The Shock Absorber Handbook

Second Edition

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Senior Lecturer in Engineering Mechanics
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Preface to Second Edition

In view of the tremendous worldwide production of automotive dampers (shock absorbers), the former absence of a book devoted to this topic is surprising. During some years of damper design, research and commercial testing, the author has become aware of a need for a suitable book to present the fundamentals of damper design and use, for the benefit of the many designers of vehicles such as passenger cars, motorcycles, trucks, racing cars and so on, since the necessary body of knowledge is far from readily available in the research literature. Damper designers themselves will already be familiar with most of the material here, but may find some useful items, especially with regard to installation motion ratios and behaviour of the vehicle as a whole, but in any case will probably be pleased to see the basic material collected together.

As in my previous work, I have tried to present the basic core of theory and practice, so that the book will be of lasting value. I would be delighted to hear from readers who wish to suggest any improvements to presentation or coverage.

Amongst many suggestions received for additions and improvements to the first edition, there was clearly a desire that the book should be extended to cover extensively the effect of the damper on ride and handling. The extra material would, however, be vast in scope, and would greatly increase the size and expense of the book. Also, in the author's view, such analysis belongs in a separate book on ride quality and handling, where the effect of the damper can be considered fully in the context of other suspension factors.

Instead, the general character of the first edition has been retained, with its emphasis on the internal design of the damper. Considerable efforts have been made to eliminate known errors in the first edition, and substantial detailed additions and revisions have been made. In many areas the material has been reorganised for greater clarity. The variety of damper types found historically is now more fully covered, and the recent developments in magnetorheological dampers are now included. Conventional damper valve design is considered much more carefully, and more space is allocated to detailed variations in valve design, including stroke-sensitive types. Many new figures have been added. On this basis, it is hoped that the new edition will offer a worthwhile service to the vehicle design community, at least as an introduction to the complex and fascinating field of damper design.

Finally, the title *The Shock Absorber Handbook* has been controversial, as it was said that the subject was not shock absorbers and it was not a handbook. It would probably have been better to use the technically correct term *damper*, with a title such as *The Automotive Damper*. However, a change of title has been deemed impractical given that the book is well established under its original name, and it has been decided to remain with the devil that we know for this, second, edition.

John C. Dixon

Acknowledgements

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1

Introduction

1.1 History

The current world-wide production of vehicle dampers, or so-called shock absorbers, is difficult to estimate with accuracy, but is probably around 50–100 million units per annum with a retail value well in excess of one billion dollars per annum. A typical European country has a demand for over 5 million units per year on new cars and over 1 million replacement units, The US market is several times that. If all is well, these suspension dampers do their work quietly and without fuss. Like punctuation or acting, dampers are at their best when they are not noticed - drivers and passengers simply want the dampers to be trouble free. In contrast, for the designer they are a constant interest and challenge. For the suspension engineer there is some satisfaction in creating a good new damper for a racing car or rally car and perhaps making some contribution to competition success. Less exciting, but economically more important, there is also satisfaction in seeing everyday vehicles travelling safely with comfortable occupants at speeds that would, even on good roads, be quite impractical without an effective suspension system.

The need for dampers arises because of the roll and pitch associated with vehicle manoeuvring, and from the roughness of roads. In the mid nineteenth century, road quality was generally very poor. The better horse-drawn carriages of the period therefore had soft suspension, achieved by using long bent leaf springs called semi-elliptics, or even by using a pair of such curved leaf springs set back-to-back on each side, forming full-elliptic suspension. No special devices were fitted to provide damping; rather this depended upon inherent friction, mainly between the leaves of the beam springs. Such a set-up was appropriate to the period, being easy to manufacture, and probably worked tolerably well at moderate speed, although running at high speed must have been at least exciting, and probably dangerous, because of the lack of damping control.

The arrival of the so-called horseless carriage, i.e. the carriage driven by an internal combustion engine, at the end of the nineteenth century, provided a new stimulus for suspension development which continues to this day. The rapidly increasing power available from the internal combustion engine made higher speeds routine; this, plus the technical aptitude of the vehicle and component designers, coupled with a general commercial mood favouring development and change, provided an environment that led to invention and innovation.

The fitting of damping devices to vehicle suspensions followed rapidly on the heels of the arrival of the motor car itself. Since those early days the damper has passed through a century of evolution, the basic stages of which may perhaps be considered as:

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(1) dry friction (snubbers);
(2) blow-off hydraulics;
(3) progressive hydraulics;
(4) adjustables (manual alteration);
(5) slow adaptives (automatic alteration);
(6) fast adaptives (‘semi-active’);
(7) electrofluidic, e.g. magnetorheological.

