HYDRAULICS

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The purpose of a vehicle's suspension is to isolate or filter the shocks created by the unevenness of the road surface, in order to ensure: the comfort of the passengers, and also the protection of the mechanical parts, the vehicle's stability and roadholding.
For the best possible comfort, the suspension should be soft, with large wheel movements: in other words, it should be very flexible. For the best roadholding, it is necessary to maintain the wheels in contact with the surface while controlling the oscillating movements of the vehicle caused by the unevenness of the surface, without stiffening the suspension: this is the role of the damper. These two parameters, flexibility and damping, must not vary too greatly according to the vehicle's load, otherwise the operation of the suspension may change for the worse. A soft suspension sinks under a load and loses its flexibility. If the vehicle is lightened too much, its centre of gravity rises and its roadholding is compromised. It is difficult to reconcile all these requirements in a conventional mechanical suspension. In order to resolve these problems when the DS was being designed, Citroen had recourse to advanced technology: hydropneumatics. The technique was first tried out in 1953 on the rear suspension of the 15 CV, 6-cylinder Traction Avant, and was fully developed for the launch of the DS in 1955.
The use of a hydropneumatic system for the suspension involved the creation of a high-pressure supply system which could then be used for other vehicle functions: steering, brakes, gear changing. This very suitable and reliable system of hydraulic assistance was subsequently adopted for the GS, SM, CX and BX, ensuring that the exceptional reputation of Citroen cars for safety and comfort was maintained.

PRINCIPLES OF HYDROPNEUMATICS

Two fluids form the working medium of the hydropneumatic system: a liquid (mineral oil) and a gas (nitrogen).
The compressibility of a gas, governed by a simple relationship between the volume occupied by a mass of gas and the pressure exerted on it, allows the design of a high-pressure supply system using the liquid as the means of pressure transfer between the various components involved.
Gases and liquids respectively obey two fundamental laws:
- Mariotte's Law: for a given mass of gas, at a constant temperature, the product of the values of volume and pressure is a constant:

$$P \times V = \text{constant}$$

- Pascal's Theorem: A liquid at rest transmits and exerts at each and every point, whatever pressure it is subject to.

DISTRIBUTION AND REGULATION OF PRESSURE

Every hydraulic component studied in this brochure is designed on the same principle: a cylindrical valve slides within a bore. By doing so, it connects the receiving element either with the source of high-pressure liquid, or with the return to the reservoir. There are no gaskets to ensure perfect sealing between the moving parts. The fit of each joint has to avoid any resistance to movement of the valve. Sealing is achieved purely by very close tolerances and a near-perfect state of each adjacent surface.
The tolerance on valve diameter is between 1 and 3 microns, just sufficient to allow oil-film lubrication and prevent contact.
The tolerances are achieved both on the pistons and within the bores, thanks to extremely high-precision manufacture.

Pressure distributor

A valve with a central channel slides in a housing containing three orifices (Fig. 1).
Neutral position: the valve closes both the high-pressure supply and return orifices. The feed orifice to the service system is uncovered at all times.
Pressure supply: even the smallest force applied to the valve is sufficient to move it. In the supply sense, the feed and high-pressure supply orifices are placed in communication. Pressure is thus transmitted uniformly throughout the service system.
Exhaust: when movement takes place in the exhaust sense, the service system is connected to the return to the reservoir and pressure in the service system falls.
The operation of the distributor is independent of the size of the force causing the displacement of the valve.
By contrast, the regulator delivers a pressure proportional to the force exerted on its valve.

Pressure regulator

A valve with a central channel slides in a housing containing three orifices together with an orifice (d) which connects the service system with a chamber A situated at one end of the valve and containing a spring (r).
Static position (Fig. 2a): the valve under the influence of the spring (r) causes the service system to exhaust to the reservoir. If a pressure gauge were connected to the service system exhaust, it would read zero.
Regulating position (Fig. 2b): a force F applied to the valve causes it to move. The return orifice is closed and the high-pressure supply orifice is connected to the service system, and thus also to the chamber A.

The valve assumes a position of balance in which the force acting on its section (F = P × S) is equal to F (r being negligible).
Example: If the force F on the valve is 10 kg (98.1 N) and its section is 0.5 cm^2 (0.0005 m^2) then the regulated pressure is:

$P = \frac{F}{S}$ $P = \frac{10}{0.5} = 20$ kg/cm^2 = 2841 b/in^2

If F = 25 kg (245.3 N) the pressure will be 50 kg/cm^2 or 7111 lb/in^2, and so on. Thus the pressure in the service system is proportional to the force on the valve but independent of the pressure in the high-pressure supply system.

CONNECTIONS BETWEEN HYDRAULIC COMPONENTS

LHM liquid

This is a green-coloured mineral hydraulic fluid. Its viscosity of 15 centistokes at 50degC varies with temperature: it does not absorb water. The liquid remains stable over long periods, allowing the hydraulic components to achieve extreme reliability.

Circuits

Metallic: metal pipes are used for all high-pressure liquid feeds. Their exterior diameter is 3.5, 4.5 or 6.35 mm; they are formed from copper-treated steel sheet rolled to double thickness and then heat-treated to ensure complete diffusion of the copper. Finally, a protective zinc coating is applied.
Plastic: plastic pipes are used for leakage return runs and for venting to atmosphere.
Rubber: rubber pipes are used for liquid return runs after passing through the service systems, and for the LHM feed from the reservoir to the pump. These pipes are marked with a green tracer throughout their length.
The total length of the metallic piping in the CX is 26 m (85 ft), as is the length of the flexible pipes, making a total pipe run of 52 m (170 ft).

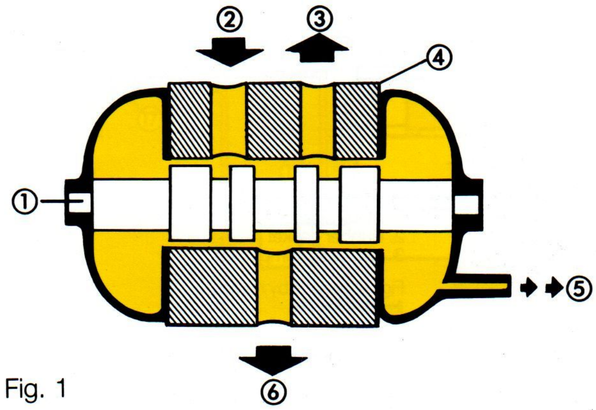


Fig. 1

Fig. 1 : Pressure distributor
1. Slide valve
2. High pressure
3. Return
4. Bore
5. Leakage return
6. Outlet to use

Fig. 2 : Pressure regulator
1. Slide valve
2. High pressure inlet
3. Return to reservoir
4. Outlet to use

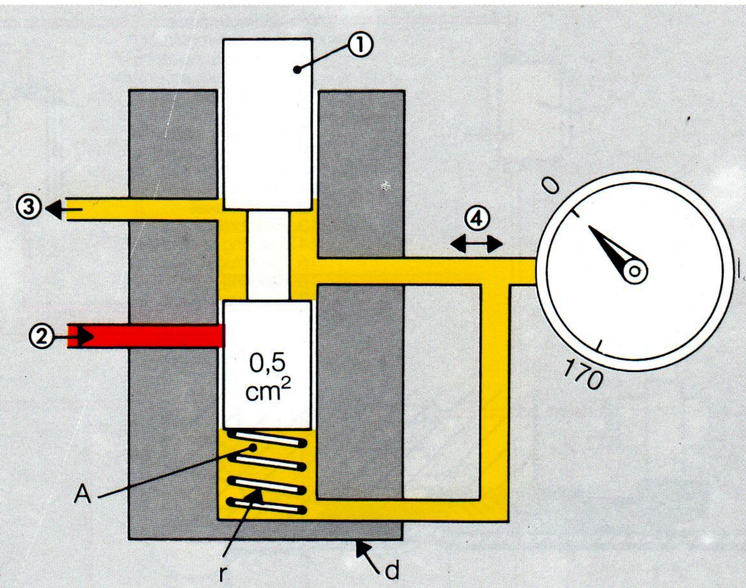


Fig. 2a

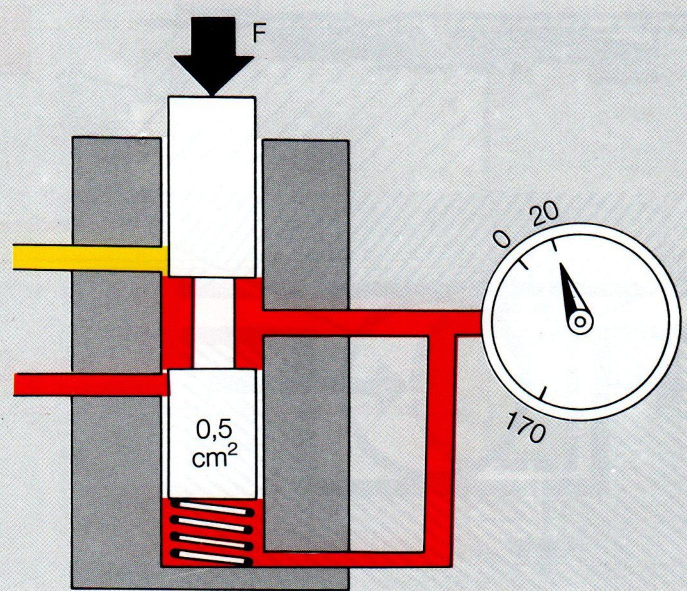


Fig. 2b

Fig. 3: Rubber gasket
1. Metal pipe
2. Rubber gasket
3. Hydraulic component

Fig. 4: Sealing by ring seal
1. Joint in use
2. Joint relaxed

Fig. 5: General layout of hydraulic system

Fig. 6: Layout of CX hydraulic circuit
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Front brake accumulator
6. Safety valve
7. Front height corrector
8. Front suspension
9. Rear height corrector
10. Rear suspension
11. Brake control unit
12. Front brakes
13. Rear brakes
14. Steering control box
15. Centrifugal regulator
16. Steering
17. Leakage return

Sealing methods

Rubber gasket (Fig. 3): for the attachment of a metal pipe to a component. Sealing is achieved by the deformation of the gasket under the action of the securing nut.
Screw clip: for the connection of a rubber pipe to a metal or plastic pipe, or to a component. During assembly, it is necessary to insert a rubber collar between the screw clip and the rubber pipe.
Ring seal (Fig. 4): sealing is achieved by deformation of the ring under pressure. For this type of seal to be effective, the diameter of the ring must be less than the width of the groove but greater than its depth.
Junction plate: for joining a group of pipes to a component or to another group.
Teflon seal: to achieve sealing between parts capable of relative movement (such as the power steering jack and the suspension cylinders).

HYDRAULIC SERVICE SYSTEMS

General principle

The service systems for the suspension, the brakes and the steering, are all supplied by stored pressure energy (Fig. 5 and 6).

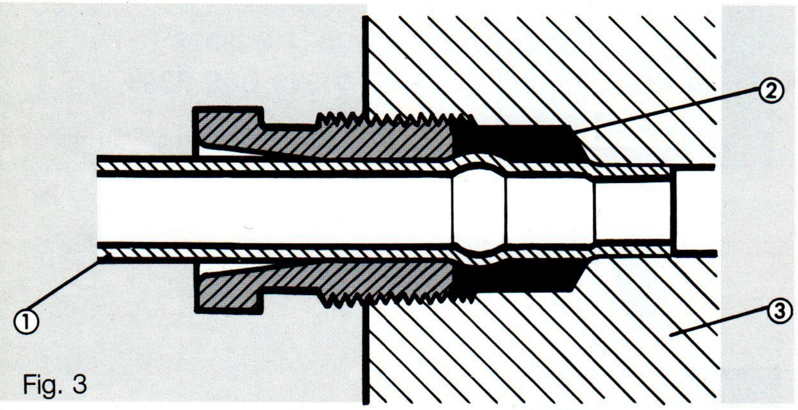


Fig. 3

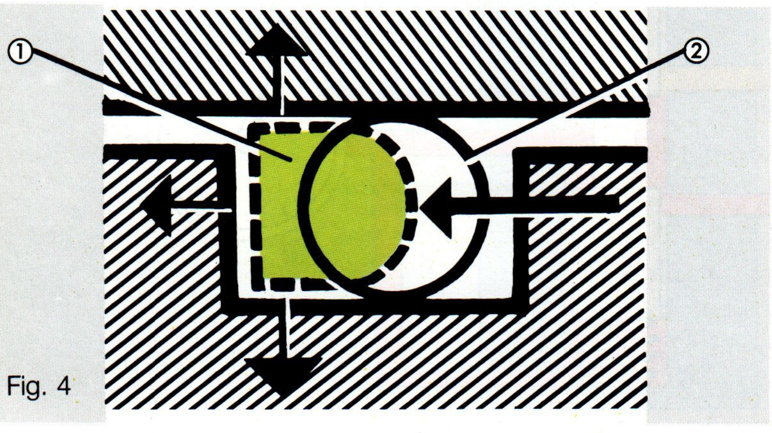


Fig. 4

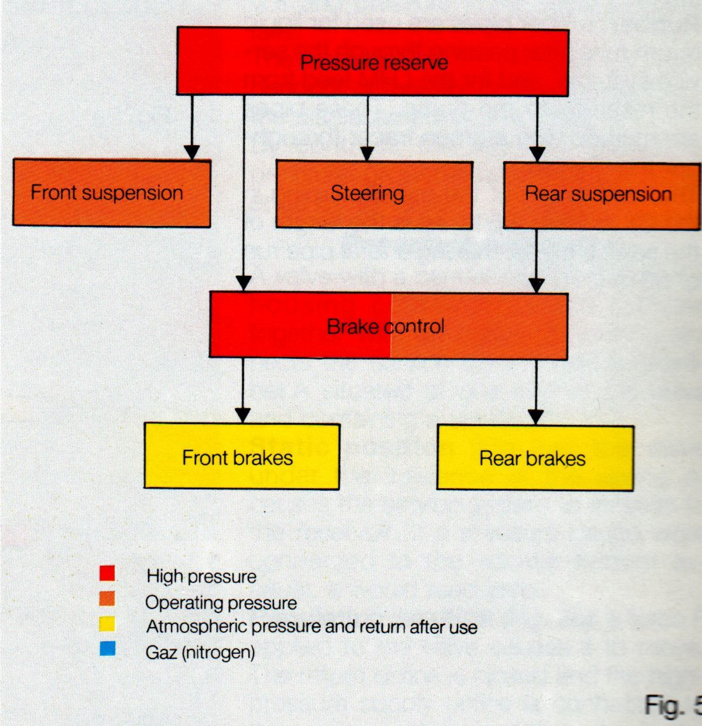


Fig. 5

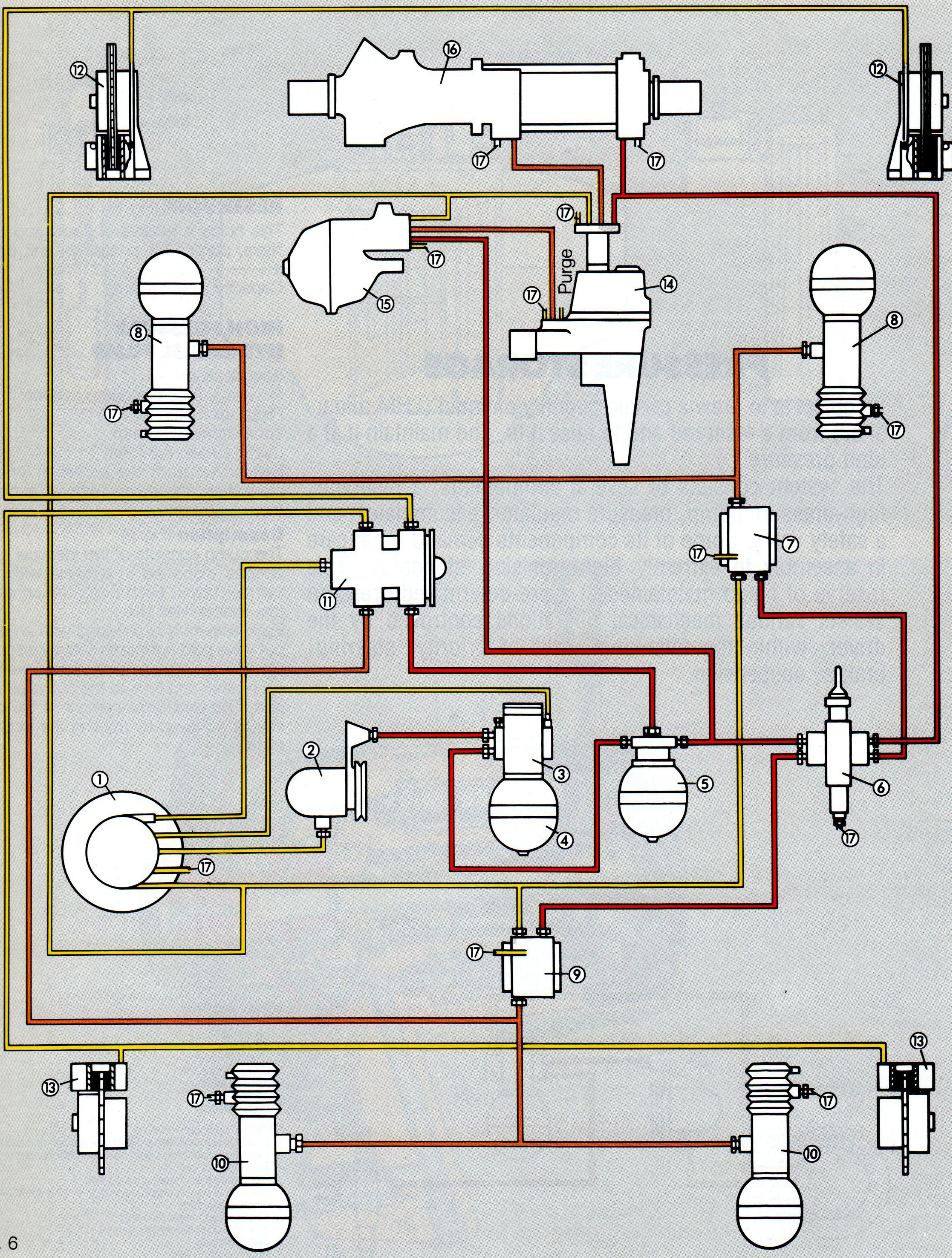


Fig. 6

PRESSURE STORAGE

Its object is to draw a certain quantity of liquid (LHM mineral oil) from a reservoir and to raise it to, and maintain it at a high pressure.
The system consists of several components: a reservoir, high-pressure pump, pressure regulator, accumulator, and a safety valve. Some of its components demand great care in assembly to extremly high-precision standards. This reserve of liquid maintained at a pre-determined pressure assists various mechanical operations controlled by the driver, within the following order of priority: steering, brakes, suspension.

RESERVOIR (Fig. 8)

This holds a reserve of liquid and also filters, purifies (de-emulsifies) and cools it.
Capacity: about 4 litres.

HIGH PRESSURE HYDRAULIC PUMP

Specifications
Flow rate: 5 cc per pump rotation
Piston diameter: 12 mm
Total stroke: 9.85 mm
Useful stroke: 8.37 mm
Belt-driven from the camshaft or the crankshaft, the pump turns at a maximum 3,600 rpm.

Description (Fig. 9)

The pump consists of five identical axial pistons disposed in a circle within a cylinder block. Each piston (4) contains four inlet orifices (10).
Each assembly is provided with an output valve held against its seat by a spring (8). All the output passages are linked to each other and thus to the pump output port. The axial displacement of the pistons is achieved by rotating the inclined plate (7).

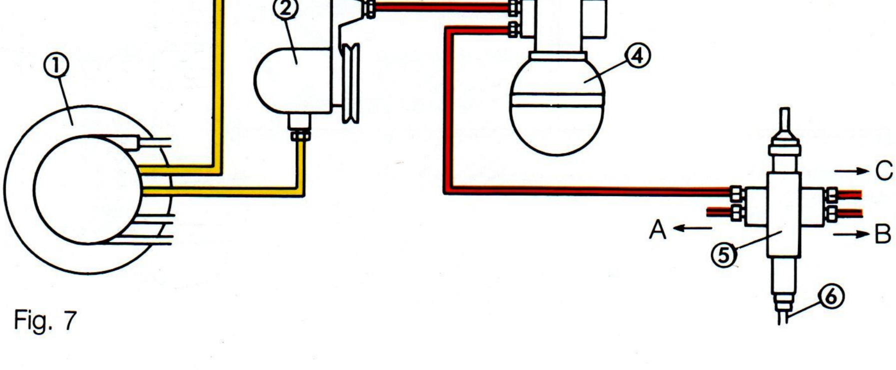


Fig. 7

Fig. 7: Layout of pressure storage circuit
A. Front suspension
B. Rear suspension
C. Steering
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Accumulator
5. Safety valve
6. Leakage return

Fig. 8: BX hydraulic reservoir
1. Leakage return from front and rear suspension cylinders
2. Leakage return from safety valve and front and rear height correctors
3. Return line from brake control valve
4. Return line from pressure regulator and front and rear height correctors
5. Feed to high pressure pump
6. Filter in high pressure pump feed
7. Sediment trap
8. Filter for return fluid
9. Level indicator float with electric contact

Fig. 8

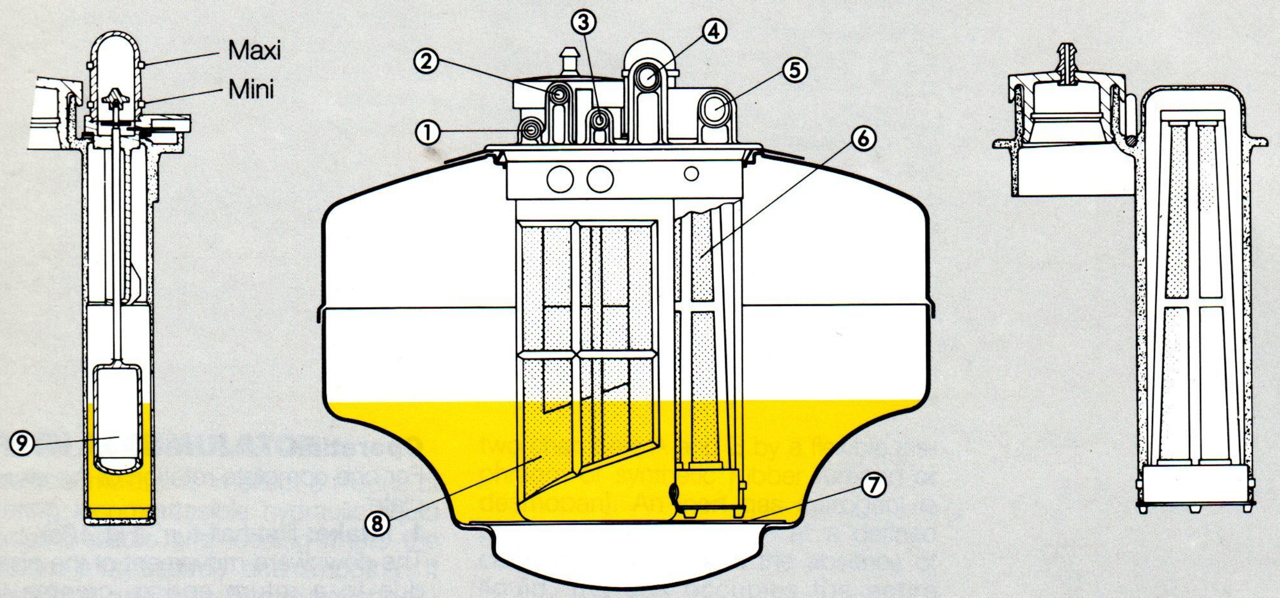


Fig. 9

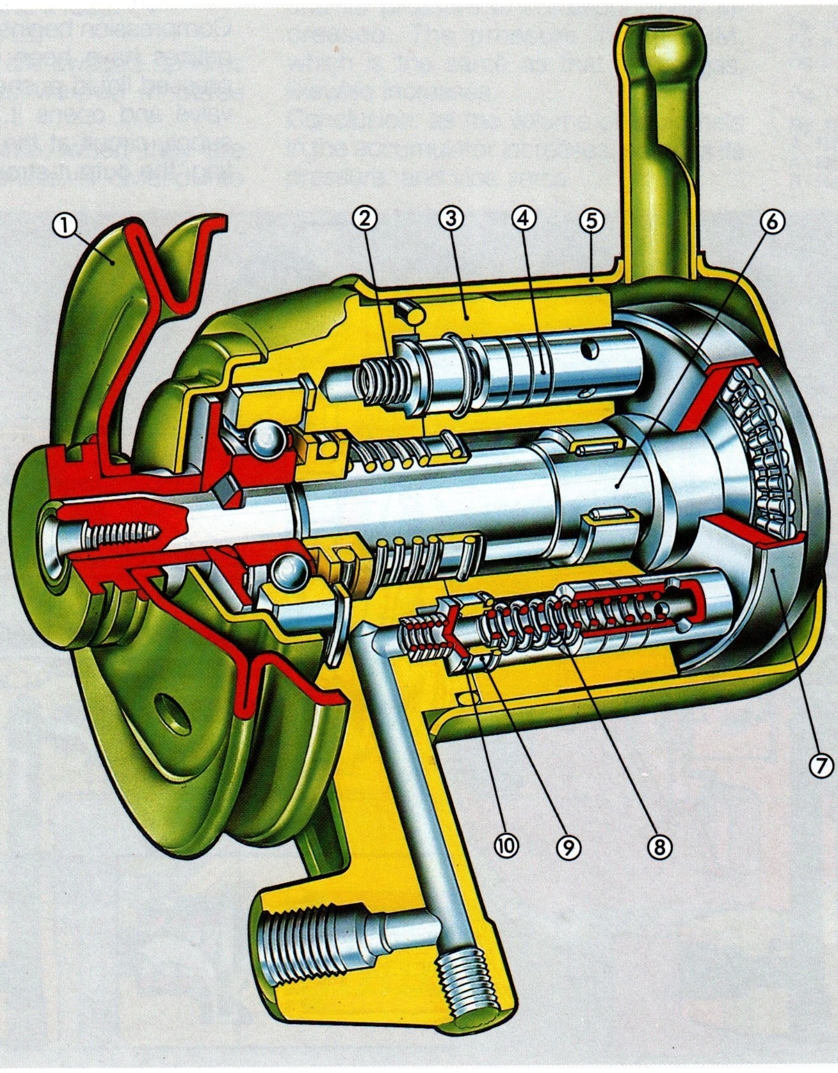


Fig. 9: High pressure hydraulic pump:
Description
Outlet to use

1. Drive pulley
2. Valve return spring
3. Cylinder block (housing)
4. Piston with holes
5. Pump shield
6. Pump shaft
7. Swashplate
8. Piston return spring
9. Valve seat
10. Valve

Operation
For one complete rotation of the swashplate

1. Intake: first half-turn (Fig. 10a)
The downward movement of the piston, due to a return spring, creates low pressure within its housing. When the inlet orifices are uncovered, the liquid contained in the surrounding jacket is drawn into the cylinder: the intake stroke.

2. Output: second half-turn (Fig. 10b)
Compression begins as soon as the inlet orifices have been covered. The compressed liquid pushes against the outlet valve and opens it, to be fed into the supply circuit at the valve pressure setting: the output stroke.

Fig. 10a

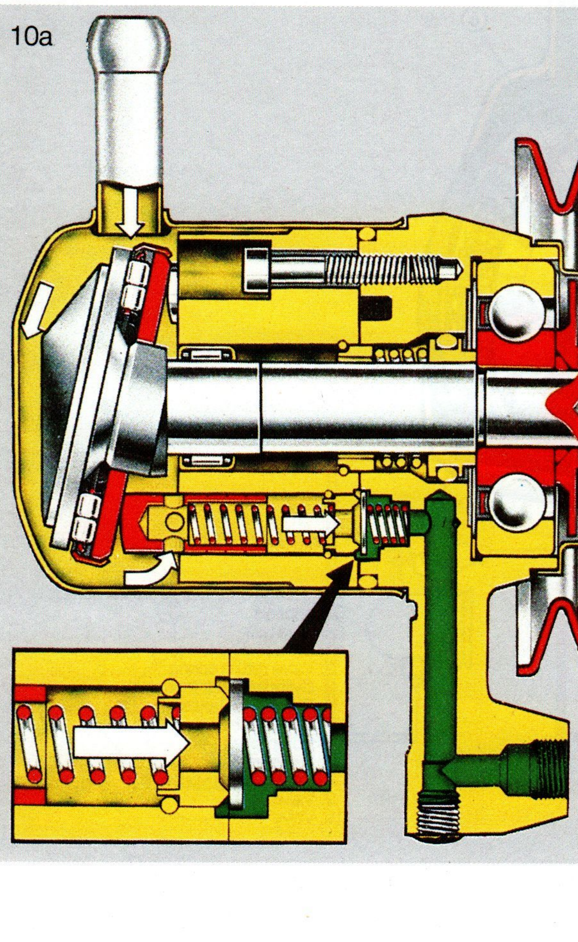
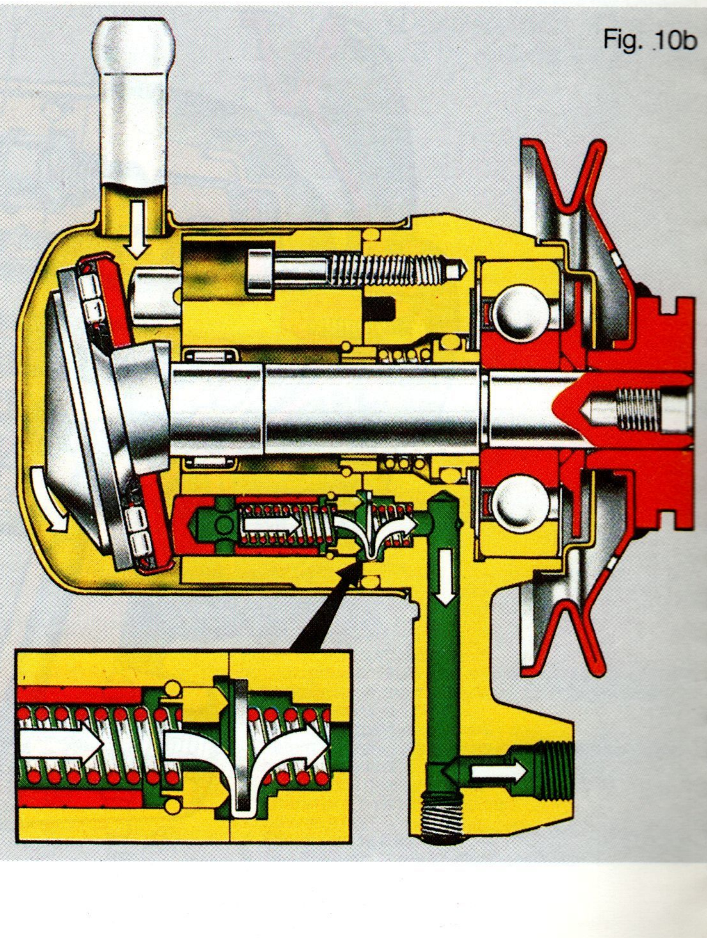


Fig. 10b



MAIN ACCUMULATOR

The accumulator is in effect a means of storing incompressible hydraulic liquid under pressure and feeding it into the system progressively and smoothly. It therefore prevents hydraulic shock-loading, ensures an adequate supply of liquid at moments of high demanded flow, compensates for internal leakage, and avoids the need for the pump to operate under constant load.

Description (Fig. 12)

The accumulators are swaged spheres with end-sections welded in place (Fig. 11).

Their interior volume, when they are mounted to the vehicle, is divided into two chambers A and B by a flexible disphragm of synthetic rubber (urepan or desmopan). An inert gas (nitrogen) is pumped into chamber A at a defined calibration pressure. In the absence of liquid, the gas occupies the entire volume of the sphere.

As soon as the chamber B is filled with any volume of hydraulic liquid, the volume of gas in chamber A is reduced and its pressure is correspondingly increased. The pressure in the LHM, which is the same as that in the gas, likewise increases.

Conclusion: as the volume of liquid held in the accumulator increases, so does its pressure, and vice versa.

Fig. 10: High pression hydraulic pump: operating principle
Fig. a: intake
Fig. b: output

Fig. 11: Stages in the manufacture of a suspension sphere

Fig. 12: Accumulator
A - Nitrogen at calibration pressure
A - Nitrogen at operating pressure
B - Reserve of pressurised liquid

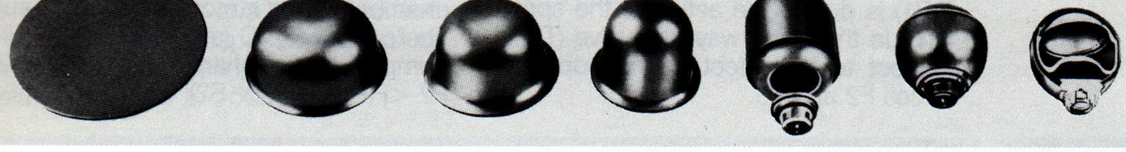


Fig. 11

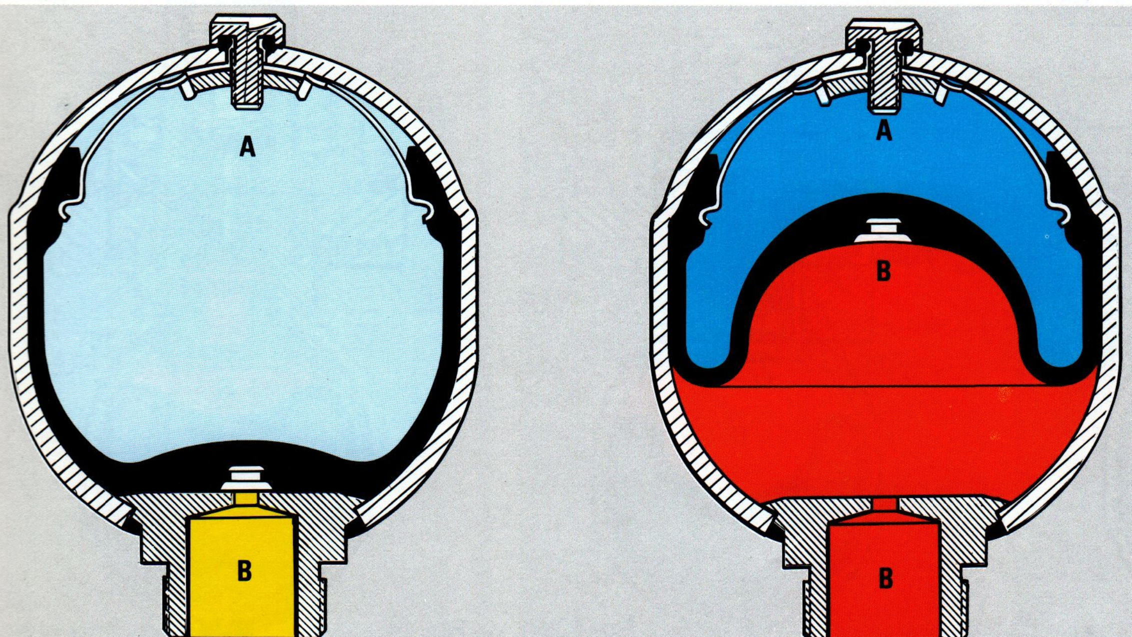


Fig. 12

PRESSURE REGULATOR

This forms an integral part of the main accumulator. Its purpose is to ensure that the pressure of the liquid held in the accumulator lies between certain maximum and minimum values.

