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''Design and Modification of vacuum braking system"

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Abstract

Vacuum brakes are first used in place of the air brake in railway locomotives. This braking system uses a vacuum pump for creating vacuum in the brake pipe. The integral construction of the brake cylinder uses this vacuum reservoir for the application of brakes. Nowadays most of the light vehicles are fitted with vacuum-assisted hydraulic braking system where vacuum is created from the engine which reduces the driver effort on foot pedal.

The vacuum braking system was modified from above said reasons and the same was tested for implementation in both light and heavy vehicles. In this work, vacuum is created and used for the application of brakes. The system operation is somehow similar to air braking system. The main difference with air brake system is that vacuum is used instead of compressed air. The design and modified system also includes the Vacuum brake system i.e., the loss of vacuum will cause the brake to be applied due to spring force.

Key words: *Air braking system, Fail safe condition, Heavy vehicle, Hydraulic brake, Light vehicle, Vacuum braking system* .

1. Introduction

Brakes are mechanical devices which increases the frictional resistance that retards the turning motion of the vehicle wheels. In vacuum assisted hydraulic brake system, a constant vacuum is maintained in the brake booster by the engine. When the brake pedal is depressed, a poppet valve opens and air pushes into the pressure chamber on the driver's side of the booster.

Vacuum braking system uses the vacuum for the application of brakes. Many research works were carried out in the area of vacuum brakes. Some of them are briefly explained below.

Bartlett [1] worked on the vacuum-powered brake booster in a passenger vehicle becomes disabled, the brake force gain of the system is reduced significantly, and the brake pedal force required to lock the tires increases beyond the ability of some adults. In such cases, the maximum braking deceleration achieved by those individuals will be something less than the upper boundary as defined by available traction.

Goto et al [2] developed the optimal braking effect and feel for the brake master cylinder for the heavy vehicles. In this, braking effect was enhanced during a vacuum failure condition by operating the smaller bore. Thus, the vacuum failure detection and the increase output pressure are performed mechanically. By this development, it has contributed to the design of the optimal brake system.

Shaffer and Alexander [3] determine whether the performance-based brake testing technologies can improve the safety of the highways and roadways through more effective or efficient inspections of brakes of the road commercial vehicles. However, the performance-based technologies were able to detect a number of brake defects that were not found during visual inspection.

Saeed Mohammadi and Asghar Nasr [4] found that for the heavy haul trains. Coupled often, there is no alternative to the air brake system. In these trains, the cars at the end of the train brake a few seconds later than those at the front. The time delay between the braking of the adjacent cars depends very much on the transmission speed of the pressure wave (brake signal) in the main brake pipe, which is about 10-25% less than the speed of sound in free air. The later braking of the cars at the rear of the trains means that the rear cars run into the front cars, producing large compression forces on the buffers and couplings. These compression forces are longitudinal in nature and are considered to be responsible for large amount of expenses regarding rolling stock and track sub- and super-structures repairs, as well as the deterioration of safety operation of the trains.

Chinmaya and Raul [5] suggested a unique of decoupling feature in frictional disk brake mechanisms, derived through kinematic analysis, enables modularised design of an Anti-lock Braking System (ABS) into a sliding mode system that specifies reference brake torque and a tracking brake actuator controller. Modelling of the brake actuation, vehicle dynamics, and control design are described for a scaled vehicle system. The overall control scheme is evaluated by hardware-in-the loop testing of the electromechanical brake system.

Bharath et al [6] deals with nonlinear lumped multicapacity models with train pipe capacity and brake cylinder capacity lumped separately to predict pressure rise in the pneumatic brake cylinders for step the type of pressure input. The first model is a two-capacity system in which all the brake cylinder capacitances and the entire pipe line capacitance are lumped separately. The second model is multicapacity system in which the train pipe capacitance between the brake cylinders of adjacent wagon is lumped near the brake cylinder capacitance in each wagon separately. The third model is also of multicapacity type, similar to the second model, but it includes the effect of varying brake cylinder capacity in its formulation.

Chen et al [7] took up the traditional purely hydraulic braking pedal features the research object. The brake pedal control model of the regenerative braking integrated system is established by using trajectory tracking control strategy. The simulation results showed that, the model can achieve a predetermined vehicle brake pedal feel, and get the brake demand and pedal feel demand by the resolving the brake pedal state motion. The research also provides a theoretical basis for the design of regeneration brake pedal system for the electric vehicle and hybrid vehicle.

