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ABSTRACT

A new visco transmission has been incorporated in the powertrain of an all-wheel-drive vehicle. The torque characteristic, specially the torque progression of the visco coupling (called "humping") is discussed. The influence of the silicone oil on the shear behavior is elaborated. Some aspects of drive dynamics affected by the visco transmission are added.

1. INTRODUCTION

The majority of motor vehicles on the road today have only one driven axle.

This is perfectly sufficient for many driving situations. For special situations, however, such as winter driving in the mountains, off-road driving and in countries with inadequate road systems, all-wheel drive is an advantage. This is why in recent years it has been increasingly applied to almost all types of vehicles.

The aim is a drive system which, ideally without the intervention of the driver, improves traction and also cornering dynamics whenever this is required by the frictional conditions.

This objective is achieved by an axial hydraulic coupling - referred to in the following as "visco coupling" - in the drive train of an all-wheel-drive vehicle.

This operationally quite unusual component, which is very much a newcomer when being used as a transmission member in the field of automobile drive engineering, confronted me and my colleagues with so many questions in the course of the advance development of a new passenger-car all-wheel-drive system that it was a challenge to penetrate into the research of the hydrodynamic transfer mechanism of the visco coupling. A major role was also played in this connection by the compilation of the chemical-physical properties of the silicone oil used in the coupling. As the result of this work, an interpretation of the peculiar torque characteristics of the visco coupling is presented and its impact on the driving dynamics of an all-wheel-drive vehicle is described.

1.1 STATE OF THE ART OF ALL-WHEEL-DRIVE SYSTEMS

All-wheel drives for motor vehicles have been known virtually since the inception of the automobile - and that was almost 100 years ago.

During the early days of the automobile, when the roads were still shaped by the requirements of horse-drawn traffic, the "rolling" automobiles had a difficult time of it, because the traction capability of the four-legged competition was inherently better on unpaved roads than of the wheel-driven motor vehicles.

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With the improvement of the roads for automobiles and provision of asphalt or concrete surfaces as standard procedure, all-wheel drive lost its primary raison d'être. Merely in winter in mountainous regions and under off-road conditions was there and still is there a need for all-wheel-drive vehicles.

Recently in third-world countries the already existing paved road systems have in some cases been returning to the original state of the dirt-track roads. Accordingly, the need for all-wheel-drive vehicles will again rise in these countries.

In quite general terms, however, experience in Europe and North America, particularly in winter, has been so positive that all-wheel drive is becoming more and more established, even in smaller vehicles.

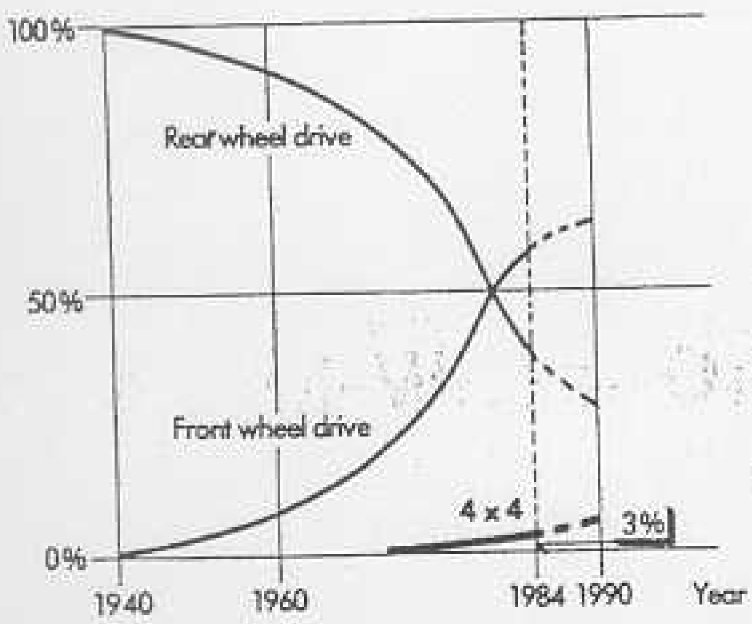

Fig. 1 Trends of rear-axle, front-axle and all-wheel drives in Germany

The electrical systems known from the pioneer days with wheel-hub motors (Lohner/Porsche system) and also hydraulic drives remain, however, the reserve of special-purpose vehicles and are of no significance on the whole.

Mechanical drive trains predominate in present-day road vehicles.

1.1.1 Selectable all-wheel-drive systems - The selectable system can be regarded as the standard. The auxiliary driven axle is engaged usually by means of a lever or pull-knob (sometimes with servomotor). In this case, the driver is the operator, the one who determines when two or when four wheels are to be driven.

Therein lies the first detectable weakness of such systems. Usually, the second axle is engaged too late, namely after the vehicle, powered by one axle only, has already become stuck (off-road).

Conversely, the system may also be maloperated if, for example, on a good road the vehicle is constantly driven with the second axle engaged where this is totally unnecessary. This then increases the tractive resistances as a result of the distortions that occur when cornering in systems without a center differential. Furthermore, in the event of fluctuations in the friction coefficient, adhesion may be lost and the vehicle may thus lose in cornering stiffness. There may be problems in tight curves. Many manufacturers of such simple systems have therefore drastically limited the maximum speed for all-wheel-drive operation.

