Temperature Compensation with Thermovariable Rate Springs in Automatic Transmissions

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Temperature Compensation with Thermovariable Rate Springs in Automatic Transmissions

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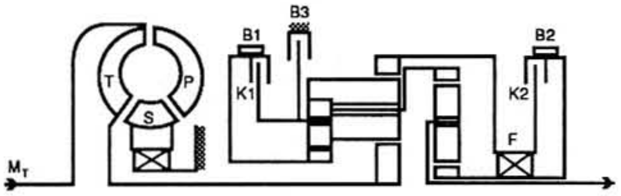
ABSTRACT

The shifting comfort of automatic transmissions of diesel engines at low temperatures can be substantially improved by using springs with temperature dependent rates in the control valves. These springs utilize the shape memory effect of Ni-Ti alloys. They provide a simple and economic way to control both shifting pressure and shifting time. The Mercedes- Benz automatic transmission uses two different springs with thermovariable rate (TVR) in the shifting pressure system to adapt the pressure in the switching elements to the lower torque of cold diesel engines. One spring is used in the shifting pressure control valve and one in the accumulator system.

INTRODUCTION

In the Mercedes-Benz 4-speed automatic transmissions W4A040 and W4A020 a total of 5 shifting elements are involved in the shifting processes (see Fig. 1). To engage a gear, two shifting elements each must be involved. Shifting up and shifting down is achieved by engaging one of these shifting elements and disengaging another one.

The quality of upshifting depends strongly on the pressure build-up in the shifting element engaging. This shifting pressure is adapted to the condition of the engine at operating temperature. Therefore, a number of problems arise for hydraulic transmission control during cold starting of the engine. Low temperatures cause an increase in oil viscosity, in friction coefficients of the shifting elements and in the preload of the springs in the control valves. Another problem is the fact that engines deliver less torque in cold conditions versus warm conditions. Since the mean shifting pressure changes only slightly at differing transmission oil temperatures, it is too high for the small torque of cold engines. In conjunction with the increased friction coefficients, this results in a reduction of the shifting times and leads to rough, uncomfortable gear changes.



GEAR	K1	K2	B1	B2	B3	F
1		●		●		●
2			●	●		
3	●			●		
4	●	●				
R		●			●	●

Fig. 1: Schematic of automatic transmissions W4A020 and W4A040

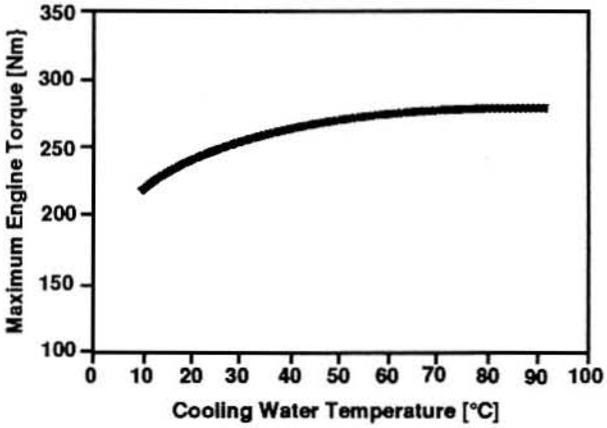


Fig. 2: Diesel engine torque vs. temperature

This temperature dependent torque change is particularly distinct in diesel engines (Fig.2). For this reason, controlling the automatic transmission requires an adaptation of the shifting times to the temperature conditions. As the temperature of the engine and the transmission increases largely identical, an adaptation can be achieved by applying a lower shifting pressure at low transmission oil temperatures compared with normal operating conditions.

There are several methods of influencing controlled oil pressure as a function of temperature directly at the hydraulic control unit:

a) by the temperature-related increase of a piston area acting upon the control valve (Pat. US-PS 30 51 194).
b) with the help of an additional bimetallic actuator acting upon the control valve (Pat. DE-OS 20 17 238).
c) by utilizing the thermal elongation of a plastic pin, in order to increase the preload of a spring in the control unit (Pat. DE 31 09 431 C2).
d) by using an electrohydraulic solenoid valve which is actuated in a temperature-dependent way.

All these methods have several disadvantages. The most serious ones are:

- small effect on controlled pressure (a, c)
- bulky; therefore limited usability for hydraulic control plates(b, c, d)
- considerable design effort necessary to implement the solutions (a, d)
- calibration at operating temperature necessary; i.e. element must be accessible from outside (b)
- expensive solution (d)

These disadvantages prompted us to search for an alternative to the above mentioned methods. An innovative approach is the use of springs with temperature dependent rates in the control valves. This unusual behavior can be found in springs made from Ni-Ti shape memory alloys.

Ni-Ti THERMOVARIABLE RATE SPRINGS

The rate of a spring is directly proportional to the shear modulus of the spring material. In conventional materials the shear modulus is not a strong function of temperature. Therefore, the spring rate and thus the performance of the spring is basically temperature independent. Certain materials, however, exhibit a rather dramatic change in shear modulus within the operating temperature range. Springs made from these materials, accordingly, show a pronounced change in their spring rate with changing temperature (1)*.