Historically, the zeitgeist regarding dampers has changed considerably over the years, in roughly the following periods:

(1) Up to 1910 dampers were hardly used at all. In 1913, Rolls Royce actually discontinued rear dampers on the Silver Ghost, illustrating just how different the situation was in the early years.
(2) From 1910 to 1925 mostly dry snubbers were used.
(3) From 1925 to 1980 there was a long period of dominance by simple hydraulics, initially simply constant-force blow-off, then through progressive development to a more proportional characteristic, then adjustables, leading to a mature modern product.
(4) From 1980 to 1985 there was excitement about the possibilities for active suspension, which could effectively eliminate the ordinary damper, but little has come of this commercially in practice so far because of the cost.
(5) From 1985 it became increasingly apparent that a good deal of the benefit of active suspension could be obtained much more cheaply by fast auto-adjusting dampers, and the damper suddenly became an interesting, developing, component again.
(6) From about 2000, the introduction, on high-price vehicles at least, of controllable magnetorheological dampers.

Development of the adaptive damper has occurred rapidly. Although there will continue to be differences between commercial units, such systems are now effective and can be considered to be mature products. Fully active suspension offers some performance advantages, but is not very cost effective for passenger cars. Further developments can then be expected to be restricted to rather slow detail refinement of design, control strategies and production costs. Fast acting control, requiring extra sensors and controls, will continue to be more expensive, so simple fixed dampers, adjustables and slow adaptive types will probably continue to dominate the market numerically for the foreseeable future.

The basic suspension using the simple spring and damper is not ideal, but it is good enough for most purposes. For low-cost vehicles, it is the most cost-effective system. Therefore much emphasis remains on improvement of operating life, reliability and low-cost production rather than on refinement of performance by technical development. The variable damper, in several forms, has now found quite wide application on mid-range and expensive vehicles. On the most expensive passenger and sports cars, magetorheologically controlled dampers are now a popular fitment, at significant expense.

The damper is commonly known as the shock absorber, although the implication that shocks are absorbed is misleading. Arguably, the shocks are ‘absorbed’ by the deflection of the tires and springs. The purpose of dampers is to dissipate any energy in the vertical motion of body or wheels, such motion having arisen from control inputs, or from disturbance by rough roads or wind. Here ‘vertical’ motion includes body heave, pitch and roll, and wheel hop. As an agglomeration of masses and springs, the car with its wheels constitutes a vibrating system that needs dampers to optimise control behaviour, by preventing response overshoots, and to minimise the influence of some unavoidable resonances. The mathematical theory of vibrating systems largely uses the concept of a linear damper, with force proportional to extension speed, mainly because it gives equations for which the solutions are well understood and documented, and usually tolerably realistic. There is no obligation on a damper to exhibit such a characteristic; nevertheless the typical modern hydraulic damper does so approximately. This is because the vehicle and damper manufacturers consider this to be desirable for good physical

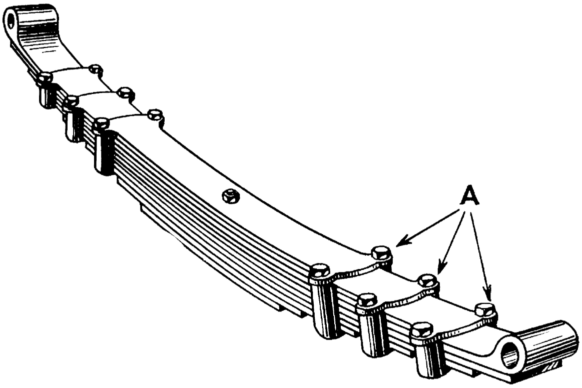

Figure 1.1.1 Dry friction damping by controlled clamping (adjustable normal force) of the leaf spring (Woodhead).

behaviour, not for the convenience of the theorist. The desired characteristics are achieved only by some effort from the manufacturer in the detail design of the valves.

Damper types, which are explained fully later, can be initially classified as

- (a) dry friction with solid elements;
  - (i) scissor;
  - (ii) snubber;
- (b) hydraulic with fluid elements;
  - (i) lever-arm;
  - (ii) telescopic.

Only the hydraulic type is in use in modern times. The friction type came originally as sliding discs operated by two arms, with a scissor action, and later as a belt wrapped around blocks, the ‘snubber’. The basic hydraulic varieties are lever-arm and telescopic. The lever-arm type uses a lever to operate a vane, now extinct, or a pair of pistons. Telescopics, now most common, are either double-tube or gas-pressurised single-tube.