1.1.2 Permanent systems - Permanently engaged systems are at a higher level. They have a mechanical center differential (spur- or bevel-gear differential) between the axles in the drive train. The permanent systems with mechanical center differentials (e.g. Audi Quattro) have a fixed drive-power distribution, e.g. 50/50 % for the bevel-gear differential or approx. 40/60 % for planetary-gear differentials.

In either case, the distribution is not optimal for all driving situations.

In addition, such mechanical differentials require a mechanical or visco-elastic locking device, which, in difficult driving conditions, guarantees traction even when adhesion is lost at one axle or also at one wheel.

Instead of this, the new permanent system described below has a visco coupling which assumes the function of the differential and, furthermore, provides slip-controlled (demand-sensitive) transitionless engagement.

The slip-controlled system with the visco coupling has variable drive-power distribution, which offers some advantages in vehicle operation with regard to driving safety:

1. The system engages automatically and progressively it is always at the ready and is present with both axles virtually whenever moving off.
2. There is scarcely a change in handling characteristics as compared with the basic model (with single-axle drive); the driver does not therefore have to become accustomed to the new system.
3. Maloperation is impossible since there is nothing for the driver to operate.
4. The drive-dynamic cornering performance is neutralized (as a function of slip). Front-drive vehicles show less tendency to understeer; the tendency of rear-drive vehicles to oversteer is reduced.
5. The stopping distances are slightly shorter than with single-axle drive.
6. Overstressing of the drive train is prevented.
7. Vibrations in the drive train are damped by the silicone fluid.

2. VISCO COUPLING

2.1 CONSTRUCTION AND OPERATING PRINCIPLE - The visco coupling consists of a drum-shaped housing which is enclosed on all sides. Inside it are two independent, perforated and slotted steel-plate packs, of which one is splined to a shaft end driven by the propeller shaft. Of these drive plates, the second plate pack is driven by a viscous silicone oil, whereby these plates drive the outer drum, likewise by means of a splined connection. The outer drum is rigidly connected to the pinion shaft of the rear-axle drive.

The visco coupling is thus of similar construction to a multi-plate axial clutch. In contrast to such clutches, however, the visco coupling does not have a disengaging device. The plates are free to move in the housing and on the shaft and are slightly spaced apart; power is transmitted mainly through the silicone oil by its resistance to shear.

Couplings of this type have the characteristic that, with very small differences in rotational speed, they allow a slight slip between input and output, but "stiffen" as the difference in rotational speed increases - which, with further increasing shearing forces, results virtually in a friction-type drive. The friction heat generated in the silicone oil during shearing leads to the expansion of the fluid, which results in a rise in pressure in the housing.

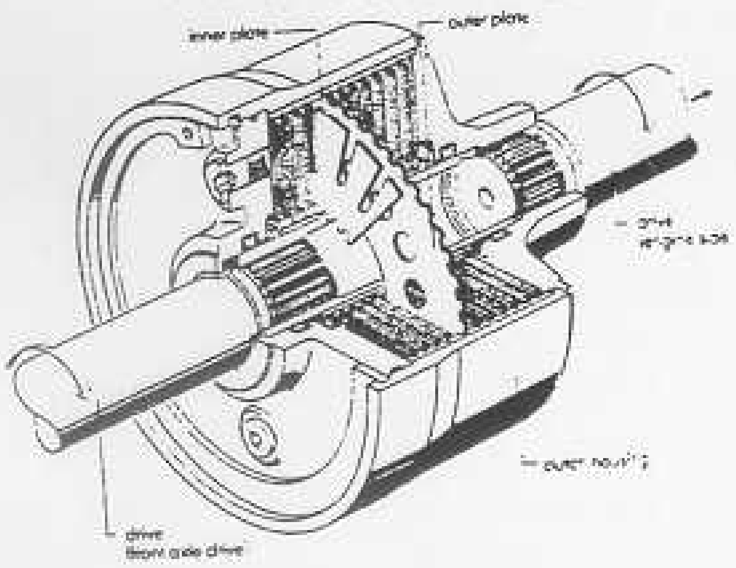

Fig. 2 Construction of visco coupling

To prevent excessive pressures in the hermetically sealed coupling housing, a small air bubble is included. This controls the extent of the pressure rise, which also influences the torque characteristics of the coupling. Through further effects occurring, among other things, at the molecular level of the silicone oil it is possible for the transmitted torque to increase to such an extent that one may speak almost of a rigid lock-up. This is then where a self-regulating effect occurs. Since, in this condition, there is virtually no longer any relative motion between the plates, the temperature falls again, thereby reducing the pressure; both temperature and pressure finally settle at a certain level according to the instantaneous tractive effort.

2.2 FLUID - High-viscosity silicone oil is used for visco couplings because, in contrast to mineral oil, the viscosity of silicone oil falls to a lesser degree with rising temperature, and, furthermore, the fluid remains stable even at very high temperatures. Although it is known that siloxanes do not have any marked lubricating properties, particularly not between steel/ steel, precisely this fact appears in the present arrangement to guarantee the desired torque progression (hump). The siloxane fill is regarded as a life-long fill. Silicone oils will be discussed in further detail in Section 3.

2.3 PLATES - The plate pack also has a decisive influence on the ability of the visco coupling to transmit forces and torques. Both the thickness and thus the number of the plates as well as their surface quality have an effect on the shear behavior. Their diameter is also a major factor. (The torque is proportional to the 4th power of the effective radius).

