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A Review on Technologies of Passive Suspension System with Variable Stiffness

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***Abstract*— The parameters of the passive suspension system should be such that they provide an optimized ride comfort and ride stability. As the suspension characteristics such as stiffness and damping coefficient etc., are static, no much improvement was possible. There was a requirement for these characteristics to be varied dynamically to achieve ride quality and ride stability. Hence suspensions with variable stiffness were introduced. This paper reviews technologies involved in passive suspension system having variable stiffness using the patent data.**

Keywords—variable stiffness; passive suspension; spring; coil; ride stability; ride comfort

I. INTRODUCTION

The history of the suspension dates back to 1333 BC in the Tutankhamun era where the chariots had tunable spring-damper suspension system with ball joint and damped split axle for semi-independent suspension [1]. The Romans too were way ahead of their time. They used leaf springs on their two wheeled vehicle called a Pilentum. The first steel spring mounted on a vehicle was a single flat plate used in the 18th century. As the need for a better and improved suspension was felt, inventors came out with leaf and spring suspensions. One such leaf spring called the venerable leaf spring was invented by Obadiah Elliot of London in 1804. The first patent (British Patent: 792) on coil spring was issued to R. Tredwell in 1763, which is being used widely till date [2]. The suspension system has evolved from Tutankhamun's era to Roman's Pilentum to first conventional spring suspension, in terms of stability and comfort. The advent of crude shock absorbers in 1897 by A. Gimmig and that by Truffault in 1898 paved way for improved ride quality and ride comfort [3]. Since then many improvements were made, to achieve the required compromise between ride quality and ride stability. One such improvement was the use of variable stiffness suspension systems. Conventional passive suspension systems having a spring of single stiffness are unable to sustain variable loading conditions of the vehicle [4]. A heavy load vehicle having a stiff suspension will be able to perform when the vehicle is loaded but will be considerably stiff in the unloaded condition compromising on the ride comfort. On the other hand a heavy load vehicle with softer suspension will provide comfort during unloaded condition but when loaded, the ride height would decrease with little or no suspension effect. In order to avoid this, spring with variable stiffness were introduced, which would provide ride comfort and ride stability. The paper briefly discusses active and semi-active suspension systems along with a detailed discussion on technologies of passive suspension system with variable stiffness.

II. ACTIVE SUSPENSION

Active suspensions are suspensions with actuators alone or with optional passive components i.e. spring and damper assisted by actuators. The efficiency of active suspension is more as compared to semi active and passive suspension. An example of active suspension is a Bose suspension that uses linear electric motors instead of conventional spring- damper, system. Sardellitti et.al.[5] proposed an approach for controlling stiffness of variable stiffness actuator using linear quadratic regulators. Though the active suspension provides the best of comfort and ride stability, it comes at a price of high cost and energy consumption.

III. SEMI-ACTIVE SUSPENSION

Semi active suspensions are suspensions with passive components having characteristics to adjust damping coefficient.

Magneto Rheological (MR) fluids have been identified as unique element for suspension system. The properties of the fluids are such that they can be controlled by magnetic field. The fluids have suspended magnetic particles which align themselves on the application of the magnetic field. As the motion of the particles is magnetically controlled, the damping of the suspension can be controlled i.e. the damping has variable characteristics. Dong Xiao-min et.al.[6] pointed out few drawbacks of using MR fluid which included particle settling and wear of magnetic particles. Additionally the use of MR fluids required seals to prevent leakage eventually increasing the cost of the entire system. Dong suggested MR elastomers as an alternative to MR fluids. It was concluded that the MR elastomer could reduce vibration in a wide frequency range. Xingyu Wang et.al.[7] pointed out that using air springs, valve in cylinder device or two MR controllable dampers were complicated and less reliable. Xingyu suggested the use of MR valve, connected to two stiffness units, to regulate damping by controlling the said MR valve. P.B. Benschop [8] investigated system with continuously adjustable suspension and suspension with discreet values of adjustments. It was found that chassis acceleration could be reduced upto 50% of the passive value.