The early days of car suspension gave real opportunities for technical improvement, and financial reward. The earliest suspensions used leaf springs with inherent interleaf friction. Efforts had been made to control this to desirable levels by the free curvature of the leaves. Further developments of the leaf spring intrinsic damping included controlled adjustment of the interleaf normal forces, Figure 1.1.1, and the use of inserts of various materials to control the friction coefficients, Figure 1.1.2.

Truffault invented the scissor-action friction disc system before 1900, using bronze discs alternating with oiled leather, pressed together by conical disc springs and operated by two arms, with a floating body. The amount of friction could be adjusted by a compression hand-screw, pressing the discs together more or less firmly, varying the normal force at approximately constant friction coefficient. Between 1900 and 1903, Truffault went on to develop a version for cars, at the instigation

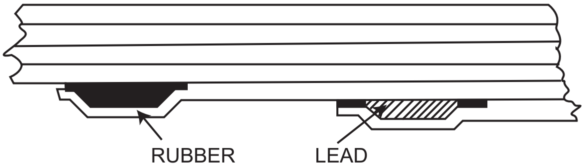

Figure 1.1.2 Leaf spring inserts to control the friction coefficient and consequent damping effect.

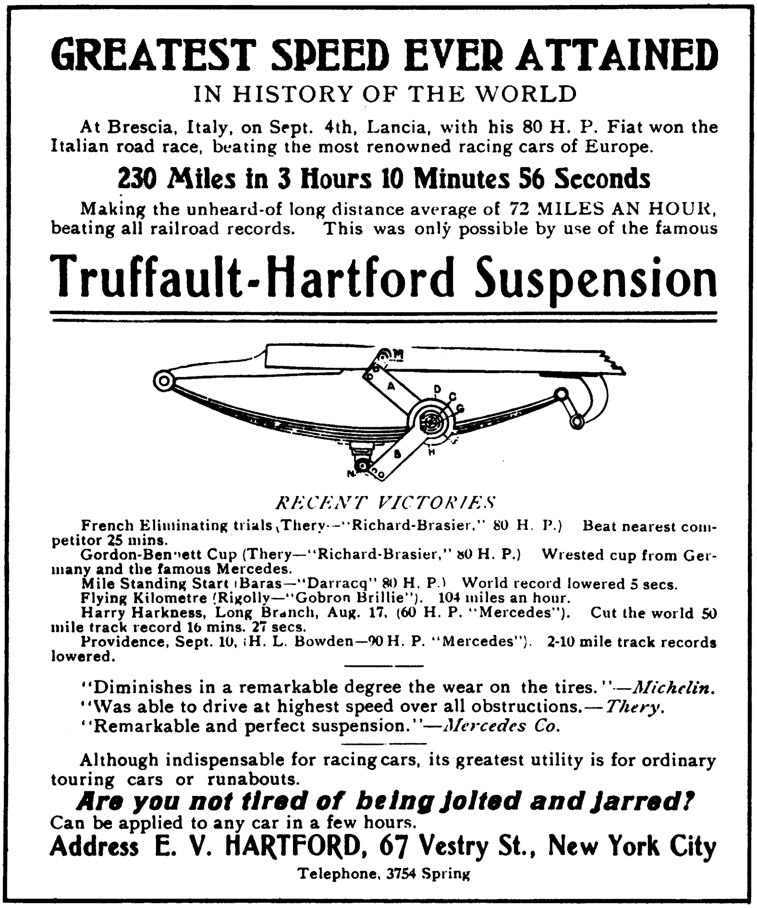

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Figure 1.1.3 An advertisement from 1904 for the early Truffault designed dry friction scissor damper manufactured by Hartford.

of Hartford in the US, who began quantity production in 1904, as in Figures 1.1.3–1.1.5. Truffault, well aware of the commercial potential, also licensed several other manufacturers in Europe, including Mors and Peugeot in France, who also had them in production and use by 1904. A similar type of damper was also pressed into service on the steering, Figure 1.1.6, to reduce steering fight on rough roads and to reduce steering vibrations then emerging at higher speeds and not yet adequately understood.

Figure 1.1.7 shows an exploded diagram of a more recent (1950s) implementation from a motorcycle. This is also adjustable by the hand-screw. Subsequent to the Truffault–Hartford type, The Hartford Telecontrol (the prefix *tele* means remote) developed the theme, Figure 1.1.8, with a convenient Bowden cable adjustment usable by the driver *in situ*. A later alternative version, the Andre Telecontrol, had dry friction scissor dampers, but used hydraulic control of the compression force and hence of the damper friction moment.