The thickness of the plates tested varied between 0.25 and 0.9 mm. the plates are provided with slots and holes which, shaped by empirical means, promote the torque and shear behavior and the shape stability.

2.4 WEAR - The latest test results from the endurance-run test bench revealed quite different wear patterns on the surfaces of the plates.

Whereas one mating-surface pair of two neighboring plates shows clear signs of smoothing, no wear at all is detectable on the surfaces of the next immediately adjacent pair. The appearance of the surfaces is as when installed, namely virtually as new. This phenomenon applies alternately to the entire set of plates. (However, with some exceptions: Two or more adjacent pairs were also found to have no signs of wear, just as two or more adjacent pairs were found with wear marks.)

2.5 SEALS - Since pressures of up to 100 bar may occur in extreme operation, high demands are placed on the shaft seals, especially as silicone oils have exceptionally high creepability, i.e. they tend to creep through the narrowest of gaps even when under no pressure. This results in tightly fitted seals which consequently produce a basic friction of up to 30 Nm.

3. SILICONES

Silicones are silicone compounds which may be combined, firstly, with oxygen and, secondly, with organo-groups (R - methyl or phenyl end groups).

The designation "silioxanes" is in fact better and more appropriately describes the Si-O-Si structure with corresponding end groups).

1. Silicones are polymeric and in many cases form organic macromolecules (chains) of helical shape, whereby the organo-ends with the Si cores form tetrahedrons which are linked together by the oxygen molecules.

2. They represent silicon-oxygen compounds, related to silicic acids and silicates (i.e. also similar to amorphous glass).

3. They contain hydrocarbon residues which are a part of silicon-organic chemistry.

The molecular weight depends on the number of n connecting members and thus also determines the viscosity. Even long chains with more than 2000 connecting members are still liquid at room temperature.

3.1 VISCOSITY - One of the most typical properties of liquids is their low resistance to shearing. They start to flow even when subjected to low shearing forces.

Conversely, however, certain liquids are perfectly able also to exhibit elastic properties if the load is applied quickly enough. These properties of the second order, the basic principles of which have not yet been entirely explained, will, among other things, be used to explain the (so strange) "humping" of the visco coupling.

3.2 TEMPERATURE BEHAVIOR - The viscosity of silicone oils is, like that of all other liquids, dependent on temperature. However, compared with mineral oils, the influence of temperature is clearly lower. Fig. 6 shows the relationship between viscosity and temperature (Wacker-Chemie). Shown by the broken lines for purposes of comparison are two mineral oils which exhibit a relatively great decline.

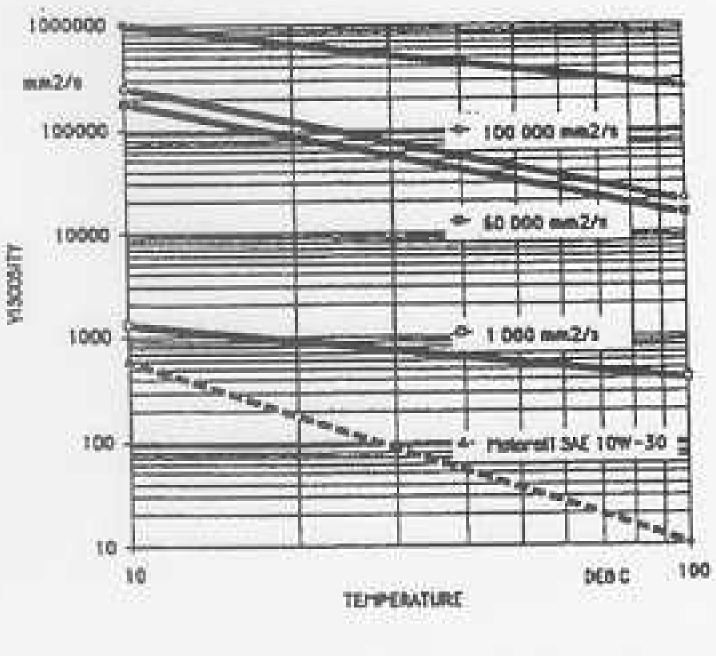

Fig. 3 Viscosity of siloxanes as a function of temperature

The helical shape of the chain-polymeric siloxane molecules is the reason for the low temperature dependence as far as the viscosity is concerned. An explanation may consist in the fact that although the average distances between molecules increase with rising temperature the helical chains simultaneously stretch, thereby virtually compensating for the increase in the distances between molecules, because there are more frequent contact points between the chain molecules.

3.3 SHEAR RATE - A so-called lower limiting viscosity, or zero viscosity for short, is established at low shear rates. The effect of the shear rate or deformation rate on viscosity depends greatly on the properties of the fluid.

Liquids, whose viscosity falls with rising shear rate, are termed intrinsically viscous. Silicone oils also exhibit this property.

The siloxanes of higher basic viscosity belong without doubt to the fluids of the second order, some of which exhibit considerable deviations from Newtonian linear behavior. This is demonstrated by a model experiment described below.

3.4 LUBRICITY - The designation silicone "oil" is in fact misleading when one considers the property of "lubricity". Noll /3/ emphasizes that silicone oils cannot be counted as lubricants: "The bearing capacity of a film of methyl silicone oils is slight as a result of the weak intermolecular forces in these phases." Satisfactory results are provided mererly by bearing materials, such as polyamides, phenolic resins or polystyrenes.