Lie and Sung [8] investigated the braking performance and safety for a bicycle riding on a straight and inclined path. The equations of motion for a wheel model as well as for the ideal synchronous braking are derived to acquire the shortest braking distance to improve the riding stability. The optimal design of the bicycle braking is obtained based on the simulation results with various bicycle geometries, ratios of brake force, and road friction.

Park et al [9] attempt to establish an analytical tool to evaluate the braking feel to help optimal design of brake systems. First, mathematical models of brake systems are developed and are confirmed through computer simulations. Second, mechanical impedance at brake pedal is modelled based on the developed brake system models. The brake pedal feel is represented in the form of impedance surface. Third, to provide a guideline to design optimal braking feel, relations between pedal force, pedal stroke and vehicle deceleration are investigated. An expert test driver's evaluation process is modelled based on his subjective ratings of brake systems. Moh Nasr [10] study of focused on the noise generation by the actuation part of the brake system, specifically the vacuum Mastervac. In this paper the noise types, their acoustic signatures in both time and frequency, as well as the current acoustic treatment impact, were discussed with the objective of establishing a common and standardized terminology.

Ding et al [11] developed providing an efficient and reliable means of friction and pressure estimation algorithm, based on wheel speed signals and control commands for hydraulic valve operation. Estimated results are achieved by comparing the sums of squared speed errors between the measured wheel speeds and those based on the brake pressure model and wheel dynamics. Performance of the algorithm is evaluated using ABS test data under various braking conditions.

Yang and Hong [12] consider the braking force produced by tugboat has been scarcely examined and little data on the proper characteristics of the braking force were obtained. In that work, the braking force characteristics of tugboat-self in braking condition are obtained and the related unstable phenomena is pointed out and analyzed according to the results of model experiments. Furthermore, some new understanding on the braking operation using tugboat was predicted. Liang and Chon [13] modified the sliding control with variable control parameter was introduced to reduce the large change of pressure feedback in the hydraulic brake control process of automated highway vehicles. An average decay function was used to smooth both the high and low frequency oscillations of the desired diaphragm force and output force in the vacuum booster to remedy the oscillations generated by using the pushrod force at the end-brake control. Simulation results indicate that the variable parameter sliding control significantly reduces the speed and space tracking errors in the large brake processes, and the errors experienced during these processes are dominated by the large brake pressure lag rather than the switching delay time between throttle and brake.

2. Construction of vacuum braking system

Vacuum braking system as shown in fig .1 consists of brake cylinder, compressor, vacuum reservoir, direction control valve, flow control valve, brake hoses, brake linkages, drum brake and foot brake pedal.

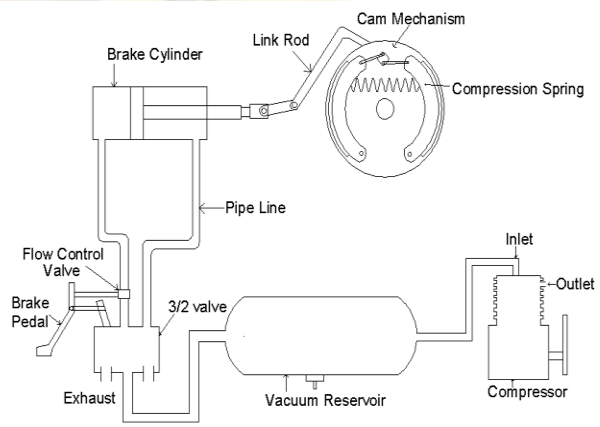
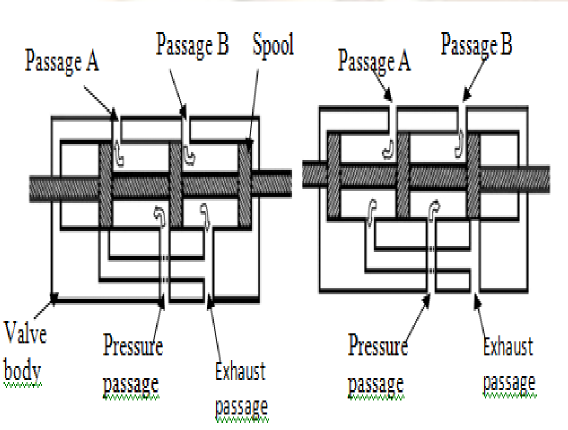