In 1915, Claud Foster invented the dry friction block-and-belt snubber, Figure 1.1.9, manufactured in very large quantities by his Gabriel company, and hence usually known as the Gabriel Snubber. In view of the modern preference for hydraulics, the great success of the belt snubber was presumably based on low cost, ease of retrofitment and reliability rather than exceptional performance.

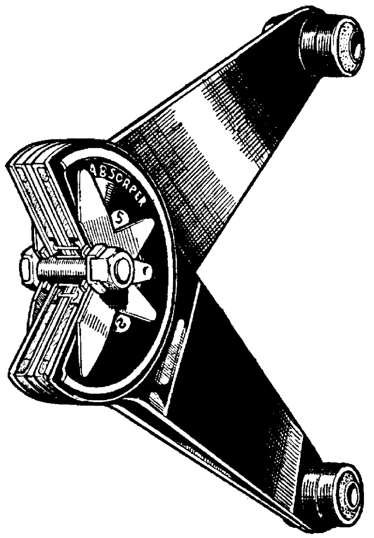


Figure 1.1.4 The Andre–Hartford scissor-action dry friction damper.

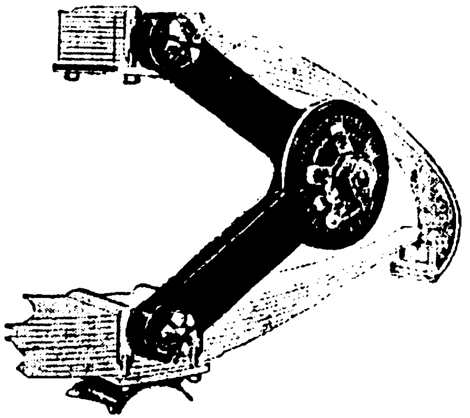
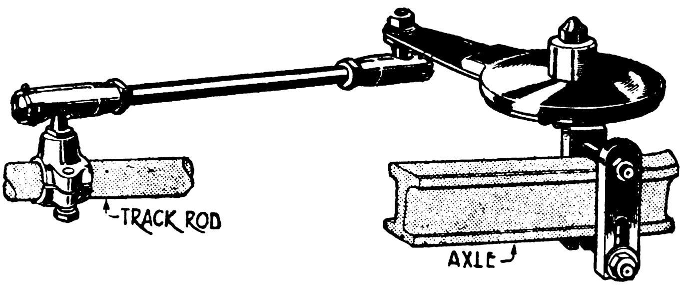


Figure 1.1.5 Installation of a dry-friction scissor damper on three-quarter-elliptic leaf springs (from Simanaitis, 1976).



A Damping Device for Preventing Wheel Wobble
on Rigid-Type Front Axles.

Figure 1.1.6 Use of the Truffault–Hartford rotary dry friction damper on steering.

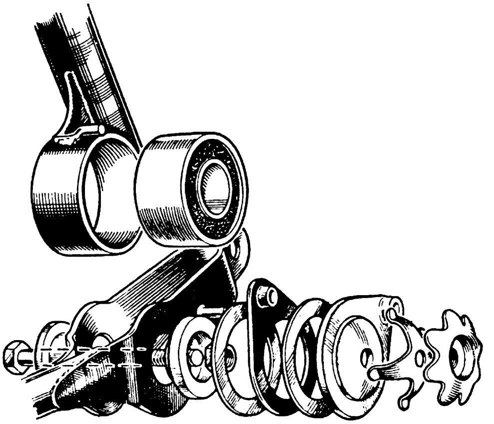


Figure 1.1.7 The Greeves motorcycle front suspension from around 1950 had a rubber-in-torsion spring, using an integral rotary dry friction damper easily adjustable by hand.

The spring-loaded blocks are mounted on the body, in particular on the chassis rails in those days, with the leather belt being fixed to the wheel upright or axle. In upward motion of the suspension, the snubber has no effect, but the spring-loaded blocks take up any slack. Any attempt by the suspension to extend will be opposed by the belt which has considerable friction where it wraps over itself and around the blocks. Hence the action is fully asymmetrical. The actual performance parameters do not seem to have been published. Some theoretical analysis may be possible, derived from the standard theory of wrapped circular members, with friction force growing exponentially with wrapping angle, for prediction of the force in relation to block shape, spring force and stiffness and belt-on-belt and belt-on-block coefficients of friction. The overall characteristic, however, seems to be an essentially velocity-independent force in extension, i.e. fully asymmetrical Coulomb damping. The characteristics could have been affected in service conditions by the friction-breaking effect of engine vibrations.