Calibration pressure: 911 ± 30 psi
Cut-in pressure: 2060 to 2200 psi
Cut-out pressure: 2425 to 2575 psi

Operation

1. Static (Figs. 13 a and b)

The pump turns and feeds the pressure regulator, with the purging screw open: the liquid entering the regulator lifts the ball freed by the opening of the purging screw (b) and escapes back to the reservoir.

Pressures maintained:

Chambers A, B, C: atmospheric pressure.

The non-return valve (a) is open.

The valves (T1) and (T2) are in the static position.

2 Filling and discharge (Figs. 14 and 15)

When the purging valve is closed, pressure increases progressively and simultaneously in the chambers A, B and C. Chamber D, which is connected with the reservoir, remains at atmospheric pressure.

The valve (T1) is then subject to the actions of two opposing forces F1 and F(R1).

F1, created by the pressure existing in the chamber B and acting on the surface S1: F1 = P × S1.

F(R1) is due to the action of the spring (R1). In the same way, the valve (T2) is subject to the effect of the opposing forces F2 and F3.

F2 = P × S2.

F3 is the sum of two forces: F(R2) which is exerted by the spring (R2), and F'2 which results from the pressure in chamber C, which is identical to that in chamber B but acts on the surface S2.

F'2 = P × S2

F3 = F(R2) + F'2

As soon as F1 exceeds F(R1), the valve (T1) moves and opens the chamber C to the chamber D (which is at atmospheric pressure).

Thus: F'2 = 0.

As a result: F3 = F(R2).

F2 therefore becomes preponderant (F2 > F3).

The valve (T2) therefore moves and discharge takes place: the high-pressure pump exhausts into the reservoir, unpressurised and the non-return valve (a) closes.

3. Charging (Figs. 16 and 17)

As soon as a small amount of liquid has been used in the service systems (in the suspension, for example) the pressure in B falls and the valve (T1) therefore returns to its initial position.

F(R1) > F1

The chambers C and D are therefore connected as well as the delivery to the high-pressure pump (all at atmospheric pressure).

If consumption continues to rise, the pressure in B falls further and as soon as F2 < F(R2), the valve (T2) also returns to its initial position. As it does so, it isolates the high-pressure pump circuit from the chamber D (at atmospheric pressure). The pressure in C (still linked to the HP pump) thus rises sharply and pushes T2: F2 <F(R2) + (P × S2)

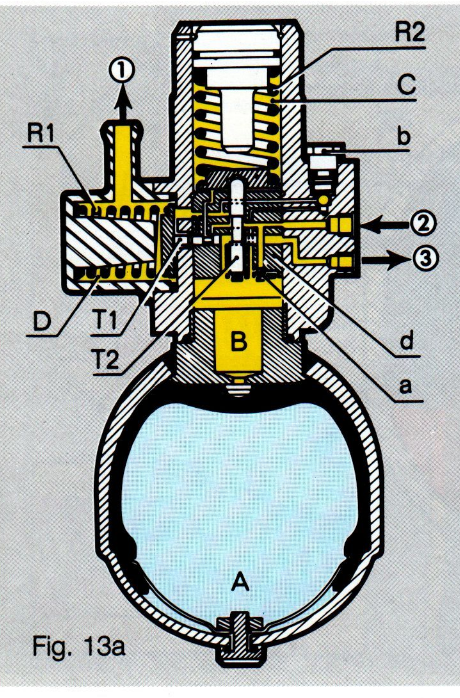


Fig. 13a

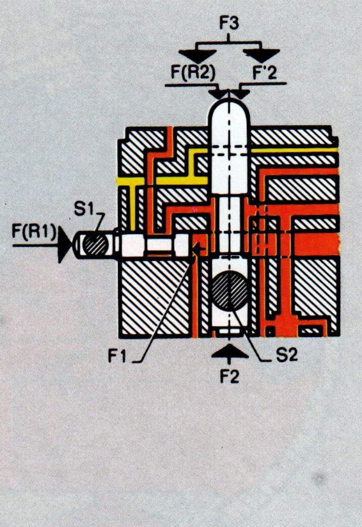


Fig. 13b

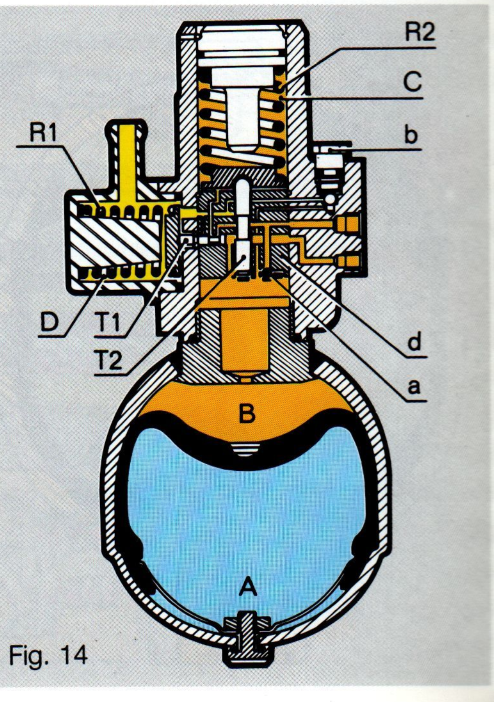


Fig. 14

F2 < F3
Charging therefore takes place, with the non-return valve (a) opening. Pressure once again rises in chambers A, B and C.

SAFETY VALVE

Purpose
The pressure reserve is shared between the car's suspension, braking and steering systems.
The safety valve accords priority to the safety-related systems: the brakes and steering.
It isolates the front brakes from the front and rear suspension systems should one of the circuits fail, allowing either front or rear braking to be retained according to the actual position of the failure.

Description (Fig. 18)
The valve has four channels:
- pressure feed
- outlet to the front brakes and/or steering (according to vehicle type)
- outlet to the front suspension
- outlet to the rear suspension.

The first two channels are always linked, but may be isolated from the others by means of a valve.

Operation
Pressure is allocated to the circuits:
- if it is less than a value P (defined by the setting of the calibration spring (2), liquid is fed only to the front brakes and the steering.
- if it is greater than P, the liquid is able to force across the valve in order to feed the front and rear suspension as well as the brakes and steering.

Value of P: 1200 to 1500 psi.

Fig. 13: Pressure regulator
1. Return to reservoir
2. High pressure pump
3. Output

Fig. 14: Pressure regulator
Filling

Fig. 15: Pressure regulator
Discharging

Fig. 16: Pressure regulator
Operating

Fig. 17: Pressure regulator
Charging

Fig. 18: Safety valve
1. Spring setting washer
2. Slide-valve spring
3. Valve body cover
4. Slide valve
5. Valve body
6. Failure detection pressure switch
A. High pressure from main accumulator
B. Steering
C. Front corrector
D. Rear corrector
E. Leakage return

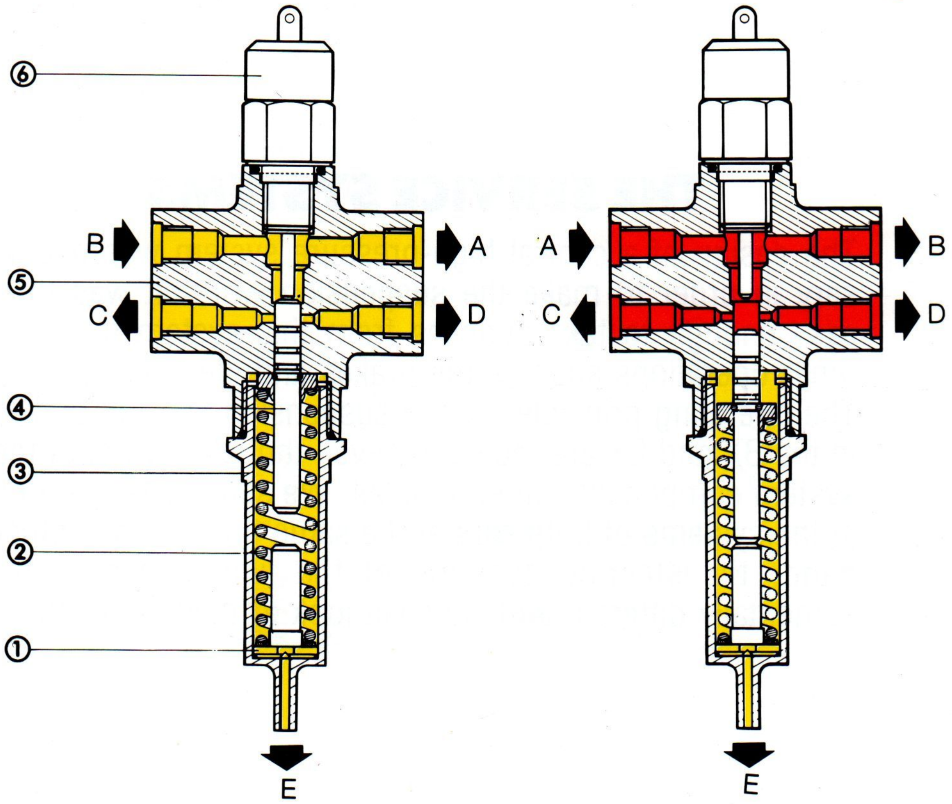


Fig. 18

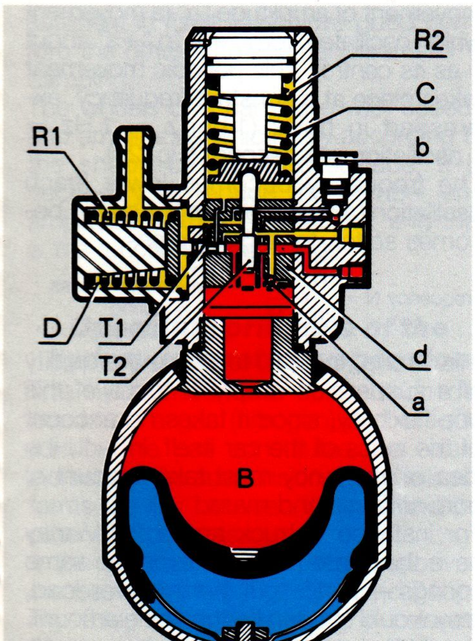


Fig. 15

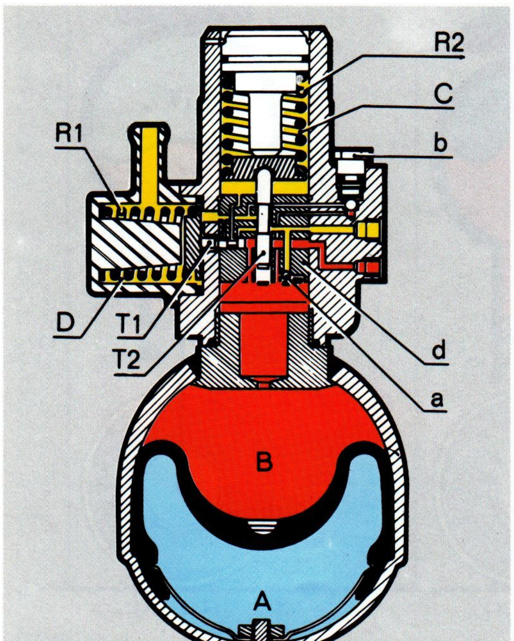


Fig. 16

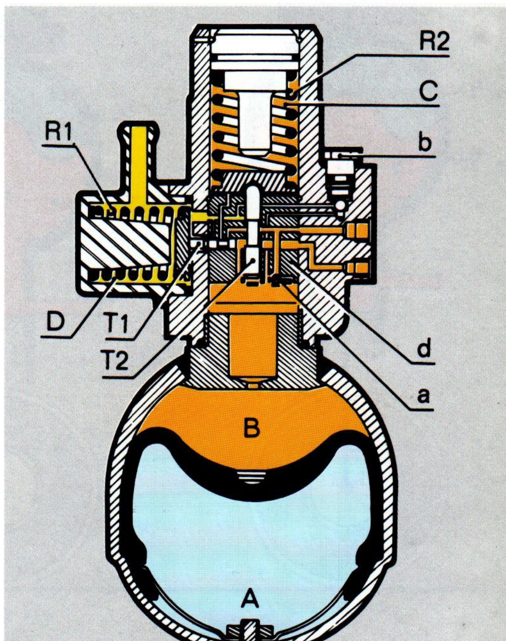


Fig. 17

THE SERVICE SYSTEMS

The design of a central high-pressure system was necessary in order to make the suspension work. It was then easy enough to take supplies from this system to assist other operations such as the brakes and steering.
The operating principles of the suspension and the brakes in the BX and CX are the same, even though several of the system components differ in detail. We shall therefore look at the systems of both cars at the same time. On the other hand, the steering systems of the two cars are fundamentally different and we shall look at them separately.

THE SUSPENSION

Main features of a suspension

- to allow the wheels to follow an uneven surface without transmitting severe shocks to the body;
- to ensure that the wheels remain in contact with the surface;
- to reduce the motion, of the body and its occupants as far as possible.

The simplest form of suspension consists of a suspended mass and a spring. The first parameter to be taken into account when developing a suspension is the natural frequency of the axles. The first step in this fundamental process is to define the characteristics (stiffness, flexibility) of the spring which joins the axle to the body.

The flexibility F of a spring is expressed as its change in length under a given load, and may be expressed for instance as millimetres per 100 daN (mm/100 daN).
The stiffness K is the inverse of the flexibility F ((Fig. 19), being the load necessary to change the length of a spring by one unit. It may thus be expressed, for instance, as pounds per inch (lbs/in) or kg/m.

$$K = \frac{F}{X}$$

Consider a mass M supported by a spring of stiffness K.
Displace the mass a distance "a" from its statically balanced position 0. If the force holding the mass is suddenly removed, it will rebound a distance of "2a" in the other direction; in fact it begins a periodic movement of amplitude "a" (a movement which oscillates from "−a" to "+a" about 0 as its centre). This periodic movement takes place at a constant frequency, expressed in hertz (1 hertz = 1 Hz = 1 oscillation per second) (Fig. 20).
The frequency becomes lower (each oscillation takes longer) as the spring becomes softer, for a given mass.

$$\text{Frequency } N = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

where M = mass
K = spring stiffness

It is wrong, though, to define the quality of a suspension simply in terms of this one flexibility, since it takes no account of the mass of the car itself. In fact, the idea of frequency must take account of both stiffness and mass.
For instance: a truck and a 2 CV may have the same flexibility, even the same springs — that is to say, for a given load, they would shorten by the same amount. But their suspended mass, when empty, would be very different and the 2 CV, so

much lighter than the truck which is heavy even when empty, would in effect have no suspension at all.
The "static deflection" is an expression of the shortening of the spring under a given load, and does not depend on the natural frequency of the system.
Experiment shows that for a given frequency (obtained by the different possible combinations of K/M) the value of the static deflection always remains the same. For a frequency of 1 Hz, the static deflection is about 25 cm (10 ins).
In the pioneering days of motoring, specialists thought that the ideal frequency was that of a man's footsteps, about 1.3 Hz. In fact, experience has shown that the frequency needs to be less than 1 Hz before a suspension becomes really comfortable.
The lower the frequency, the larger the wheel movements become, and a good suspension must allow for large wheel movements.
This table gives an outline classification of suspension comfort rating:

Frequency Hz	Suspension quality
0.5 to 1.0	Soft, very comfortable
1.0 to 1.3	Firm quite comfortable
1.3 to 1.5	Hard uncomfortable
over 1.5	Very hard and uncomfortable

The frequency is only one condition, not sufficient in itself to achieve good comfort; the other fundamental parameter is damping.
The wheels of a car move with speeds and amplitudes which vary according to the shape of the road surface. It is necessary to reduce the number and amplitude of these oscillations, and that is the function of damping.

Operating principle of the hydropneumatic suspension

The hydropneumatic suspension depends on a gas (nitrogen) and a liquid (LHM). The gas constitutes the elastic element of the suspension, and the liquid forms the link between the gas and the other components.
• the pressure in the suspension increases with load (Figs. 21a and 21b).
Fig. 21a: the system being in balance, the pressures are equal: P1 = P2.
Fig. 21b: an extra load C1 is added to C.
The volume of gas is reduced to V'1 = V1 − v and:
• the height falls from H to H'
• the pressure in the gas rises to P'1 since by Mariotte's Law, P × V = constant.
In the new equilibrium position P'1 = P'2 and therefore P'2 > P2.
• the pressure in the suspension is independent of the height of the vehicle.
Fig. 21c: if the tap R is opened, the volume of liquid increases to V''2 = V'2 + v and is compensated for by a reduction in the volume of gas.

The sphere returns to its initial height H. Compared with figure 21b, the volume of gas has thus not varied other than according to the pressure it exerts: P''1 = P'1.

Fig. 19: Spring flexibility

Fig. 20: Frequency: 1 Hertz
1. Amplitude
2. 1 second
3. 1 oscillation

Fig. 21: Operating principle of hydropneumatic suspension

Fig. 19

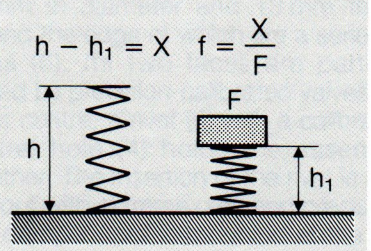
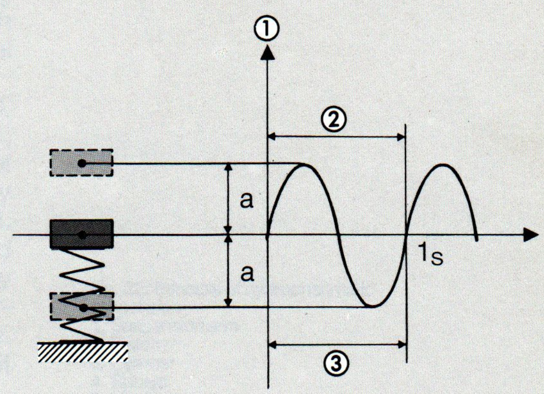


Fig. 20



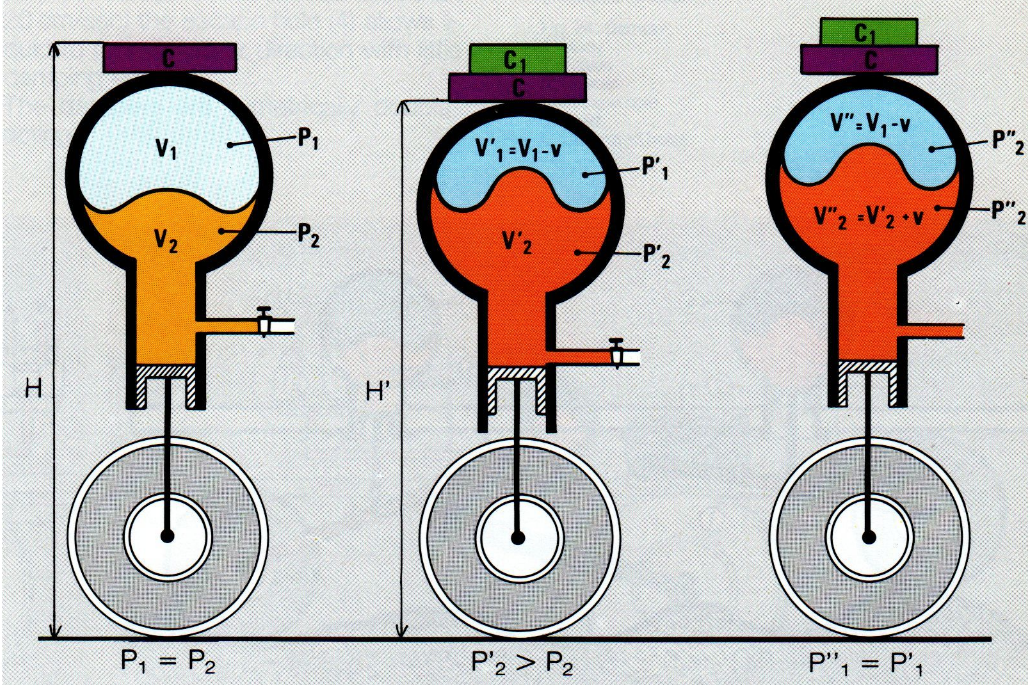


Fig. 21

Description (Fig. 22)
Each wheel is independently suspended by an arm (1) which attaches it to the body.
A piston (2) attached to the arm slides in a cylinder (3) and acts upon a liquid which, by way of a membrane, acts upon a constant mass of gas contained in a sphere (4).

Operation (Fig. 22)
Whenever the wheel strikes an obstacle, the piston is displaced in its cylinder. As it passes over a bump, the piston pushes liquid out of the cylinder towards the sphere. The gas is compressed.
When passing over a pothole, the piston descends and the liquid passes from the sphere towards the cylinder; the gas expands.
The compression or expansion of the gas absorbs the energy of the shock without passing it on to the body or its occupants.

Height correction (Fig. 23a, b, c)
This maintains a constant ride height regardless of the static loading of the car or changes in the profile of the road surface. Adjustment is effected by changing the volume of liquid between the piston and the sphere membrane.
A mechanical selector allows the ride height of the car to be changed when necessary, for instance to clear obstacles or when changing a wheel.

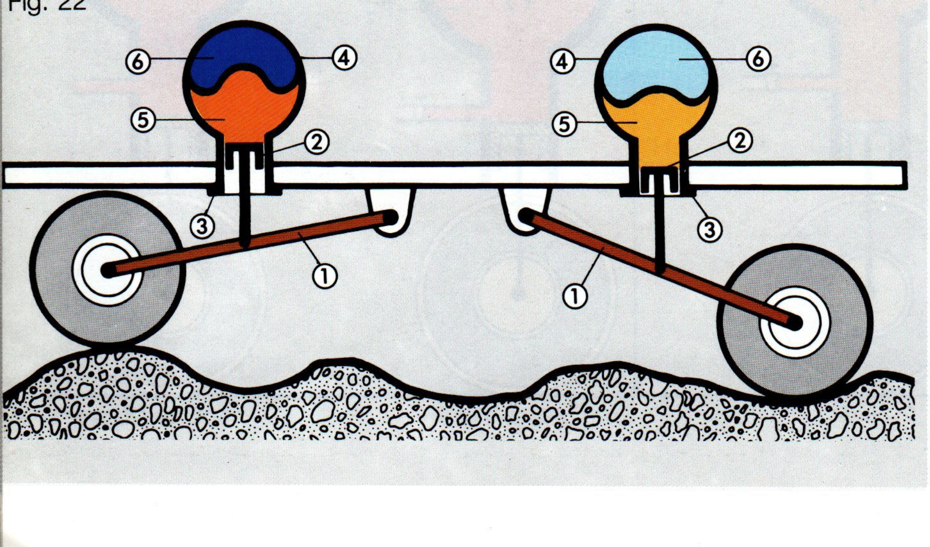
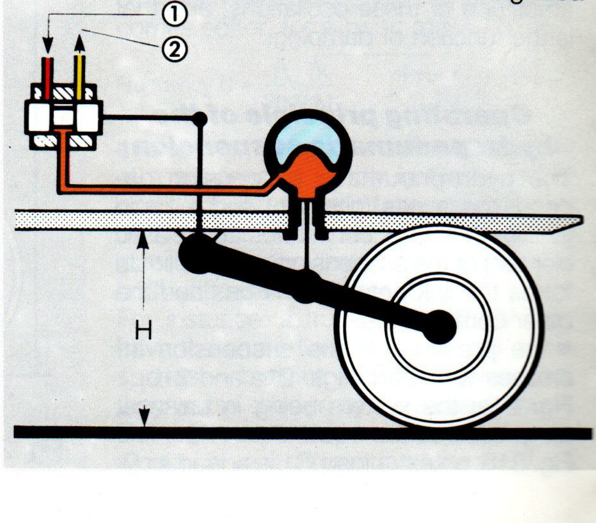
Fig. 22


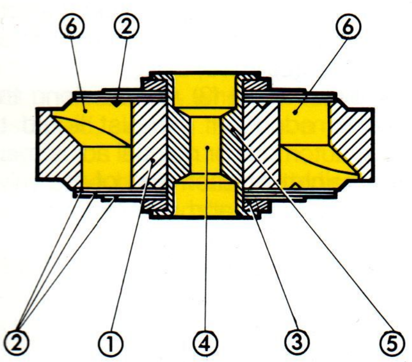
Fig. 23a


For an increase in load P, the car falls and the volume of gas decreases. In order to maintain constant ride height, this decrease must be balanced by a corresponding increase in the volume of liquid.
For a decrease in load P, the car rises and the volume of gas increases. It is therefore necessary to withdraw a volume of liquid in order to return the car to its original ride height.
The necessary addition or substraction of liquid is made by an automatic "tap" — the height corrector.

Hydropneumatic suspension components

The sphere
This resembles the main accumulator in its construction. The gas (nitrogen) which it encloses forms the elastic element of the suspension. The gas pressure differs according to the type of car.

Fig. 24



The damper (Fig. 24)

In order to control the amplitude of the oscillations, bouncing of the wheels and heaving of the body, a damper is inserted between the sphere and the cylinder. It forms an integral part of the suspension and, because it works in a permanently pressurised environment, it runs no risk of cavitation. By achieving laminar flow of the liquid passing through it, it damps even the smallest wheel movements.
The damper is a disc of sintered steel, 27 mm in diameter and 13 mm thick, around the edge of which are a series of holes (6). Its two faces are partially closed by precision-calibrated valves (2). At its centre, a rivet (5) with a calibrated central hole (4) holds the assembly together. The insertion of the rivet is carried out with extreme care and precision. The damper itself is mounted at the exit from the suspension sphere.
Damping is achieved by laminar flow of the liquid through the holes which are more or less closed by the valves. For very low vertical wheel speeds (less than 20 cm/sec) the escape hole (4) allows liquid to pass in either direction with little damping effect.
The dampers are symetrically double-acting.

Fig. 22: Principle of hydropneumatic suspension
1. Suspension arm
2. Piston
3. Cylinder
4. Sphere
5. Liquid
6. Gas

Fig. 23a, b, c: Height correction
1. Incoming pressure
2. Return to reservoir
3. height corrector

Fig. 24: Damper
1. Body
2. Valves
3. Spacer
4. Escape hole
5. Rivet
6. Calibrated holes

Fig. 23b

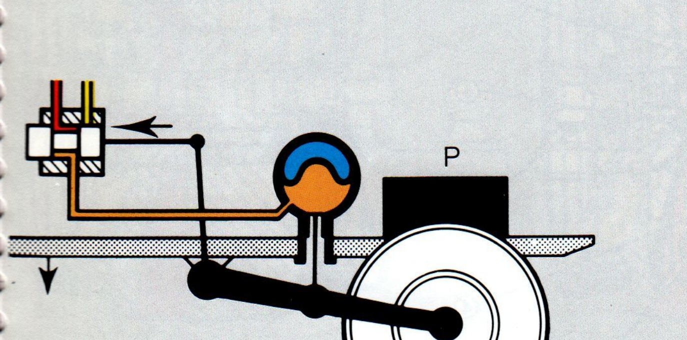
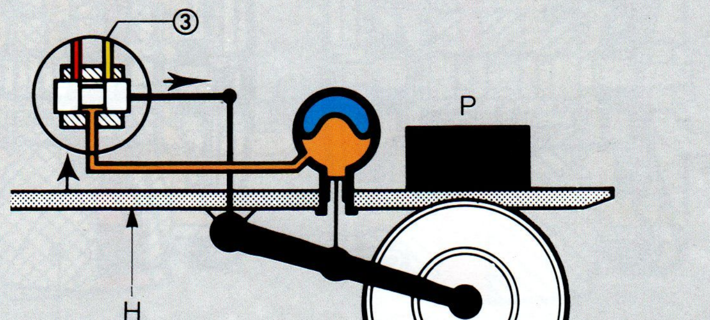


Fig. 23c



The cylinder

Mounted on the body, this carries the sphere at one end and encloses a piston, and liquid under pressure.

Its length and diameter vary according to its position (front or rear) in the car and to the type of car (BX or CX).

The height correctors

There are two correctors, one for the front suspension and the other for the rear. They are mounted on the body and linked to the suspension anti-roll bars by a spring in order to achieve automatic height correction.

They alter the height of the car by:

- admitting liquid from the pressure reserve system to the suspension circuit,
- exhausting liquid to the reservoir, using the same working principle as the pressure distributor.

Description (Fig. 25)

Each height corrector consists of a light alloy body (1) containing a press-fitted steel sleeve (2).

A distributor valve (3) moves along the sleeve to admit or exhaust liquid to achieve automatic or manual adjustment of ride height. At each end of the valve are chambers (C) and (D) filled with un-

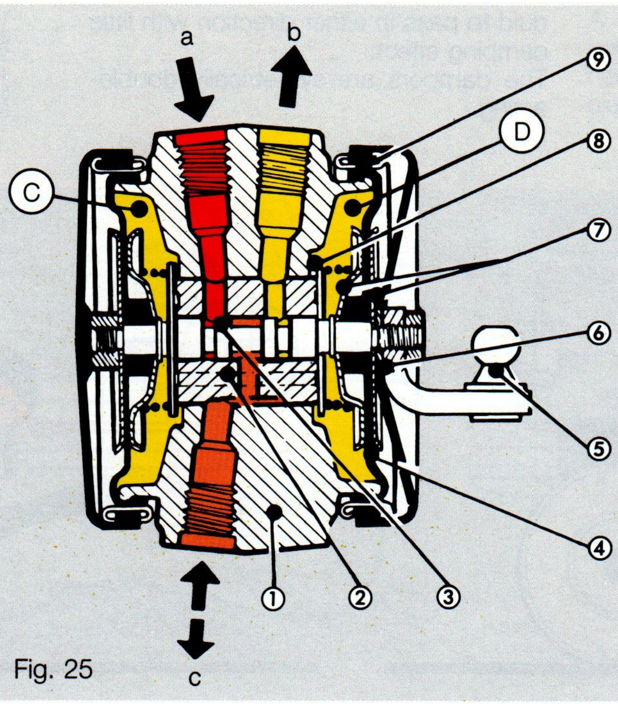


Fig. 25

pressurised liquid. Two channels 0_1 and 0_2 allow liquid to move from one chamber to the other.
The channel 0_1 contains a series of calibrated washers forming a dashpot to slow down the passage of liquid.
The valve is able, via holes bored radially in the body sleeve assembly, to link the suspension circuit with either the high-pressure supply system or the reservoir.

Operation (Fig. 26)

• **Increased load in the car:** the height corrector valve is pushed towards the admission position by the anti-roll bar. It links the suspension circuit with the high-pressure supply system. The increase in the volume of liquid in the cylinders causes the body to rise, but the movement of the valve is damped to avoid over-rapid adjustment. Once it has moved from the neutral to the admission position, the valve (8) is operated by the end of the valve, closing off 0_2. The liquid passes from (D) to (C) through the "dashpot" in channel 0_1 where its movement is restricted, slowing the movement of the valve.
When the body returns to the normal position, the opposite action of the anti-roll bar returns the valve to the neutral position. The suspension circuit is once again isolated.
When the valve returns to the neutral position, the liquid passes from (C) to (D) through the unobstructed channel 0_2, its shutter having opened with the withdrawal of the valve. This ensures that the valve quickly and accurately regains its original position.

• **Unloading the car:** the same process takes place, but in the opposite sense.
The valve moves in the other direction and links the suspension circuit with the exhaust to the reservoir. As the body descends, the anti-roll bar returns the valve to the neutral position. The movements of the valve in both directions are damped in exactly the same way as when compensating for increased load.

• **Manual operation:** this allows the driver to adjust the ground clearance according to the condition of the road surface: metalled, rough track or broken ground.
It is also used when changing a wheel, since the ability to raise the body hydraulically greatly reduces the effort needed by the driver to operate the jack.

Fig. 25: Description of height corrector
1. Body
2. Sleeve
3. Slide valve
4. Flexible membrane
5. Adjustment knob
6. Dust cover
7. Cups
8. Valve
9. Retaining ring
10. Dashpot
a. Intake
b. Return
c. Operation

Fig. 26: Operation of height corrector
a) Intake
b) Return to neutral
c) Neutral

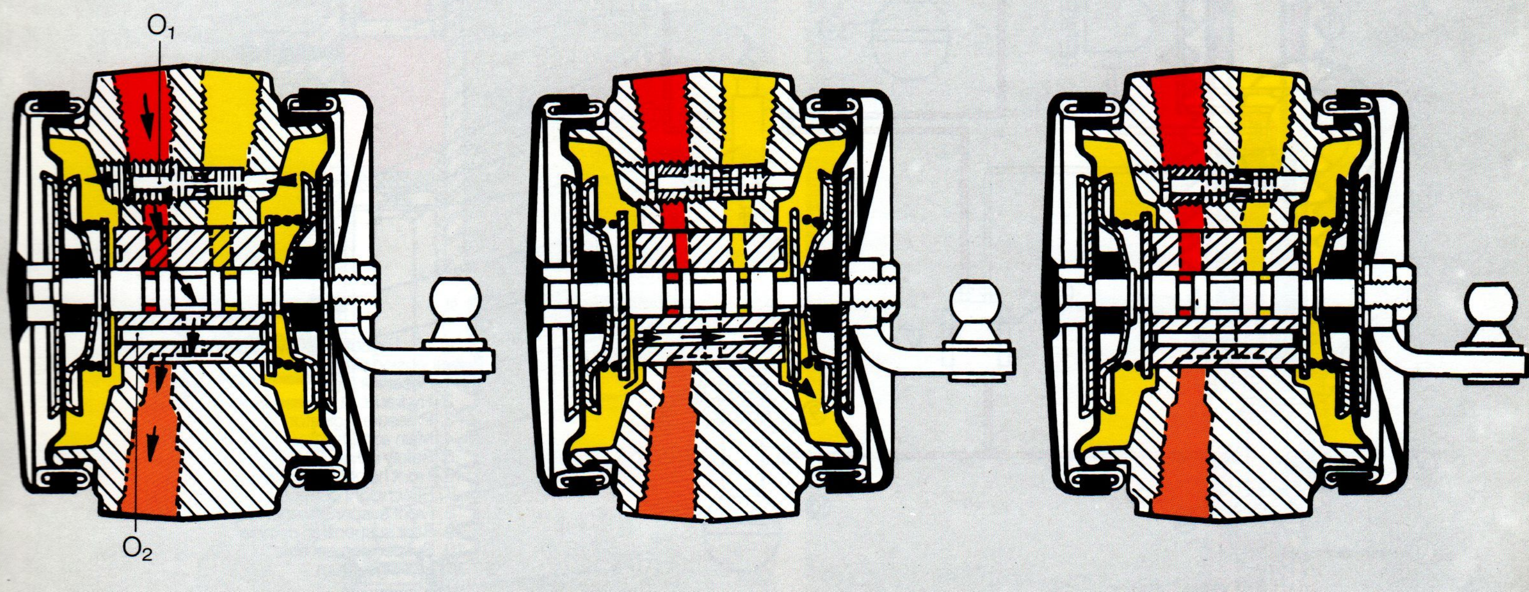


Fig. 26a

Fig. 26b

Fig. 26c

BX suspension

The BX suspension works according to the principles already discussed (Fig. 27). What follows is a more detailed examination of specific parts of its system.