IV. VARIABLE STIFFNESS PASSIVE SUSPENSION

Suspensions using conventional spring damper system are passive suspensions. Lot of research has been undertaken in developing suspension system with varying stiffness. The prime reason for this is that the passive suspension has always been a low-cost and a low-energy system.

Joseph Jerz Jr. [9], described a variable stiffness suspension system, as shown in Fig. 1, having two springs 16a and 17a arranged in series. The springs are connected by a clamp 18a. Spring 16a is stiffer than spring 17a. On application of load, lower spring 17a compresses rapidly. The cross sectional and coil diameter of spring 16a is more than that of spring 17a. The upper end of spring 17a and lower end of spring 16a are seated in the clamp 18a. The lower end of spring 17a is seated in the spring seat mounted on the unsprung mass 14a while the upper end of spring 16a is seated in the spring seat mounted on the sprung mass 13a. The spring assembly is placed on a shock absorber 49. The shock absorber cylinder has two stopper elements 56 and 57 placed on either sides of clamp 18a. The stopper elements are further placed between flanges 62 on either side. The stoppers restrict the compression of spring 17a, which is a softer spring, on application of light load. When the load increases further, spring 16a starts compressing to sustain the increased load condition. Thus the suspension system is in a position not only to sustain increased load but also vary the stiffness according to the load.

In yet another disclosure by Joseph Jerz Jr. [10] overload springs 14 in parallel arrangement along with conventional spring 13 is described (Fig. 2). The overload spring system shown in Fig. 3 comprises of a higher stiffness spring 15 and a lower stiffness spring 16 arranged in series around a shock absorber 37. The upper end of spring 15 is connected to sprung mass while the lower end of spring 16 is connected to unsprung mass. The upper and lower clamped coils of spring 15 and 16 are secured annularly instead of being secured helically. The lower end of spring 15 is connected to stopper element 27. The axial thickness of the flange is increased by mounting two annular shims 28 and 29. The upper end of

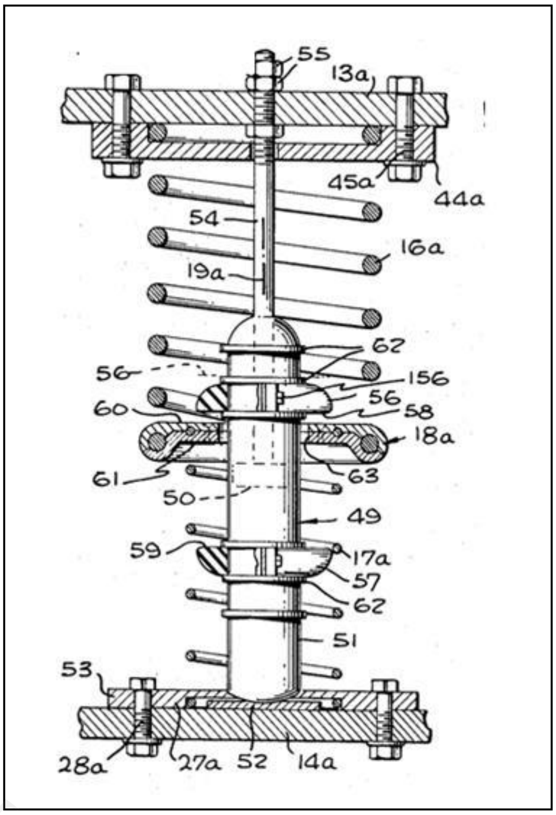

Fig. 1: Series Arrangement of Spring with Stopper and Flanges [9]

spring 16 is spaced vertically apart from shim 28 or to stopper element 27, if shim 28 is dismounted. In the normal loading condition the conventional spring controls the riding characteristics. When the load increases, overload spring system 14 comes in action. Initially the spring 16 of the system comes into play and the shim 28 moves downwards until it comes in contact with stopper 135, preventing the compression of spring 16. Spring 15 starts compressing at this point. Thus spring 16 and spring 15, along with the annular shims provide for a variable stiffness as each spring compresses variably depending on the load.