An early form of hydraulic contribution to damping was the Andrex oil-bath damper, Figure 1.1.10. This had metal and leather discs as in the dry damper, but was immersed in a sealed oil bath. There may also have been a version with separated metal discs relying on oil in shear. Another version, Figure 1.1.11, was adjustable from the dashboard, with oil pressure transmitted to the dampers to control the normal force on the discs, or perhaps in some cases to adjust the level of oil in the case. The pressure gauge in Figure 1.1.11 suggests that this type was controlling the normal force.

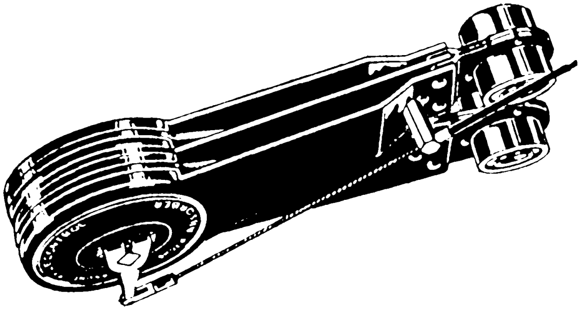


Figure 1.1.8 The Hartford Telecontrol damper was adjustable via a Bowden cable, and hence could be controlled easily from the driving seat, even with the vehicle in motion.

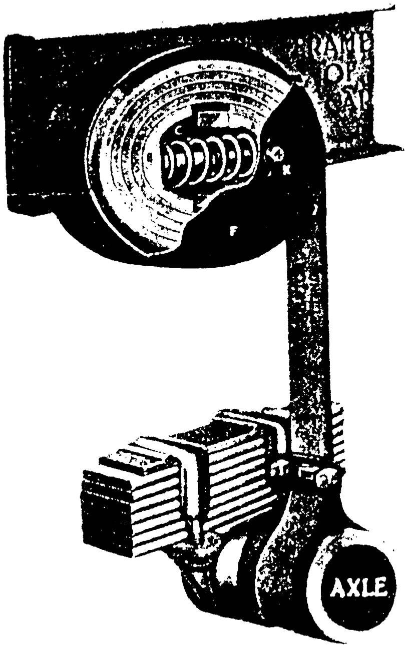


Figure 1.1.9 The Gabriel Snubber (1915) used a leather strap around sprung metal or wooden blocks to give restraint in rebound only (from Simanaitis, 1976).

The early development timetable of dampers thus ran roughly as follows:

1901: Horock patents a telescopic hydraulic unit, laying the foundations of the modern type.
1902: Mors actually builds a vehicle with simple hydraulic pot dampers.
1905: Renault patents an opposed piston hydraulic type, and also patents improvements to Horock's telescopic, establishing substantially the design used today.
1906: Renault uses the piston type on his Grand Prix racing cars, but not on his production cars. Houdaille starts to develop his vane-type.
1907: Caille proposes the single-lever parallel-piston variety.

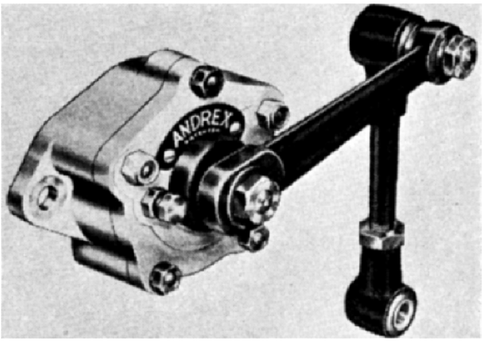


Figure 1.1.10 The Andrex multiple discs-in-oil-bath damper.

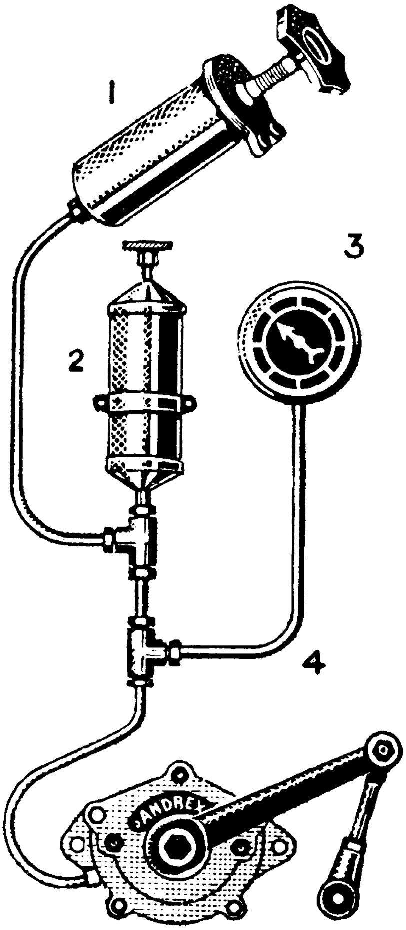


Figure 1.1.11 The adjustable version of the Andrex oil-bath damper included pump, reservoir and pressure gauge.