Front suspension member (Fig. 28)

This consists of an assembly, part of which is shown in red with the rest in green.

The red parts are joined to stub-axle and move with it vertically, and may be considered as one. The green parts are joined to the body shell and move with it. When the car moves, vertical movement of the body relative to the stub-axle, or vice versa, causes the green parts to slide inside the red parts, the sliding being controlled by the flexible bearing (9) and by the cylinder guide (12).

Rubber bump-stops (20) and (22) limit movement in bump and rebound respectively.

A minimum quantity of LHM liquid, shown in yellow, inserted during assembly and topped up through internal leakage within the suspension system, lubricates the interior of the sliding tube. A channel with a valve (15) allows any excess liquid to return to the reservoir.

The inlet port (6) links the suspension unit with the height corrector which governs the supply of liquid to the suspension or drains it as necessary.

Except for the rubber bump-stops and the nylon guides (9) and (14), the suspension unit is made entirely of steel. A rubber sleeve (10) protects against the entry of dust and dirt.

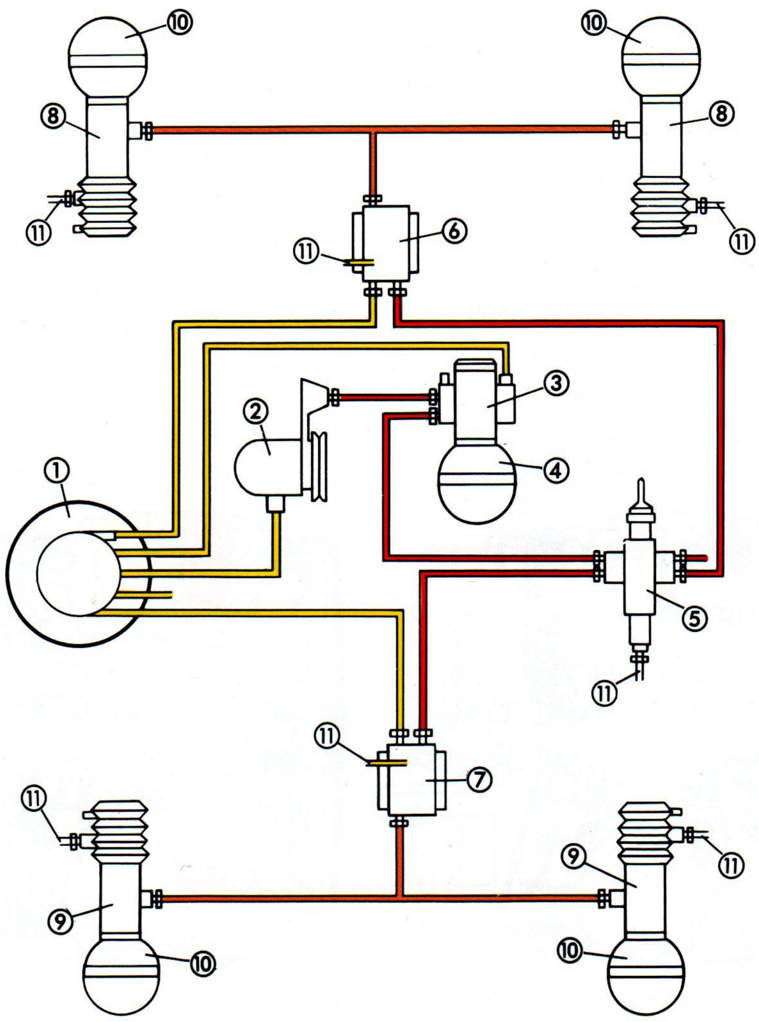


Fig. 27

Fig. 27: Layout of BX hydropneumatic suspension circuit
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Safety valve
6. Front height corrector
7. Rear height corrector
8. Front suspension cylinder
9. Rear suspension cylinder
10. Suspension spheres
11. Leakage return

Rear suspension cylinder (Fig. 29)
The cylinder is attached to the body and carries the sphere screwed into place. It houses a piston, and liquid under pressure.
It is made of light alloy, its bore being ground to ensure smooth sliding of the piston. Two grooves at its lower end house seals; two orifices allow entry of high-pressure liquid, and for return to the reservoir of any liquid which leaks between the piston and the cylinder.
The steel piston is attached to the suspension arm by a pushrod and so follows its movements.
The pressurised LHM liquid is the (incompressible) fluid which transmits force from the displacement of the suspension arm to the gas, by way of the membrane, and which loads the piston against its bearing. A rubber gaiter protects the unit against dirt.

CX suspension

The CX hydropneumatic suspension works on exactly the same principles as that of the BX.
Both the front and rear suspension units are similar in design to those of the rear suspension of the BX, differing only in detail (see technical specification table on page 32).
The height correctors are identical. Manual height adjustment is carried out by the driver moving a switch on the centre console which operates an electric motor to alter the position of the levers connecting the anti-roll bars to the height correction valves.

Advantages of hydropneumatic suspension

- improved suspension when unladen, since the suspension stiffness varies with load;
- extremely flexible suspension yet compact installation;
- light, totally reliable dampers built into the suspension units themselves;
- suspension arms always ideally placed between the bump-stop limits;
- constant ride height regardless of load (allowing the centre of gravity to be lowered);
- the ride height can be varies in order to cross difficult terrain;
- less effort is needed during wheel-changing;
- maintenance needs are much reduced.

Fig. 28: Section through BX front suspension unit
1. Sphere
2. Gas (nitrogen)
3. Membrane
4. Pressurised liquid
5. Damper
6. Hydraulic liquid intake
7. Cylinder
8. Flexible mounting
9. Flexible bearing
10. Dust gaiter
11. Piston guide rod
12. Rebound stop
13. Piston
14. Guide tube
15. Oil return valve
16. Sliding tube
17. Oil reserve
18. Stop washer
19. Centring washer
20. Bump stops

Fig. 29: Section through BX rear suspension cylinder
1. Sealing screw
2. Ring seal
3. Cup
4. Pneumatic unit
5. Membrane
6. Ring seal
7. Damper
8. Cylinder
9. Piston
10. Thrust-pad
11. Centring washer
12. Teflon gasket
13. Ring seals
14. Felt washer
15. Dust gaiter
16. Suspension rod
17. Ball

A. Liquid from height corrector
B. Leakage return
C. Breather pipe

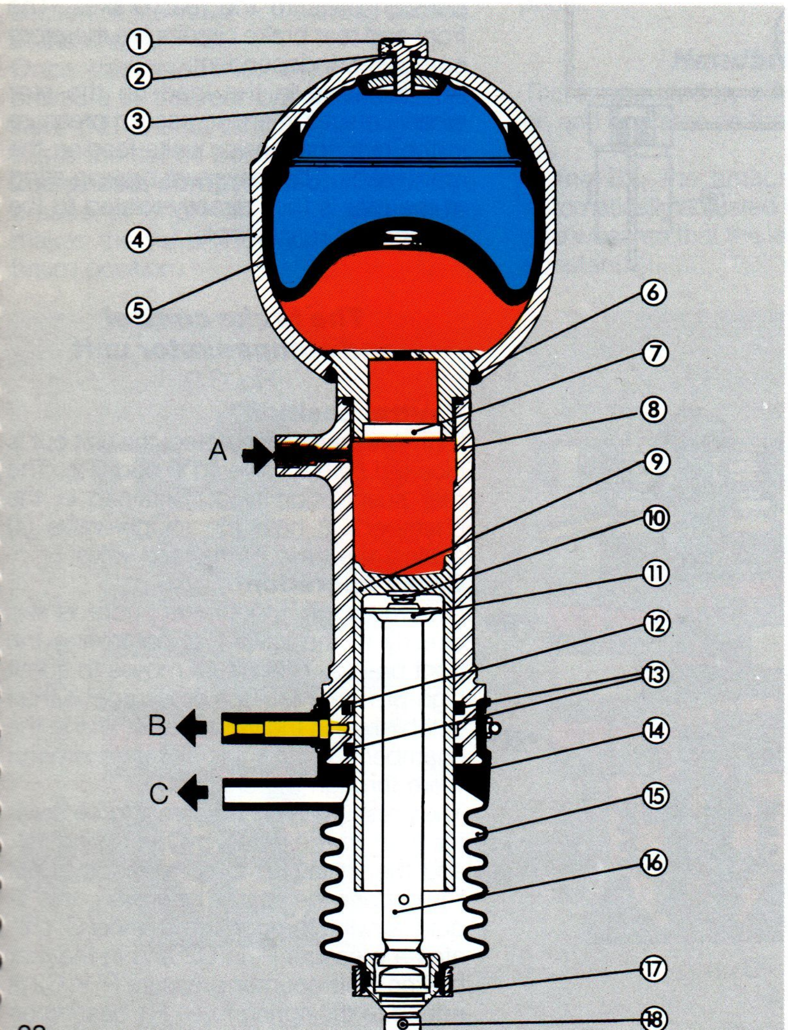


Fig. 28

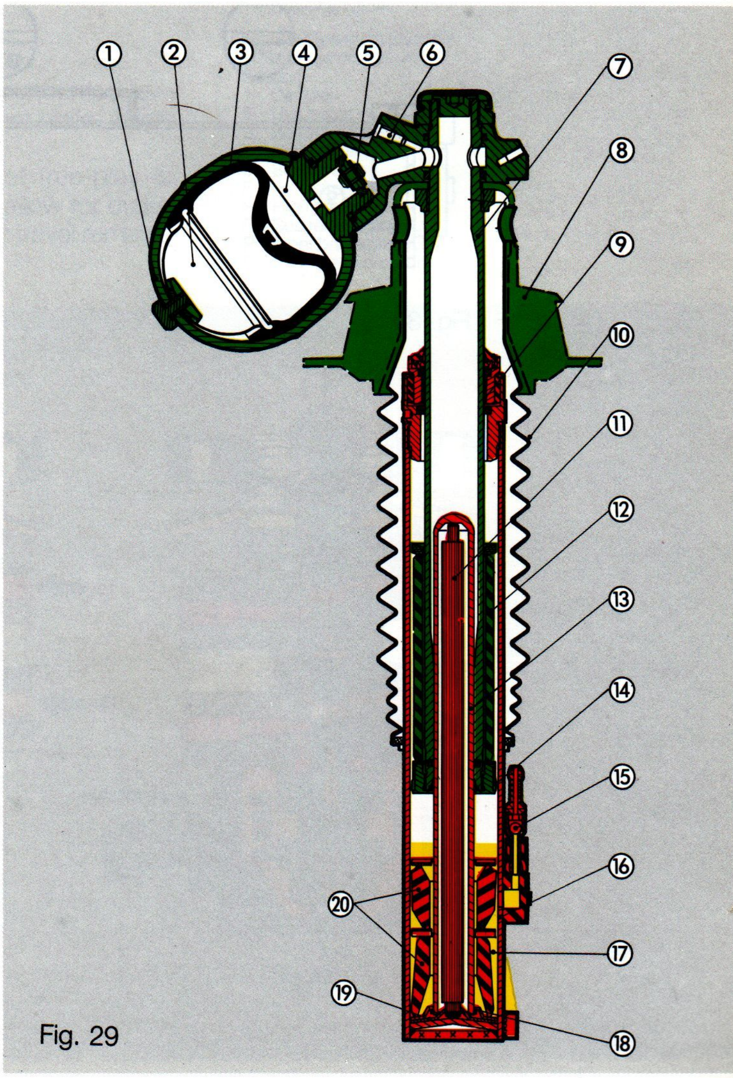


Fig. 29

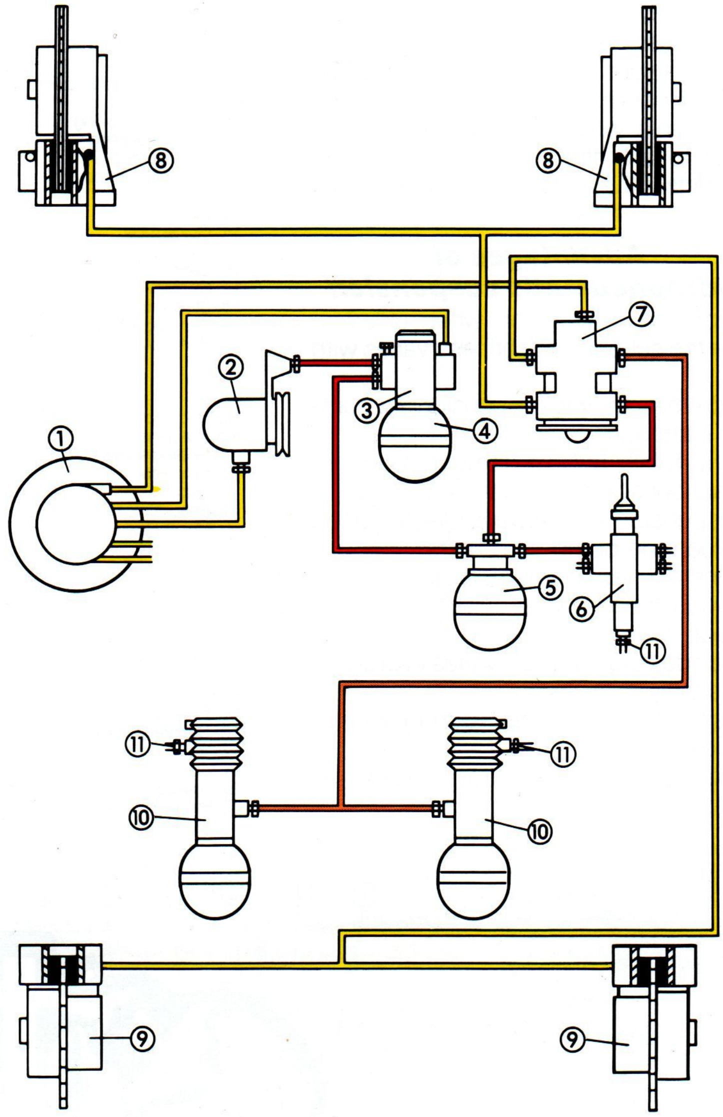


Fig. 30

BRAKES

The BX and CX are equipped with hydraulic brakes using stored energy, with double circuits working on four discs (Fig. 30).
The CX braking system draws its energy from a brake system accumulator in the high-pressure supply circuit, and from the rear suspension units. In the BX, energy is drawn from the main high-pressure accumulator and from the rear suspension units. The control unit is a feed valve with a built-in compensator which allows the braking effort to the rear wheels to be optimised for all load conditions.

Operating principle

Brake operation is achieved by direct action of the brake pedal on a feed valve/compensator which works in the same manner as the pressure regulator. The movement causes two valves to be displaced: the first allows high-pressure liquid from the main accumulator (in the BX, or the braking accumulator in the CX) to feed the front brakes, while the second admits liquid from the rear suspension units to the rear brakes. The front and rear brake circuits are therefore completely independent.
Any increase in the load on the rear wheels results in an increase in pressure in the rear suspension units feeding the rear brakes. The maximum braking effort at the rear is thus directly related to the load on the rear wheels.

The brake control and compensator unit

(Fig. 31)

Neutral position
High-pressure liquid enters the unit but is blocked by the valves (T1) and (T2). The rear suspension fluid contained in the chamber C3 hold the shuttle valve (4) against the base of the feed valve.

Brake operation
Any force on the brake pedal is fed directly to the valve (T1) controlling the front brakes. This in turn moves to admit high-pressure liquid. A pressure P is then established in the front brakes and in the chamber C1, the liquid being transferred there through the channel 0.
The pressure in C1 creates a force greater than that exerted by the spring R1, and the valve (T2) thus moves to admit liquid from the rear suspension; this liquid, arriving through the channel G, creates a pressure P' in C2 and in the rear brakes. This counter-pressure P' in C2 is added to the spring force R1 bearing on the lower end of (T2) and balances the force P acting on the upper end.

The valve (T2) therefore stops moving and the pressure in the rear brakes stabilises. Next, the valve (T1) also stops moving and the pressure P in the front brakes stabilises. A relationship has thus been established between the force on the brake pedal and the pressure delivered to the front and rear brakes, rising at the same rate: control of the brakes is thus possible and easy.
The shuttle valve (4) has not moved.

Compensating operation

This is concerned solely with the pressure in the rear brakes and allows the braking effort to be adjusted according to the load carried by the back wheels.

1st phase: cutt-off point. This limits the operation of the control unit though the combined action of the counter-pressure acting on section B of the shuttle valve (4) and of the spring R3. When these together become greater than the force created by the rear suspension pressure on the section A of the shuttle valve (4), the shuttle moves to make contact with the stop (5) on the valve (T2). This new configuration effectively increases the lower surface of (T2) which then becomes equal to the cross-section of the valve + the cross-section of the shuttle = S.
Once this happens, any increase in pressure in the rear brakes moves the valve (T2) to shut off the incoming fluid: this is the cut-off point.

2nd phase: compensation. Further increase of effort on the brake pedal makes the valve (T2) find a new equilibrium position.

Any increase in the pressure in the front brakes, acting on the section "S" creates a higher counter-pressure (pressure in the rear brakes) which acts on the section "S" of T2.
This is the compensation phase, in which the pressures in the front and rear brakes both increase, but at different rates. The rear brake pressure can thus rise until it reaches the pressure in the rear suspension system, after which it remains constant.

A - Brake operation: pressures in the front and rear brake systems rise simultaneously and at the same rate.

B - Cut-off point: the shuttle valve moves into contact with the stop. The spring R3 is adjusted so that the cut-off point falls 410 psi below the rear suspension pressure, which varies according to load.

C - Compensation: the pressure in the rear brakes continues to rise, but at a slower rate than the front brake pressure.

D - The pressure in the rear brakes reaches the pressure in the rear suspension. It remains constant no matter how much extra effort is exerted on the brake pedal.

Handbrake

This is operated by a floor-mounted lever, and operates on the front brake calipers.
In the BX, the amount of free-play is automatically adjusted to allow for brake pad wear, so that the lever travel remains constant.

Fig. 30: CX brake circuit layout
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Brake accumulator
6. Safety valve
7. Control unit
8. Front brakes
9. Rear brakes
10. Rear suspension units
11. Leakage return

Fig. 31: Operating principle of BX brake control unit
Section
1. Damper
2. Unit body
3. Return to reservoir
4. Shuttle valve
5. Shuttle stop
F Force from pedal
HP High pressure
PS Suspension pressure
P Front brake pressure
P' Rear brake pressure

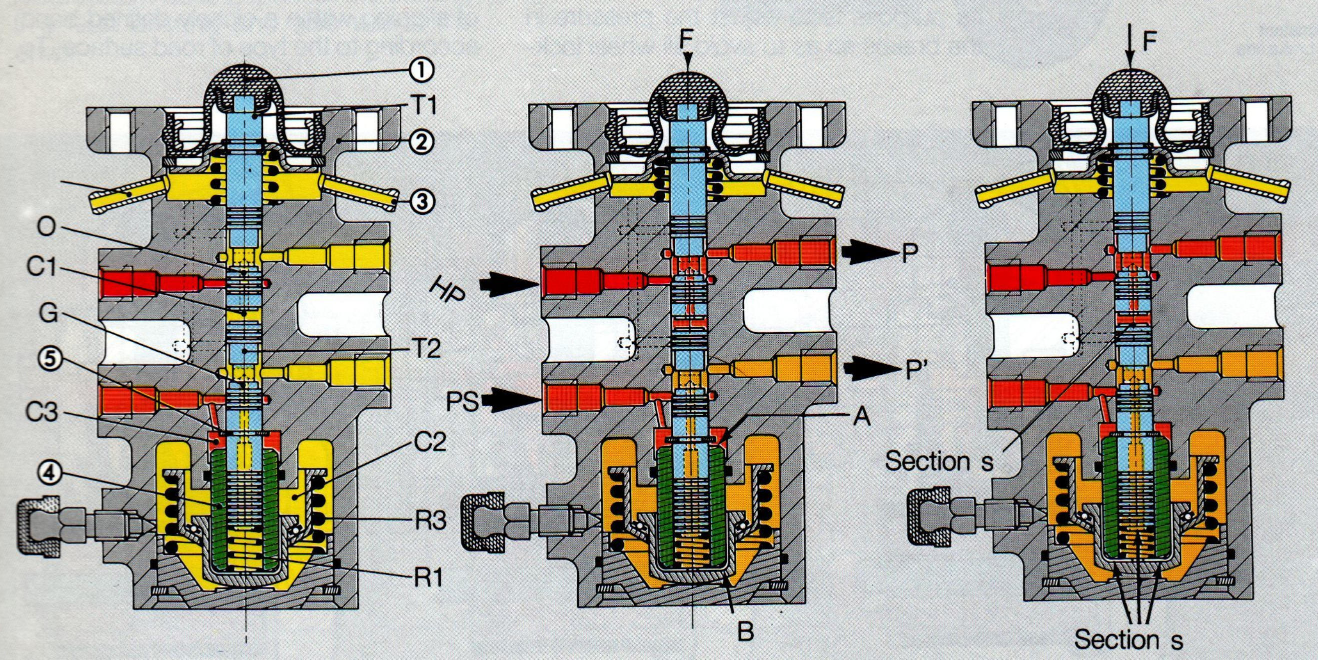


Fig. 31

Self-Adjustment

General principle (Fig. 32b):
The distance (D) is maintained constant by increasing the distance D as the brake pads (11) wear thinner.

Hydraulic brakes (Fig. 32a)
The hydraulic pressure makes the piston (9) move progressively along F until it contacts the stop-washer (6) above the ball-bearing (7).
If braking does not take place before this happens, the piston continues further and the stop-washer (6) acts through the ball-bearing (7) to rotate the nut (8).
In order to move axially, the nut must turn about the thread (5) which itself is stopped from turning by the attachment (3) to the lever. The nut (8) can only rotate in the sense allowed by the spring (13).
In operation, the action of the piston eases the spring so that the nut is freed enough to turn. Because one end of the spring is directly attached to the piston, its other end acts as a ratchet, allowing the nut to turn only in the one direction.
During mechanical braking, the spring is loaded so as to close its coils, locking the nut and stopping it from turning.

Handbrake operation (Fig. 32c)
The action of the attachment (3) displaces the thread (5), along with the nut (8) which makes contact with the piston and pushes it, forcing the brake pad (11A) into contact with the disc. The caliper (12) reacts by moving sideways, bringing the other pad (11B) into contact with the disc, and braking begins. When the tension in the handbrake cable is relaxed (brake release) the lever (1) is returned to its original position by the rubber washers (4).

ABS (anti-lock brakes)

The Bosch ABS anti-lock braking system equips the top-range CX models.
Its purpose is to adjust the pressure in the brakes so as to avoid all wheel locking and thus allow the car to remain stable and manœuvrable while achieving the shortest stopping distances possible on the road surface being traversed.

Dynamics of a braked wheel:
At the moment of braking, frictional forces are set up between the tyre and the road, causing deformation of the tyre and a sliding action: that is, the wheel turns more slowly than if it were freely rolling.
The degree of sliding is defined as the difference between the speeds, expressed by:

$$\lambda = \frac{V - Vr}{V} \times 100$$

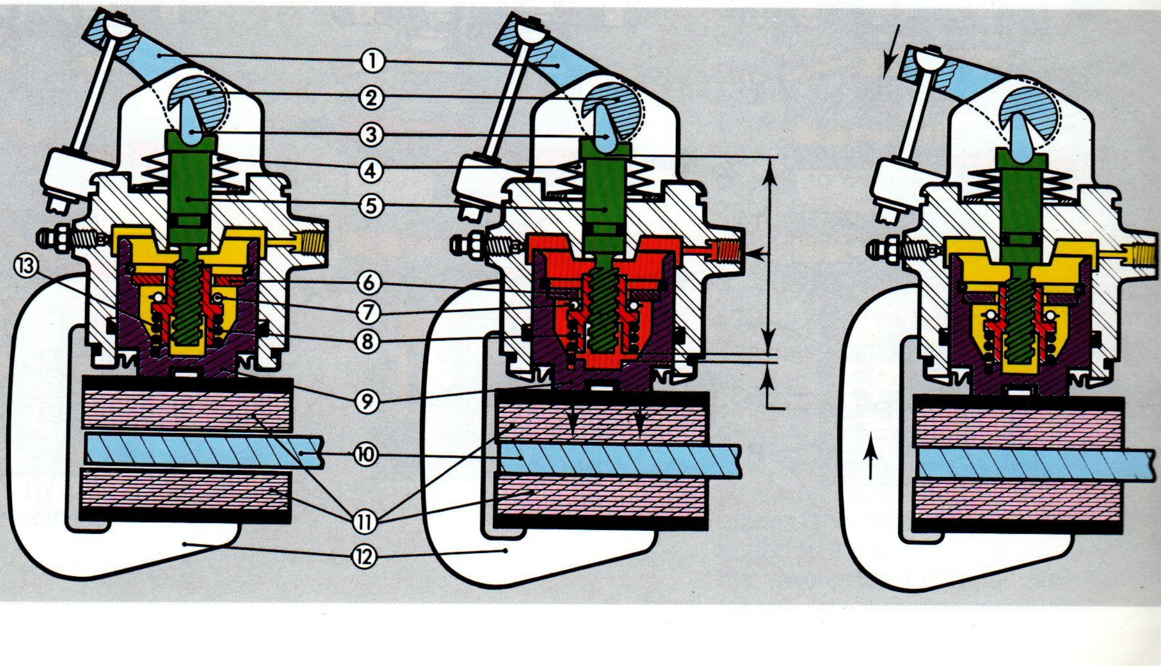
V : car speed
Vr: circumferential speed of wheel
It is a coefficient, expressed in %, and is 0% whenever the wheel is turning freely, and 100% when the wheel is totally locked.
The maximum available braking force depends on the degree of sliding as well as the nature of the road surface.
The curves below show the coefficients of longitudinal adhesion as a function of the degree of sliding λ, for various typical road surfaces.
It emerges that maximum braking is obtained, in the case of a dry surface for instance, with a degree of sliding between 10% and 30%. This implies stable braking. The sideways forces varies according to the slip angle of the wheel. The curve 1b shows that this force also grows smaller as slipping increases and becomes very small when the wheel is locked. In other words, a locked wheel loses all ability to exercice sideways force but skids straight ahead, unsteerable.
To ensure constant grip, the anti-lock system must therefore control the pressure in the brakes to maintain the degree of slipping within a closely defined band according to the type of road surface. To

Fig. 32a, b, c : Principle of automatic brake free-play adjustment
1 et 2. Lever
3. Tappet
4. Flexible washers
5. Rod
6. Thrust washer
7. Ball bearing
8. Nut
9. Piston
10. Brake disc
11A-11B. Brake pads
12. Caliper
13. Spring
P Unpressurised liquid

Fig. 33 : Anti-lock braking system
1. Pressure reserve: feeding front brakes, suspension, steering
2. Rear suspension circuit : feeding rear brakes
3. Brake control unit
4. Hydraulic block with three electromagnetic valves
5. Toothed wheels
6. Electromagnetic sensors
7. Computer
8. ABS fault warning light

Fig. 34 : Electronic valves operating principle
1. Normal position
2. Braking pressure constant
3. Pessure falls in the brake line

Fig. 32



achieve this, the ABS system takes into account the angular deceleration of the wheel and its degree of slip calculated from a measured value of wheel speed.

Description of the ABS system in the CX:
This is a four-sensor, three-channel system comprising:
- 4 toothed wheels (one per wheel)
- 4 speed sensors (one per wheel)
- 1 computer
- 3 electromagnetic valves in a hydraulic valve block (2 for the front wheels, one for the rear pair).

Operating principle (Fig. 33)
Each road wheel carries a toothed wheel, each tooth of which generates a signal pulse to the computer via an adjacent electromagnetic sensor. The frequency of the total signal varies according to the wheel speed.
The computer accepts the wheel speed and sets it against a timebase to calculate the degree of slip of each wheel, and its angular deceleration or acceleration.
The measurement of the degree of slipping of each wheel is obtained by comparing the angular speed of that wheel with a continuously calculated "reference" speed which is in effect the speed of the car.
The computer then sends a control signal to the electromagnetic valve responsible for regulating the brake pressure to that wheel, causing it to adopt and maintain optimum braking conditions.
The computer also includes a self-checking system activated when the ignition is switched on and remaining active at all times while the car is in motion. This safety provision ensures that the ABS system does not affect the braking if a fault occurs, and also warns the driver.

Hydraulic valve block (Fig. 34)
This comprises three electromagnetic valves, controlled by the computer so as to modulate the hydraulic pressure in the braking system.
Each valve is a three-way device, with a control piston able to assume one of three positions according to the voltage applied:
- in the normal position, with no applied voltage, the exhaust port is covered and the pressure inlet and brake outlet ports are linked: pressure rises normally in the brake line.
- in the half-voltage state, the pressure inlet port is closed off, and the exhaust port remains closed: the brake line is thus isolated from braking pressure and the pressure in it is held constant.
- in the full-voltage state, the exhaust port is opened and the pressure inlet remains closed: pressure in the brake line falls.

The combination of pause intervals with the three possible positions of the piston allows the brake pressure to be varied either very quickly (via a fully open passage) or more slowly, in a series of steps.

Advantages of powered braking

- reduces pedal travel
- reduced brake response time
- shorter braking distances
- smaller pedal effort required
- good performance in extreme conditions (vapour-lock, fade, oil leakage).

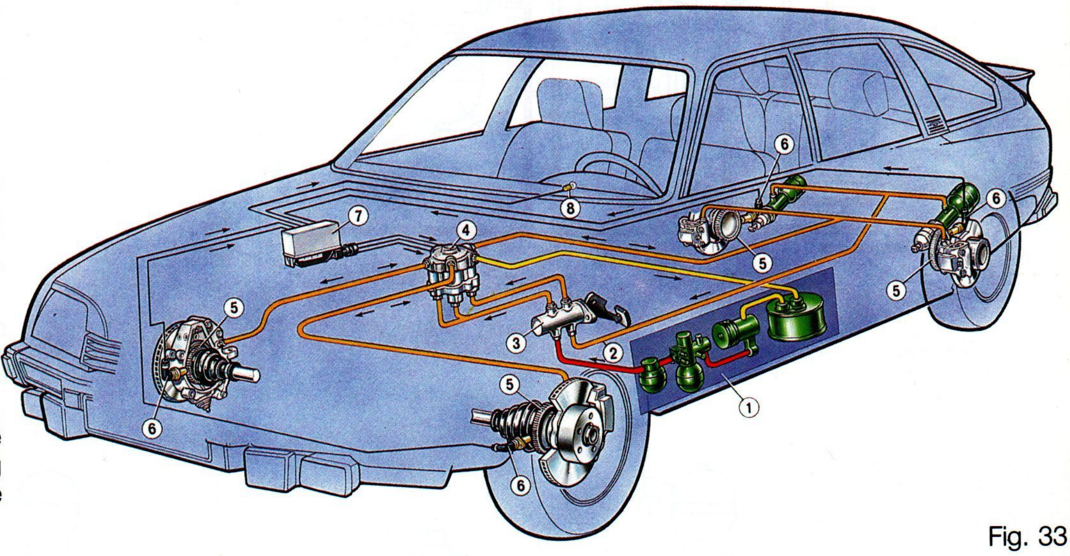
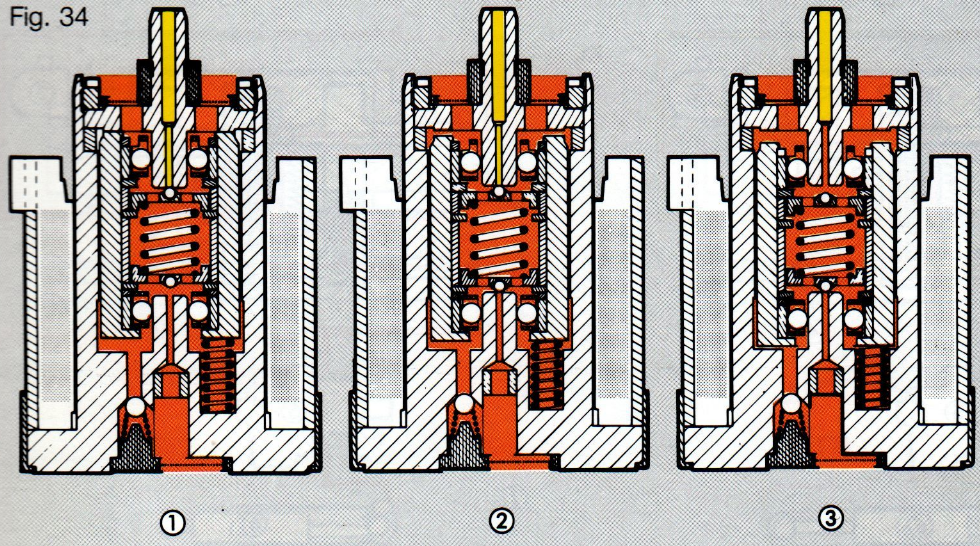


Fig. 33

Fig. 34


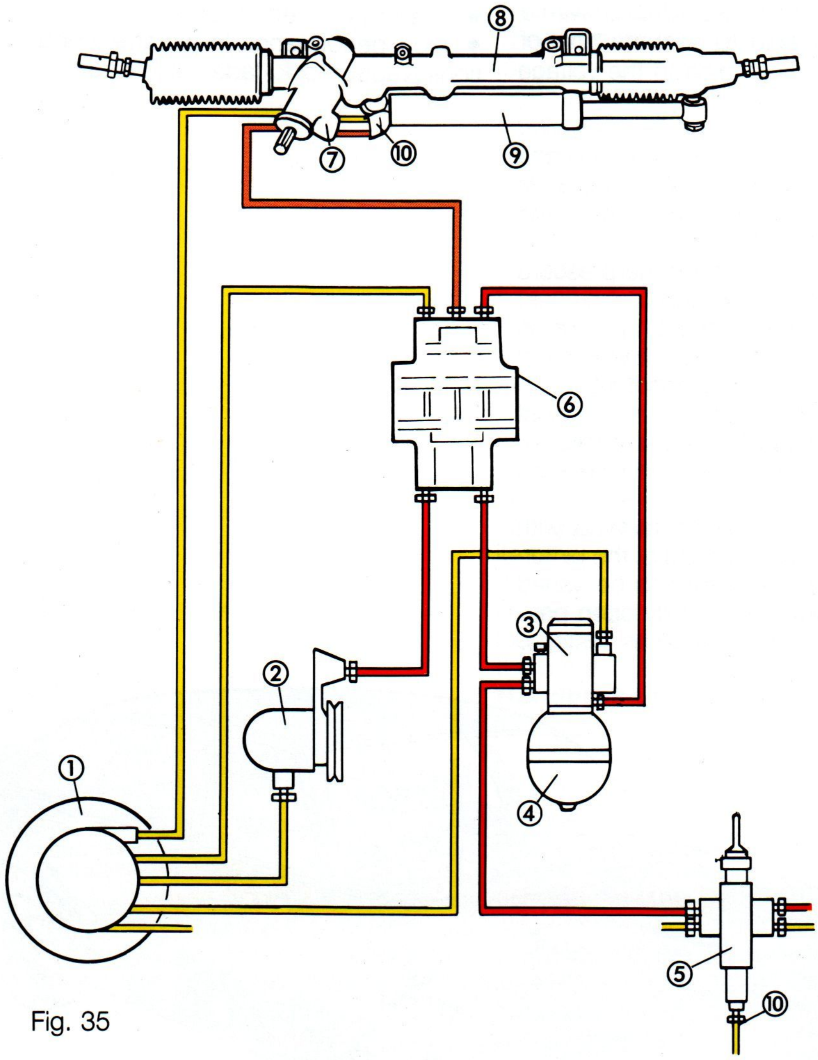


Fig. 35

STEERING

The BX and CX are equipped with completely different forms of power-operated steering.
The BX system consists of an original adaptation of the conventional "open circuit" power-assisted system (the Midget-type DBA rotary-valve) in a car equipped with an energy storage system for the "closed circuit" operation of its brakes and suspension.
The power-steering system of the CX is fed as a "closed circuit" from the same energy storage system which feeds the brakes and suspension.