Fig .1 Vacuum braking system

2.1 Direction control valve

The direction control valve is as shown in fig .2 (a) and (b) are used in this works to change the direction of air flow to and from the cylinder. The moving parts in the directional control valve will connect and disconnect internal flow passages within the valve body. This action results in control of airflow direction. The typical directional control valve consists of a valve body with four internal flow passages within the valve body and a sliding spool. Shifting the spool alternately connects a cylinder port to supply pressure or exhaust port. With the spool in the where the supply pressure is connected to passage A and passage B connected to the exhaust passage, the cylinder will extend. Then with the spool in the other extreme position, Supply pressure is connected to the exhaust port, now the cylinder retracts. With a directional control valve in a circuit, the cylinder piston rod can be extended or retracted and work will be performed. The working of direction control valve is shown in fig .2 (a) and (b).



(a) **(b)**

Fig .2 Working of direction control valve

2.2 Flow control valve

A flow control valve is as shown in fig.3 consist of a disc which opens and closes the two way connection between the 3/2 valve and brake cylinder. Operation is similar to that of a butterfly valve, which allows for quick shut off. The disc is positioned in the Y-shaped pipe, passing through the disc is a rod connected to an actuator on the outside of the valve. The need of flow control valve is for partial braking. When the valve is closed, the disc is turned so that it completely blocks off the passageway between the atmospheric path and brake cylinder.

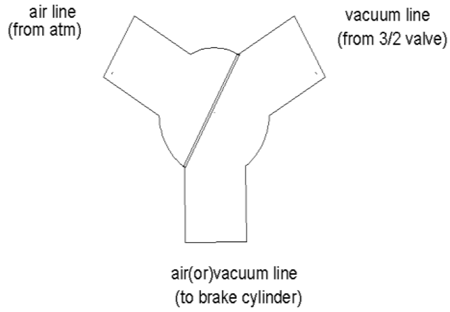


Fig.3 Flow control valve

2.3 Drum brake

Drum brake system may be of either design in practice, but the twin leading design is more effective. This design uses two actuating cylinders arranged in a manner, so that both shoes will utilize the self-applying characteristic when the vehicle is moving forward. The brake shoes pivot at opposite points to each other. This gives the maximum possible braking when moving forward, but is not so effective when the vehicle is in reverse mode.

The wheel cylinder and retractor spring of the drum brake is removed and suitable compression spring is fixed. The spring is placed in between the two cups so that it seats properly. The modified drum brake assembly is shown in fig.8. Flat shaped cam is made up of hard steel material is linked to the rectangular shaped plate made up of steel sheet are attached with the top ends of brake shoes. The other face of the cam is joined with L shaped link rod which is mounted with the piston rod end. The principle of vacuum brake is based on the pressure difference created in the actuator i.e. the brake released with a full vacuum and the brake applied with vacuum and spring force. The term "vacuum" is used to describe the region of pressure below one atmosphere of pressure, also referred to as negative pressure. The pressure in the atmospheric is defined as 0.1 N/mm^2 and reducing atmospheric pressure to zero pressure creates a near perfect vacuum which is measured as 735 mm of mercury.

The brakes are always in released condition with vacuum until the driver pushes the brake pedal. In this condition, position of piston is in cap end of the brake cylinder and cam is twisted for compressing the spring which provides free rotation of drum. When the driver pushes the brake pedal slowly then the flow control valve opens slightly to the atmosphere. Loss of vacuum causes the brake to be applied due to spring force. When the flow control valve opens fully then alternatively the direction control valve lever is moved to forward direction. The direction of flow is changed and atmospheric air enters through the exhaust port of direction control valve to piston cap end. Due to pressure difference the piston moves backward with vacuum and spring force. The movement of link rod attached with piston rod releases the cam to normal position which makes internal resistances for the brake shoes against drum. This applies the brake.Fig.4 shows the brake is applied condition.

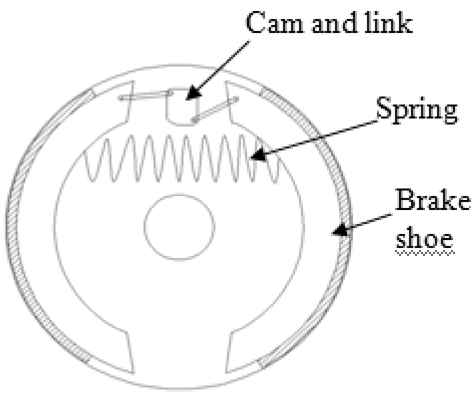


Fig.4 Cam and link mechanism after during brake

When driver releases the brake pedal, the valve lever comes back to initial position. The direction of flow is again changed and atmospheric air enters through the exhaust port of direction control valve to piston rod end. Due to the pressure difference, the piston moves forward with vacuum. The movement of link rod attached with piston rod twists the cam and compresses the spring to provide enough clearances between brake shoes and the drum. This releases the braking action. Fig.5 shows the brake in released condition.