1909: A single-acting Houdaille vane type is fitted as original equipment, but this is an isolated success for the hydraulic type, the friction disc type remaining dominant.
1910: Oil damped undercarriages come into use on aircraft.
1915: Foster invents the belt ‘snubber’ which had great commercial success in the USA.
1919: Lovejoy lever-arm hydraulic produced in the USA.
1924: Lancia introduces the double-acting hydraulic unit, incorporated in the front independent pillar suspension of the Lambda. The Grand Prix Bugatti uses preloaded nonadjustable drum-brake type.
1928: Hydraulic dampers are first supplied as standard equipment in the USA.
1930: Armstrong patents the telescopic type.
1933: Cadillac ‘Ride Regulator’ driver-adjustable five-position on dashboard.
1934: Monroe begins manufacture of telescopics.
1947: Koning introduces the adjustable telescopic.
1950: Gas-pressurised single-tube telescopic is invented and manufactured by de Carbon.
2001: Magnetorheological high-speed adjustables introduced (Bentley, Cadillac).

The modern success of hydraulics over dry friction is due to a combination of factors, including:

(1) Superior performance of hydraulics, due to the detrimental effect of dry Coulomb friction which is especially noticeable on modern smooth roads.
(2) Damper life has been improved by better seals and higher quality finish on wearing surfaces.
(3) Performance is now generally more consistent because of better quality control.
(4) Cost is less critical than of old, and is in any case controlled by mass production on modern machine tools.

During the 1950s, telescopic dampers gradually became more and more widely used on passenger cars, the transition being essentially complete by the late 1950s. In racing, at Indianapolis the hydraulic vane type arrived in the late 1920s, and was considered a great step forward; the adjustable piston hydraulic appeared in the early 1930s, but the telescopic was not used there until 1950. Racing cars in Europe were quite slow to change, although the very successful Mercedes Benz racers of 1954–55 used telescopics. Although other types are occasionally used, the telescopic hydraulic type of damper is now the widely accepted norm for cars and motorcycles.

It was far from obvious in early days that the hydraulic type of damper would ultimately triumph, especially in competition with the very cost-effective Gabriel snubber of 1915. The first large commercial successes for the hydraulic types came with the vane-type, developed from 1906 onwards by Maurice Houdaille. The early type used two arms with a floating body, a little like the dry friction scissor damper. The later type still used vanes, but had a body mounted on the vehicle sprung mass, operated by an arm with a drop link to the leaf spring suspension, Figures 1.1.12–1.1.14.

The 1919 Motor Manual (UK, 21st edition) devoted less than one of its three hundred pages to dampers, suggesting that the damper was not really considered to be of great importance in those days, stating that:

> These devices, of which there are a great number on the market, are made for the purpose of improving the comfortable running of the car, more especially on roughly-surfaced roads. The present system of springing is

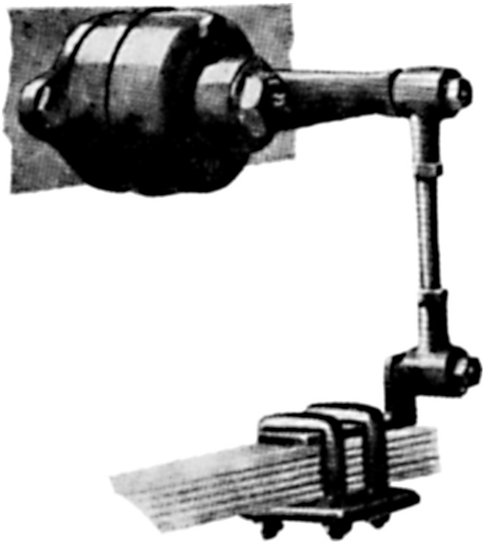


Figure 1.1.12 The Houdaille rotary vane damper, the first large quantity production hydraulic damper. This originated in 1909 and was double-acting from 1921.