General

The steering system of a car is that which allows the driver to change course at will and to point it in any direction demanded by the circumstances.
The comfort and safety of the driver, just as much as the stability of the car, depends on the system adopted. It is an essential function on which too much care can never be lavished. The perfect steering system takes account of these needs:

a) safety
b) lightness
c) precision
d) freedom from shock
e) stability
f) compatibility with the suspension.

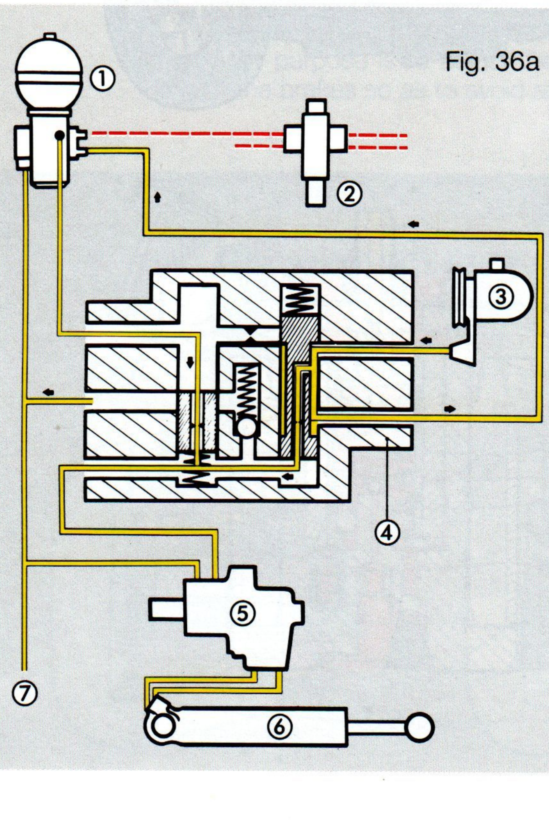


Fig. 36a

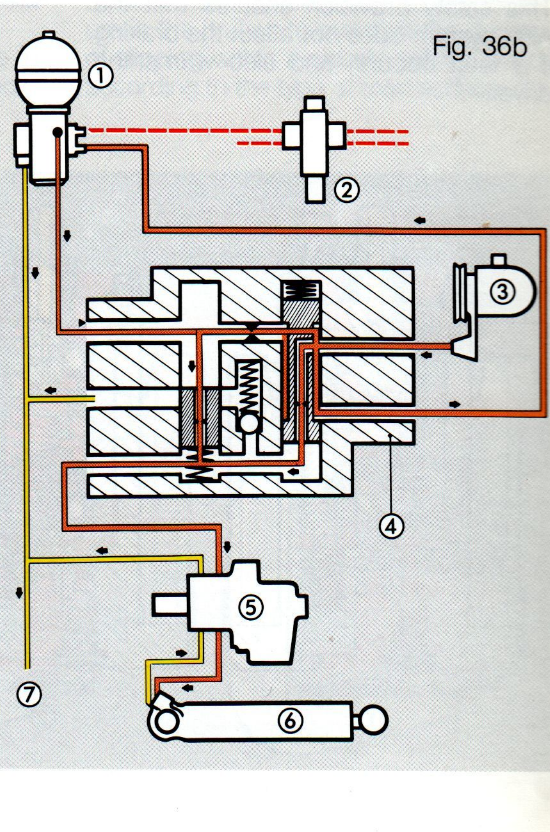


Fig. 36b

Steering problems

The comfort afforded by the steering may be summed up as the ease with which the driver can guide the car in all conditions, with the minimum of effort and fatigue and the maximum pleasure and safety.

Steering can be tiring if its movement needs large effort or is of large amplitude (large steering wheel movements).

It is impossible to reduce both effort and amplitude in conventional mechanical steering. If its gearing is reduced so as to lessen the effort needed, then the number of turns of the wheel is inevitably increased. This factor becomes more and more evident in heavier, top-range cars. By adopting power steering, the effort required may be reduced by a hydraulic jack. This in turn allows the steering system gearing to be reduced.

BX power steering

Description (Fig. 35)

The steering system comprises:

- a high-pressure hydraulic pump with increased rate of rotation to obtain a flow rate of about 21/min at idling;
- a pressure control valve with an extra outlet to supply the steering;
- a flow divider to apportion the flow between the suspension/braking circuit and the steering, and the limitation of pressure and flow in the steering circuit;
- a valve which directs the pressurised liquid to one or other chambers of a jack, or to direct it back to the reservoir;
- the assisting jack whose piston has a differential section and is pushed one way or the other by the action of the pressurised liquid, to move the rack;
- a steering box which houses the rack and pinion.

Operating principle of the flow divider

Whether steering assistance is called for or not (driving in straight line, or cornering) a careful division of flow between the general circuit and the steering circuit can save energy.

a) Control valve, in supply mode

(Fig. 36)

- When the car is running straight, the liquid coming from the pump is divided between the general and steering circuits by the dividing valve with most of the flow going to the general circuit. The steering valve is in the neutral position and the two jack chambers are filled with a minimum, unpressurised flow.
- When cornering demands assistance, supply to the steering circuit takes precedence over that of the general circuit. Pressure rises in the steering circuit. The dividing valve moves to open the second calibrated orifice into the steering system.

Fig. 35: Circuit diagram of BX power steering
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Safety valve
6. Flow divider
7. Control valve
8. Steering
9. Jack
10. Leakage return

Fig. 36: Operating principle of flow divider: charging
a) Car running straight
b) Cornering
1. Pressure regulator
2. Safety valve
3. 5-piston pump
4. Flow divider
5. Rotary valve
6. Jack
7. To reservoir

Fig. 37: Operating principle of flow divider: discharge
a) Car running straight
b) Cornering

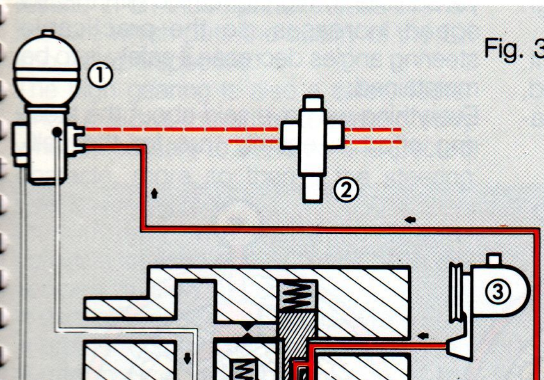


Fig. 37a

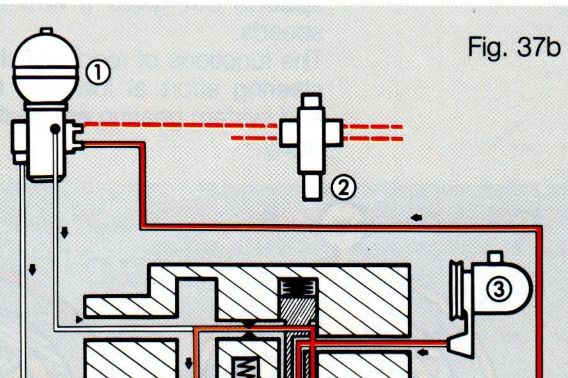


Fig. 37b

b) Control valve in discharge mode (Fig. 37, p. 25)
Whether running straight or cornering, the entire output of the pump is directed to the steering valve. The second dividing valve limits the flow to 2.31/min.

Operating principle of the valve (Fig. 38)

- **Running straight:** the pump feeds the circuit but does not pressurise it, and all the liquid supplied returns to the reservoir (open circuit).
- **Cornering to the left:** the valve rotor turns with respect to the distributor gear and thus closes the return to the reservoir while opening the feed to the two chambers of the jack. Since the section S1 of the piston is double the section S2, it moves to the right: liquid flows from the small chamber so as to keep the larger one filled.
- **Cornering to the right:** the valve rotor turns in the opposite sense with respect to the distributor gear. The large chamber remains joined to the return to the reservoir while the small chamber is supplied with pressure, and the shaft of the jack moves to the left.

CX power steering

The speed-sensitive hydraulic steering of the CX allows low efforts at parking speeds but gives a firm feel at high speeds.
The functions of road wheel movement, steering effort at low and high speed, and system gearing are dealt with separately.

- **Road wheel movement**

This is carried out entirely hydraulically, though under mechanical control. The driver merely positions the control valve which determines the wheel position. In all cases the jack is positioned hydraulically, which means that shocks felt by the wheels can never be fed back to the steering wheel, no matter how bad the road surface (potholes, bumps or whatever) and thus avoids violent reaction to any obstacle or even to a puncture.
In a word, the driver remains master of the position of his car's wheels.
Naturally, should there be a failure of the hydraulic system, the driver can still operate the steering mechanically.

- **Steering effort**

The effort felt by the driver at the steering wheel when cornering, and self-centring effect are created by a cam connected to the wheel. This effort increases both with wheel angle and with speed.
When the car is stationary or travelling very slowly, the steering effort remains low even for large steering angles, which makes driving in town or on winding roads easy and pleasant. As speed increases, so does the weight of the steering, thanks to a hydraulic servo controlled by a centrifugal regulator. The rate of increase of effort has been set so that the driver never has to exert undue effort, yet sufficiently high to remind him that as speed increases, so the practicable steering angles decrease if safety is to be maintained.
Everything we have said about the steering effort is equally true for the self-

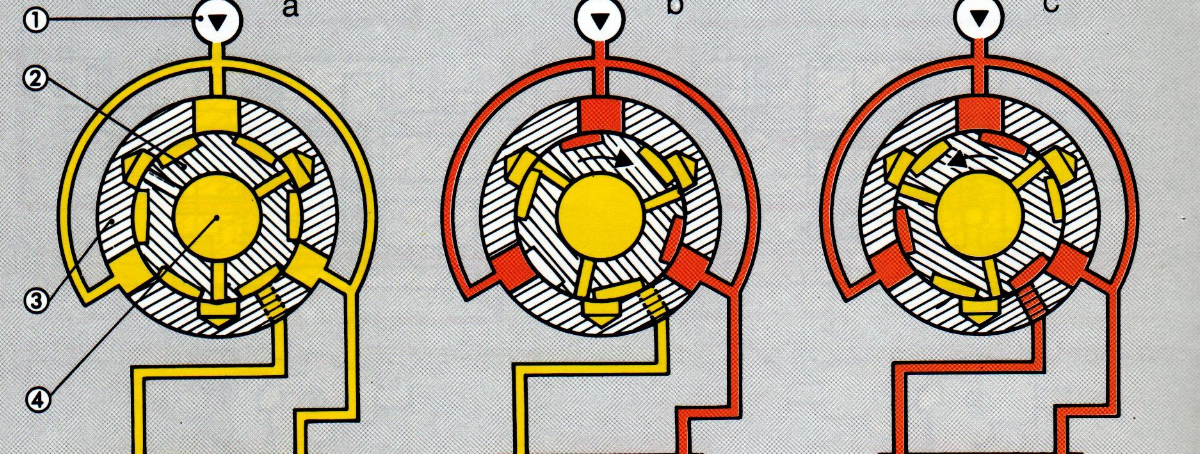


Fig. 38

centring effect which always returns the wheels to the straight-ahead, even when the car is at a standstill. This is a major advantage which assists parking manœuvre and allows one always to stop with the wheels straight, unless the steering lock is used to hold them at an angle.
On muddy surfaces, snow, sand or anywhere slippery where the driver may not always be aware of the direction in which his wheels are pointing, the straight-ahead position can always be regained simply by letting go of the steering wheel. Furthermore, as speed increases, so the self-centring effect becomes more and more positive.
It should also be noted that because the steering effort is independent of that felt at the wheels, this steering system does not (like some others) become lighter as the tyres wear out.

• **System gearing**

This has been chosen so as to allow maximum car manœuvrability. Only 21/2 turns are needed from one lock to the other.
This high gearing is a major factor in comfort in that it results in less need for arm movement and better positioning of the hands on the wheel when driving in town or on winding roads. Together with a steering wheel of reduced diameter, it results in an incomparable ease of manœuvre which puts the quality of the CX into true perspective.
The high gearing is also a safety factor since it allows the driver to react quickly when necessary to avoid an unexpected obstacle, more so than if the steering was lower-geared.
In summary, the hydraulic speed-sensitive steering of the CX has been developed to allow the driver:
- exceptional ease of manœuvre,
- greater comfort and reduced fatigue,
- total control over the position of the steered wheels,
- effective feel related to increases in the car's speed.

Description (Fig. 39)

Supplied by the pressure reserve system, the hydraulic part of the steering comprises:
- the hydraulic rack control (differential-piston jack),
- the control valve assembly with distributor and flow regulator,
- the centrifugal regulator.

Fig. 39

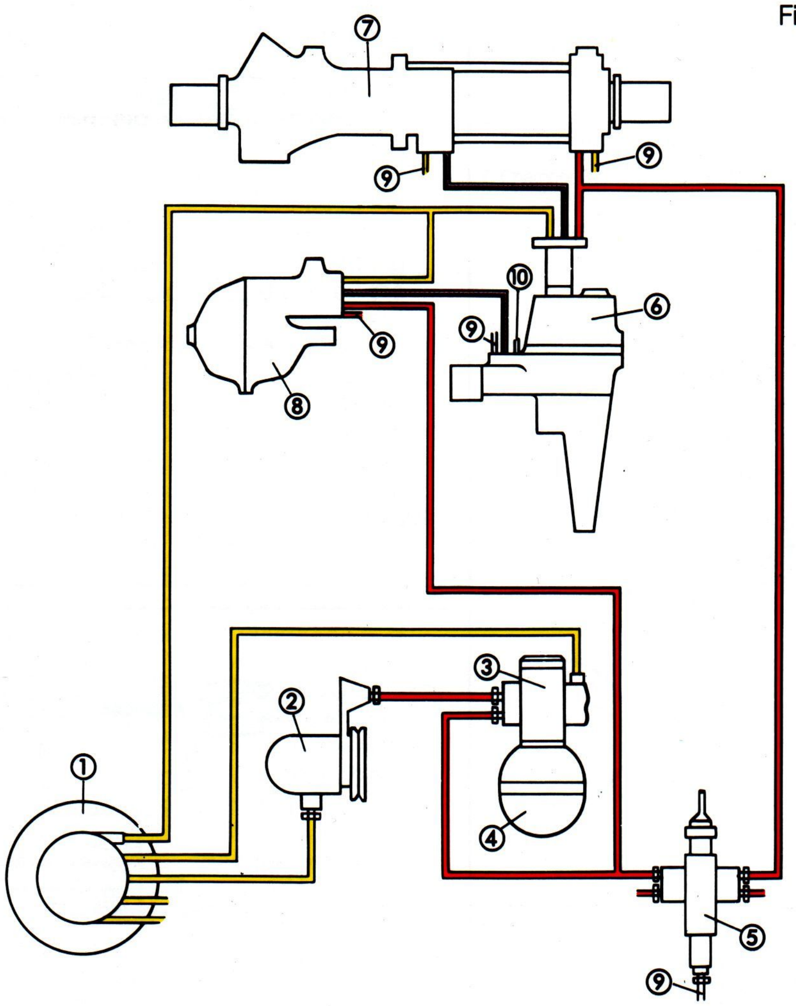
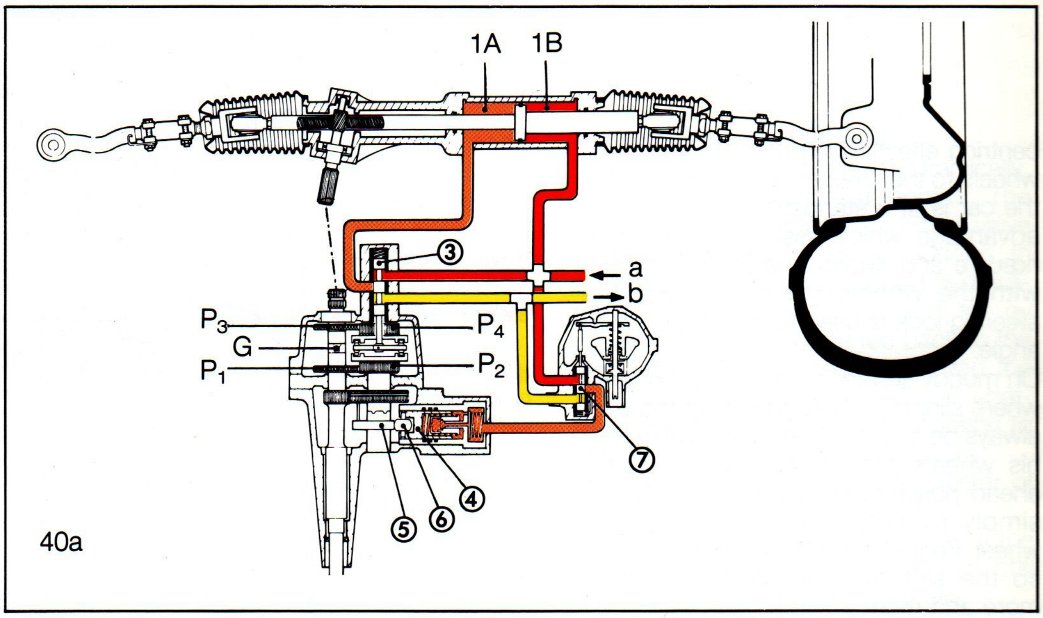
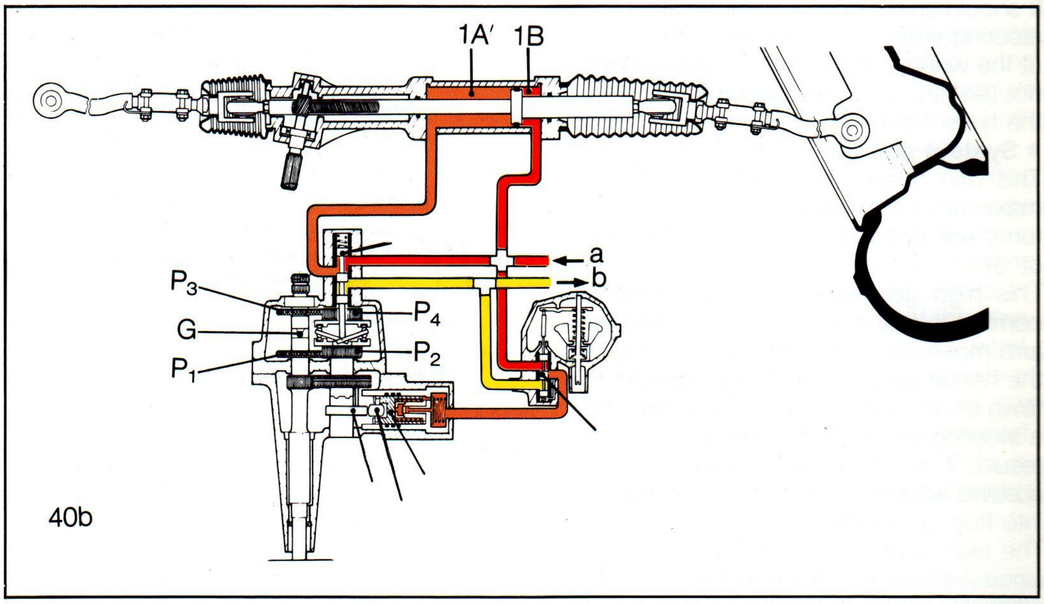


Fig. 38: Operating principle of steering valve
a: Car running straight
b: Turning right
c: Turning left
1. Pump
2. Rotor
3. Pinion
4. Return to reservoir

Fig. 39: Layout of CX power steering circuit
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Safety valve
6. Steering control unit
7. Steering
8. Centrifugal regulator
9. Leakage return
10. Purging valve





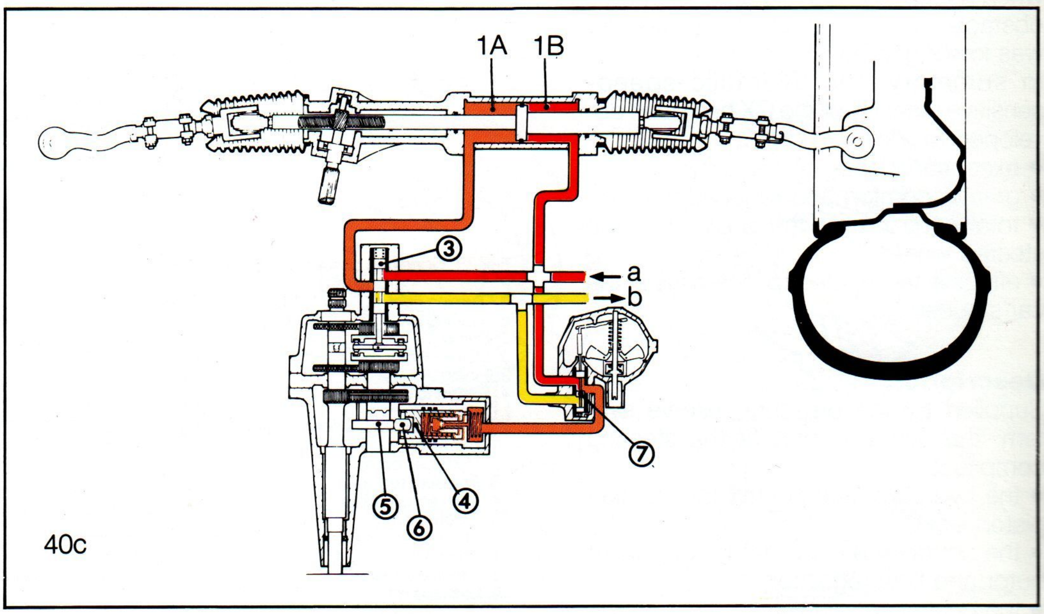


Fig. 40: Speed-sensitive self-centring of CX steering

a) Neutral position, at standstill
a. High pressure inlet
b. Return to reservoir
1. Chamber A
2. Chamber B
3. Slide valve T1
4. Self-centring piston
5. Cam
6. Roller
7. Slide valve T2

b) Turning left
a. High pressure inlet
b. Return to reservoir
1. Chamber A
2. Chambre B
3. Slide valve T1
4. Self-centring piston
5. Cam
6. Roller
7. Slide valve T2

c) Neutral position at 40 km/h (25 mph)
a. High pressure inlet
b. Return to reservoir
1. Chamber A
2. Chamber B
3. Slide valve T1
4. Self centring piston
5. Cam
6. Roller
7. Slide valve T2

Operation (Fig. 40, a, b, c)
Hydraulic assistance:
The rack operating piston is subject to two opposing forces:

chamber A $F_1 = \frac{P}{2} \times S$

chamber B $F_2 = P \times \frac{S}{2}$

This balance is constantly achieved thanks to the distribution valve T1: $F_1 = F_2$.
Steering is achieved:
- to the right, by a reduction of pressure in the chamber A (exhausted through movement of the distributor valve),
- to the left, by an increase in pressure in the chamber A (pressure inlet opened by movement of the distributor valve).

Pressure distributor
Within the permitted play "J" of the pin G, any movement of the steering wheel results in rotation of the pinion (P1) and therefore also of (P2). This acts upon the valve slide (T2) through the linkage; the toothed slide (P4), which contacts the pinion (P3) in turn mechanically linked to the fixed rack pinion, remains stationary. The movement of the valve (T1) causes a variation of pressure in the chamber A and results in movement of the rack. As long as the wheel is held in the cornering position, the pinions (P1) and (P2) remain stationary.
The flow into the chamber A, achieved as described, allows the rack to continue moving. The rack control gear then causes the pinions (P3) and (P4) to rotate and these, working through the linkage, return the valve (T1) to its neutral position.

Steering feel as a function of speed
This is achieved mechanically by means of a variable force applied to the steering column.
The self-centring piston, feed by the centrifugal regulator, applies a force to a cam via a roller which thus allows the wheels to self-centre.
The size of the force depends on:
- the pressure produced by the centrifugal regulator,
- during cornering, the steering wheel angle.

Centrifugal regulator
This allows the steering effort to be related to the car's speed.
Car stationary: the linked masses are in the rest position, and the pressure supplied by the centrifugal regulator to act on the self-centring piston is small.
Car moving: under the action of centrifugal force, the masses move further apart and compress the spring R2. The valve (T2) moves, causing the pressure on the self-centring piston to increase, in turn increasing the self-centring effect.

Speed-sensitivity of self-centring
As soon as the cam, with its eccentric axis, moves from the straight-ahead position, an angle is formed between the line through the came and roller, and the line through the centre of the roller and the point at which the cam contacts the roller. The product of the force resulting from the pressure on the self-centring piston and the lever arm created by the angle, constitutes a turning moment tending to force the cam back to the straight-ahead position. This moment tends to zero as the steering wheel angle is reduced. The pressure delivered by the centrifugal regulator acts on the self-centring piston via a variable-flow regulator which ensures that the centring effect is smooth and progressive.

Neutral position (Fig. 41)
The pressure coming from the centrifugal regulator is the same in chambers A, B and C. There is no load on the spring (R) and the orifice (0) is shut off.

Cornering (Fig. 42a)
The rotation of the cam moves the self-centring piston, and the flap-valve (2) lifts to allow liquid to return to the centrifugal regulator. The spring (R) is loaded and moves the sleeve to open the orifice (0).

Steering wheel released (Fig. 42b)
Should the driver let go of the steering wheel, the piston tends to return to the neutral position, causing a rapid fall in pressure in the chamber C. The flap-valve closes.
The liquid coming from the centrifugal regulator enters the chamber B and moves the sleeve which progressively closes the orifice (0).
The reduction in force due to spraying determines the flow into the chamber (C) according to the setting of the spring (R). The load on the spring (R) reduces with the self-centring, the flow into the chamber (C) reduces and so results in the progressive slowing down of steering wheel movement until it stops in the straight-ahead position.

Advantages of hydraulic steering

- reduced steering effort,
- higher system gearing,
- improved manœuvrability,
- irreversible hydraulic operation of the steering preventing feedback of shocks from the wheels.

Fig. 41 : Automatic self-centring (description)
A. Leakage return
B. Purge valve
C. Centrifugal regulator
0. Calibrated orifice
1. Spray
2. Valve
3. Roller
4. Cam
5. Self-centring piston
6. Chamber A
7. Chamber B
8. Chamber C

Fig. 42 : Automatic self-centring (operation)

Fig. 41

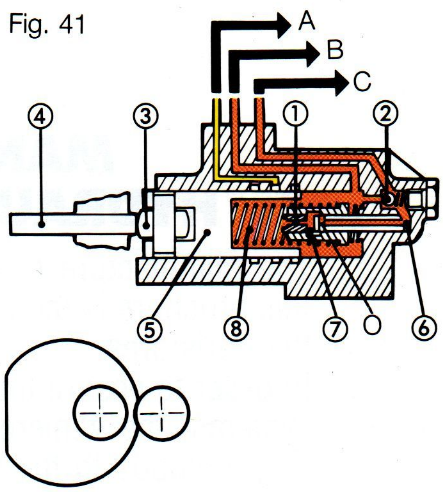
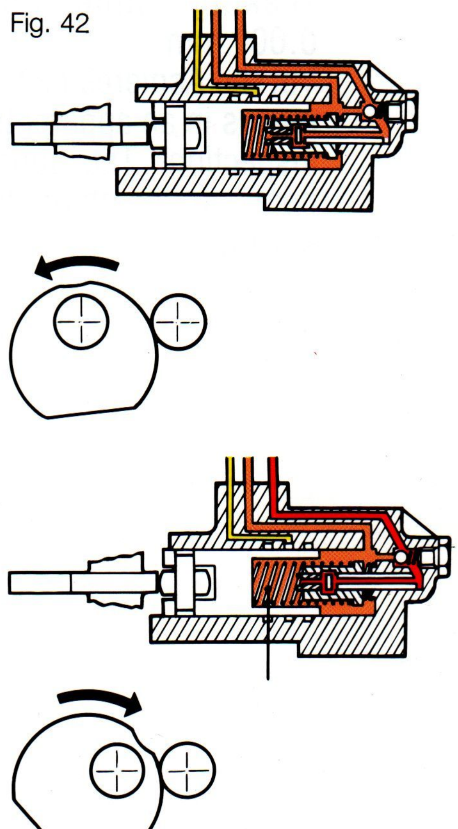


Fig. 42



MANUFACTURE OF HYDRAULIC COMPONENTS

The manufacture of the hydraulic components studied in this brochure is the responsibility of the Asnieres factory in the Paris area.
In order to ensure the proper functioning of such hydraulic systems, the Asnieres factory has had to take manufacturing methods to the very limits of mechanical precision.
While ordinary mechanical workshops work normally to tolerances of 0.2 mm, or to 0.02 mm for real precision, Asnieres must live with standards 200 times more precise, seeking "super-finishes" with tolerances of some 0.001 mm.
Yet the Asnieres factory works to these incredibly fine tolerances in an apparently normal way. The secret? Automatic inspection. The super-finishing men grind their components to the third decimal place and hone them to the fourth.

The amazing precision of manufacture results in the interchangeability of tens of thousands of slide valves and housing so that there is no question of detail adjustment being necessary during assembly. Such ultra-precision manufacturing techniques call for equally precise manufacturing machinery. This too is designed and built by Citroën.

Tolerances	In dimensions	In roundness	In surface finish
Male or female components	0.001 mm to 0.002 mm	0.0005 mm to 0.001 mm	0.0003 mm for steel parts 0.0008 mm for cast iron parts
Male-to-female assembly tolerance: 1 to 3 microns.			

Assembling a few prototype valve slides and housings, or even a pilot production batch, to near-micron standards poses no serious mechanical problem. To repeat the operation 44,000 times a day is a major industrial feat. Today, the workers at Asnieres treat the micron with astonishing ease: the component rejection rate for quality defects is no higher than in most traditional production facilities.

A record:
Since 1954, over 5,000,000 Citroen cars have been fitted with 70,000,000 hydraulic components.

CONCLUSION

The widespread use of hydraulic systems in industry (in machine tools, civil engineering machines, mining, storage systems) and above all in aviation, had led to a deserved confidence in its qualities.
We have tried, in this brochure, to give an account of the application of high-pressure hydraulics to the suspension, braking and steering of motor cars.
The strength and efficiency of the systems adopted by Citroen have been proved many times in some of the toughest international car rallies: Morocco, London-Sydney, Senegal, etc.

The sum of all these techniques, of perfect reliability, is the result of a long history of research, development and experiment; but it has resulted in significant steps forward in the area of the active safety of the motor car. And this has been achieved with acceptable production cost, and reduced maintenance cost.

The importance of high-pressure hydraulics in promoting active safety deserves to be spelt out once more as follows:

- a very high level of comfort, and the possibility of assisting the operation of those controls which demand significant effort, to the major gain in fatigue on the part of the driver,
- excellent roadholding and extreme comfort even in the worst road conditions,
- extremely rapid brake response without needless roughness,
- very high braking system efficiency even in the most difficult circumstances,
- the rapid response of the car to movements of the steering wheel, when necessary,
- the ability to maintain the driver's chosen line whatever the external circumstances.