The change in modulus with temperature is the result of a solid state phase transformation, commonly known as thermoelastic martensitic transformation. It is the basis for the so-called shape memory effect, the ability of certain materials to "remember" a previous shape even after deformation. Thermo-variable rate springs are, in fact, shape memory springs.

The most important alloys showing this particular martensitic transformation are Ni-Ti alloys. They are the standard shape memory alloys and have been used for a variety of

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* Numbers in parentheses designate references at end of paper.

applications for approximately 20 years.

THERMOELASTIC MARTENSITIC TRANSFORMATION IN Ni-Ti ALLOYS. Above a certain transformation temperature the crystalline structure of Ni-Ti alloys is "body centered cubic" with a very specific arrangement of the nickel and titanium atoms. In this condition, the alloys are "austenitic". Cooling below the transformation temperature converts the material into the "martensitic" state. This transformation is diffusionless, i.e. the atoms do not change their locations relative to each other in the lattice. The martensitic structure is a zigzag or harmonica-type arrangement of the lattice planes, called "twinned structure". There is no macroscopic shape change that accompanies the transformation from austenite to martensite. The transformation is reversible, i.e. heating above the transformation temperature will convert the martensite into austenite (2).

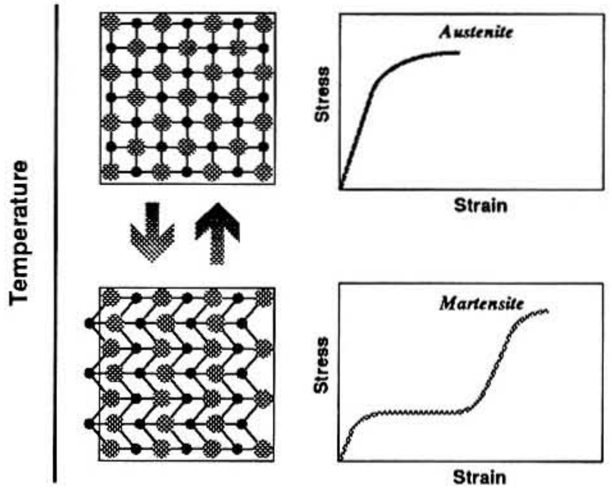


Fig. 3: Martensitic transformation and tensile behavior of Ni-Ti alloys

The mechanical properties of the austenite and the martensite state of Ni-Ti alloys are quite different. As shown in Fig. 3, the austenitic curve looks like that of a "normal" material. However, the martensitic one is quite unusual. On exceeding a first yield point, several percent strain can be accumulated with only little stress increase. After that, stress increases rapidly with further deformation. The deformation in the "plateau region" is non-conventional in nature. Deformation occurs by reorientation of the twins to form a parallel register, which is essentially complete at the end of the plateau (after approx. 8% strain). This process is also called "detwinning". It is fundamentally different from the conventional deformation by gliding, and can be recovered thermally, i.e. heating above the transformation temperature will restore the original shape. Deformation exceeding the second yield point cannot be recovered. At this point, the material is plastically deformed in a conventional way.

DESIGN OF THERMO-VARIABLE RATE SPRINGS - The most important material property determining the performance of a spring is the shear modulus. In Ni-Ti alloys the shear modulus changes almost an order of magnitude over a rather narrow temperature range, increasing from low to high temperature. This produces an increase in spring rate, since spring rate R is directly proportional to the shear modulus G (3):

$$R=\frac{Gd^4}{8nD^3} \tag{1}$$

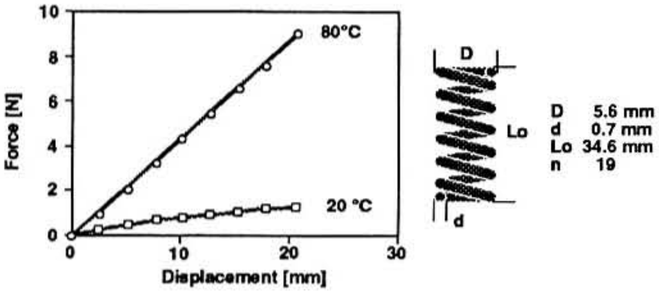


Fig. 4: Spring rate change with temperature of a Ni-Ti TVR spring

Consequently, Thermovariable Rate, or TVR, springs have a low spring rate below the transition temperature of the Ni-Ti alloy and a high spring rate above this temperature. Fig. 4 shows the force/deflection characteristics of a Ni-Ti TVR spring at room temperature and at 80°C.