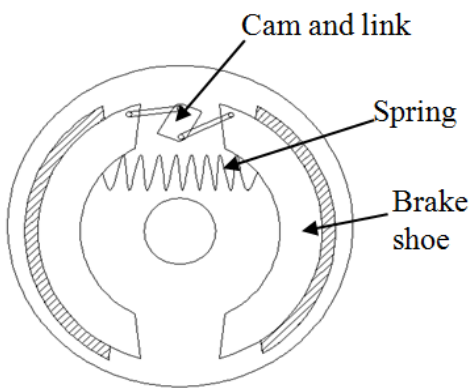


Fig.5 Cam and link mechanism the release brake

2.4 Design and modification of components

2.4.1 Dimension of brake drum

Material Chosen : High carbon steel (C95 steel)

Physical properties of high carbon steel:

Shear stress = 570 N/mm^2

Modulus of rigidity = 7.7$\times$10^4 N/mm^2

Force developed on brake shoe, F = P x A

The dimension of brake drum is shown in fig. 6

Width of brake shoe, w = 39 mm

Radius of brake drum, r = 115 mm

Area of brake shoe, A = $2\pi r \times \frac{2\theta}{360} \times w$

= 16438 mm^2

Assume safe pressure, p = 0.20 N/mm^2

(From Design Data book)

Force developed, F = 0.20$\times$164384

= 3288 N

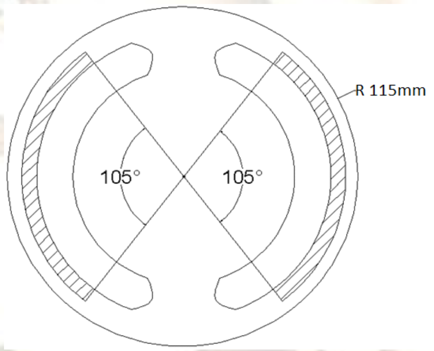


Fig. 6 Dimensions of brake drum

2.4.2 Design of compression spring

Spring was designed using standard formulae as listed in the table.1.

Table 1: Specification of spring parameter

Spring parameters	Values
Safe pressure(p)	0.2 N/mm^2
Spring index(C)	4
Wahl's stress factor, K_s	1.40325
Stress ($_y$)	570 N/mm^2
Standard size of wire diameter(d)	9 mm
Mean coil diameter(D)	36 mm
Deflection(y)	20 mm
Stiffness(q)	164.4 N/mm
Number of active turns(n)	8
Total number of turns(N)	10
Solid length(L_s)	90 mm
Free length(L_f)	110 mm
Pitch(p)	12.22 mm

Fig.7 Compression spring

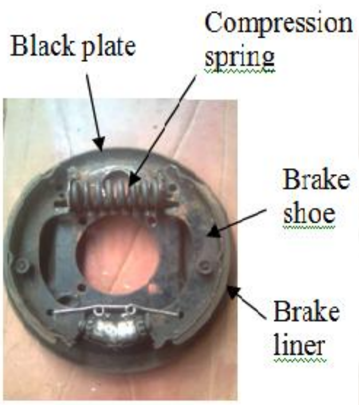


Fig.8 Modified Brake Assembly

According to this specification the required spring is purchased. The manufactured spring is shown in fig.7.After designing the compression spring, it is fitted in modified brake assembly as show in fig.8.

2.4.3 Design of cam mechanism

Consider the brake applied condition, the force developed by the piston rod to brake shoes transmitted through link rod and the cam mechanism. The design of cam and links photo view is shown in fig.9.

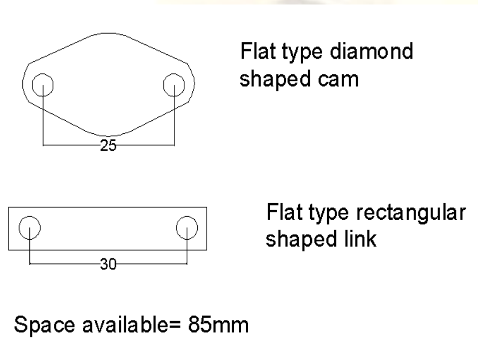


Fig.9 Design of cam and links

2.4.4 Design of brake cylinder

Each wheel has one brake cylinder. The atmospheric airs in brake cylinder, connecting hoses, vacuum reservoir are removed by suction force created by the compressor. The specifications of brake cylinder is shown in fig.10.The following assumptions were made during the design of brake cylinder are listed in the table 2.