James Aardema [11], discloses multiple tapered plates 38, 40 and 42 as shown in Fig. 4. The sides with tapered edges protrude between the two adjacent coils of the spring 12. The plates are mounted on the bolts 28. These bolts can move sideways, i.e. towards and away from the spring. This movement of the tapered plates constrains the motion of the spring, changing the spring stiffness. The movement of the plates towards the longitudinal axis of the spring increases the stiffness and that away from the plate decreases the stiffness. The length of the plates decreases from top to bottom and

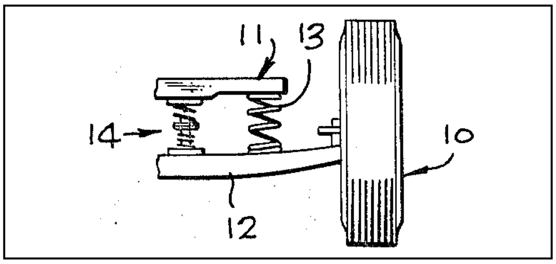

Fig. 2: Parallel Arrangement of Springs [10]

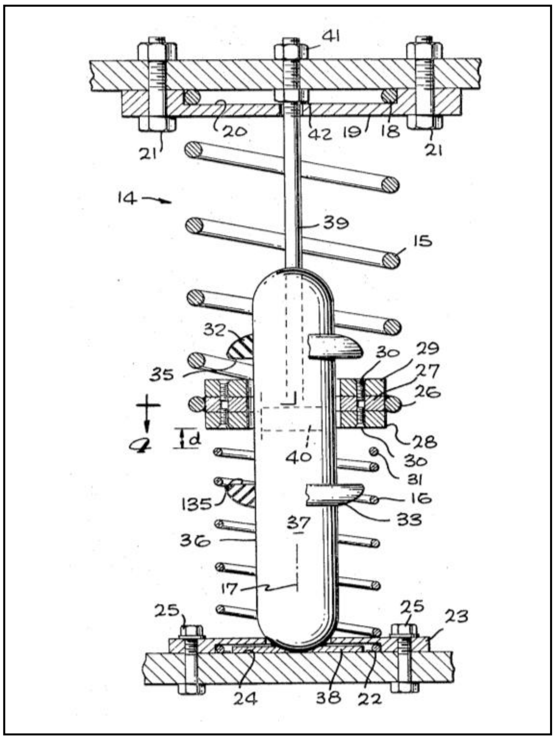

Fig. 3: Overload Spring System [10]

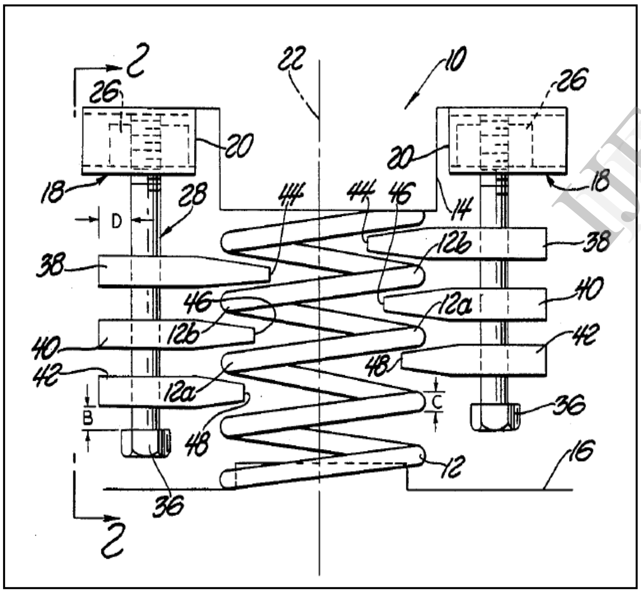

Fig. 4: Coil Spring Suspension with Tapered Plates [11]

therefore the engagement of the plates with the coils will differ along the length of the spring. This provides a progressive stiffness to the spring. In the Fig. 4, 12a and 12b represents locked coils due to the insertion of the tapered plates, thus rendering coils beneath 12a as active coils.