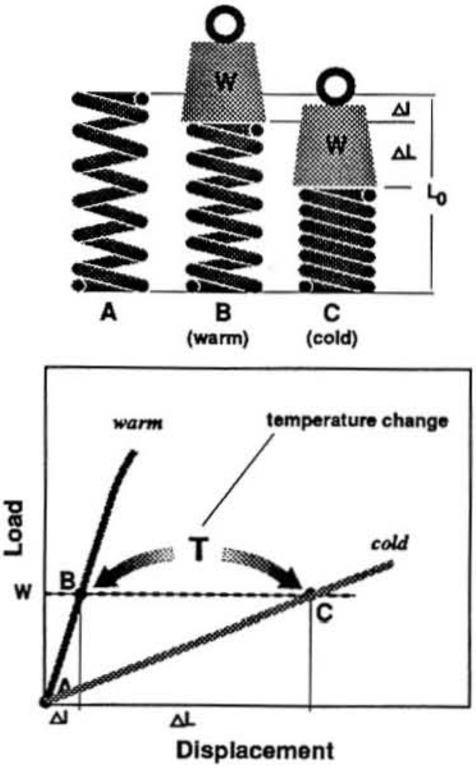


Fig. 5: TVR spring response to a constant load

The design of TVR springs is based on the different stress/strain curves of the austenite and the martensite, and the corresponding spring rates. As an example, Figure 5 shows the force/deflection curves of a helical compression spring at high and low temperature. The high temperature shape of the spring with no load is Lo (A). If the spring is loaded with a constant load W in the austenitic condition (warm) the spring is compressed along A - B with the displacement Δl (B). Upon cooling below the transition temperature, the spring converts into martensite (cold). Now the load W compresses the spring to point C on the martensite curve with the displacement ΔL. Repeated heating/cooling cycles will then move the displacement between points B and C.

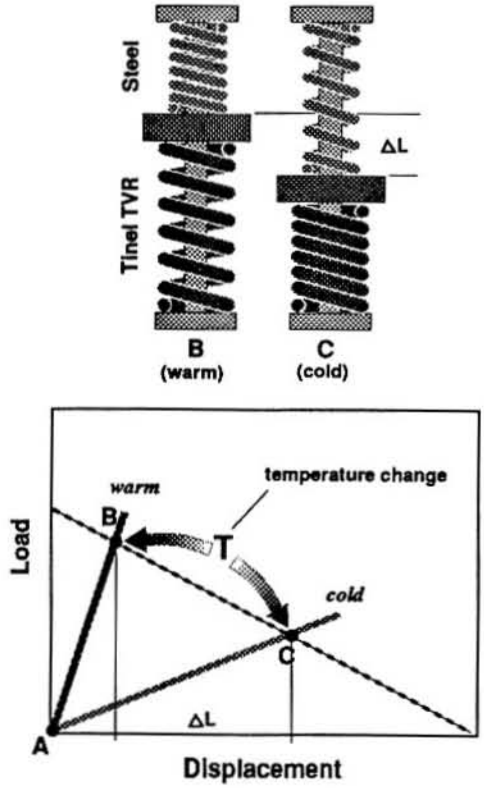


Fig. 6: TVR spring response to a biasing spring

If, instead of a constant load, a steel biasing spring is used, the force/deflection curve for this spring has to be superimposed to the austenitic and martensitic spring characteristics of the Ni-Ti spring. This is shown in Figure 6. A Ni-Ti TVR compression spring works against a steel biasing spring. At high temperatures (in the austenitic condition) the Ni-Ti spring is strong enough to compress the steel spring. However, at low temperatures (in the martensitic condition) the steel spring is able to compress the Ni-Ti spring. Again, repeated heating and cooling cycles between points B and C (4).

TRANSITION TEMPERATURES AND HYSTERESIS - As can be seen from Fig. 7, the transformation and thus the spring rate change does not occur at the same temperature on heating and cooling. An important characteristic of the effect is the temperature *hysteresis*. Standard Ni-Ti alloys show a hysteresis of 30 to 50°C. Through alloy modifications, however, it is possible to either reduce the hysteresis to about 10 to 15°C (narrow hysteresis alloys), or extend it to over 100°C (wide hysteresis alloys).The hysteresis loop is described by the transformation temperatures As, Af and Ms, Mf (*Austenite Start, Austenite Finish, Martensite Start, Martensite Finish*). Transformation temperatures can be altered between approximately -100°C and +100°C by changing the alloy composition.

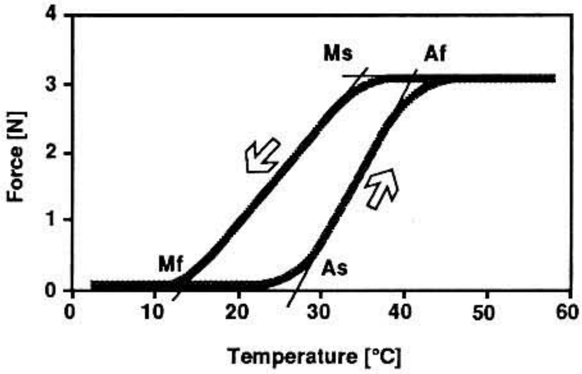


Figure 7: Force/temperature hystresis of a Ni-Ti TVR compression spring constrained to a certain length