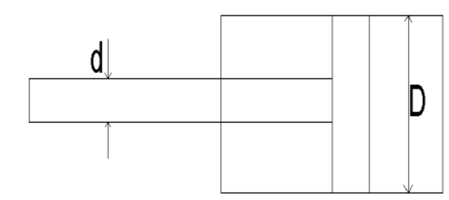


Fig.10 Design of brake cylinder

Table 2: Specification of brake cylinder

Properties	Values
Vacuum pressure	0.01 N/mm^2
Cylinder diameter	D=4d

According to the nearest standard diameter, cylinder size is taken as 200 mm.

2.4.5 Design of brake pedal linkages

The linkage is a mechanical lever with one side pivoted to the pedal and the other end to the 3/2 valve lever. The return force is applied by torsion spring which is hinged to the frame. The brake pedal is also linked with another valve known as flow control valve which functions like as butterfly valve. The function of brake pedal is shown in fig.12.

2.4.6 Design of L-shaped link rod

A mechanical link rod is an assembly of bodies connected together to manage forces and movement. The movement of a body, or link, is studied using geometry, by considering link as rigid.

Material chosen: Steel rod
Assume stress = 20 MPa
= 20 N/mm^2
Load subjected = 3288 N
Cross sectional area, A = F/ A
= 3288/20
$4\,d^2$ = 164.4
d = 14.46 mm
= 15 mm

One end of the L shaped link rod is bolted with the piston rod end of the brake cylinder and the other end is pivoted with the cam mechanism. The photo view of fabricated link rod is shown in fig.11.

Fig.11 Link rod

2.4.7 Frame

All the components are assembled on the frame and it prevents the components from any misalignment. The following components were used for the fabrication of vacuum brake system are listed in table 3, fabricated model photo view as show in fig.12.

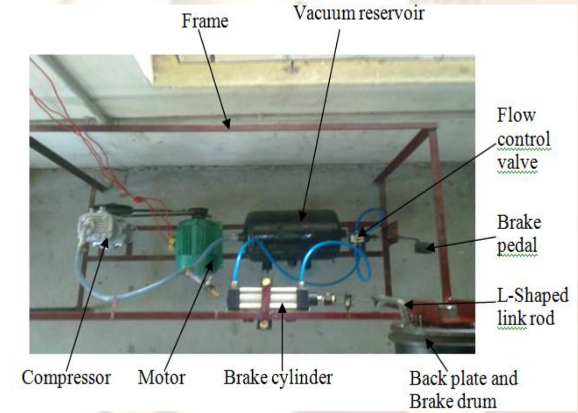


Fig. 12 Fabricated models

3. Results and discussion

3.1 Effect of air pressure on spring tension

Fig.13 shows the plot of spring tension Vs air pressure. Initially the spring tension is 3200 N at 0.1 bar of air pressure. As the air pressure increases in steps of 0.2 bar, reduce to approximately 1 N at 1 bar air pressure, because of air pressure increases the spring tension decreases. The spring is held in the compressed state by the vacuum generated by the suction effect of the compressor. As the spring is released from the compressed state, the brake gets applied.

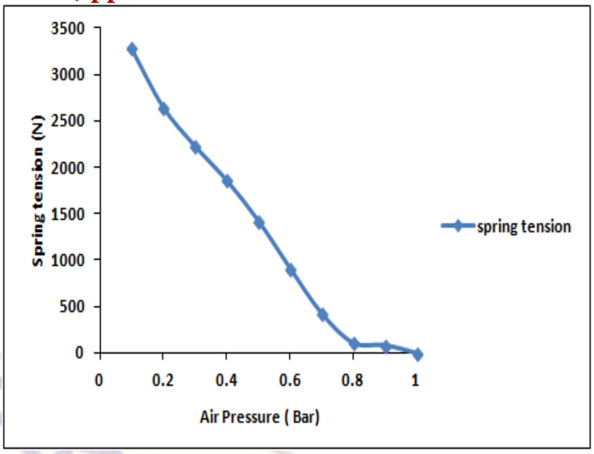


Fig.13 spring tension Vs air pressure

3.2 Effect of air pressure on brake force

Fig. 14 shows the plot of brake force Vs air pressure, the brake force increases with increase in air pressure. The increase in pressure permits the spring to be released from its compressed state, allowing the brake shoe to press upon the brake drum leading to application of brake. From the graph, it is clear that as the air pressure Increases in steps of 0.2 bar, the brake force increase to 10000 N at 1 bar air pressure.