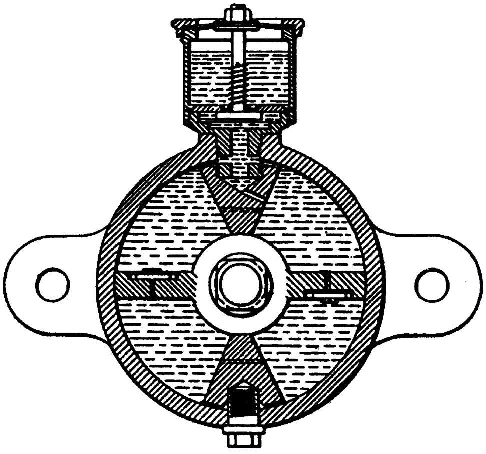


Figure 1.1.13 Cross-section of slightly different version of Houdaille rotary vane damper (from Simanaitis, 1976).

> admittedly not perfect, and when travelling on rough roads there is the objectionable rebound of the body after it passes over a depression in the road, which it is desirable should be reduced as much as possible. The shock from this rebound is not only uncomfortable for the passengers, but it has a bad effect on the whole car. Hence these shock absorbers are applied as the best means available so far to check the rebound. They are made on various principles, generally employing a frictional effect such as is obtainable from two hardened steel surfaces in close contact. Another principle is that of using the fluid friction of oil, practically on the lines of any of the well-known dash-pot devices, viz., a piston moving in a cylinder against the resistance offered by the oil contained within it, the oil passing slowly through a small aperture into another chamber. This type of device is probably the best solution of the problem.

Up to 1920 hydraulic dampers were single acting, in droop only, but from 1921 a more complex valve system allowed some damping in bump too. At this point the operating characteristics of the

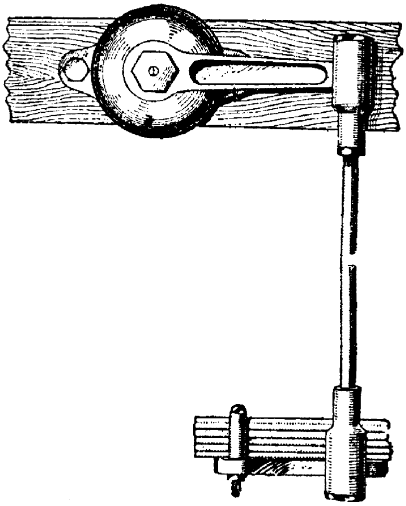


Figure 1.1.14 An early configuration of hydraulic damper, a rotary vane device with a drop arm to the axle. Note the wooden chassis rail (artist's impression, The Motor Manual, 1919).

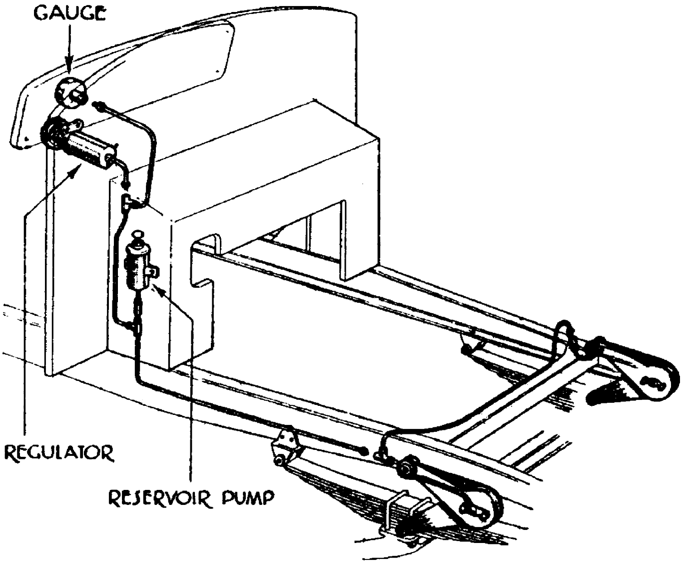


Figure 1.1.15 Layout of the hydraulically remote Andre Telecontrol damper, shown here on a front axle (The Motor Manual, 1939).

hydraulic damper had largely reached their modern form. More recent developments have had more to do with the general configuration, so that the lever-operated type has given way to the telescopic piston type which is cost-effective in manufacture, being less critical with regard to seal leakage, and has better air cooling, although lacking the conduction cooling of a body-mounted lever-arm damper. Most importantly perhaps, the telescopic type lends itself well to the modern form of suspension in terms of its mounting and ease of installation.