Mauro Bianchi [12], discloses a spring suspension with flexible armoring as shown in Fig. 5. Suspension has a helicoidal spring 2. Spring has armor 3 with upper 4 and lower 6 securing elements. Longitudinal elastic strip 5 connects the two securing elements 4 and 6. The upper windings of the coil are in a prestressed state. Due to the prestressing, the effect of load on the suspension will be different on different parts of springs, i.e. stressed and un-stressed parts, thus resulting in a spring system with variable stiffness.

Brady Matthew Schroeder [13] discussed a suspension system with a stiffness changing mechanism. The system is as shown in Fig. 6. In order to convert the ride to a stiff ride, the springs have to be compressed. The knob 40 is rotated in an anticlockwise manner so that the shaft 8 enters into threaded

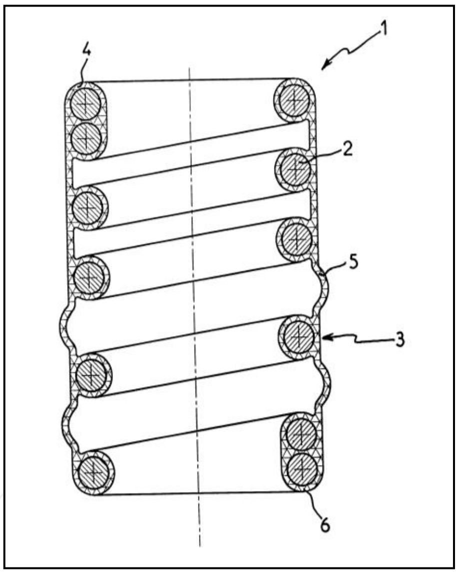

Fig. 5: Helicoidal Spring [12]

bolt 31. The coupler 32 attached to the bolt 31 is unturned due to restriction from spring ends 15 and 21 of springs 10 and 20 respectively. The coupler 32 is then driven to the end 3 of threaded bolt 31. Due to the turning of the knob the softer spring 10 compresses reducing the spring length. This compressed spring 10 along with the firm spring 20 results in an overall suspension with stiff riding characteristics. On the contrary when the knob 40 is turned in a clockwise manner the overall spring stiffness results in softer riding characteristics.

Jacky Rhein [14], disclosed a variable stiffness suspension system with deformable bushings which imparts the variable stiffness characteristic as shown in Fig. 7. The deformable bushing 17 is attached to the either side of the spring 13.The supports 14 and 15 support the bushings. The bushing is made of elastomer material and a predefined thickness. The material and thickness of the bushing decide the stiffness characteristic. When the bushings are completely compressed the stiffness of the bushing equates to that of the spring and cannot be compressed further.

Kalyani et.al.[15], discloses variable stiffness mechanism for spring suspension by changing the number of active coils thereby changing the stiffness of the spring. The system comprises of spring 132 having active coils 138, spring retainer 140. The spring retainer has threads on the inner surface166 to accommodate the inactive spring coils. The spring retainer is rotated to change the number of active coils and hence the stiffness of the spring. The spring retainer may be actuated using motor regulated by a motor controller. When the retainer is rotated counter clockwise (CCW) as shown in Fig. 8, the active spring coils 138 accommodate in the threads of the retainer 166, thus reducing the overall active coil count. This change in the active coil count makes the spring stiffer in nature. To increase the softness of the spring the retainer is rotated in the clockwise manner to increase the active coil count.