"For the material combination of steel/steel, methyl silicone oils have no significant lubricating properties in the range of dry friction."

Phenyl groups instead of methyl end groups quite clearly improve the bearing capacity of lubricating films.

3.5 THERMAL EXPANSION - A decisive factor as regards the torque behavior of the visco coupling is the pressure which is generated through dissipation, i.e. through the heat of friction. The rise in pressure is determined by the cubical expansion coefficient. For siloxanes with methyl organo-groups this lies in the temperature range of

$$25^{o}C \text{ to } 175^{o}C \text{ at } 95 \text{ to } 100*10^{-5} \text{ deg}^{-1}.$$

It is thus possible to calculate the dissipation pressure in the coupling under the simplifying assumption that the housing is considered rigid.

4. MODEL EXPERIMENTS

Only very vague assumptions exist concerning the flow conditions in the coupling, and even the relevant literature was not of any real use, expecially as almost all publications, both recent and older, were concerned with the resistances on high-speed flow machines.

The basic difficulty consisted in the fact that the very narrow gaps between the plates allow virtually no access, if any at all, into the "working area" in order to make measurements. I therefore restricted myself to visual experiments or observations on the most varied transparent plexiglass models, which provided interesting findings.

4.1 THE SILICONE-RUBBER MODEL - At a later point in the experiments, when it had become clear that the problem was not so much one of a boundary-layer flow but rather the phenomenon of the "crawling motion" of a non-Newtonian fluid, a smaller, yet very rugged acrylic model was made.

To be able to evaluate the effects of an extremely high-viscosity silicone oil on the shear behavior at the plates, silicone oil, or more accurately, silicone paste or rubber, with 600 000 cSt, was laid between two 10 mm thick acrylic-glass disks.

When the disks are turned in opposite directions by means of handles, a very high resistance is obtained. The mass begins initially to shear and the to "roll". Individual zones form "sausages" with rotation axes which are directed at the center of rotation. A special, observable feature is that the mass is pushed into the spaces of the slots in that the edges of the slots scrape off the material and then slowly push it outward, where it is conveyed in several "sausages" over the disk edges "into the open". This observable "rolling up" of the silicone rubber points to material properties which differ greatly from the shear behavior of purely Newtonian fluids and which have their basis in the normal-stress behavior of siloxane.

5. TORQUE CARACTERISTIC

The torque is the primary characteristic of the operation of the visco coupling. Since it converts only the rotational speed, the input and output torqües are always identical. However, the input and output powers are different. The difference is the loss.

In terms of a model, the visco coupling should be considered as the parallel connection of two sets of plates, with, for example, one set of 29 shaft plates alternating in a housing with a further set of 30 housing plates (see Fig.5.1). Assuming idealized conditions, they transfer - by "linear power branching" - the input torque form the shaft and the shaft plates through the silicone oil to the housing plates and thus to the output.

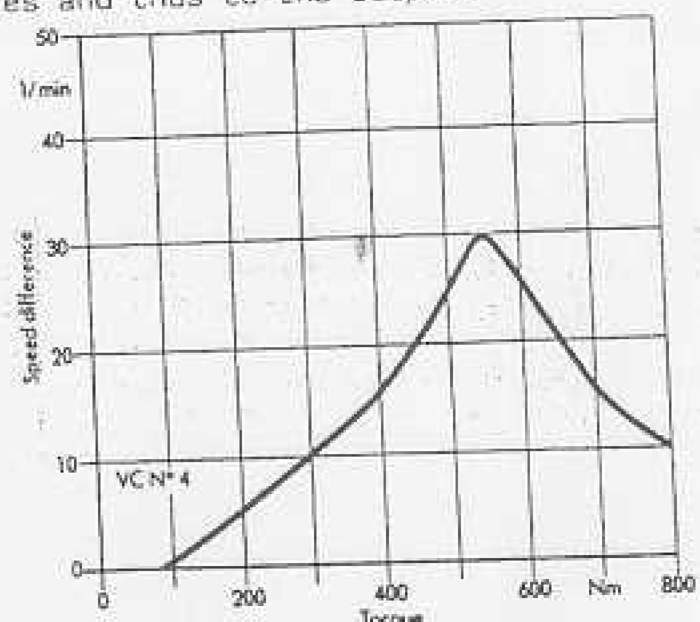

Fig. 5 .1 Diagrammatic representation of visco coupling

In the present case, therefore, there are m = 29 shaft plates and n = 30 housing plates in shear. This results in m + n - 1 8 58 working faces which are responsible for the friction power producing the torque. Various maeasuring methods are described below which are intended to help grasp the characteristics of the visco coupling.

5.1 TORQUE-RPM CHARACTERISTIC - A completely linear characteristic would in fact be expected if it were possible to eliminate the influence of temperature and time. In this case, a temperature increase is not detectable; the thixotropic property of siloxane makes itself noticeable. The noted drop in viscosity under shear is attributable to the elongation and orientation in the shear direction of the initially randomly convolute chain molecules under the influence of the shear loading.

If one plots torque, input power and output power versus the rpm ratio (Fig. 5.2), one obtains a characteristic which is very similar to that of a Föttinger coupling.