Technical specification table for hydraulic systems

		BX saloon	BX estate	CX saloon	CX estate
Pressure reserve circuit					
Hydraulic circuit capacity		4.2 litres		4.2 litres	
High pressure pump output		5 cC/rev		5 cc/rev	
Diameter of HP pump pistons		12 mm		12 mm	
Useful stroke of HP pump pistons		8.37 mm		8.37 mm	
Charging pressure setting		2060 to 2200 psi		2060 to 2200 psi	
Cut-out pressure setting		2425 to 2575 psi		2425 to 2575 psi	
Pressure regulator valve T1 diameter		4 mm		4 mm	
Pressure regulator valve T2 diameter		6.35 mm		6.35 mm	
Pressure regulator spring R1 load		47 lb		47 lb	
Pressure regulator spring R2 load		101 lb		101 lb	
Main accumulator calibration pressure		910 psi		910 psi	
Main accumulator volume		400 cc		400 cc	
Front suspension					
Sphere volume		400 cc	500 cc	500 cc	
Sphere calibration pressure		810 psi		1100 psi	
Cylinder piston diameter		22 mm		CX 20 35 mm	CX 20 35 mm
				CX 22 35 mm	Other types 37 mm
				CX 25 37 mm	
Useful stroke of piston		160 mm		160 mm	
Stiffness measured at wheel (lbs/in)	unladen	BX 34.2	BX 16 RS 38.1	CX 20 30.2	CX 20 34.4
		BX 14 34.2	BX 19 TRS 38.1	CX 22 33.4	CX 25 TRI 41.8
		BX 16 38.1	BX 19 RD 40.0	CX 25 IE 40.6	CX 25 RD 43.8
		BX 19 GT 35.2		CX 25 GTI Turbo 42.4	CX TRD Turbo 46.3
		BX 19 D 44.8		CX 25 RD 42.4	
		BX Sport 35.9		CX 25 RD Turbo 44.1	
				CX Limousine 46.3	
				CX Prestige 46.3	
	laden	BX 47.9	BX 16 RS 48.3	CX 20 52.1	CX 20 53.3
		BX 14 47.9	BX 19 TRS 48.3	CX 22 52.1	CX 25 TRI 62.2
		BX 16 52.8	BX 19 RD 50.9	CX 25 IE 60.2	CX 25 RD 65.1
		BX 19 GT 49.1		CX 25 GTI Turbo 60.9	CX 25 TRD Turbo 66.7
		BX 19 D 59.6		CX 25 RD 61.5	
		BX Sport 50.0		CX 25 RD Turbo 62.9	
				CX Limousine 62.9	
				CX Prestige 61.5	
Frequency (hertz)	unladen	BX 0.65	BX 16 RS 0.80	CX 20 0.607	CX 20 RE 0.626
		BX 14 0.65	BX 19 TRS 0.80	CX 22 0.622	CX 25 TRI 0.658
		BX 16 0.67	BX 19 RD 0.80	CX 25 IE 0.652	CX 25 RD 0.664
		BX 19 GT 0.77		CX 25 GTI Turbo 0.659	CX 25 TRD Turbo 0.673
		BX 19 D 0.81		CX 25 RD 0.659	
		BX Sport 0.77		CX 25 RD Turbo 0.666	
				CX Limousine 0.673	
				CX Prestige 0.673	
	laden	BX 0.71	BX 16 RS 0.83	CX 20 0.692	CX 20 RE 0.696
		BX 14 0.71	BX 19 TRS 0.83	CX 22 0.692	CX 25 TRI 0.724
		BX 16 0.74	BX 19 RD 0.83	CX 25 IE 0.718	CX 25 RD 0.768
		BX 19 GT 0.83		CX 25 GTI Turbo 0.719	CX 25 TRD Turbo 0.735
		BX 19 D 0.86		CX 25 RD 0.721	
		BX Sport 0.83		CX 25 RD Turbo 0.726	
				CX Limousine 0.726	
				CX Prestige 0.721	
Rear suspension					
Sphere volume		400 cc	500 cc	500 cc	700 cc
Sphere calibration pressure		600 psi	600 psi	600 psi	515 psi
Cylinder piston diameter		35 mm	37 mm	35 mm	42.5 mm
Useful stroke of piston		215 mm	215 mm	220 mm	
Stiffness measured at wheel (lbs/in)	unladen	BX 19.3	BX 16 RS 19.9	CX 20 19.4	CX 20 RE 25.8
		BX 14 19.3	BX 19 TRS 19.9	CX 22 19.4	CX 25 TRI 24.7
		BX 16 19.9	BX 19 RD 19.1	CX 25 IE 20.6	CX 25 RD 23.8
		BX 19 GT 19.6		CX 25 GTI Turbo 20.1	CX 25 TRD Turbo 25.6
		BX 19 D 20.4		CX 25 RD 18.8	
		BX Sport 25.2		CX 25 RD Turbo 20.1	
				CX Limousine 22.4	
				CX Prestige 22.4	
	laden	BX 55.5	BX 16 RS 68.3	CX 20 58.1	CX 20 RE 88.9
		BX 14 55.5	BX 19 TRS 68.3	CX 22 58.1	CX 25 TRI 88.9
		BX 16 56.6	BX 19 RD 67.5	CX 25 IE 59.3	CX 25 RD 88.9
		BX 19 GT 64.9		CX 25 GTI Turbo 59.3	CX 25 TRD Turbo 88.9
		BX 19 D 57.2		CX 25 RD 58.3	
		BX Sport 72.7		CX 25 RD Turbo 58.3	
				CX Limousine 60.9	
				CX Prestige 61.5	
Frequency (hertz)	unladen	BX 0.61	BX 16 RS 0.69	CX 20 0.680	CX 20 RE 0.696
		BX 14 0.61	BX 19 TRS 0.69	CX 22 0.685	CX 25 TRI 0.690
		BX 16 0.61	BX 19 RD 0.69	CX 25 IE 0.692	CX 25 RD 0.685
		BX 19 GT 0.72		CX 25 GTI Turbo 0.689	CX 25 TRD Turbo 0.695
		BX 19 D 0.60		CX 25 RD 0.680	
		BX Sport 0.81		CX 25 RD Turbo 0.689	
				CX Limousine 0.704	
				CX Prestige 0.704	
	laden	BX 0.80	BX 16 RS 0.90	CX 20 0.864	CX 20 RE 0.908
		BX 14 0.80	BX 19 TRS 0.90	CX 22 0.864	CX 25 TRI 0.927
		BX 16 0.81	BX 19 RD 0.89	CX 25 IE 0.867	CX 25 RD 0.907
		BX 19 GT 0.89		CX 25 GTI Turbo 0.867	CX 25 TRD Turbo 0.907
		BX 19 D 0.80		CX 25 RD 0.865	
		BX Sport 1.02		CX 25 RD Turbo 0.865	
				CX Limousine 0.872	
				CX Prestige 0.875	
Front brakes					
Disc diameter		10.47 in		10.24 in	
Disc thickness		10 mm		20 mm	
Piston diameter		50 mm		42 mm	
Number of pistons		2, opposed		4, opposed	
Total pad friction surface		21.7 sq in		34.1 sq in	
Rear brakes					
Disc diameter		8.82 in		8.82 in	9.25 in
Disc thickness		7 mm		7 mm	18 mm
Piston diameter		30 mm		30 mm	40 mm
Number of pistons		2, opposed		2, opposed	
Total pad friction surface		10.5 sq in		10.5 sq in	22.5 sq in
Brake operating unit					
Slide valve diameter		7.5 mm		7.5 mm	
Shuttle valve diameter		15.0 mm		15.0 mm	
Loading of spring R3		83 lb		83 lb	
Steering					
Wheel diameter		15 in		15 in	
Turns of wheel between locks		2.83		2.5	
Steering ratio		15.5:1		13.5:1	
Turning circle :					
- between walls		36.8 ft		41.0 ft	44.0 ft
- between kerbs		34.0 ft		38.4 ft	41.0 ft
Steering jack diameter		2.5 cm^2 — 5 cm^2		4.25 cm^2 — 8.50 cm^2	

Editechnic Documents
Printed in France - August 1986 - Mape et Rouire
RCS Nanterre B 642 050 199

CITROËN INFORMATION AND
PUBLIC RELATIONS DEPARTEMENT
62, boulevard Victor-Hugo F - 92200 Neuilly-sur-Seine

HYDRAULICS

DRAWING PLATES

from I to XXVIII

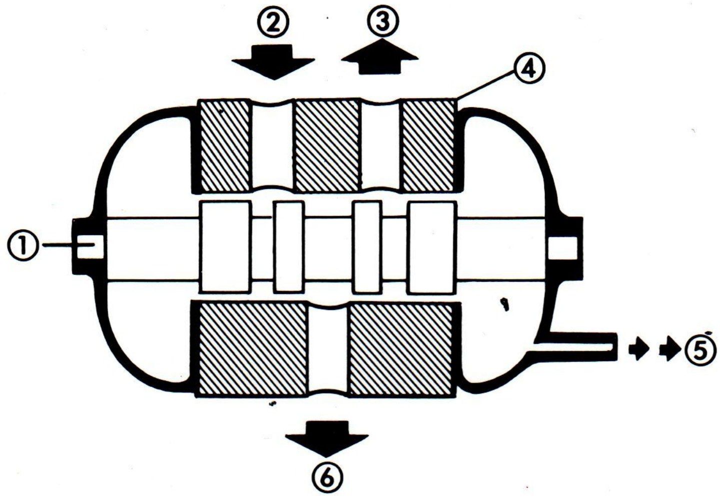


Fig. 1: Pressure distributor
1. Slide valve
2. High pressure
3. Return
4. Bore
5. Leakage return
6. Outlet to use

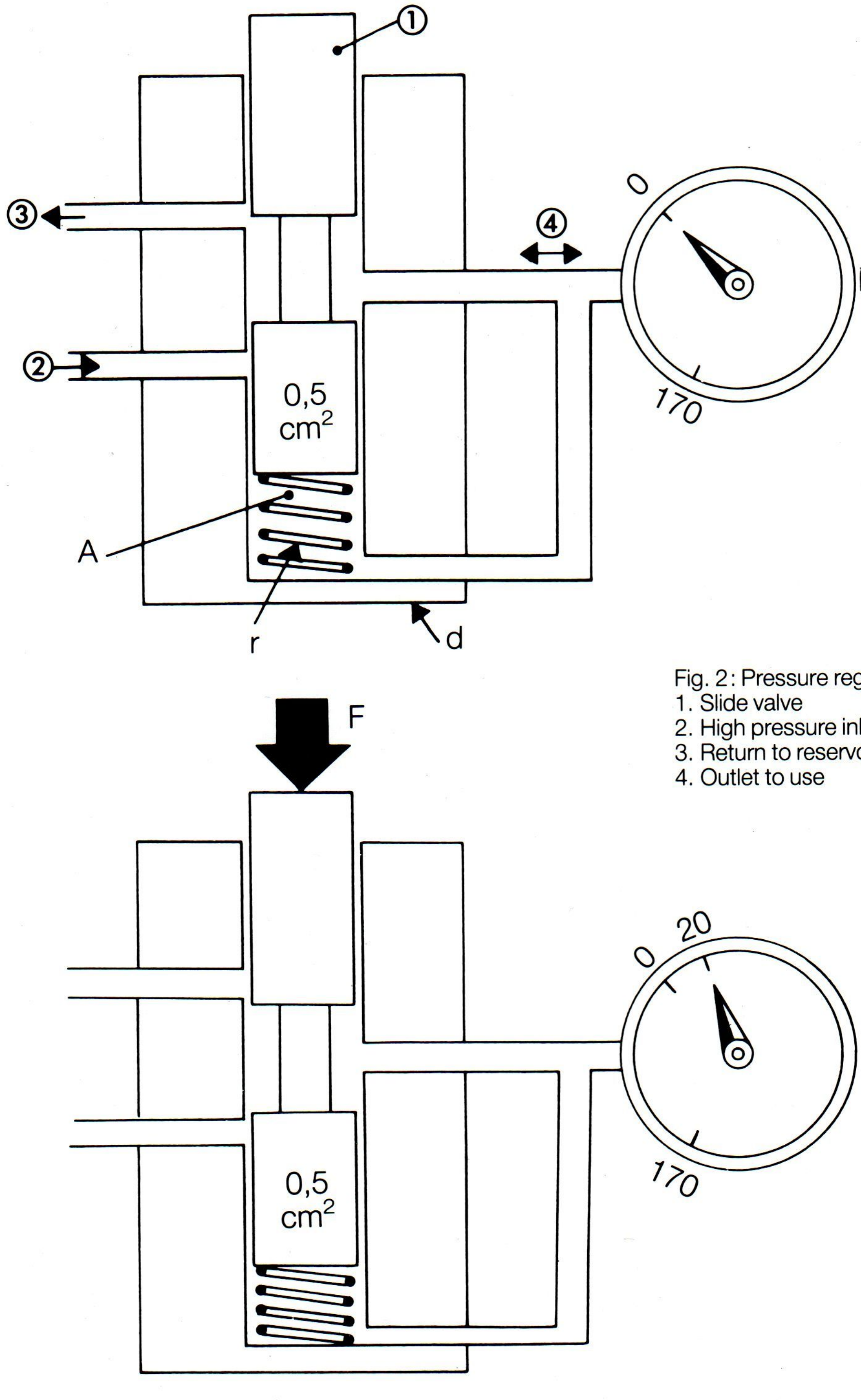


Fig. 2: Pressure regulator
1. Slide valve
2. High pressure inlet
3. Return to reservoir
4. Outlet to use

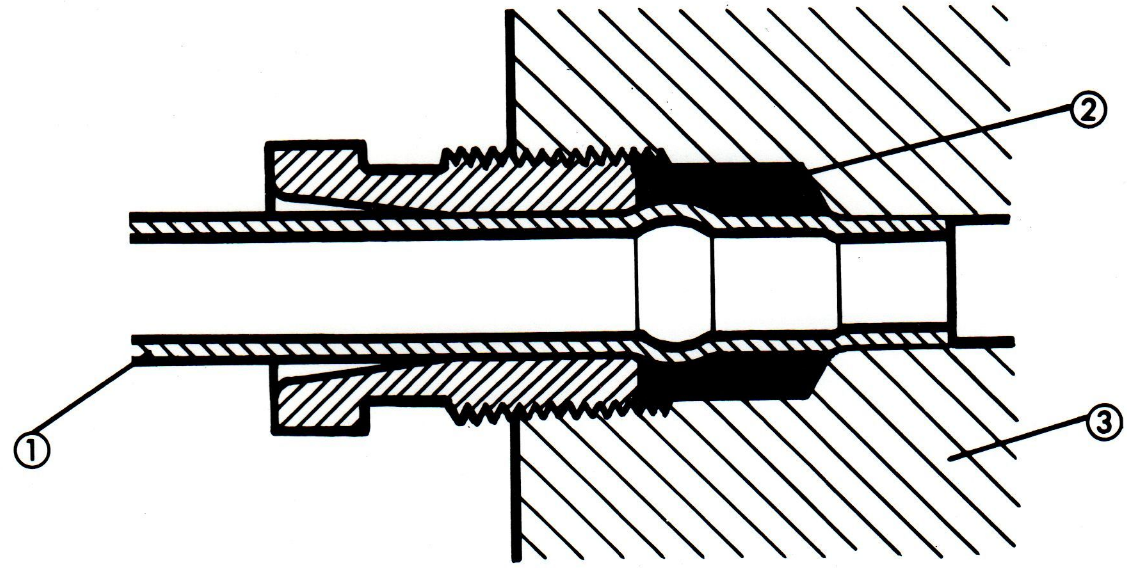


Fig. 3: Rubber gasket
1. Metal pipe
2. Rubber gasket
3. Hydraulic component

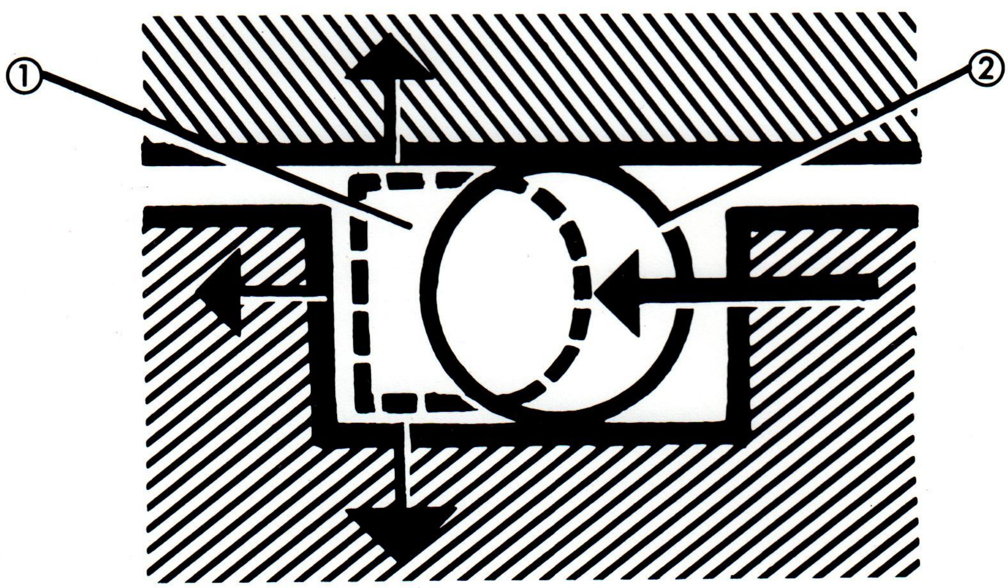


Fig. 4: Sealing by ring seal
1. Joint in use
2. Joint relaxed

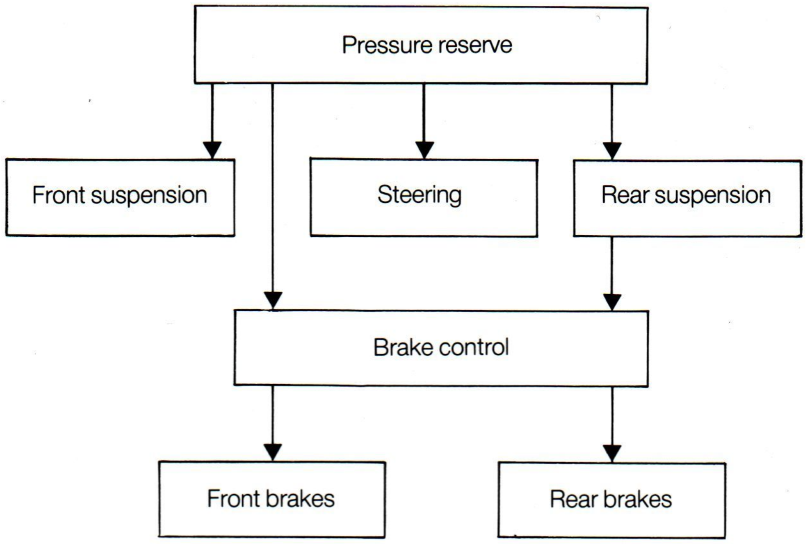


Fig. 5: General layout of hydraulic system

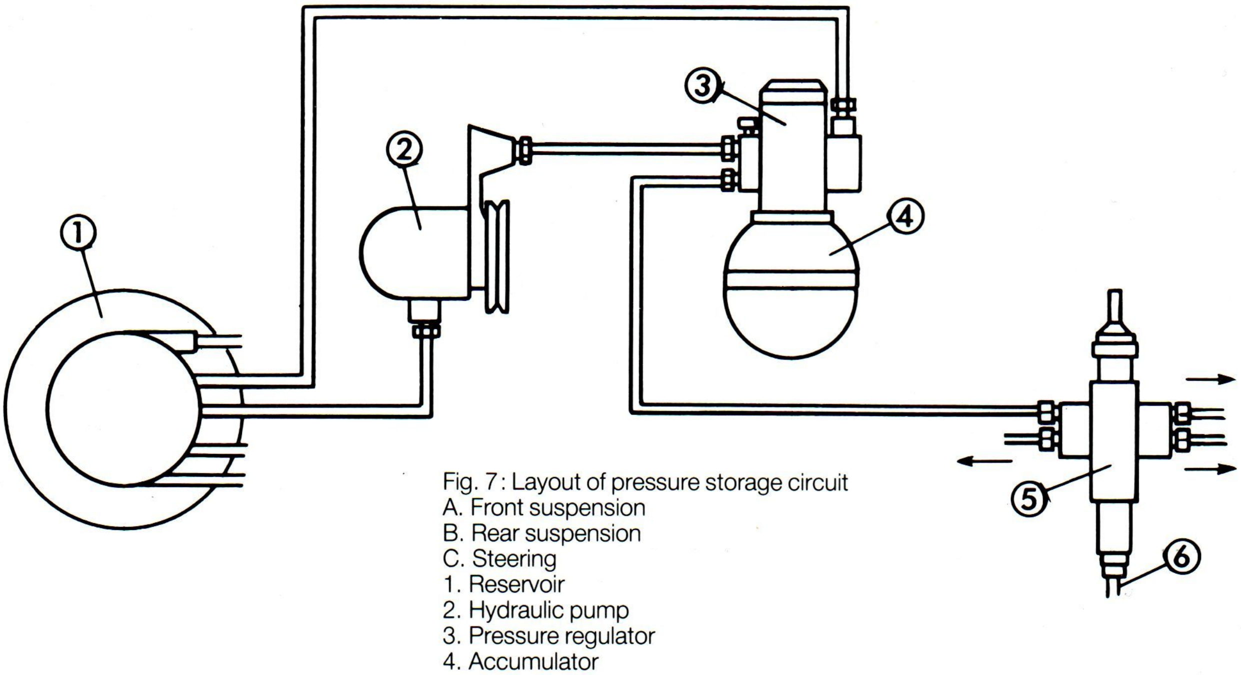


Fig. 7: Layout of pressure storage circuit
A. Front suspension
B. Rear suspension
C. Steering
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Accumulator
5. Safety valve
6. Leakage return

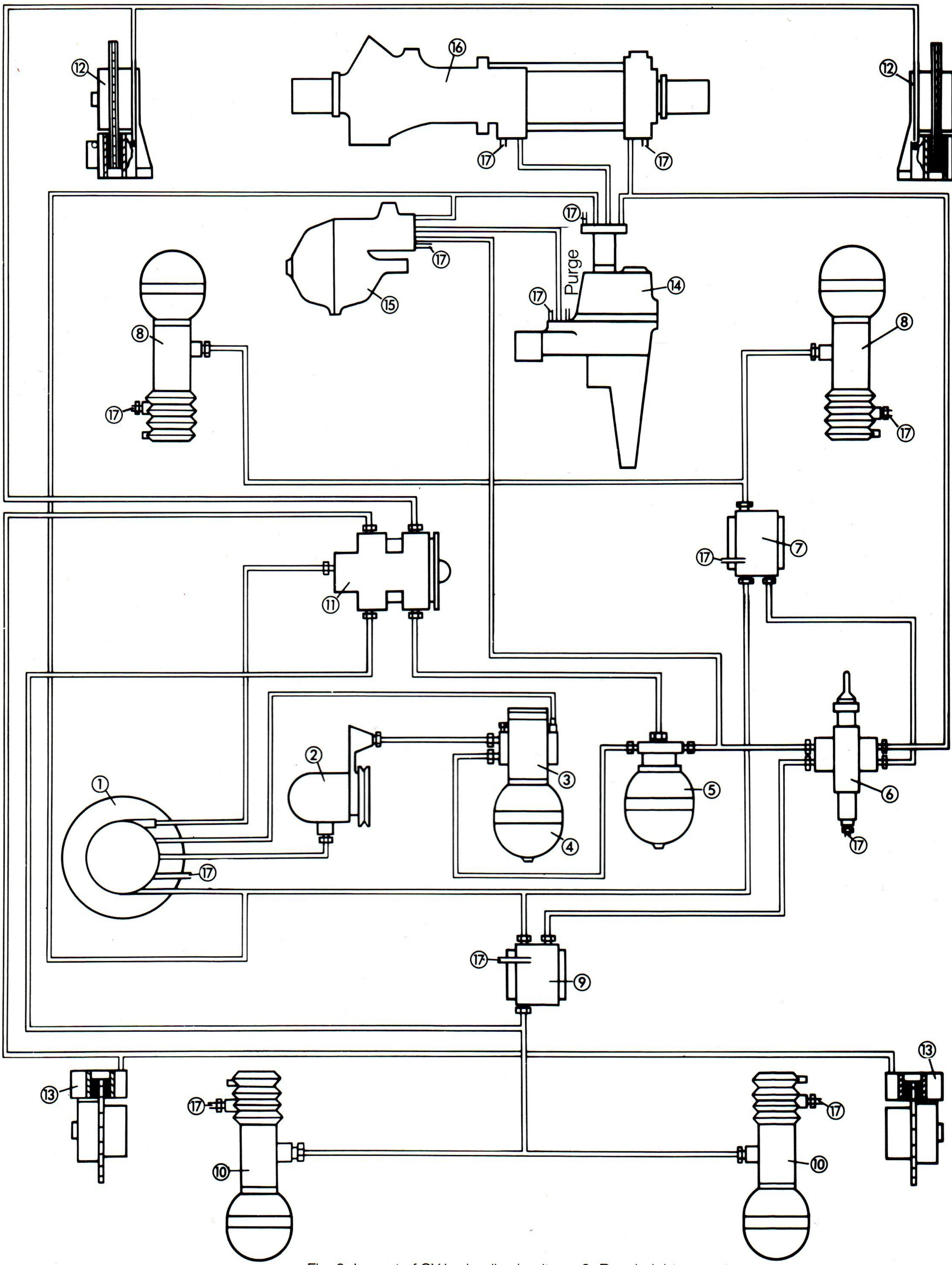


Fig. 6: Layout of CX hydraulic circuit

1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Front brake accumulator
6. Safety valve
7. Front height corrector
8. Front suspension
9. Rear height corrector
10. Rear suspension
11. Brake control unit
12. Front brakes
13. Rear brakes
14. Steering control box
15. Centrifugal regulator
16. Steering
17. Leakage return

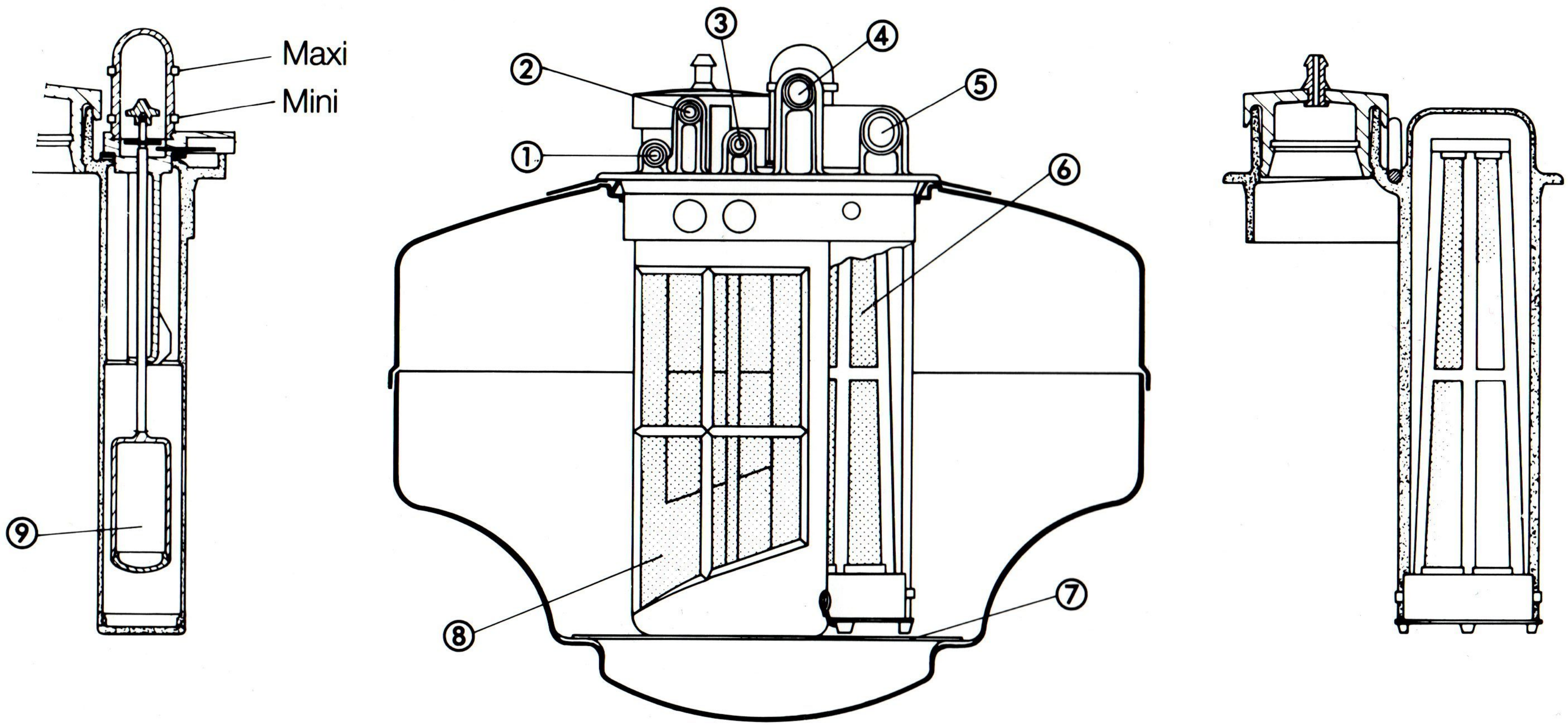


Fig. 8: BX hydraulic reservoir
1. Leakage return from front and rear suspension cylinders
2. Leakage return from safety valve and front and rear height correctors
3. Return line from brake control valve
4. Return line from pressure regulator and front and rear height correctors
5. Feed to high pressure pump
6. Filter in high pressure pump feed
7. Sediment trap
8. Filter for return fluid
9. Level indicator float with electric contact

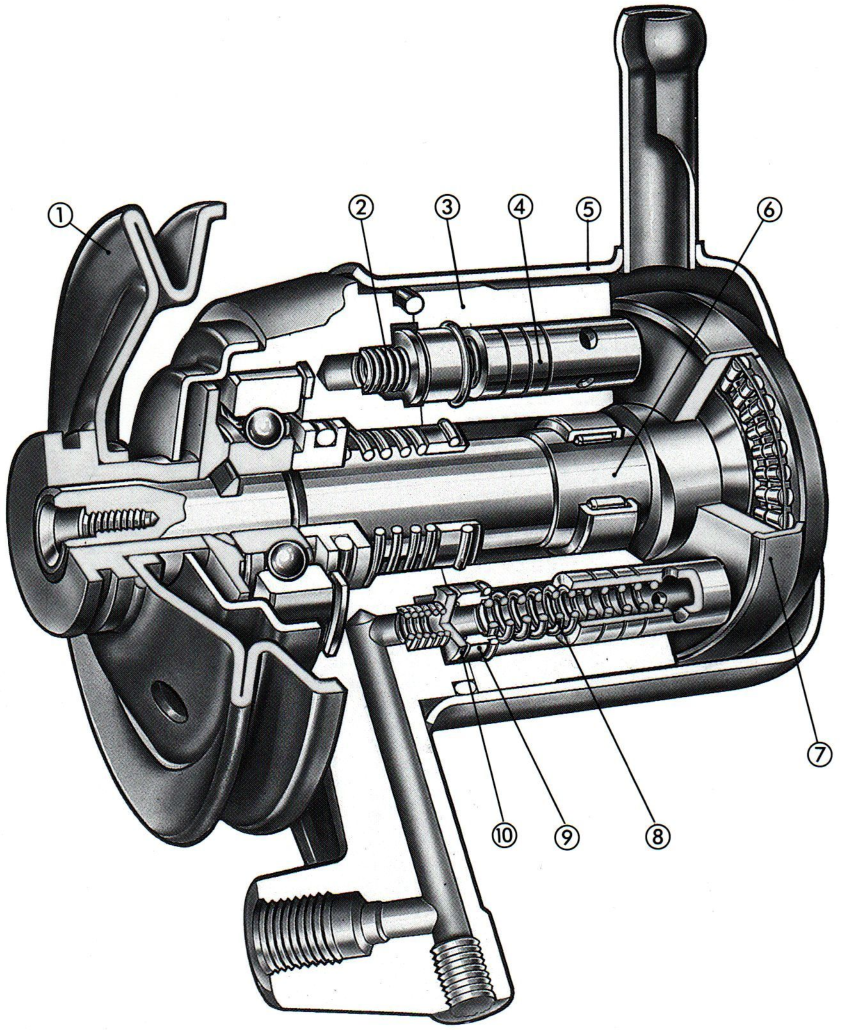
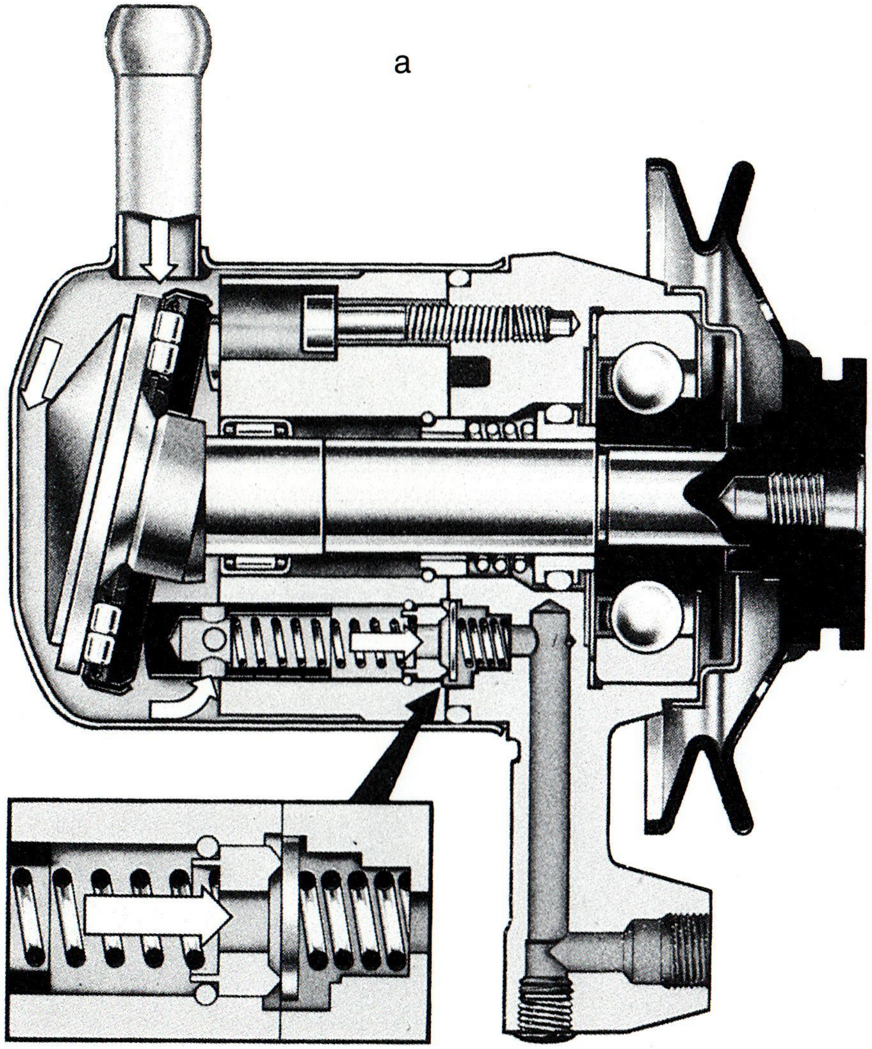