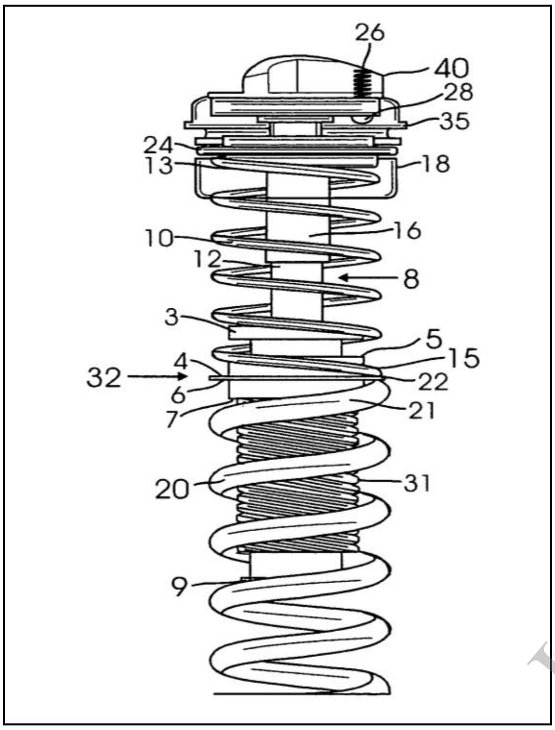

Fig. 6: Adjustable Spring Coil Suspension [13]

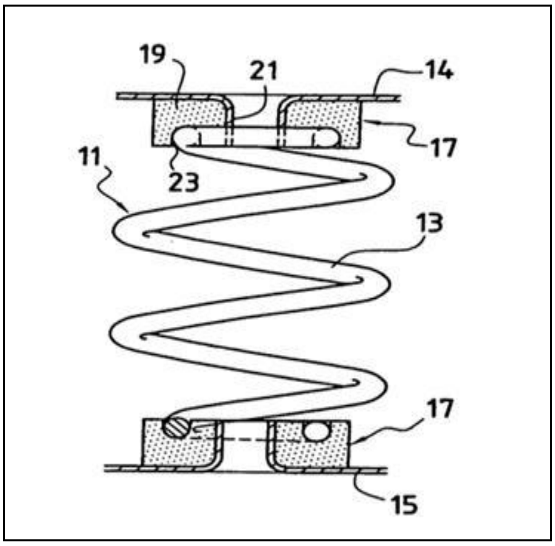

Fig. 7: Coil Spring with Compressible Bushings [14]

Anubi et.al. [16] introduced a variable stiffness suspension 100 for front wheel as shown in quarter car model Fig. 9. The system comprises of upper wishbone 106 and lower wishbone 108. The wishbone assembly is coupled the wheel assembly on one end and frame assembly of vehicle on the other. The lower side of two coil springs 121 and 122 of same spring constant are mounted on the lower wishbone 108. The upper ends of the springs 121 and 122 are connected to the lever 130 by revolute joints. Another spring 104 is mounted on the lever 130. The top end of spring 104 is connected to the sprung mass. A pivot element 140 is mounted in such a manner that it is free to slide in the slot 135 provided in the lever 130.An actuator 150 is connected to the midpoint of the pivot element 140. The actuator 150 is a linear actuator. The actuator is controlled by a controller. The resultant stiffness of the system can be varied by moving the pivot point along the slot 135. The pivot element remains vertical thereby causing the lever 130 to tilt. This tilting results in compression of either one of springs with constant stiffness and expansion of the other resulting in the net variable stiffness. The actuator 150 can be removed, thus converting the system into variable stiffness passive suspension.