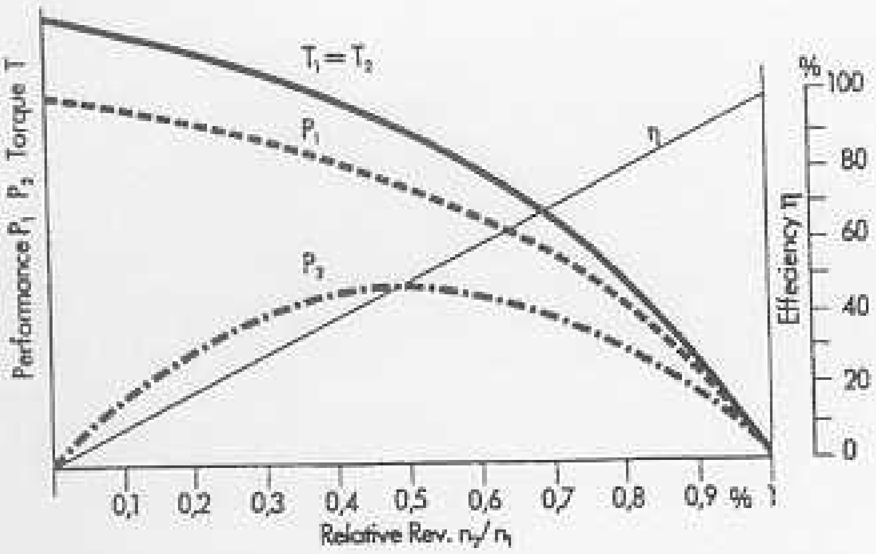

Fig. 5.2 Characteristic of visco coupling: torque, input power and output power versus rpm ratio

5.2 TORQUE-RPM BEHAVIOR UNDER TEMPERATURE INFLUENCE - If a test bench with torque control is allowed to operate over a lengthy period with increasing load at 20 second intervals, this results due to the fluid friction (dissipation) in the heating up of the coupling. As can be seen in Fig. 5.3, this leads to a further torque degression (torque drop). This is caused by the decrease in viscosity of the siloxane which is added to the thixotropic behavior. After a while there is a rather sudden reversal of the torque behavior: as the torque is further increased, the slip speed surprisingly decreases. The corresponding temperature curve is shown by the broken line.

Under no circumstances, however, can the temperature be the cause of the exceptional rise in torque. This is because the viscosity of the silicone oil decreases with rising temperatures. The influence of temperature on the coupling becomes somewhat clearer if one considers the temperature behavior for different slip speeds. Torque measurements are performed at speeds in steps from 10 rpm to 40 rpm. There are cooling-down phases between steps. According to the power dissipation, which is formed by T x ω, the heating-up end of the experiment is brought about by the steep rise of the torque. If the test bench were allowed to continue to operate, there would be mechanical damage to the coupling or to the test bench itself.

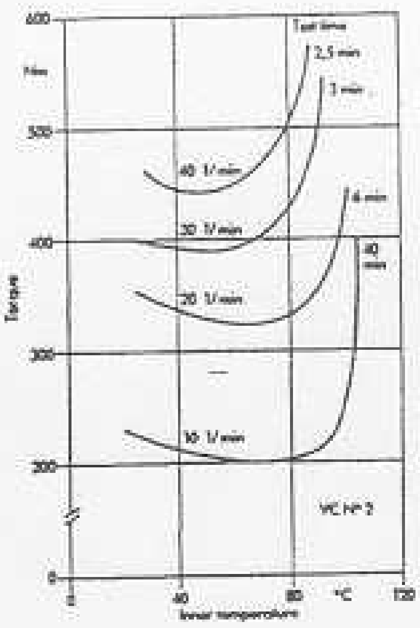

Fig. 5.3 Torque as a function of temperature for different rpm

5.3 TORQUE BEHAVIOR AS A FUNCTION OF PRESSURE - Since the housing of the coupling is closed and sealed on all sides, the heat will result in an increased pressure due to the volumetric expansion of the siloxane (95 EXP-5/degr.), which is greater than that of the steel housing (12 EXP-6/degr.). Fig. 5.4 shows the recording of the static system pressure (to be distinguished from the dynamic, visco-elastic pressure between the plates during shearing).

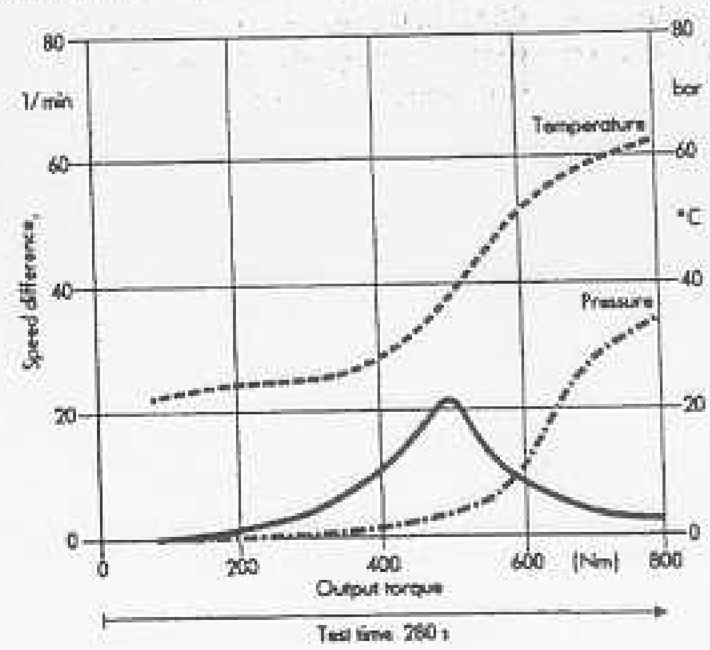

Fig. 5.4 Torque versus temperature and system pressure

It can bee seen that the torque progression starts when the primary pressure has assumed a certain magnitude. If the pressure is relieved, or if, due to a leak, it is unable in the first place to build up, then there is also no stiffening ("humping").