Fig. 9: High pressure hydraulic pump:
Description
Outlet to use

1. Drive pulley
2. Valve return spring
3. Cylinder block (housing)
4. Piston with holes
5. Pump shield
6. Pump shaft
7. Swashplate
8. Piston return spring
9. Valve seat
10. Valve

a



b

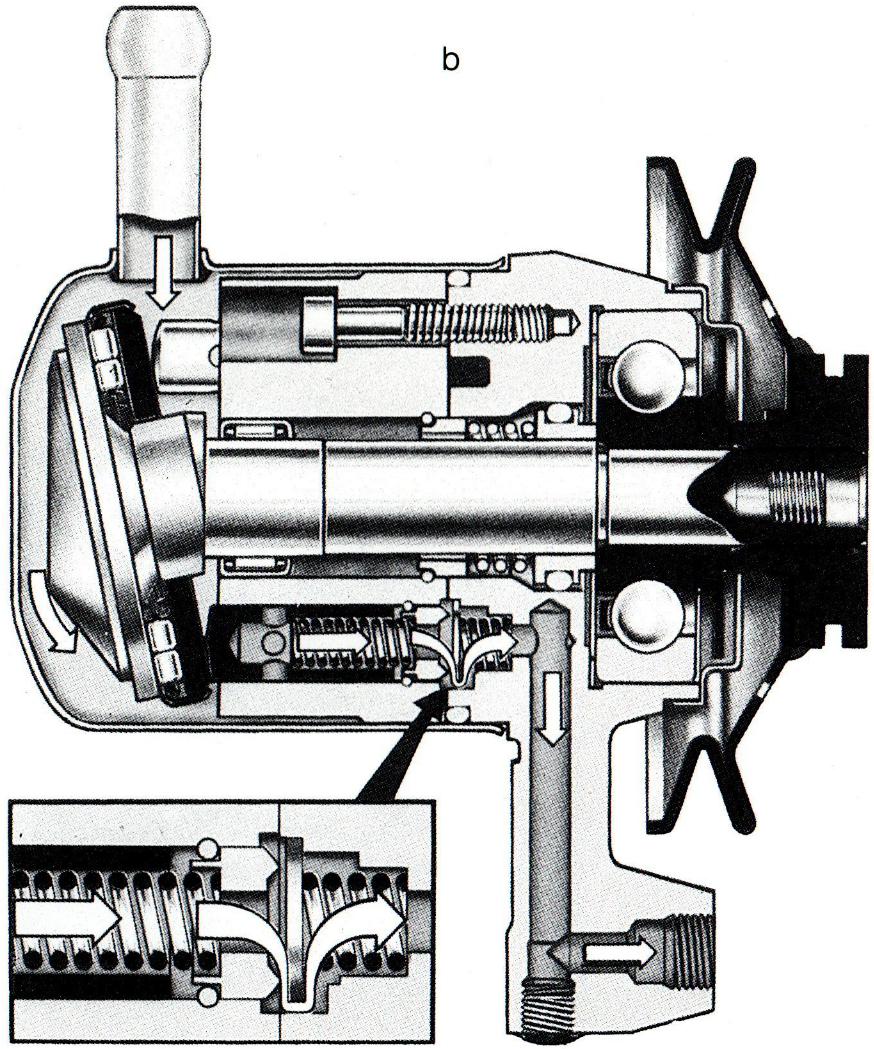


Fig. 10: High pression hydraulic pump:
operating principle
Fig. a: intake
Fig. b: output

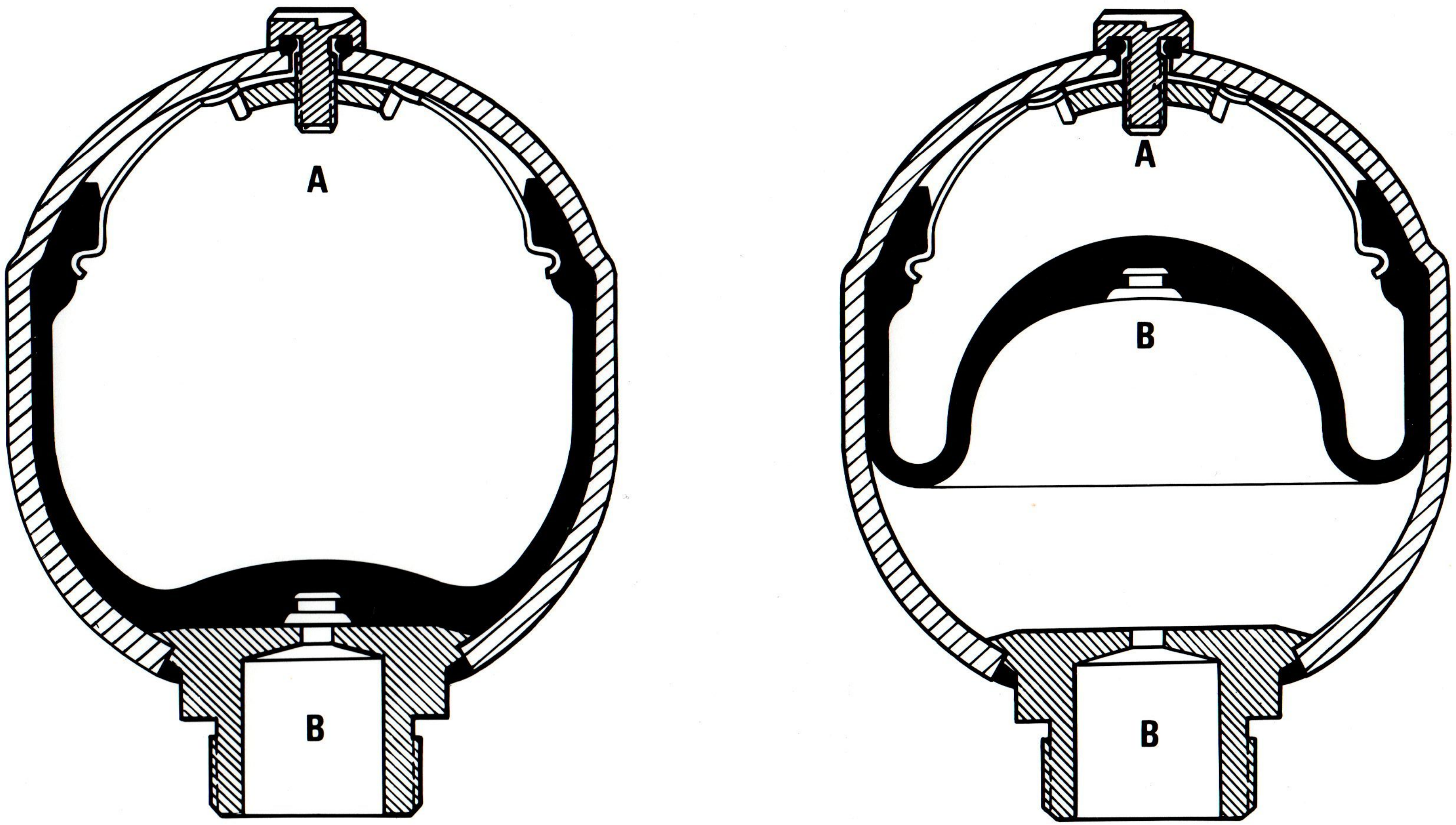
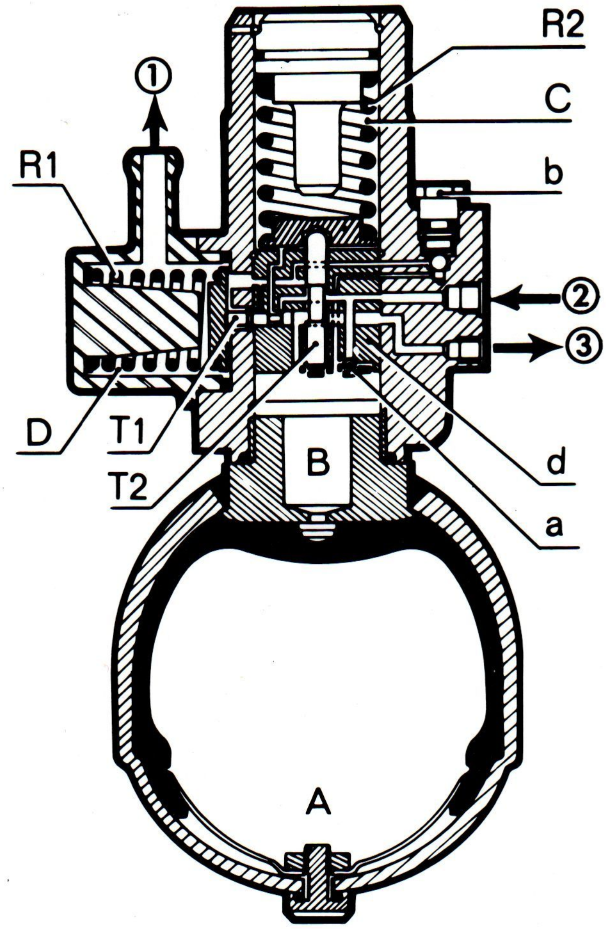


Fig. 12: Accumulator
A - Nitrogen at calibration pressure
A - Nitrogen at operating pressure
B - Reserve of pressurised liquid



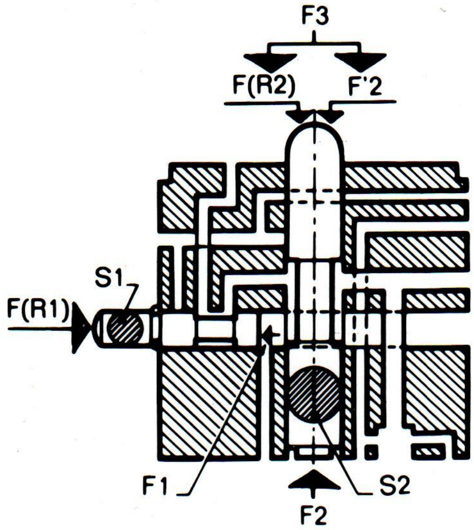


Fig. 13: Pressure regulator
1 Neutral position
2 Return to reservoir
3 High pressure pump output

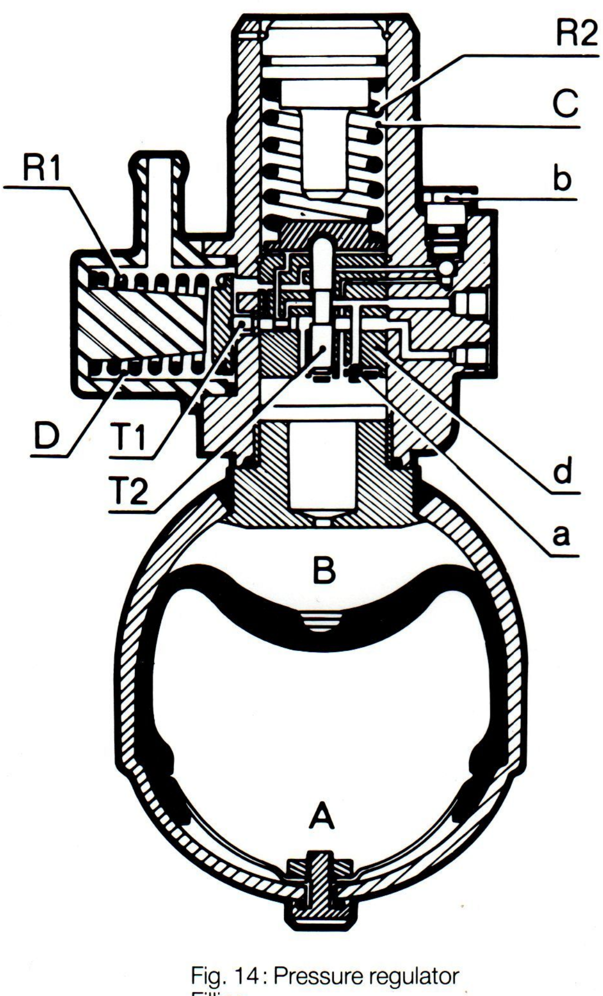


Fig. 14: Pressure regulator
Filling

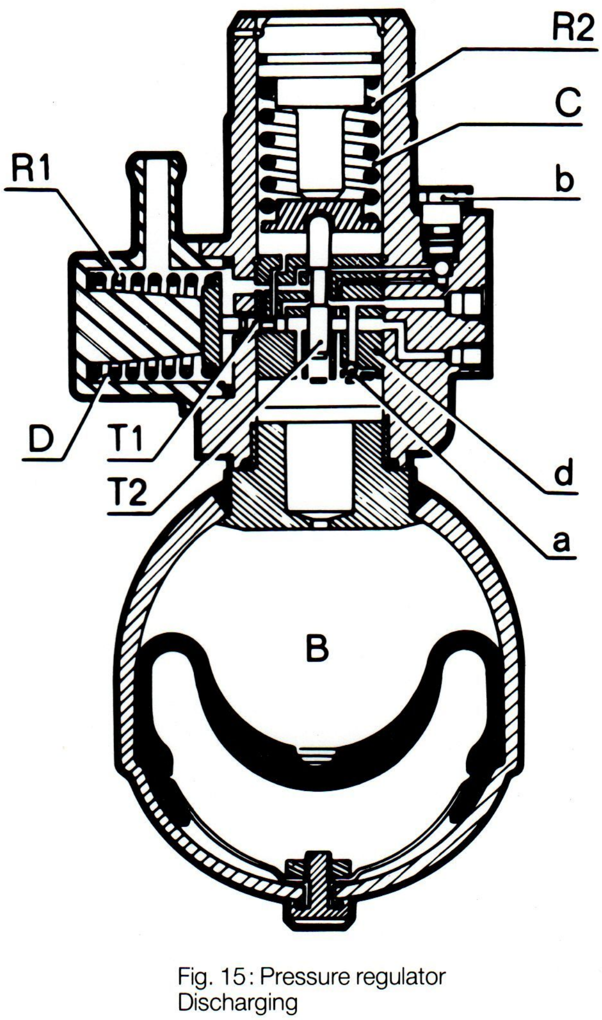


Fig. 15: Pressure regulator
Discharging

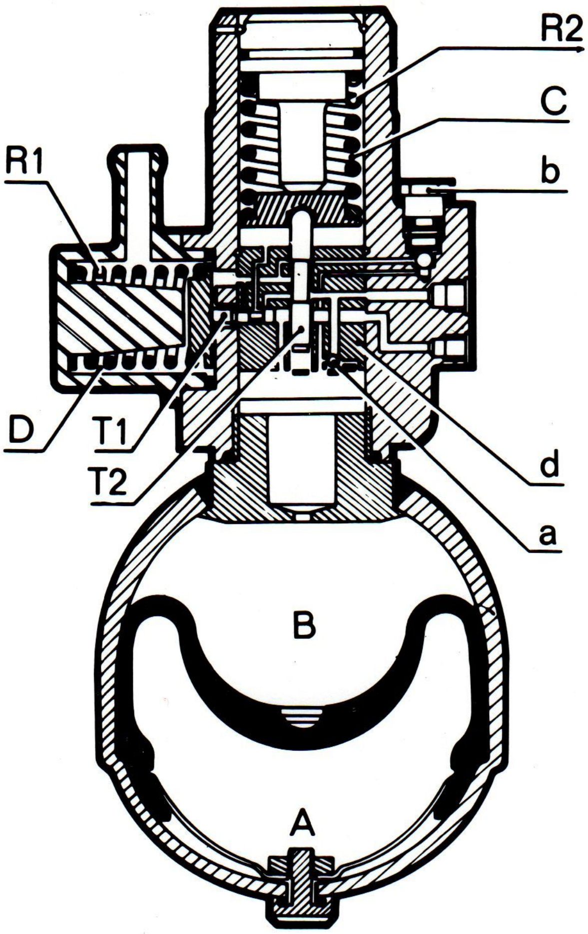


Fig. 16: Pressure regulator
Operating

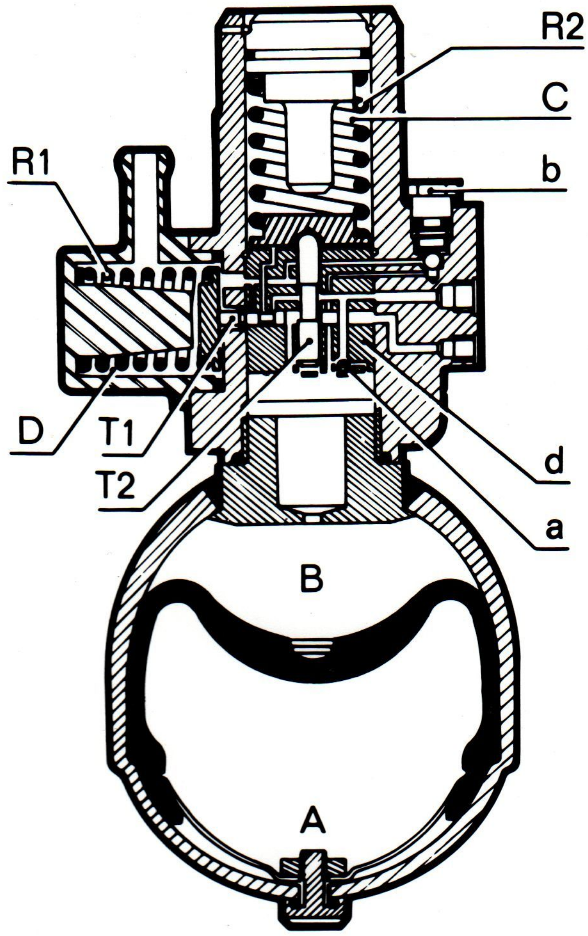


Fig. 17: Pressure regulator
Charging

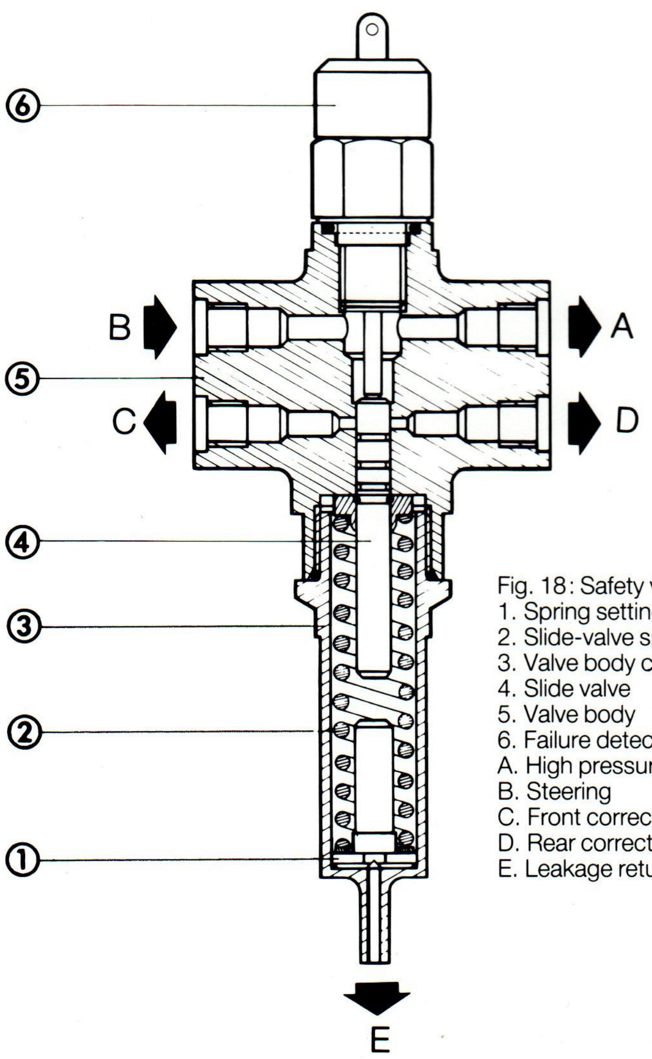
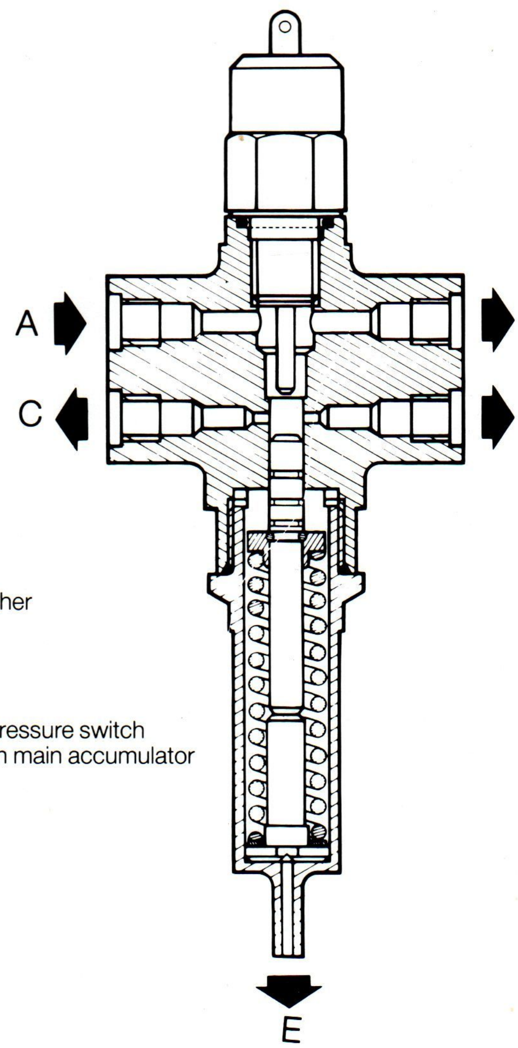


Fig. 18: Safety valve
1. Spring setting washer
2. Slide-valve spring
3. Valve body cover
4. Slide valve
5. Valve body
6. Failure detection pressure switch
A. High pressure from main accumulator
B. Steering
C. Front corrector
D. Rear corrector
E. Leakage return



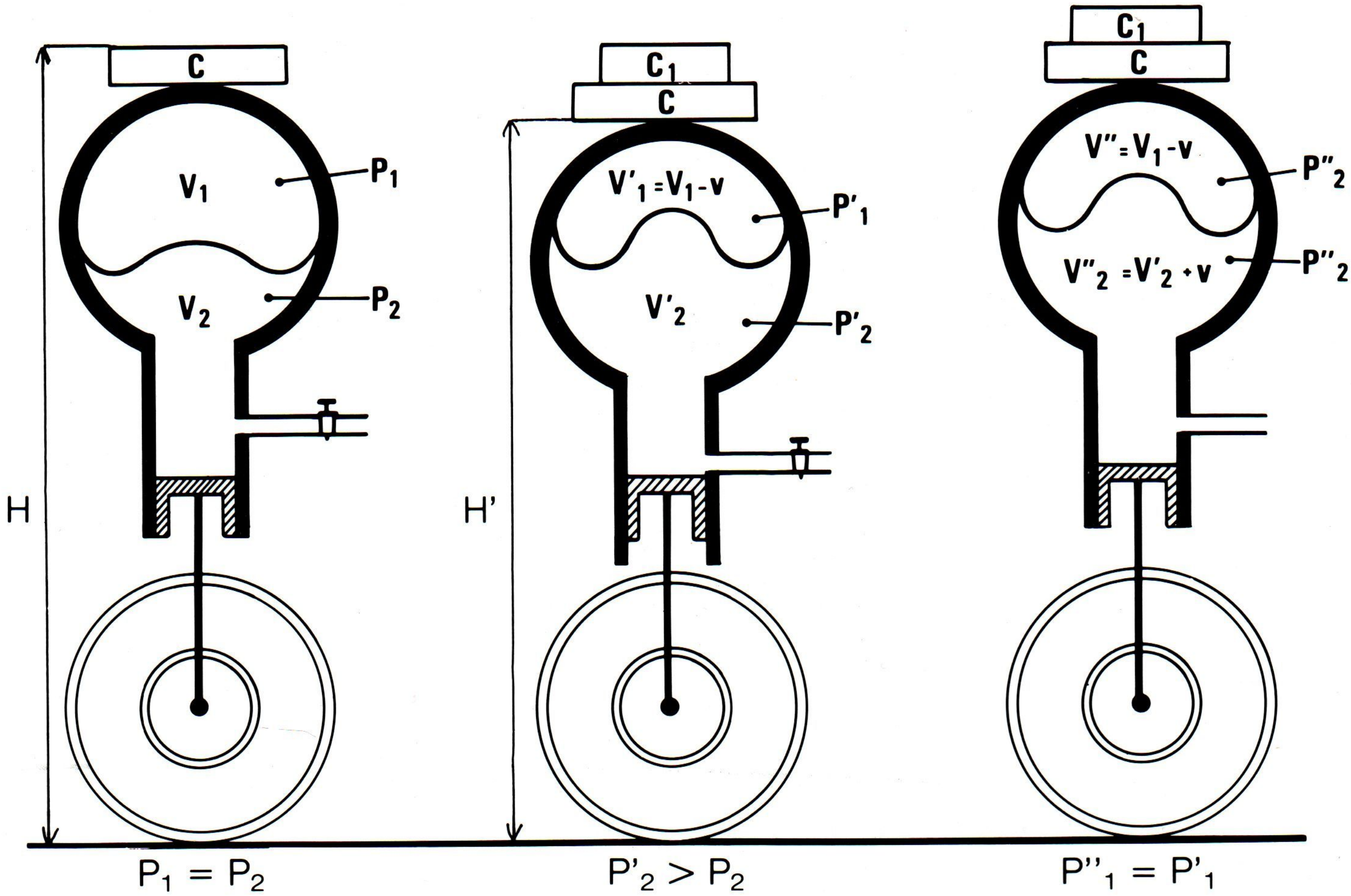


Fig. 21 : Operating principle
of hydropneumatic suspension

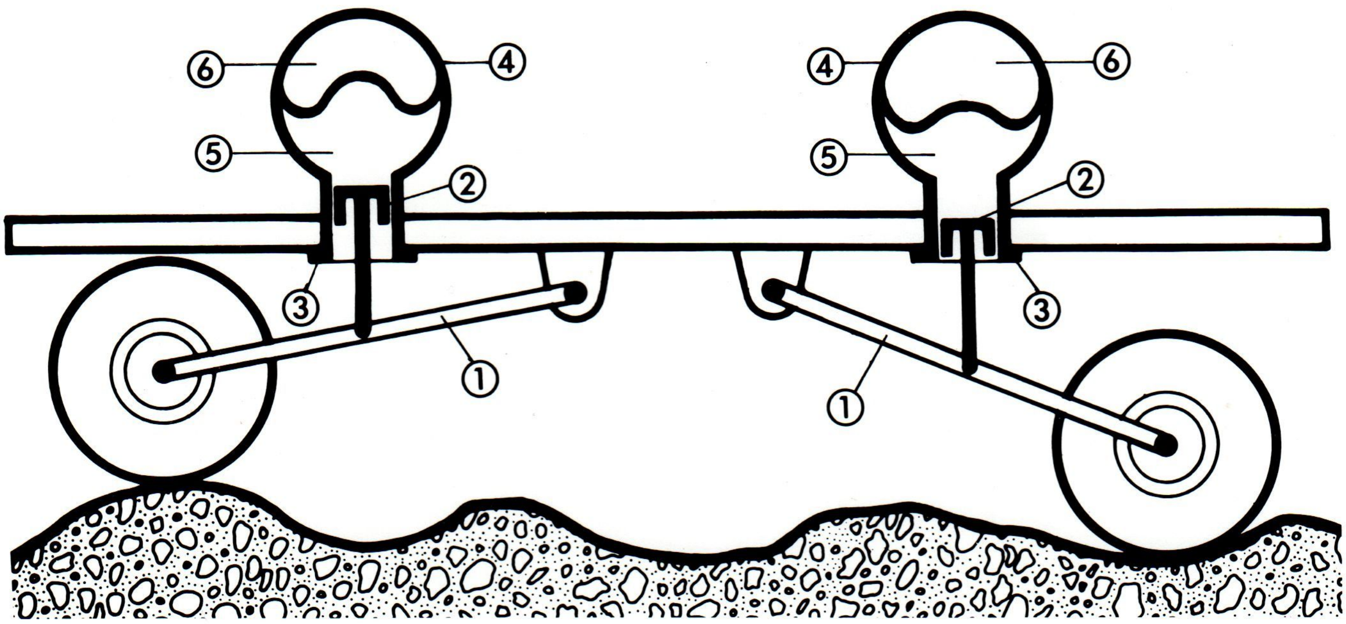


Fig. 22 : Principle of hydropneumatic suspension
1. Suspension arm
2. Piston
3. Cylinder
4. Sphere
5. Liquid
6. Gas

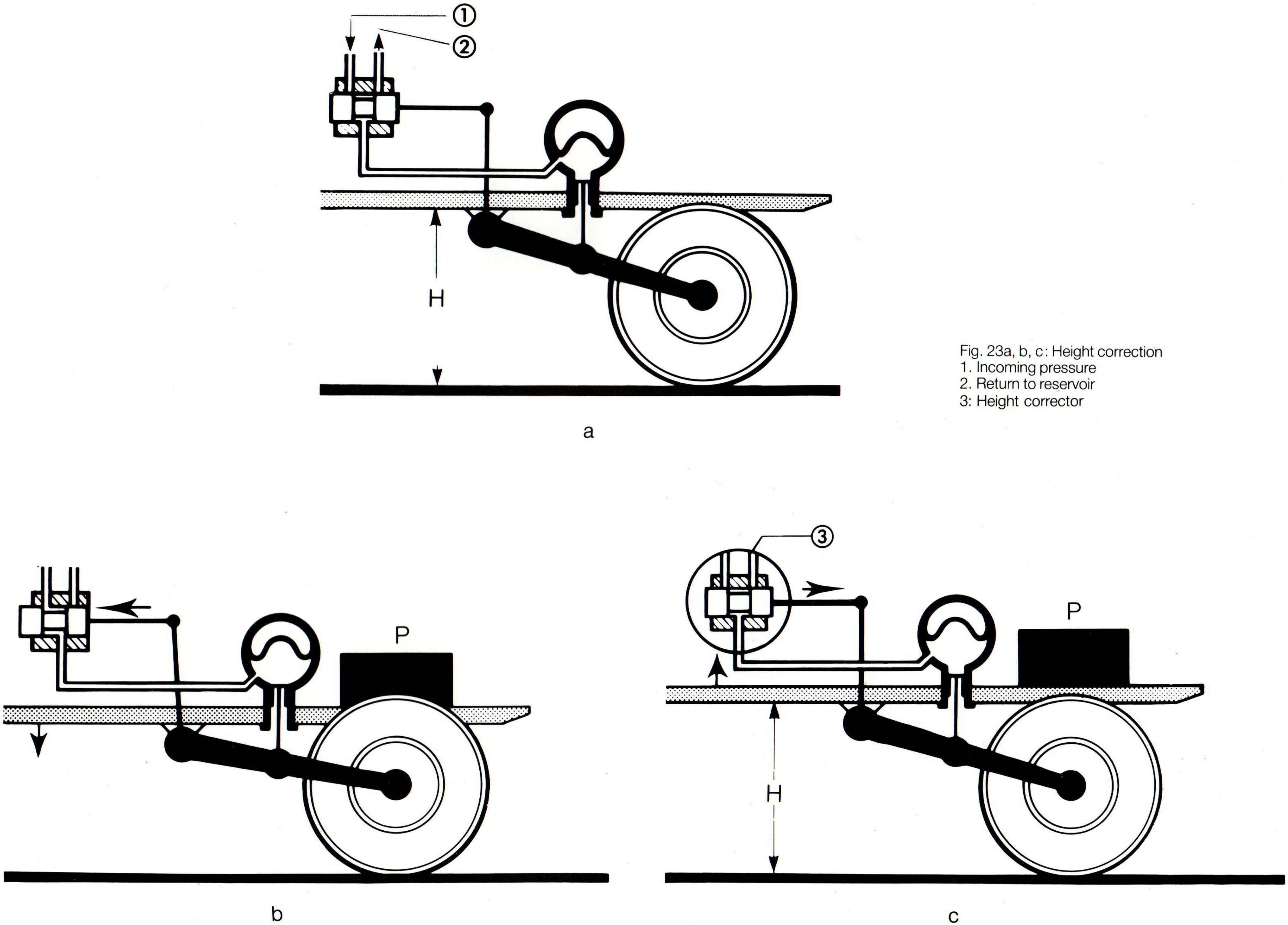


Fig. 23a, b, c: Height correction
1. Incoming pressure
2. Return to reservoir
3: Height corrector

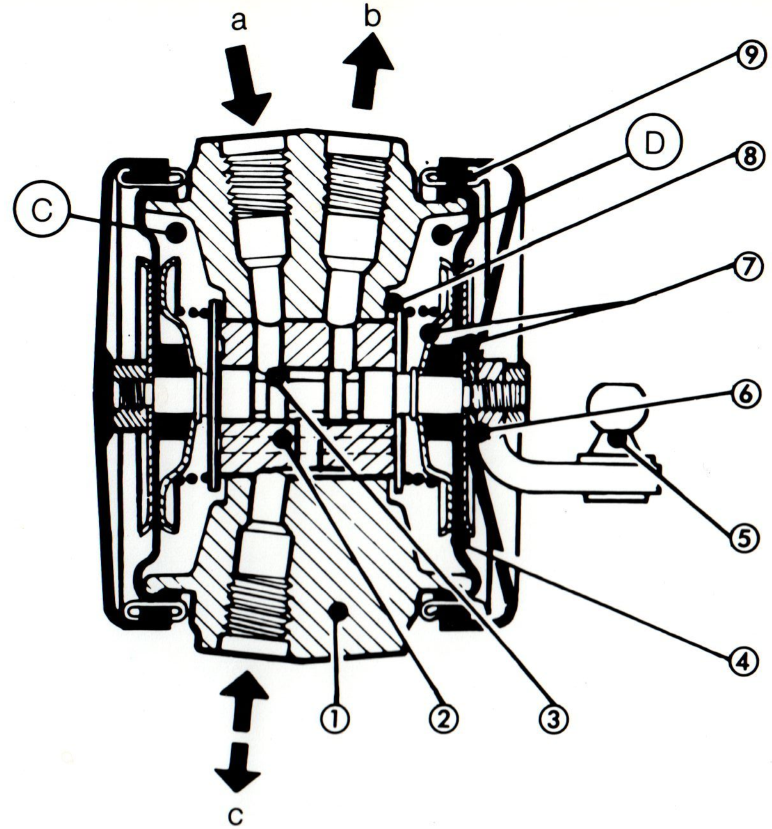


Fig. 25: Description of height corrector
1. Body
2. Sleeve
3. Slide valve
4. Flexible membrane
5. Adjustment knob
6. Dust cover
7. Cups
8. Valve
9. Retaining ring
10. Dashpot
a. Intake
b. Return
c. Operation