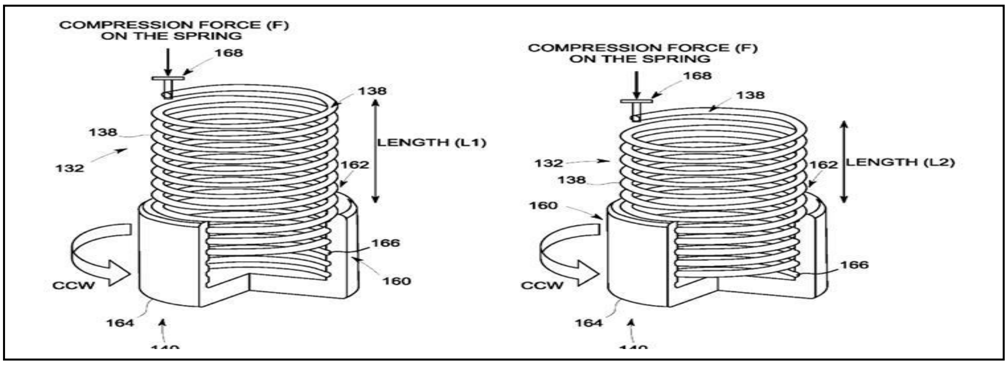

Fig. 8: Coil Springs with Spring Retainer [15]

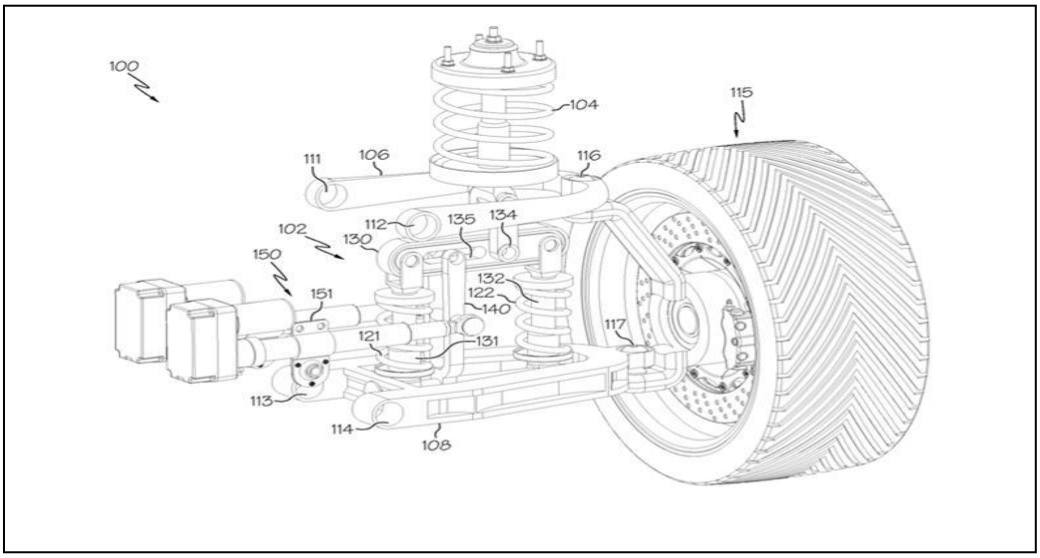

Fig. 9: Spring Suspension with Pivot-Lever Mechanism [16]

V. CONCLUSION

This paper has reviewed technologies for variable stiffness suspension system. The technologies include the use of stoppers and flanges with coil spring of variable stiffness in series, coils spring with decreasing taper of tapered plates, pre stressed helicoidal spring, coil spring with compressible bushings, springs with spring retainer to alter the number active coils to change stiffness, and series-parallel spring arrangement with pivot-lever mechanism. It can also be observed that these systems have few drawbacks. The system with tapered plates may wear out making it difficult to achieve desired stiffness. The coil spring with compressible bushings have a definite number of working cycles after which the bushings would be incompressible; disabling the system to achieve variable stiffness. The system with active coil retainer has threads which accommodates the active coils. The constant alteration of coils and load may lead to wearing of the retainer threads. This would cause the coils to slip within the retainer, thus disturbing the stiffness of the system. The last system describes the series parallel spring arrangement with pivot-lever mechanism. The sliding of pivot-lever mechanism is a concern of high wear of the components. Hence there is a need to fabricate a system such that the additional components like movable links are obviated creating a sturdy system with long life cycle maximizing ride quality and stability.

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