The 1939 Motor Manual (UK, 30th edition), devoted three pages to dampers, perhaps indicating the increased recognition of their importance for normal vehicles. An illustration was included of the Andre–Hartford dry friction scissor, and also one of the Luvax vane damper, shown later. There was also a diagram of the hydraulically adjusted, but dry action, version of the Andre Telecontrol system, as seen in Figure 1.1.15. That writer was moved to offer some additional explanation of damping and 'shock absorbing' in general, stating that:

> Whatever form of springing is employed, it is always considered necessary to damp the suspension by auxiliaries, which have become known as shock absorbers. This term is unfortunate, because it is the function of the springs to absorb shocks, whereas the 'shock absorbers' serve the purpose of providing friction in a controlled form which prevents prolonged bouncing or pitching motions, by absorbing energy. A leaf spring is inherently damped by the friction between the leaves, and it may, therefore, seem strange that after lubricating these leaves friction should be put back into the system by the use of shock absorbers. The explanation is that leaf friction is not readily controllable, whereas the shock absorber imparts a definite and adjustable degree of damping to the system.
>
> The most popular type of shock absorber is an hydraulic device which is bolted to the frame and is operated by an arm coupled to the axle. Four such devices are ordinarily fitted. When relative movement occurs between the axle and the frame, the arm on the shock absorber spindle is oscillated, and this motion is conveyed to a rotor, which fits within a circular casing. Oil in the casing in made to flow through valves from one side of the rotor to the other and so creates hydraulic resistance which damps the oscillations. In some cases the valves are arranged to give 'double action', the damping then being effective on both deflection and rebound. In other cases single-acting devices are used which can check rebound only. As a rule the action of the shock absorbers can be adjusted by means of a screw, which alters the tension of a spring and so varies the load on a ball valve.

> The hydraulic shock absorber has the important merit of increasing its damping effect when subject to sudden movements, but suffers from the defect of providing very little resistance against slower motions, such as rolling. Consequently, for sports cars many users prefer frictional shock absorbers, of the scissor (constant resistance) type, of which the most famous is the Andre–Hartford.

The final comment above is significant in a modern context, regarding the preferred velocity–force relationship, which is a regressive shape with a 'knee', rather than simply linear.

The Lancia Lambda of 1925 had sliding pillar suspension, Figure 1.1.16, now almost extinct (except, e.g. Morgan) and regarded as primitive, but highly successful at the time. It was noted for the fact that its oil-filled cylinders required no maintenance, and was very reliable. This is an attractive option for a light vehicle, because it is such a compact and light system, although lacking the ability of modern suspensions to be adjusted to desired handling characteristics by detailed changes to the geometry.

Although dry friction snubbers remained in wide use through to the 1930s, hydraulic fluid-based dampers were in limited use from very early days and continued to grow in popularity. An early successful version in the USA was made by Lovejoy, Figure 1.1.17.

Difficulties with sealing and wear of vane lever arm types led to the lever arm parallel piston system as in the Lovejoy and in the Armstrong, Figure 1.1.18, in which the valve may also easily be made

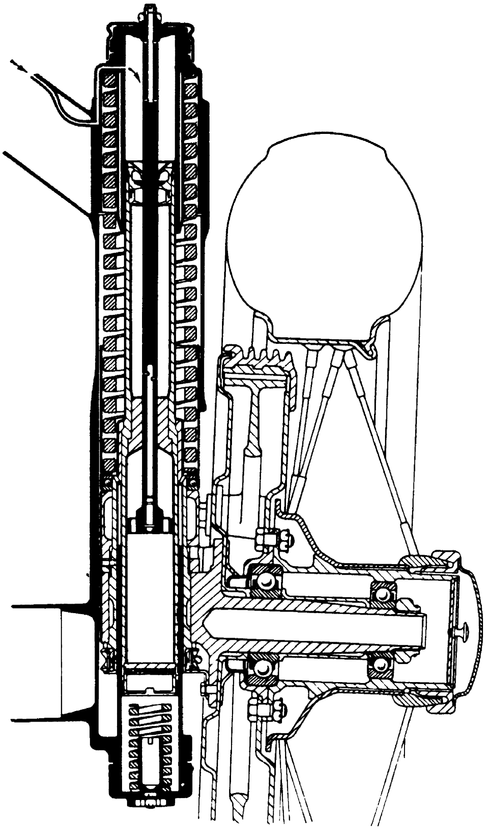


Figure 1.1.16 The Lancia Lambda sliding-pillar system had the spring and damper sealed into one unit (Lancia, 1925).