TVR SPRINGS FOR HYDRAULIC CONTROL VALVES - TVR springs have a number of advantages for use as actuators in hydraulic control plates:

- The shape and function of the actuator can be adapted to meet the relevant requirements, e.g. as Belleville disc spring, wave spring, extension or compression spring.
- Due to the geometrical configuration of helical TVR springs, no or only minor changes of the hydraulic control plate are necessary. As a consequence, only very little additional effort is required for production and assembly of the control plate.
- In the high rate condition the TVR spring actuators can generate accurately defined forces with small tolerances.
- The transition temperature can be freely selected to a certain extent by alloy selection and processing. Thus, the desired temperature related effect can be matched individually to the requirements of the relevant application.
- TVR spring actuators do not have to be calibrated (5).

In the following section, the use of Ni-Ti TVR compression springs for temperature compensation of shifting pressures in automatic transmissions of diesel engines is described. These springs can be compressed with little force when they are "cold". They stay almost compressed even after removing the load. Upon heating above their transition temperature they remember their original length and return to this shape if unconstrained. If the spring is prevented from recovering to its original shape, e.g. by constraining it in a governor valve between the housing and a control piston with defined control position, a corresponding stress or force is generated in the spring. This force can be used to control a higher pressure. The influence of temperature on spring force has been shown in Figure 7.

In the applications described below, Ni-Ti TVR compression springs directly affect the control of hydraulic pressures. These pressures must be maintained extremely accurately. Therefore, the springs must meet stringent requirements:

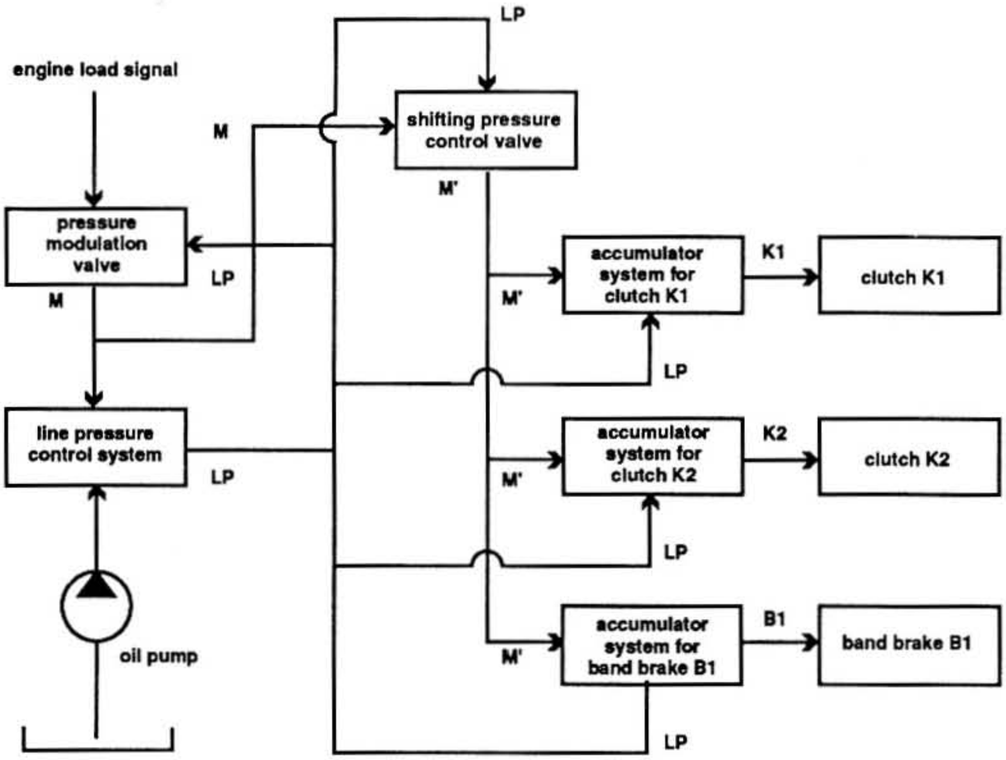
- the force must stay within a tolerance of only ±5% of the nominal force in the austenitic condition at control length even after 20,000 thermal cycles.
- the springs must be able to perform at least

10^7 mechanical cycles without failure
- they must be insensitive to automatic transmission fluid.

THE SHIFTING PRESSURE SYSTEM

The band brake B1 and the clutches K1 and K2 of the automatic transmissions W4A020 and W4A040 are the main components involved in upshifting. The pressure variations in these switching elements during a gear change is controlled by the shifting pressure system. This is a purely hydraulic control system. Figure 8 shows a functional flow diagram and the actions for controlling the shifting pressures of the individual shifting elements.