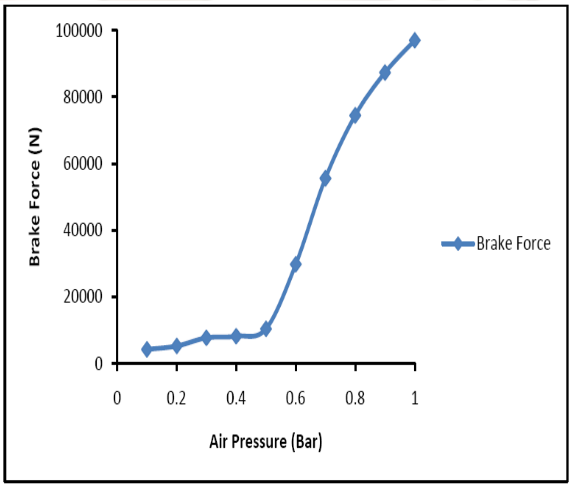


Fig. 14 Brake force Vs air pressure

3.3 Effect of spring tension on total force

Fig.15 shows the total force Vs spring tension, it is apparent that as the spring tension increases, the total force that is the normal force acting on the contact point between the brake shoe and the brake drum decreases. The spring tension is the indirect indicator of the state of the spring i.e., whether the spring is compressed or extend. From the graph, it is evident that, the total force is 20000 N initially. As the spring tension increases in steps of 500 N, the total force reduces to zero at 3300 N spring tension.

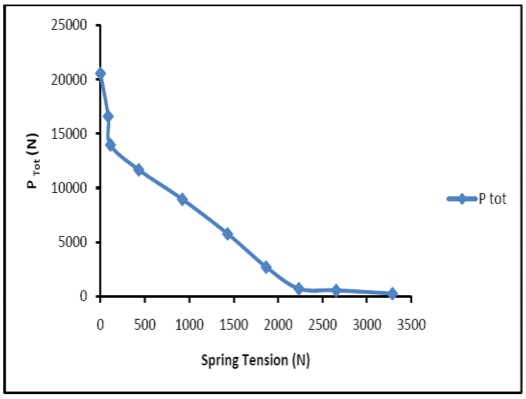


Fig. 15 Total pressure Vs spring tension

3.4 Effect of spring tension on brake force

Fig.16 shows the brake force Vs spring tension. It is apparent that with the increase in spring tension, the brake force reduces. As mentioned in the previous discussion that the spring tension is maximum since, it is in the compressed state by the suction created by the vacuum. From the graph it is understandable that at the initial stage the brake force is 100000 N.As the spring tension increases in steps of 1000 N, the brake force reduces to 2000 N at 3400 N spring tension.

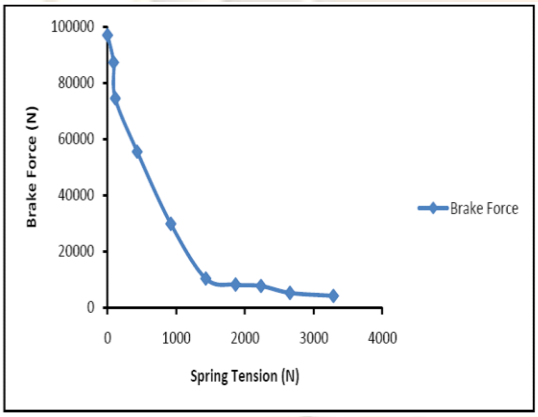


Fig. 16 Brake force Vs Spring tension

4. Conclusions

The design and fabrication of a braking system is a difficult and great task. The application of brakes using vacuum in automobiles was a difficult in the initial stages of the work. But it has been successfully proved that such brake application is possible with fail-safe condition. By implementing this idea on a heavy vehicle, it is better to replace the manually operated direction control valve with solenoid operated direction control valve to reduce driver effort and also it will also work like a brake pedal switch.

The main advantages offered by the vacuum braking system are:

- This system provides fail-safe condition.
- Compressed air can be produced.
- Less noise.

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