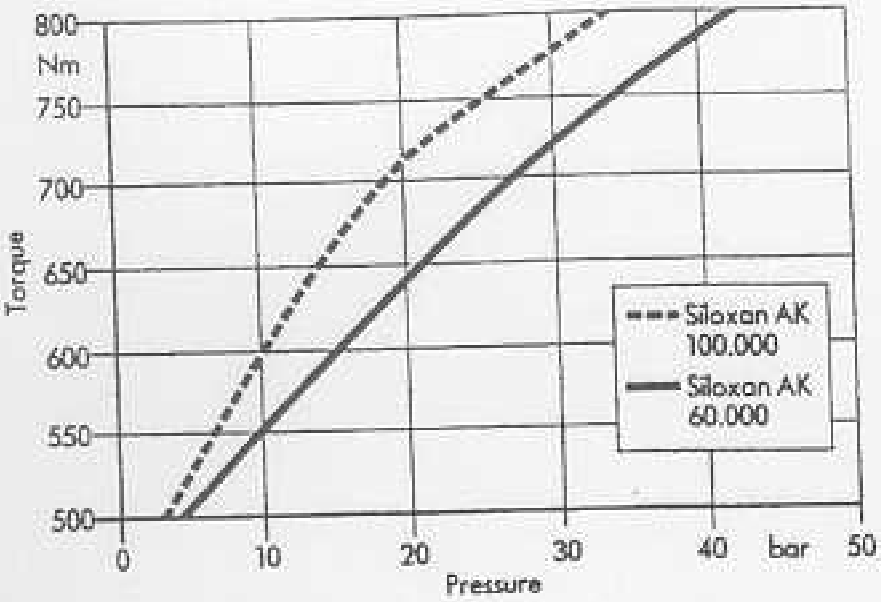

Fig. 5.5 Torque as a function of system pressure for siloxanes with two viscosities: A = 6 EXP4, B = 10 EXP4 mm²/s

The system pressure arising through the heat, therefore, determines the second area of the characteristics: the friction, which is characterized primarily not by the viscous shear, but more by the mixed friction of some of the plates. This phenomenon will be discussed separately later.

5.4 TORQUE AS A FUNCTION OF THE VISCOSITY OF THE SILOXANE - Silicone oils are produced in a large number of viscosities. They are available from 0.65 to 1 million mm²/s. Only types of high molecular weight enter into consideration for use in the visco coupling; such types must exhibit decidedly visco-elastic properties so that there is the above-described torque progression. In the case of thin fluids, the number of plates and the dimensions of the coupling become too great. In the case of types which are too viscous, filling is made more difficult, and, in the case of long-lasting shear loading, there are problems with an irreversible increase in viscosity under shear, the cause of which is to be sought only partially in the oxidation described.

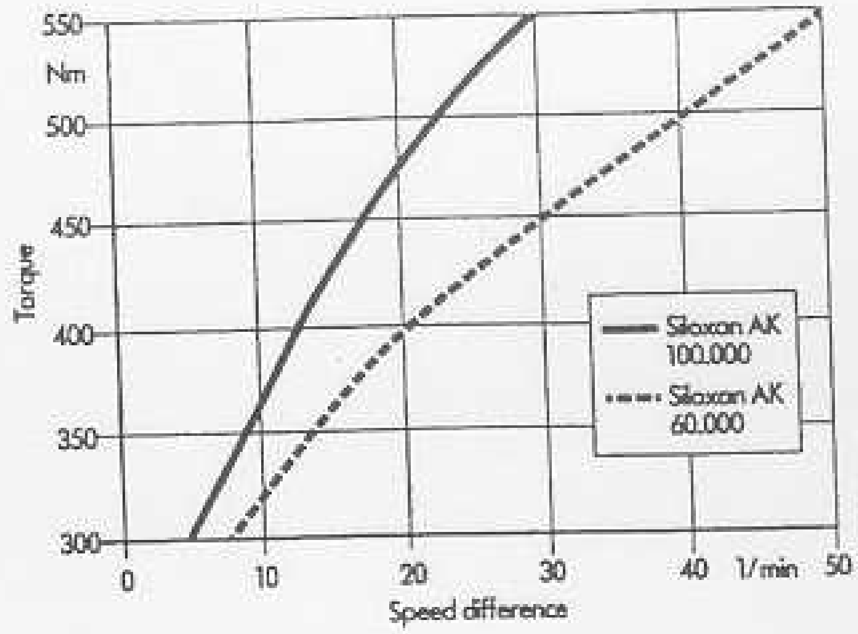

Fig. 5.6 Torque versus slip speed for two viscosities (60,000 and 100,000 mm²/s)

5.5 TORQUE AS A FUNCTION OF THE PROPORTION OF AIR - The two shaft seal rings and the closure system with lid, packing cord and snap ring can withstand only a certain system pressure. To act as a buffer and as an elastic safeguard, a samll volume of air of 5 - 10 % of the siloxane fill is applied when the coupling is filled.