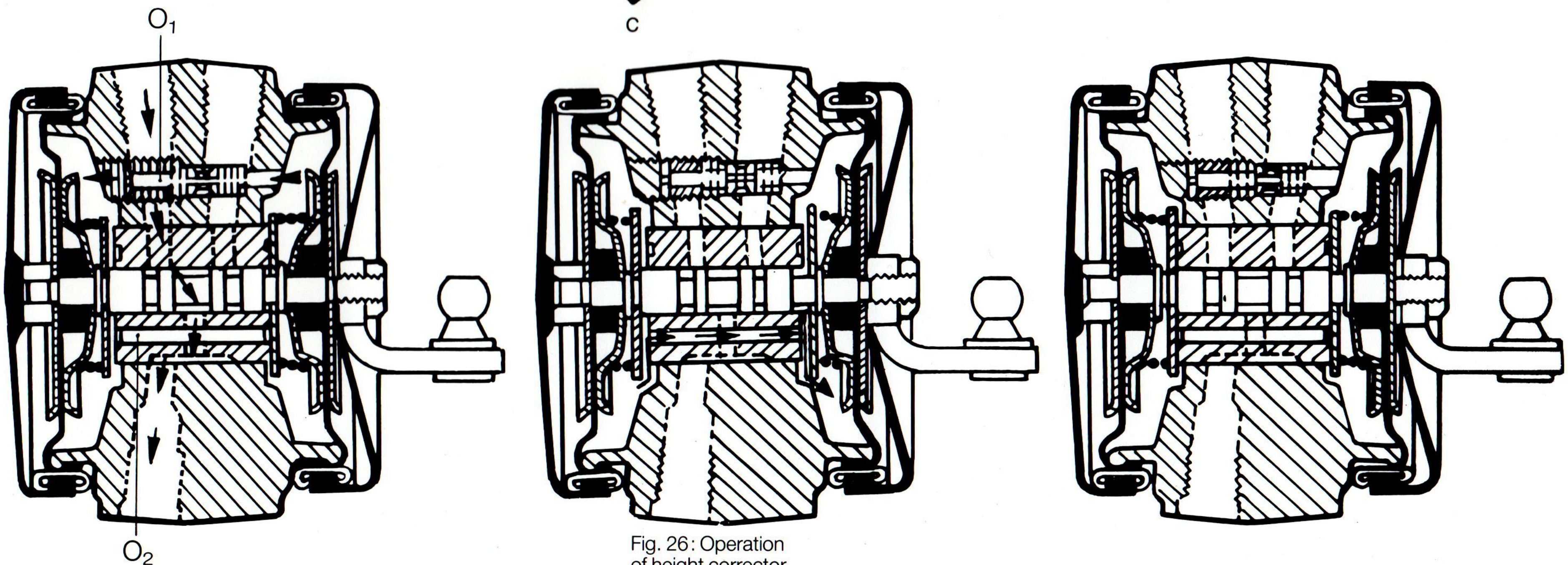


Fig. 26: Operation of height corrector
a) Intake
b) Return to neutral
c) Neutral

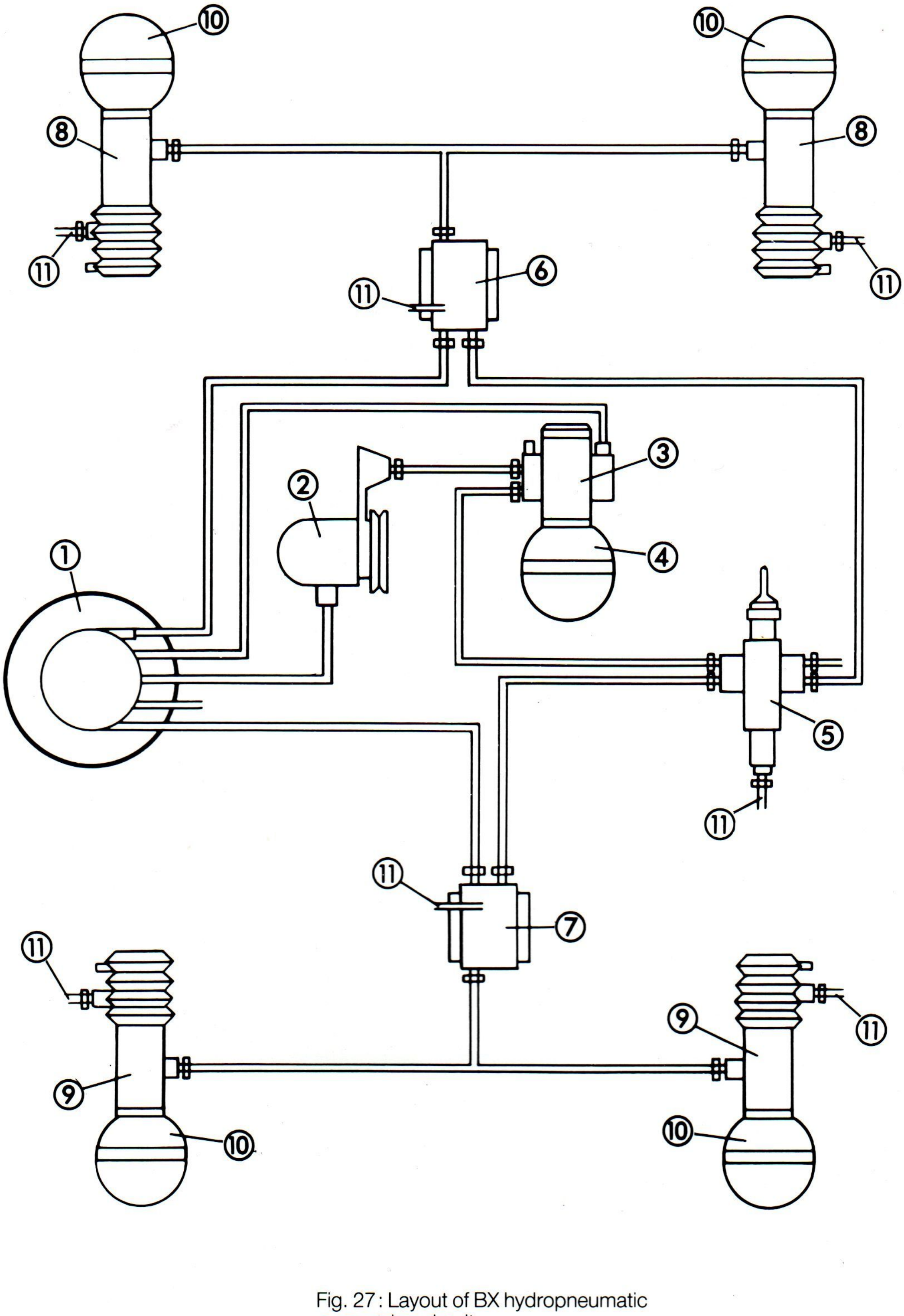


Fig. 27 : Layout of BX hydropneumatic suspension circuit
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Safety valve
6. Front height corrector
7. Rear height corrector
8. Front suspension cylinder
9. Rear suspension cylinder
10. Suspension spheres
11. Leakage return

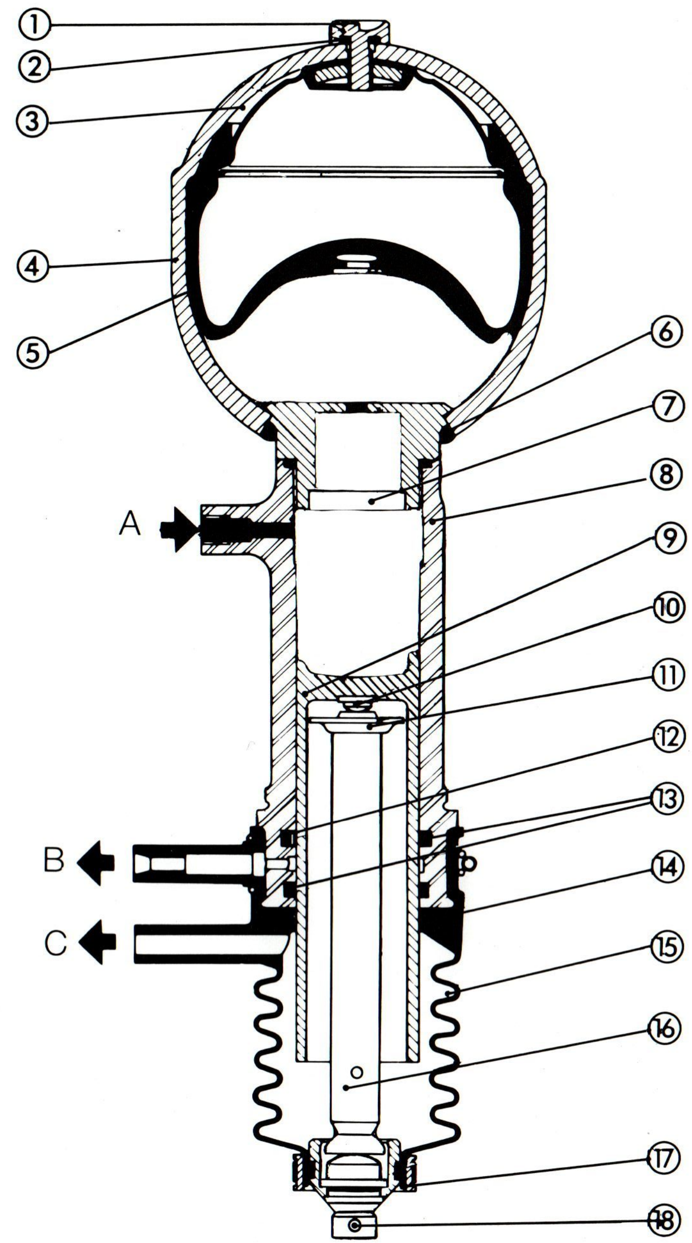


Fig. 28: Section through BX
front suspension unit
1. Sphere
2. Gas (nitrogen)
3. Membrane
4. Pressurised liquid
5. Damper
6. Hydraulic liquid intake
7. Cylinder
8. Flexible mounting
9. Flexible bearing
10. Dust gaiter
11. Piston guide rod
12. Rebound stop
13. Piston
14. Guide tube
15. Oil return valve
16. Sliding tube
17. Oil reserve
18. Stop washer
19. Centring washer
20. Bump stops

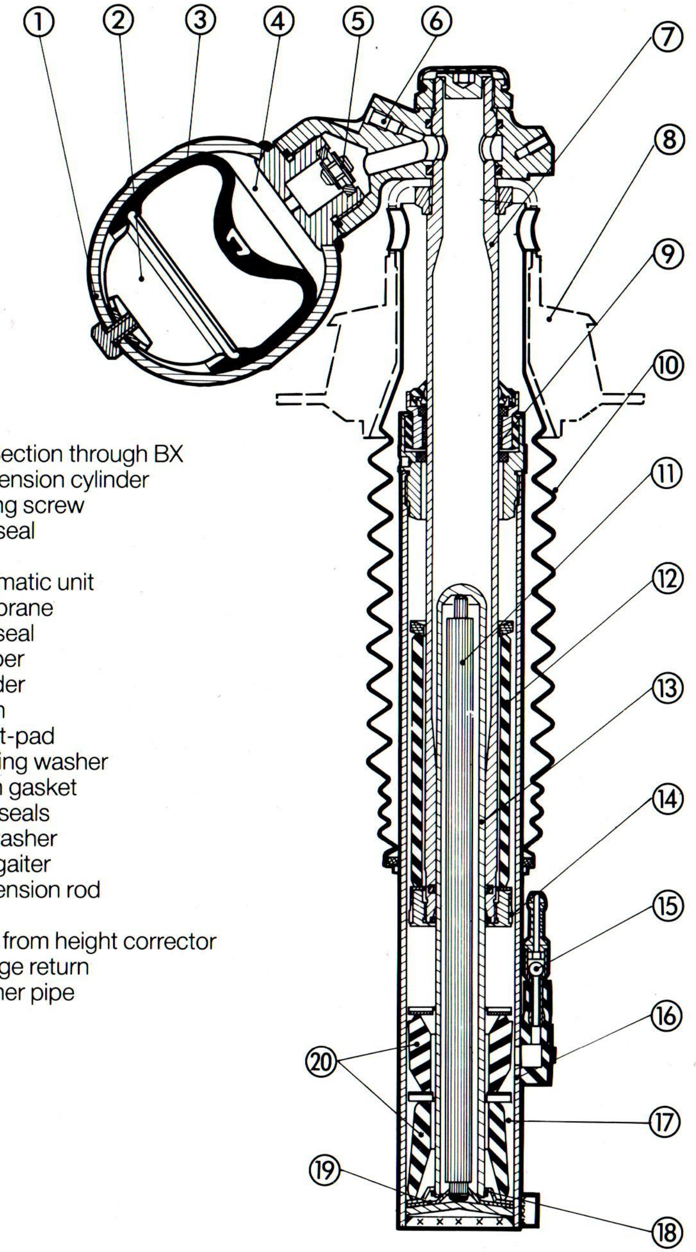


Fig. 29: Section through BX
rear suspension cylinder
1. Sealing screw
2. Ring seal
3. Cup
4. Pneumatic unit
5. Membrane
6. Ring seal
7. Damper
8. Cylinder
9. Piston
10. Thrust-pad
11. Centring washer
12. Teflon gasket
13. Ring seals
14. Felt washer
15. Dust gaiter
16. Suspension rod
17. Ball
A. Liquid from height corrector
B. Leakage return
C. Breather pipe

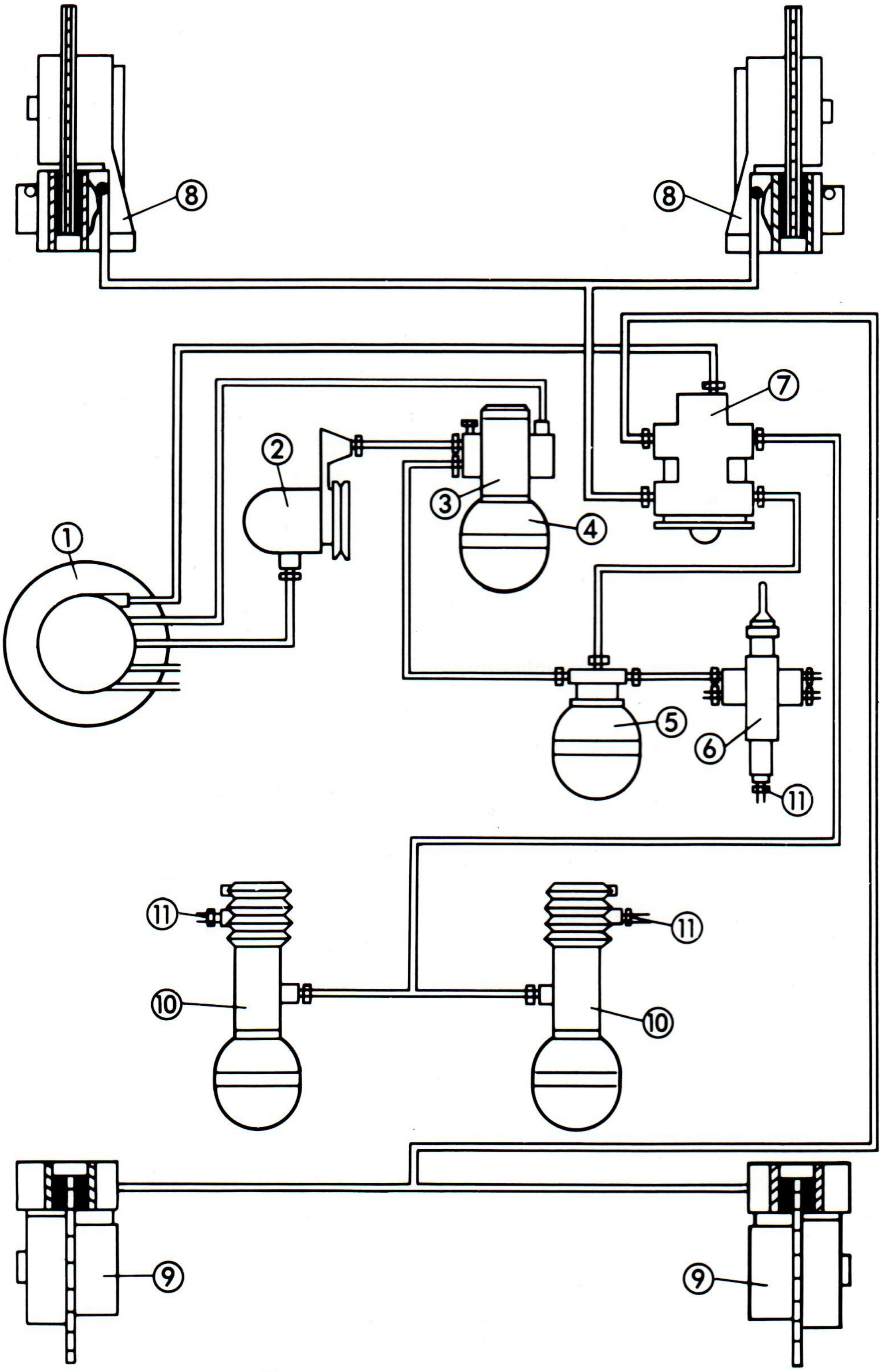


Fig. 30: CX brake circuit layout
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Brake accumulator
6. Safety valve
7. Control unit
8. Front brakes
9. Rear brakes
10. Rear suspension units
11. Leakage return

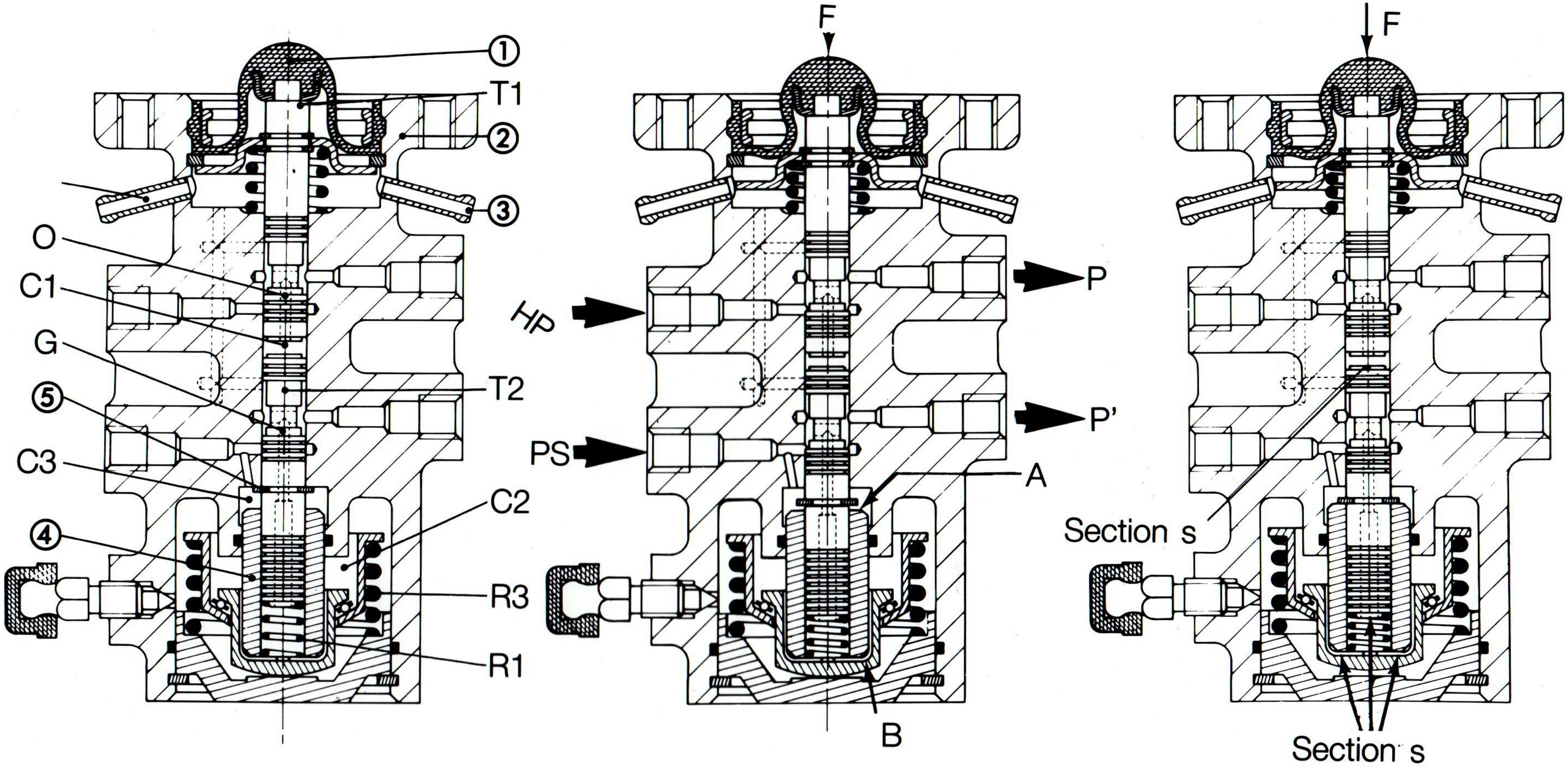


Fig. 31 : Operating principle of BX brake control unit

Section

1. Damper
2. Unit body
3. Return to reservoir
4. Shuttle valve
5. Shuttle stop

F Force from pedal
HP High pressure
PS Suspension pressure
P Front brake pressure
P' Rear brake pressure

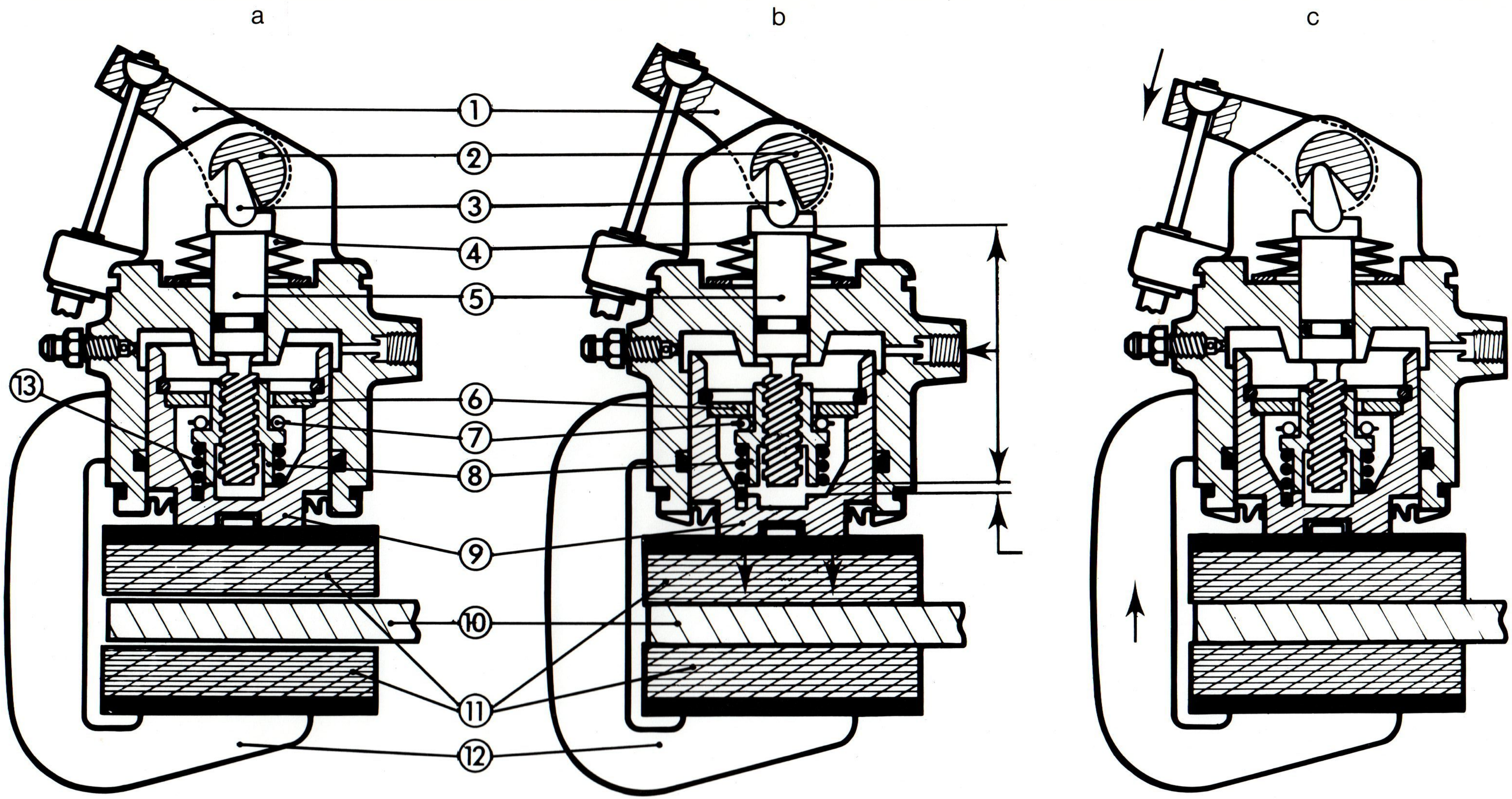


Fig. 32a, b, c: Principle of automatic brake free-play adjustment
1 et 2. Lever
3. Tappet
4. Flexible washers
5. Rod
6. Thrust washer
7. Ball bearing
8. Nut
9. Piston
10. Brake disc
11A-11B. Brake pads
12. Caliper
13. Spring
P Unpressurised liquid

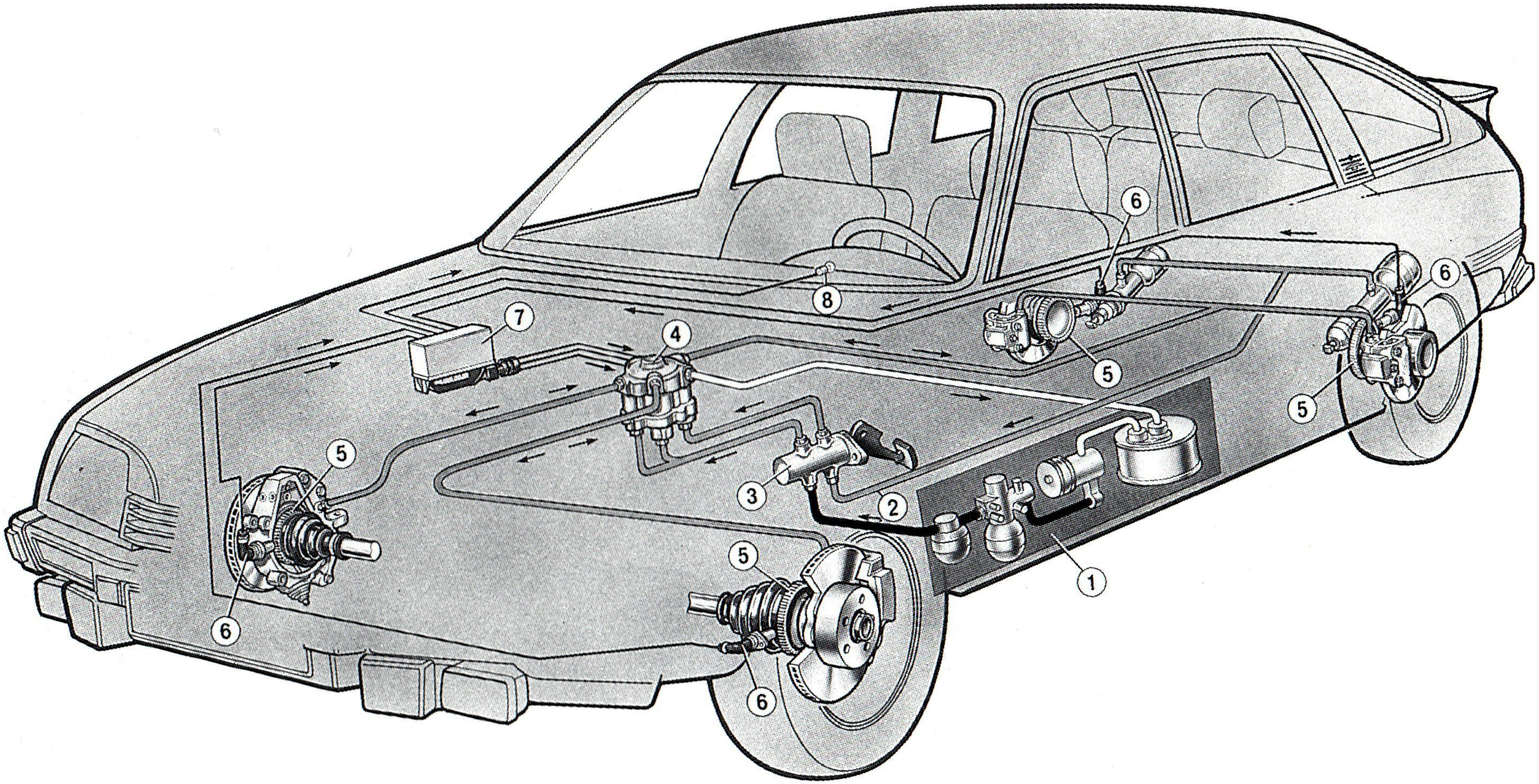


Fig. 33: Anti-lock braking system
1. Pressure reserve: feeding front brakes, suspension, steering
2. Rear suspension circuit: feeding rear brakes
3. Brake control unit
4. Hydraulic block with three electromagnetic valves
5. Toothed wheels
6. Electromagnetic sensors
7. Computer
8. ABS fault warning light

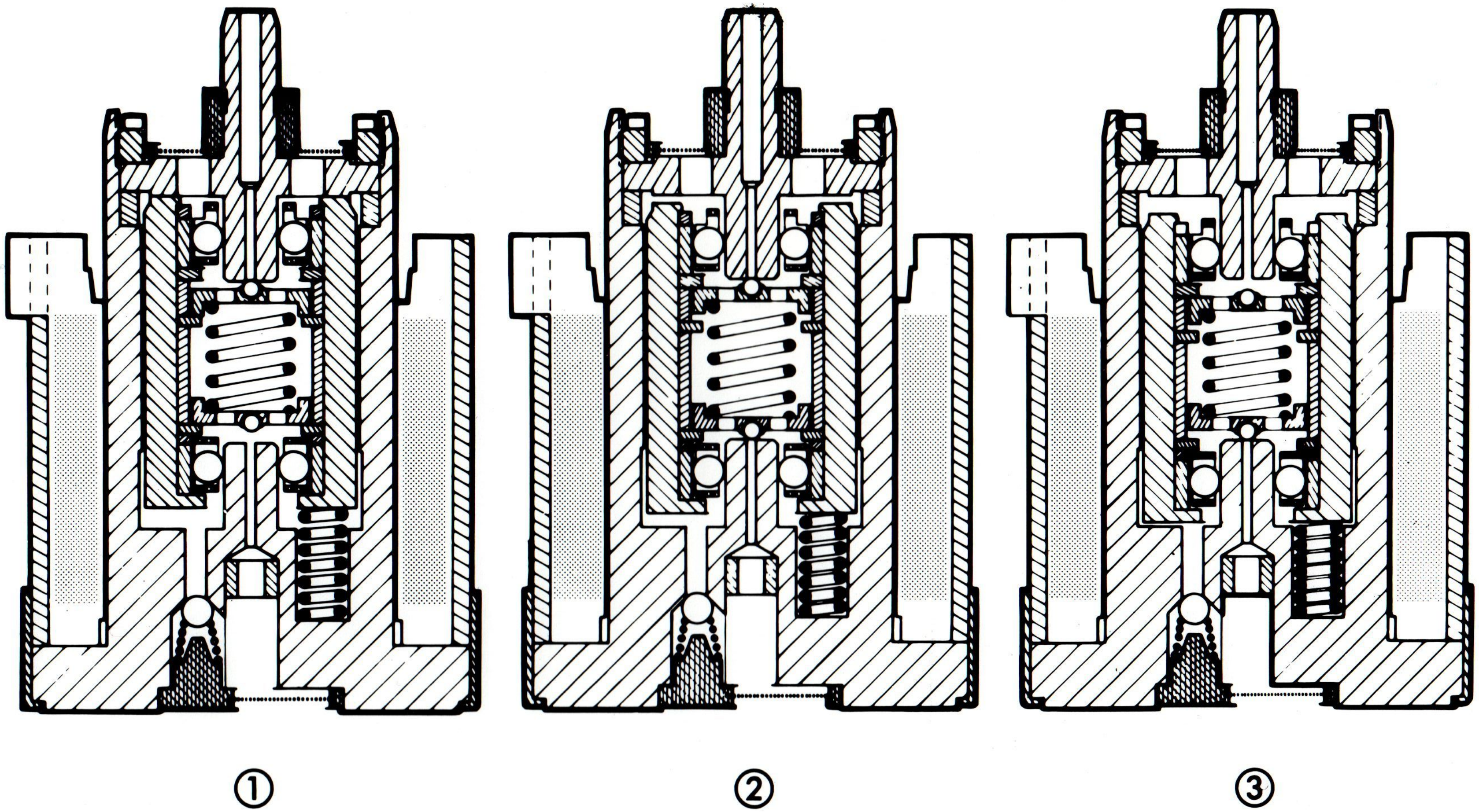


Fig 34: Electronic valves
Operating principle
1 - Normal position
2 - Braking pressure constant
3 - Pressure falls in the brake line