The pressure modulation valve serves as an interface between the engine and the hydraulic control plate of the automatic transmission. It converts the load signal of the engine to a pressure M which is proportional to the load. In the hydraulic control plate this pressure is transfered to two independent control systems: the main pressure system and the shifting pressure system. In the main pressure system, it is used to adapt the controlled pressure LP to the respective engine torque provided. In the shifting pressure system, it controls the shifting pressure control valve. This valve produces from the line pressure the pressure M' derived from pressure M. Pressure M' serves as hydraulic engine load signal for the accumulator systems K1, K2 and B1. These accumulator systems control the



M: load dependent pressure
M': load dependent pressure
LP: line pressure
K1, K2, B1: pressure applied to shifting element

Fig. 8: Functional flow diagram for the shifting pressure control system

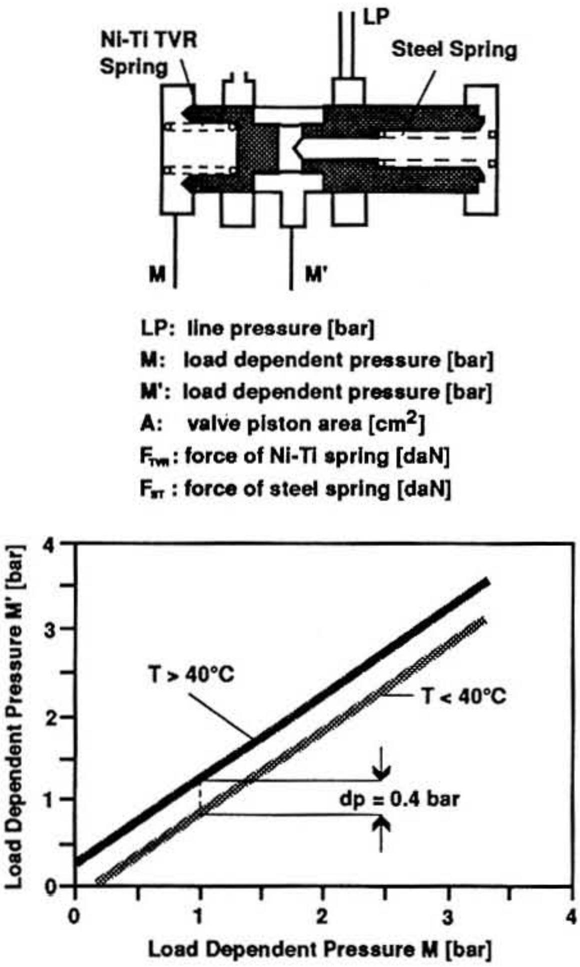
actual pressure development in the switching elements during the gear change.

To adapt the pressure in the switching elements to the lower torque of cold diesel engines, two different TVR compression springs are used in the shifting pressure system; one in the shifting pressure control valve and one in the accumulator system B1. Both springs exert different forces in the austenitic phase and, furthermore, have different transformation temperatures.

THE SHIFTING PRESSURE CONTROL VALVE - The TVR spring in the shifting pressure control valve reduces the pressure M' when the transmission oil temperature is below 40°C. Since the pressure M' influences all accumulator systems, a temperature compensation at this point effects all upshifting operations.

The design and function of the shifting pressure control valve is shown in Figure 9. It consists of a control piston and two springs, i.e. one conventional steel biasing spring and one Ni-Ti TVR spring. The springs are located opposite each other, with the piston between them. In the controlled condition, the piston will remain at a constant position relative to the housing. The controlled pressure M' is determined by the piston face area, the load dependent pressure M and the differential of the two spring forces.

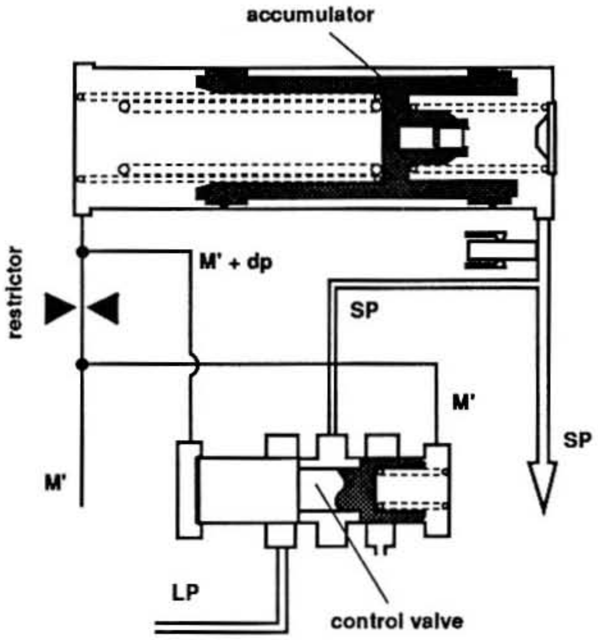
At low oil temperatures the TVR spring is in the martensitic phase. Thus, only the steel spring exerts a force on the valve piston.The pressure M' is controlled as a function of the pressure M, reduced by the amount of the steel spring force. As soon as the oil temperature exceeds the transformation point of the Ni-Ti TVR spring, it attempts to recover to its original shape. Since its expansion is prevented by the control position of the valve piston, it will generate a force. This force adds to the pressure M on the valve piston. The shifting pressure control valve will thus be caused to control a higher pressure M'.