This small "air chamber" is compressed in the course of the dissipative heating of the siloxane and disappears entirely at the limit temperature, as of which point the internal pressure rises with a very steep gradient. There is, nevertheless, still an effective protection against bursting: in the friction phase the coupling "locks" more and more as the pressure rises. This, however, reduces the dissipation. The discontinuation of the production of heat keeps the temperature rise within limits. The coupling thus in a certain manner protects itself.

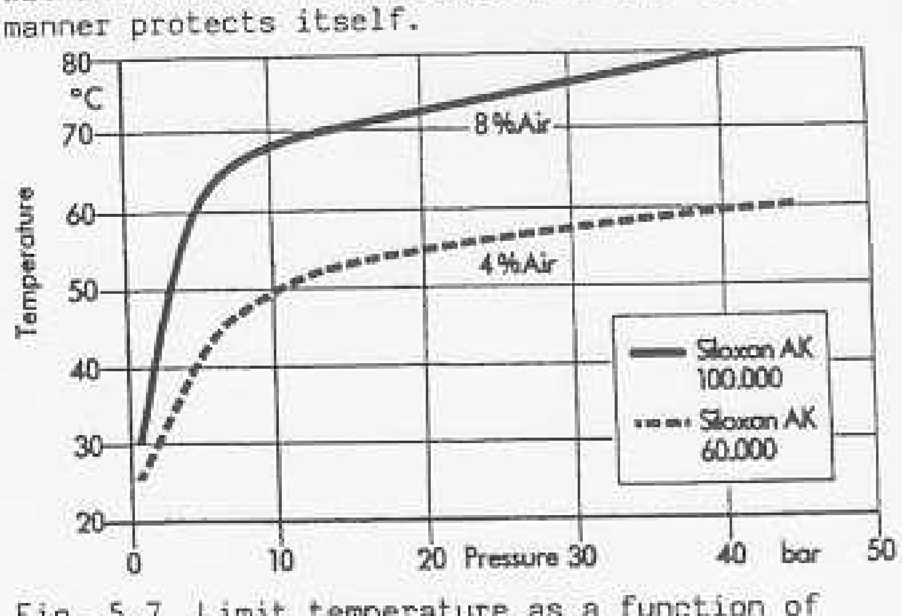

Fig. 5.7 Limit temperature as a function of the proportion of air. Progressive pressure rise after compression of air bubble

5.6 PLATES AND TORQUE (SURFACE AND PERFORATION) - The centerpiece of power transfer is the pack of plates. This consists of 0.9 or 0.6 mm thick steel plates whose surfaces are protected against wear by textured grinding and hard nickel plating. The housing accommodates just such a number of plates that, given (idealized) uniform distribution, there is a design gap of 0.2 mm. In reality, the gaps are randomly distributed, since all plates, both on the shaft as well as in the housing, are free to move axially.

5.6.1 Perforation of plates - Solid disks without holes ought theoretically to produce maximum viscous friction which is proportional to the wetted surface area. It has, however, been shown that, under the specific loading in the visco coupling, solid disks tend toward deformations which negatively change the operating behavior; the observation that, in a series of plates which were heavily loaded for a long time, one side showed more or less heavy wear marks, whereas the other side exhibited an unmarked, even as-new surface - without the slightest indication that there had been contact with the neighboring plate. Such plates had frequently abandoned their flat shape and had been deformed into a cup spring. The term "cupping" has been formed to describe this phenomenon in conjunction with the visco coupling.

A coupling with a series of such cupped plates no longer enters the friction phase - even after extremely heavy loading - there is therefore no longer a torque progression.

To prevent this, the shaft plates are provided on their circumference with 32 nicks. The plate thus remains dimensionally stable. The housing plates exhibit 20 holes in the middle of the annular area; these provide advantages when filling and help to prevent possible vibrations.

5.6.2 Distribution of "pressure and friction pairs" - As already initially mentioned, it became strikingly apparent in the analysis of used plate sets that those with wear marks alternated with others in virgin condition. The pairs without wear were termed "pressure pair" while those with wear marks or smooth spots were designated as "friction pairs". Three sets of plates were examined.

The overall result of pressure pairs to friction pairs is

$$P/F = 85/87 \sim 1$$

Statistics: Number of pairs examined n = 172
Number of friction pairs x = 87
Percentage x/n*100 = 87/172*100
= 50.58 %

The task is to find percentage p of the total basic unit, given a 10 % probability of over/undershooting.

$$P_o = 52.08\ \%$$
$$P_u = 48.01\ \%$$

It can be assumed that pressure and friction pairs will probably be in balance.

6. MEASUREMENTS IN THE VEHICLE

To evaluate the benefit of the new-type four-wheel drive with visco coupling, a comparison was made between three concepts; the comparison was performed on a vehicle:

1. front and rear axles rigidly coupled
2. front and rear axles coupled by visco coupling
3. front-wheel drive

The test vehicle was equipped on all four wheels with torque-measuring hubs. The visco coupling was provided with a temperature sensor which relayed its values inductively to a multi-recorder.

