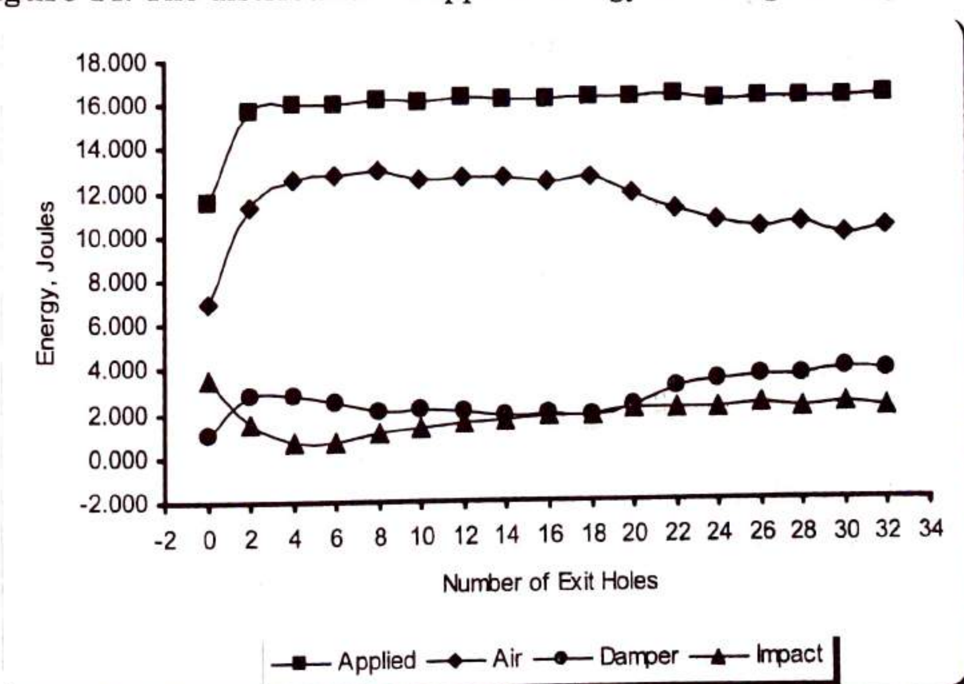


Figure 15. The distribution of applied energy at 3.0 kg loading

piston assembly touched the bottom of the air-damper causing higher piston assembly deflection. The remaining air was trapped inside the air damper at 20 mm space between the lowest level of exit ports and its bottom caused higher reading in the manometer even if all holes were opened. Higher impact effect due to the applied energy not fully absorbed by the air since it almost entirely immediately escaped was also monitored. When the piston assembly which, carried the applied load touched the bottom of the damper, the carried energy was immediately transferred to the damper, causing higher impact effect as presented graphically in figures 7 to 9.

5 Conclusions

Based on the results the following conclusions are drawn:

1. The amount of impact can be minimized by using air-damper perforated with an optimum number of tiny holes which serve as the exit ports for the escaping air.
2. There was range of optimum number of exit holes or ports in which the air inside the air-damper absorbed more of the applied energy. For 2.0 kg and 2.5 kg loading the air inside the air-damper absorbed more of the applied energy when the number of exit ports was six. For 3.0 kg loading the air inside the air-damper absorbed more of the applied energy when the number of exit ports was four.
3. Within the load range of 2.0 kg to 3.0 kg and the height of 32.60 cm the optimum number of opened exit holes was from the range of 4 to 6.
4. The impact could be minimized when the air inside the air-damper absorbed the maximum amount of applied energy.
5. The position of the exit holes or ports affected the absorption of the applied energy.

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