$$M' = \frac{M \times A + (F_{TVR} - F_{ST})}{A} \qquad (2)$$

Fig. 9: Function of the shifting pressure control valve

THE EFFECT OF THE PRESSURE M' ON THE ACCUMULATOR SYSTEM - The accumulator systems K1, K2 and B1 all operate according to the same principle and are of the same design. They consist of an accumulator with springs, a control valve and a restrictor. At one side the accumulator is connected to shifting pressure M', and at the other side to the charging line leading to the respective shifting element. The restrictor is in the feed line of pressure M'. The pressures in front and behind the restrictor act on the face areas of the control valve (Fig. 10).



LP: line pressure [bar]
M': load dependent pressure [bar]
SP: pressure in shifting element [bar]

$$t_{acc} = 0.06 \times \frac{V_{acc}}{Q_{acc}} \quad (3)$$

$$dp = \frac{F_{cv}}{A_{cv}} \quad (4)$$

$$SP = \frac{A_{acc}(M' + dp) + F_{acc}}{A_{acc}} \quad (5)$$

Aacc: area of accumulator [cm^2]
Acv: area of control valve [cm^2]
Vacc: volume of accumulator [cm^3]
Qacc: oil flow in orifice [l/min]
Facc: force of accumulator springs [daN]
tacc: accumulator running time [sec]
Fcv: force of valve spring [daN]
dp: differential pressure in orifice [bar]

Fig. 10: Design and function of the accumulator systems K1, K2 and B1

If in the case of a gear change, the line pressure is directed to the shifting element, the accumulator is pushed against the springs. Due to the movement of the accumulator, oil is displaced which then drains through the restrictor. This produces a pressure differential which causes the control valve to turn to control position. It limits the oil flow to the shifting element and reduces the running speed of the accumulator. This causes a time delay for the pressure build-up in the shifting element.

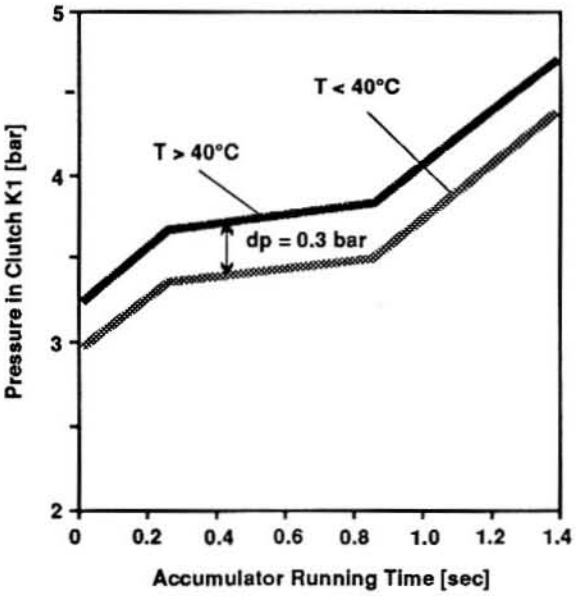
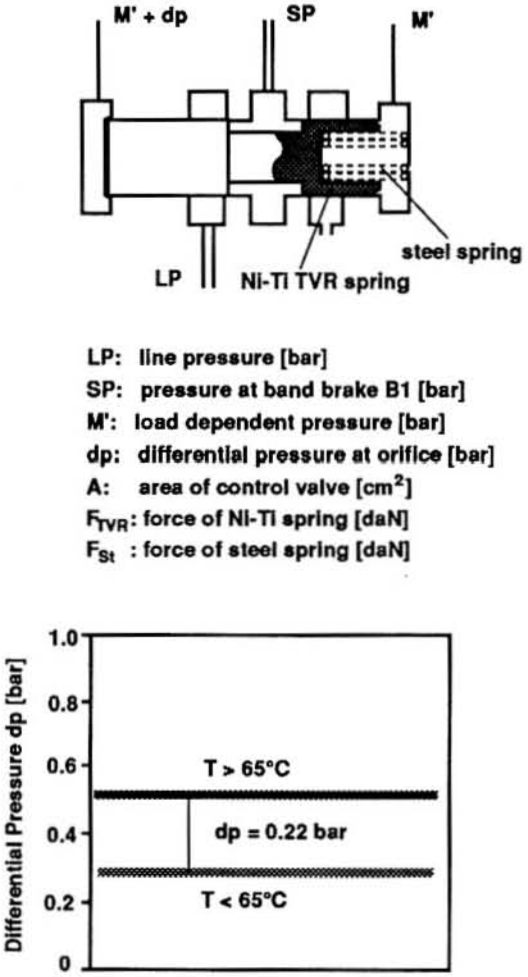


Fig. 11: Clutch pressure K1 at different oil temperatures vs.time

The response pressure of the control valve depends on the face area of its piston and the force of its spring. The running time of the accumulator is therefore constant, independent of the pressure in the shifting element. As long as the accumulator moves, the pressure build-up is determined by the accumulator springs, the pressure differential at the restrictor and the shifting pressure M'. Figure 11 shows the influence of the temperature compensation of the pressure M' on the pressure build-up in a shifting element, in the case of clutch K1.