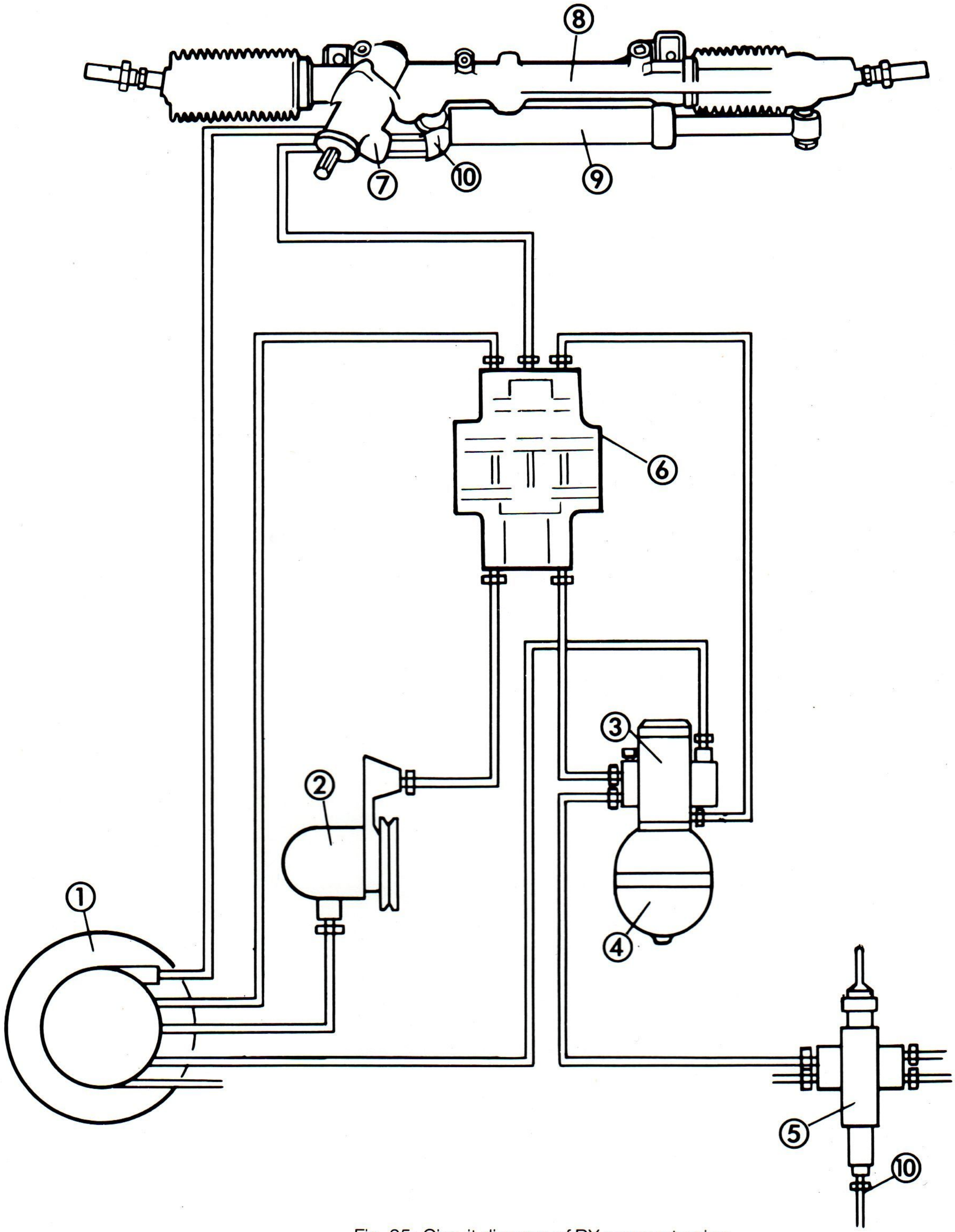


Fig. 35: Circuit diagram of BX power steering
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Safety valve
6. Flow divider
7. Control valve
8. Steering
9. Jack
10. Leakage return

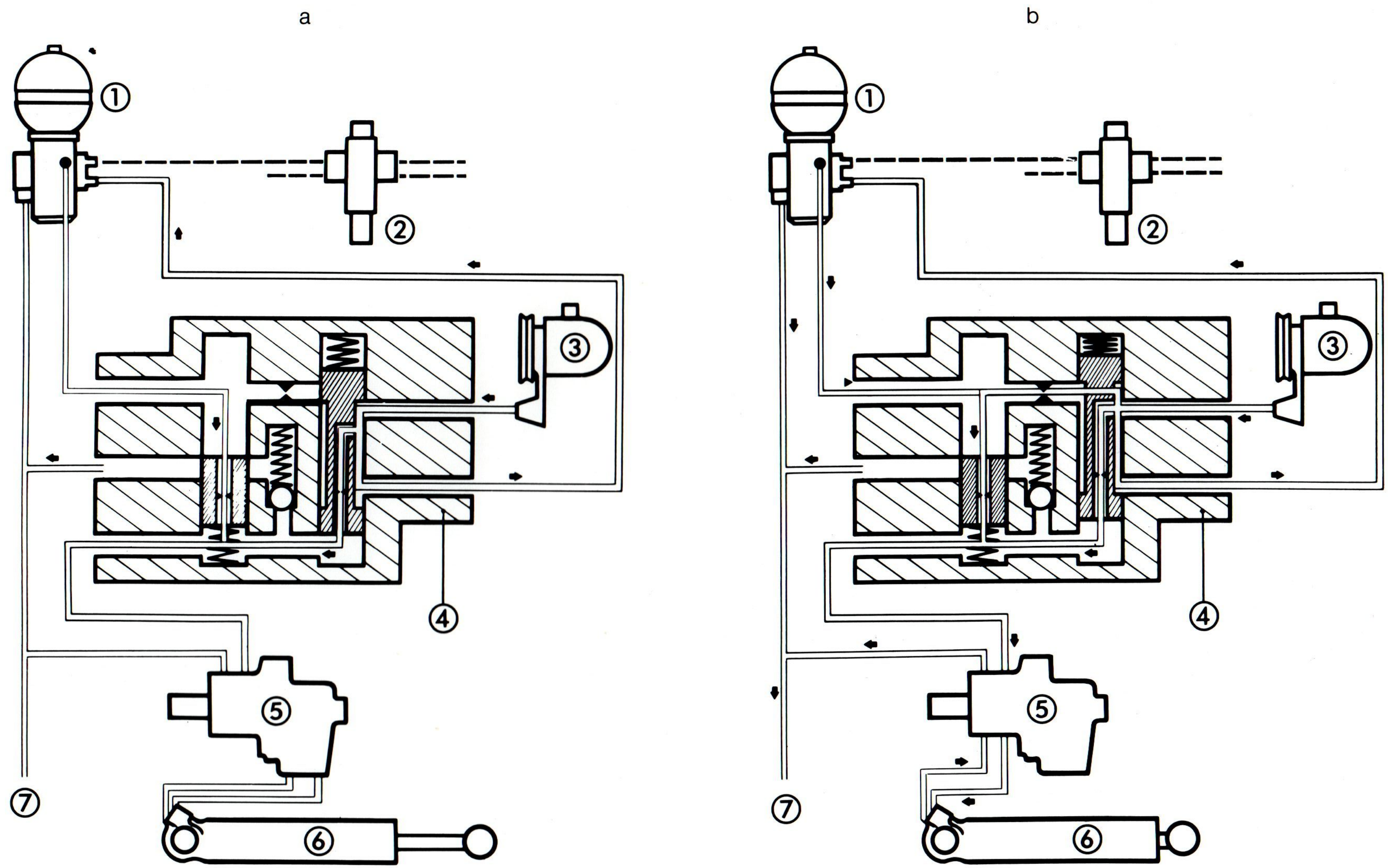


Fig. 36: Operating principle of flow divider: charging
a) Car running straight
b) Cornering
1. Pressure regulator
2. Safety valve
3. 5-piston pump
4. Flow divider
5. Rotary valve
6. Jack
7. To reservoir

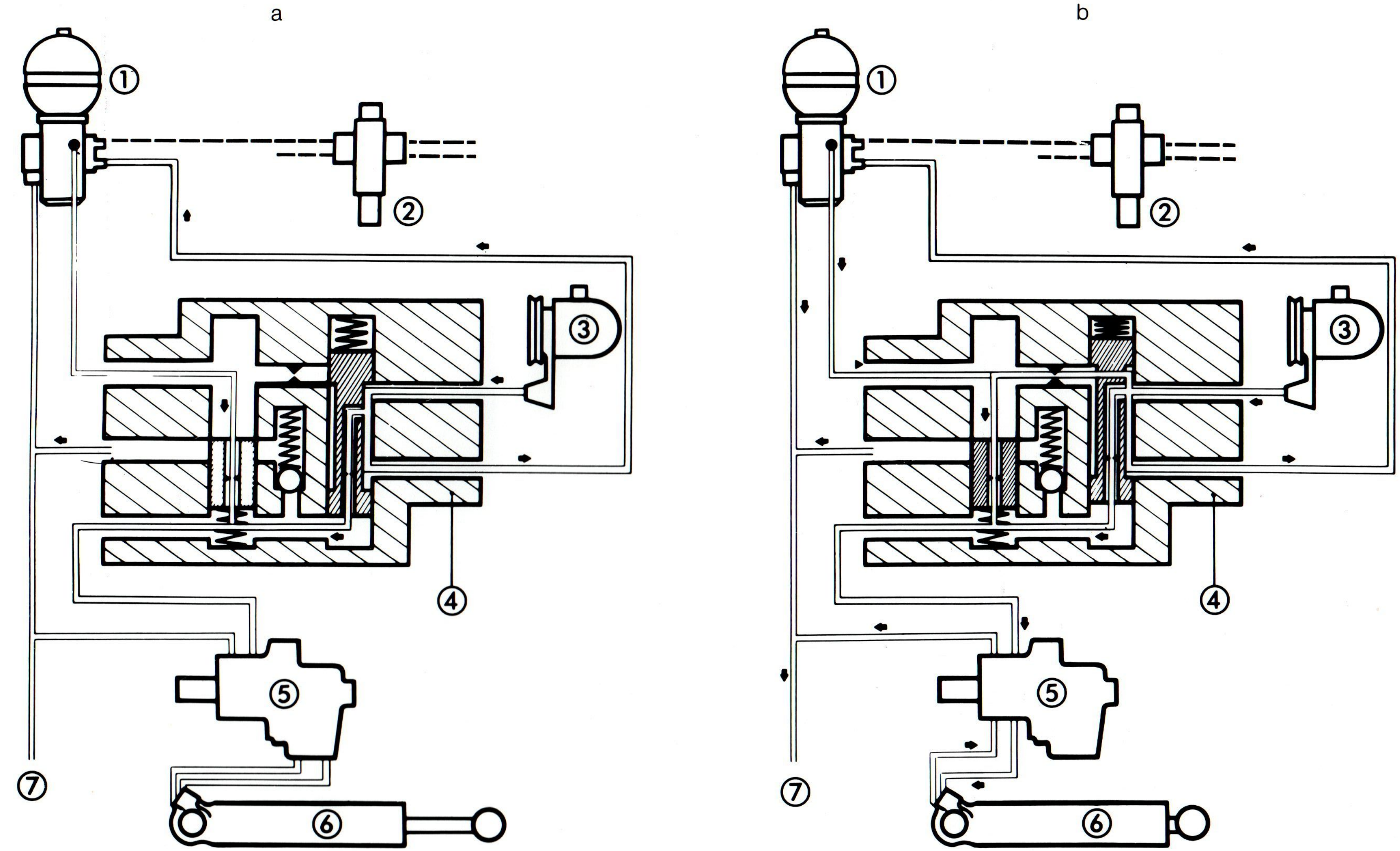


Fig. 37 : Operating principle of flow divider:
discharge
a) Car running straight
b) Cornering

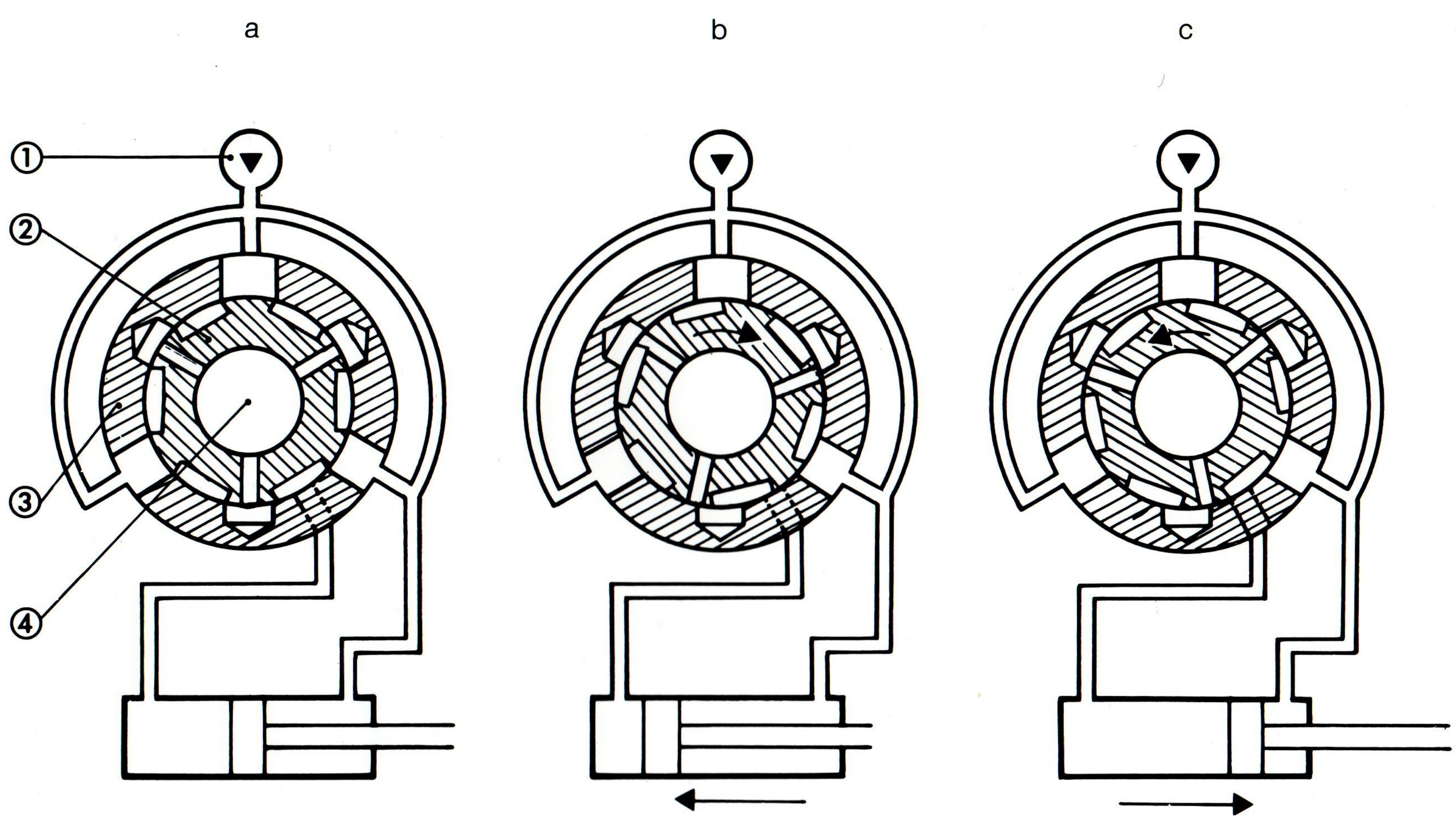


Fig. 38: Operating principle of steering valve
a. Car running straight
b. Turning right
c. Turning left
1. Pump
2. Rotor
3. Pinion
4. Return to reservoir

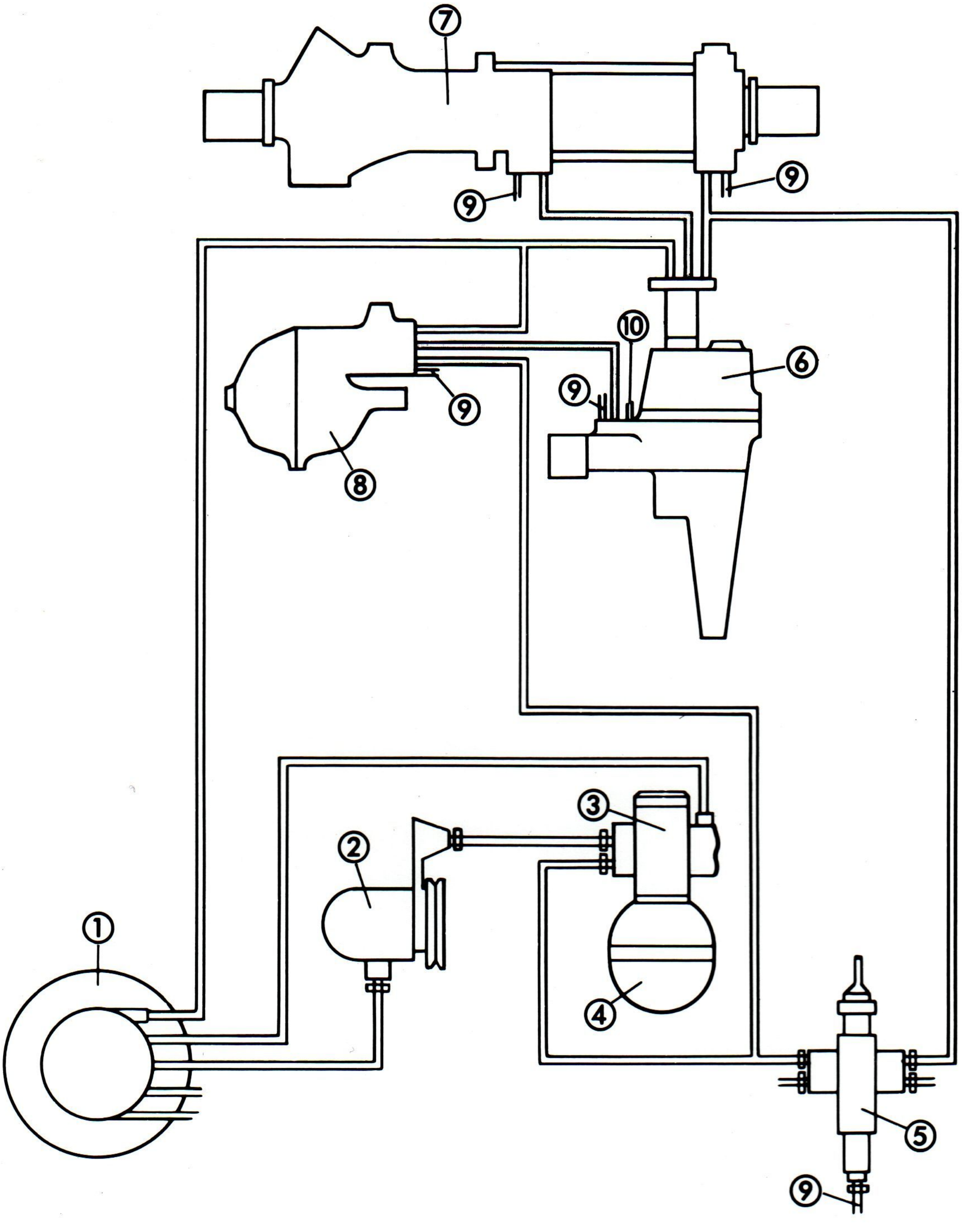


Fig. 39: Layout of CX power steering circuit
1. Reservoir
2. Hydraulic pump
3. Pressure regulator
4. Main accumulator
5. Safety valve
6. Steering control unit
7. Steering
8. Centrifugal regulator
9. Leakage return
10. Purging valve

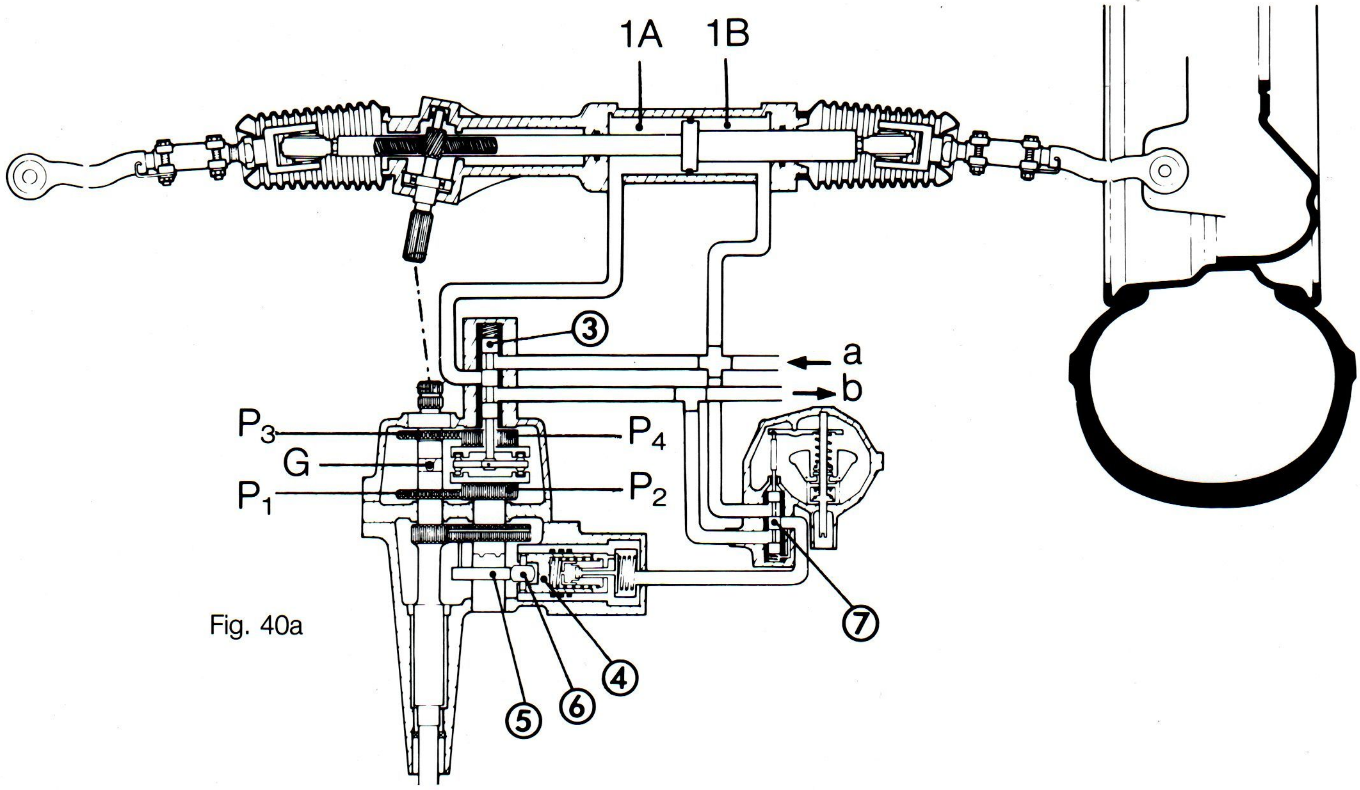


Fig. 40a

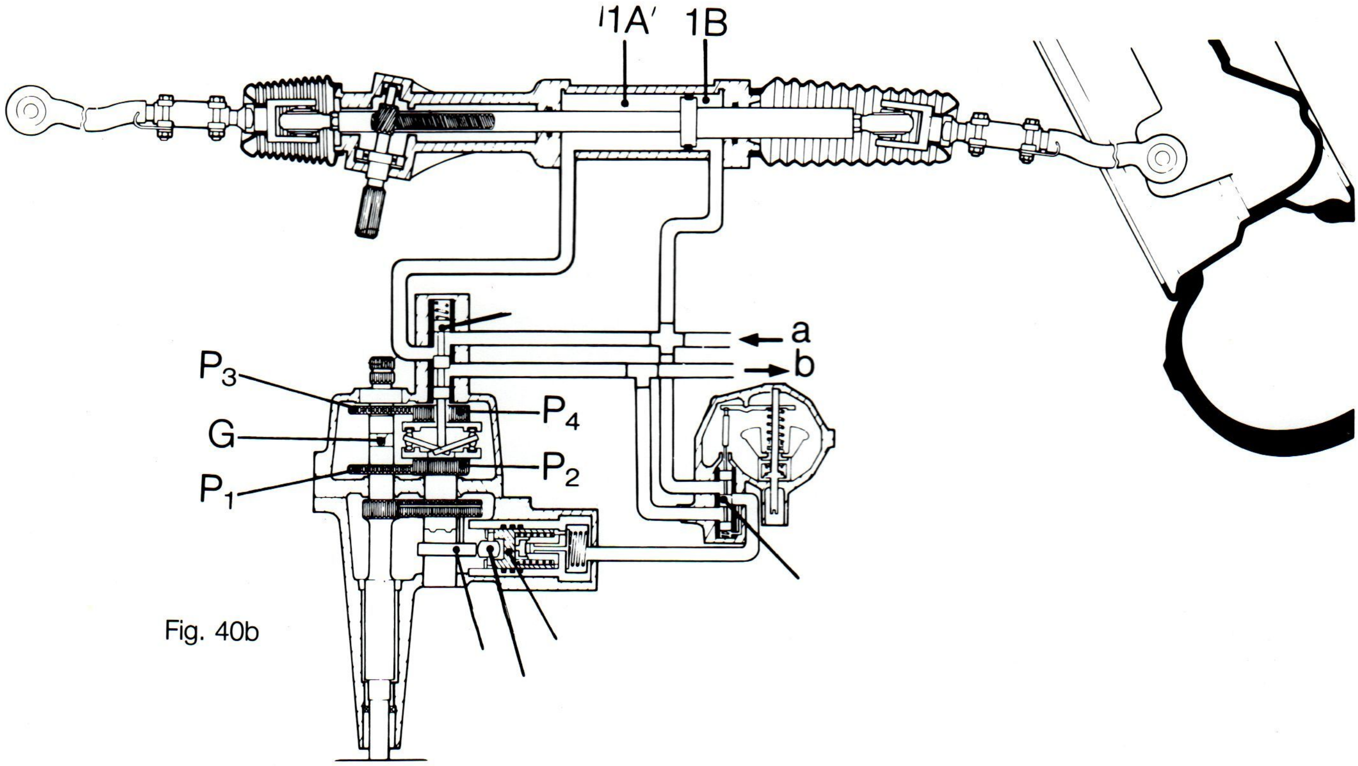


Fig. 40b

Fig. 40: Speed-sensitive self-centring of CX steering

a) Neutral position, at standstill
a. High pressure inlet
b. Return to reservoir
1. Chamber A
2. Chamber B
3. Slide valve T1
4. Self-centring piston
5. Cam
6. Roller
7. Slide valve T2

b) Turning left
a. High pressure inlet
b. Return to reservoir
1. Chamber A
2. Chambre B
3. Slide valve T1
4. Self-centring piston
5. Cam
6. Roller
7. Slide valve T2

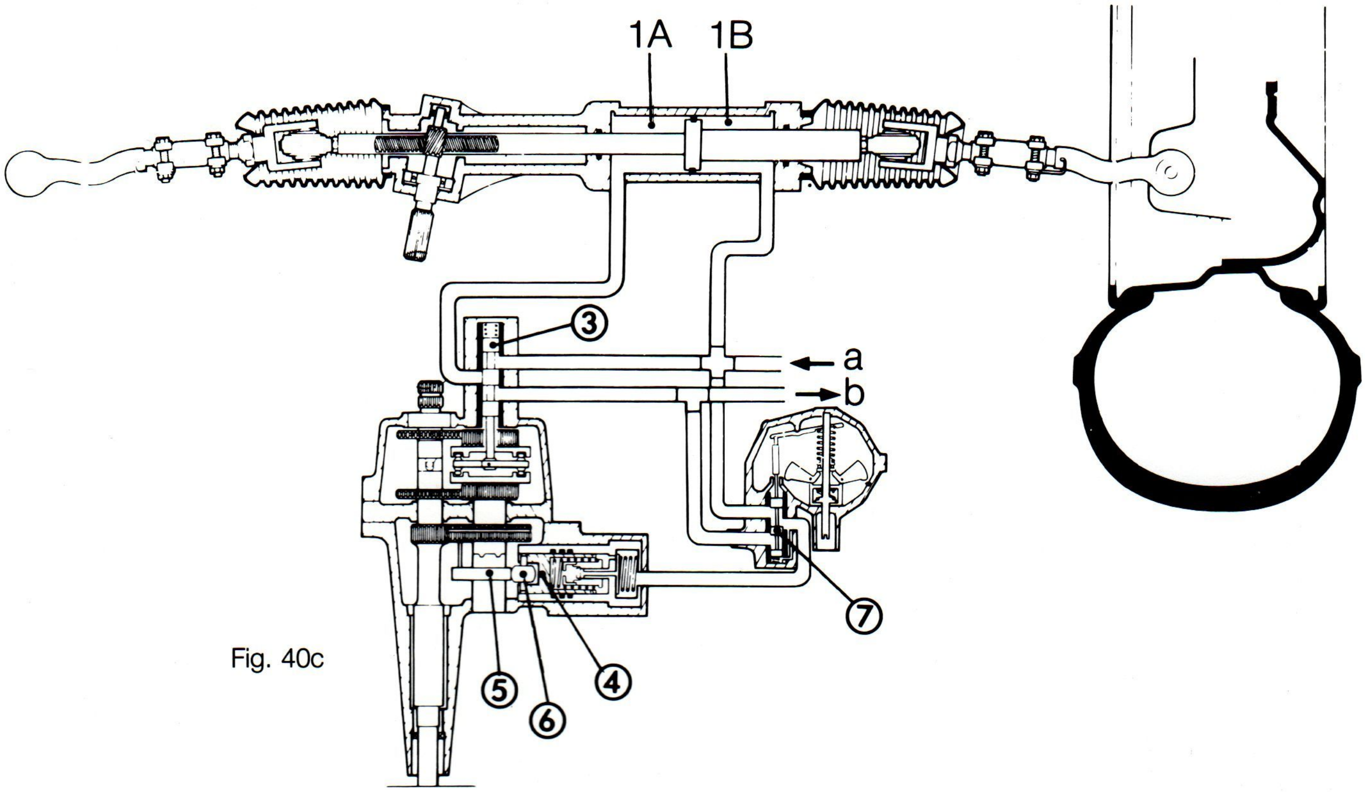


Fig. 40c

c) Neutral position at 40 km/h (25 mph)
a. High pressure inlet
b. Return to reservoir
1. Chamber A
2. Chamber B
3. Slide valve T1
4. Self centring piston
5. Cam
6. Roller
7. Slide valve T2

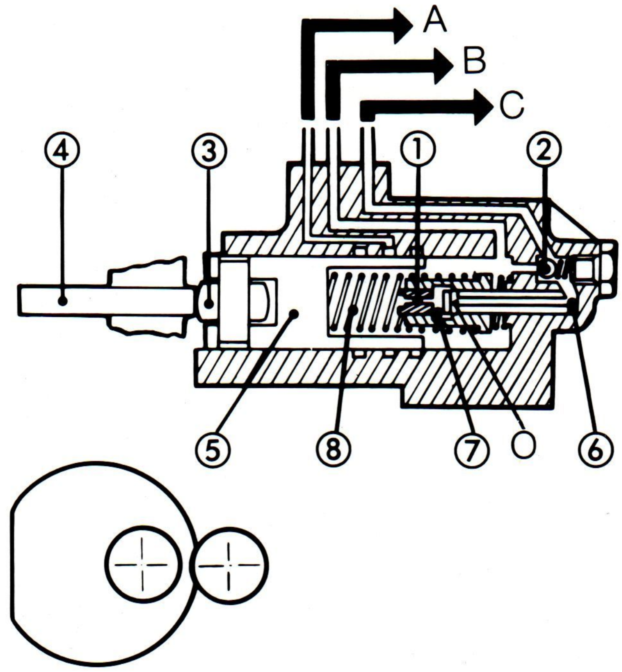


Fig. 41 : Automatic self-centring (description)
A. Leakage return
B. Purge valve
C. Centrifugal regulator
0. Calibrated orifice
1. Spray
2. Valve
3. Roller
4. Cam
5. Self-centring piston
6. Chamber A
7. Chamber B
8. Chamber C

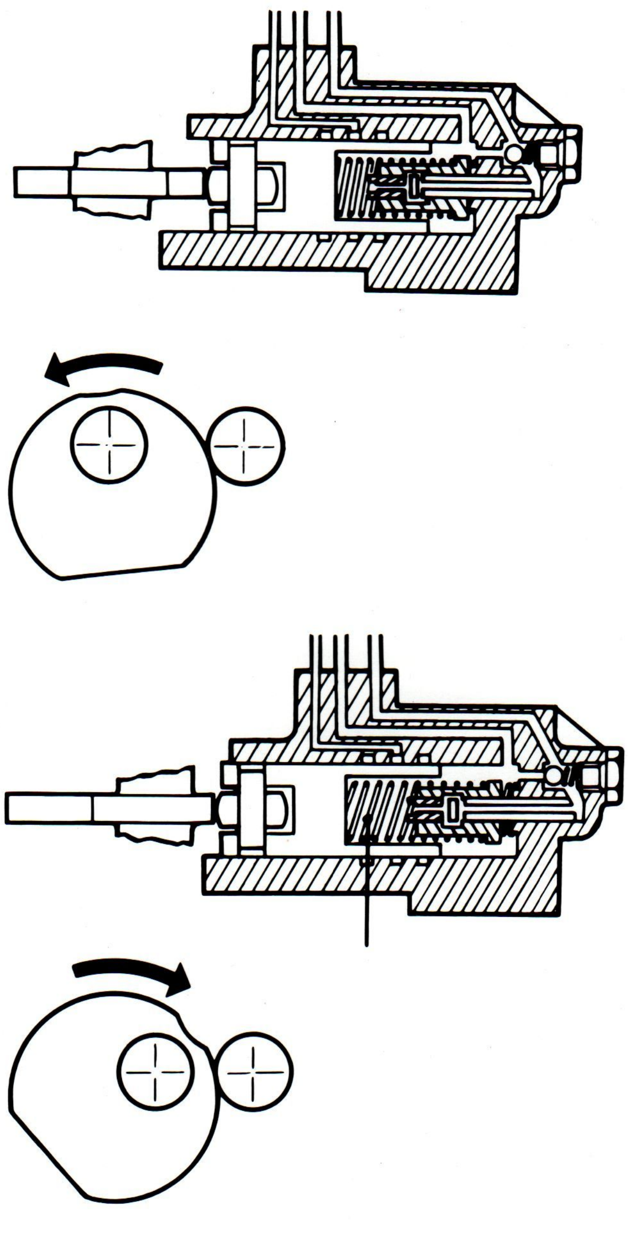


Fig. 42 : Automatic self-centring (operation)