THE ACCUMULATOR SYSTEM B1 - The band brake B1 is more sensitive to temperature dependent fluctuations of the friction coefficient than the clutches K1 and K2. Due to the large change in gear ratio occurring during 1-2 upshifting, incorrect shifting pressure levels particularly affect the shifting comfort. For this reason another Ni-Ti TVR spring has been integrated in the B1 accumulator system. Its purpose is to cause a further pressure drop at the B1 band brake, if the transmission oil temperature is below 65°C.



$$dp = \frac{F_{TVR} + F_{St}}{A} \quad (6)$$

Fig. 12: Design and function of the B1 band brake accumulator system control valve

The TVR compression spring is arranged parallel to a steel spring in the control valve of the B1 accumulator system (Figure 12). At low transmission oil temperatures, only the steel spring exerts a force on the control valve piston. After the transformation temperature of the TVR spring is exceeded, both springs will jointly generate a higher force. Thus the control valve only responds to a larger pressure drop at the restrictor of the accumulator system. A larger pressure drop means that more oil flows through the restrictor and the accumulator moves faster. Its running time will thus be shorter. Figure 13 shows a photograph of the valve plate with cut-away sections of the control valves using the Ni-Ti TVR springs.

The influence of the two TVR springs installed in the shifting pressure system on the pressure build-up in the B1 band brake is shown in Figure 14. The increase in the accumulator running time indirectly causes a pressure reduction in the shifting element during this period of time. The decrease of pressure M' further reduces shifting pressure B1.

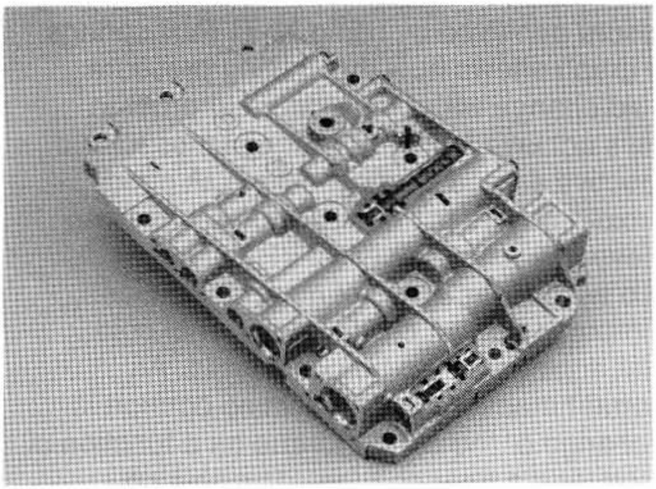


Fig. 13: Valve plate of the Mercedes-Benz automatic transmission

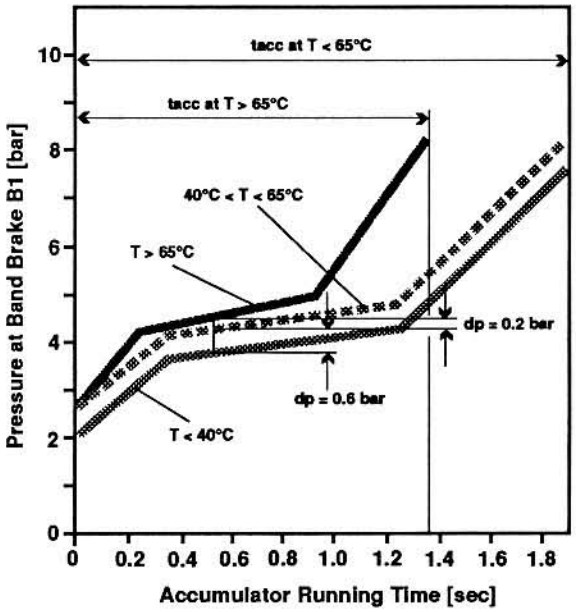


Fig. 14: Pressure at band brake B1 vs. time at different oil temperatures

THE INFLUENCE OF TEMPERATURE COMPENSATION ON THE SHIFTING COMFORT

By using Ni-Ti TVR springs in the control valves it is possible to adapt the shifting times to the temperature conditions by lowering the shifting pressure.

Figure 15 shows a comparison of the desired mean shifting pressure and the shifting pressure achieved by using Ni-Ti TVR springs. The graph shows how the shifting pressure should change with temperature in order to always achieve constant shifting times for the respective engine load conditions. A good approximation to the desired curve has been achieved by using the two TVR springs.

To assess the value of the modifications, the improvement in shifting comfort of cold diesel engines has to be considered. An important measure for the shifting comfort is the change of the output torque as a function of time during a gear change. The shifting comfort improves with a smoother transition from output torque before to output torque after the gearshift.

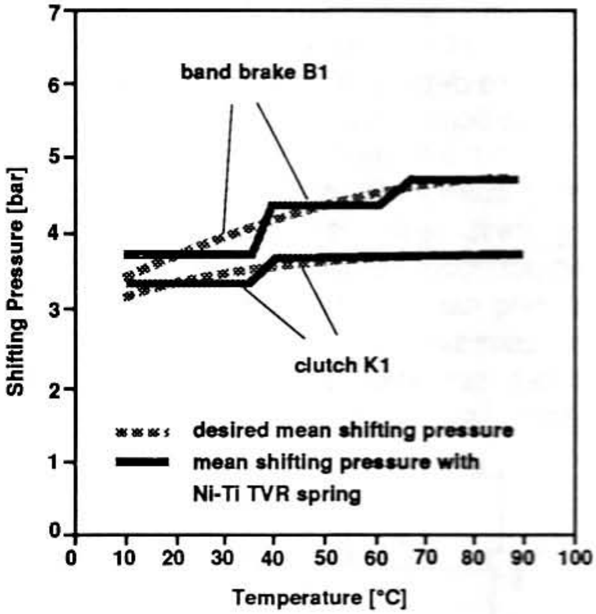


Fig. 15: Shifting pressure at clutch K1 and band brake B1

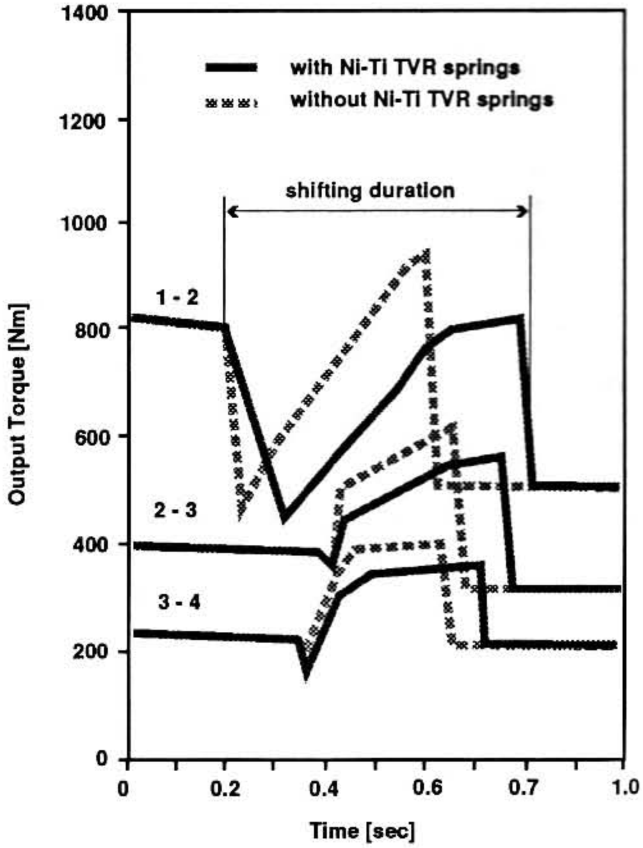


Fig. 16: Output torque during upshifting at low temperatures

Figure 16 shows the effect of the introduction of the TVR springs on the course of the output torque for the 1-2, 2-3 and 3-4 upshifts under full-load conditions. It is a comparison of the output torques of cold diesel engines with and without TVR springs. It is obvious that the output torque changes during the shifting process are smaller with the presented improvement measure than without this measure. In addition, gear changes take considerably longer. Both effects impact the shifting comfort in a positive sense.

CONCLUSION

The shifting comfort of automatic transmissions of diesel engines at low temperatures can be substantially improved by using springs with temperature dependent rates in the control valves. These springs utilize the shape memory effect of Ni-Ti alloys. They provide a simple and economic way to control the shifting pressure and shifting time. Ni-Ti thermovariable rate springs (TVR springs) are soft at low and stiff at high temperature. In control valves they allow the shifting pressure to be reduced during cold start and increased to normal levels when the engine and transmission reach operating temperature.

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NOMENCLATURE

A	valve piston area [cm2]
Aacc	area of accumulator [cm2]
Acv	area of control valve [cm2]
Af	Austenite finish temperature
As	Austenite start temperature
d	spring wire diameter [mm]
D	spring mean diameter [mm]
dp	differential pressure [bar]
Facc	force of accumulator spring [daN]
Fcv	force of valve spring [daN]
FST	force of steel spring [daN]
FTVR	force of Ni-Ti spring [daN]
G	shear modulus [MPa]
Lo	free length of compression spring [mm]
LP	line pressure [bar]
M	load dependent pressure [bar]
M'	load dependent pressure [bar]
Mf	Martensite finish temperature [°C]
Ms	Martensite start temperature [°C]
n	number of coils in spring
R	spring rate [N/mm]
SP	pressure at band brake [bar]