6.1 STARTING ACCELERATION ON ICE AND SNOW - To be able to assess the drive quality of the new-type configuration in winter operation, drive-off tests from 0-40 km/h were performed with the three concepts on packed snow; the results are shown in Table 6.1.

Concept	Time(s)
Rigidly coupled (front/rear)	3.8
Visco coupling	4.0
Front-wheel drive	7.6

Table 6.1 Acceleration times from 0-40 km/h

The vehicle with visco coupling is, therefore, almost as good on starting acceleration as the 100 % configuration (rigidly coupled).

6.2 TRACTION COMPARISON - To measure the maximum tractive forces, the vehicle was tied down with a tow bar and the tractive forces were recorded with a Sensotec RF/2548 force recorder. The results are shown in Table 6.2.

Concept	Tractive force (kp)
Rigidly coupled (front/rear)	480
Visco coupling	460
Front-wheel drive	240

Table 6.2 Tractive forces when driving off on snow

The traction of the visco coupling system is almost the equivalent of the maximum solution.

6.3 BRAKING - Once again under wintry contitins, the braking performance was tested on a frozen, snow-covered lake in Sweden; the lake was, however, cleared so that the surface was flat. The principal criterion was that of directional stability.

The virtually direct connection between front and rear axles by the visco coupling resulted in almost simultaneous locking of both axles. Of course, the front axle always has precedence since it initiates lock-up, even if the braking-force distribution is correctly matched.

With a little practice it was quite possible to detect the start of lock-up. Furthermore, reductions in stopping distance of up to 23 % were measured.

6.4 HIGH-SPEED TEST - This test investigated the influence of different tire rolling circumferences between front and rear.

Mainly the different tread depth causes differences in the rolling circumferences; conversely, loading and air pressure are of minor significance.

Test-stand measurements showed that in continuous operation with a slip speed of 5 rpm the visco coupling does not yet enter the range of torque progression.

This corresponds to the effect of a 3 mm difference in the tread depths on the 175/70 SR 13 tires between front and rear wheels at a speed of 160 km/h.

Since, however, in the meantime, endurance tests have shown that the rates of wear on front and rear axles are virtually identical in the slip-controlled permanent four-wheel drive, the danger of the visco coupling overheating at high speed due to different rolling circumferences virtually eliminates itself.

6.5 DRIVING SAFETY - Since the visco coupling can best be compared with an automatically locking differential, there are no additional levers or other operating components, as is described in the following with reference to the example of the Volkswagen Transporter syncro. The vehicle is driven like a van with rear-axle drive. The driver need not, therefore, learn any new driving techniques or observe specific or complex rituals. He can forget the four-wheel drive; it is permanently available when it is needed.

If, for example, the vehicle comes onto loose ground, onto ice or snow and the driven rear wheels begin to spin, the visco coupling immediately and imperceptibly for the driver transfers drive power to the front wheels. The distribution of the propulsion force between the axles is variable. It is perfectly possible that the rear wheels may be on an ice patch while the front wheels are on a dry road surface. When driving off under such conditions, the drive is almost entirely by means of the front wheels. Under normal circumstances - on a road with good grip - the drive power will be transmitted almost entirely by the rear wheels. The driver is not aware of this at all and can drive on uninfluenced. This new drive concept offers maximum driving safety.

However, the visco coupling also guarantees that a further driving situation is no longer so terrifying: with single-axle drive it is possible for the driven wheels to spin, e.g. on a snow-covered roadway, if the throttle is opened too much when cornering; the vehicle then breaks away at the driven axle. This would be oversteer in the case of rear-wheel drive vehicles and understeer in the case of front-wheel drive vehicles.

An inexperienced driver has difficulty in mastering such a situation. In the case of four-wheel drive with visco coupling, the visco coupling immediately and gently connects the drive to the other axle. This counteracts the incipient tendency to oversteer or understeer, and the vehicle proceeds neutrally through the curve. In most cases, the driver will not be aware at all that the wheels have developed the tendency to spin. This represents a significant contribution toward driving safety.

A further special feature of the visco coupling is that it damps vibrations and jolts in the driveline. This spares all components, such as bearings, gearwheels and drive joints.

7. THEORETICAL CONSIDERATIONS

The previously depicted torque behavior shows the unique characteristics of this component from the phenomenological side. Remarks have been made which point to an explanation of the phenomena surrounding the torque progression in the visco-elastic properties of the silicone oil.

The following theoretical considerations from the classical as well as the fluid mechanics of non-Newtonian fluids are intended to help to complete the circle of knowledge by linking phenomenon and applied laws.

After examining the Reynold number it had become clear that there is a crawling flow between the plates. Consequently, some phenomena in the visco coupling can be evaluated mainly with the laws of rheology. These are principally the relationships surrounding the

- o torsional moment due to viscous shear
- o and the normal forces due to visco-elasticity.

The dissipation and the associated pressure buildup in the housing are a thermodynamic problem.

The torque stiffening (humping) with mixed friction cannot be satisfactorily quantified.

It is largely impossible to verify the influence on the torque of the empirically applied slits and holes (perforation) in the plates. (Examinations on the effect of circular surface interruptions have been performed by Wiegand, but only for turbulent boundary layers at constant pressure; Wiegand found that elevations are just as resistance-increasing as corresponding depressions.)

7.1 TORQUE - The most important characteristic with regard to the use of the visco coupling in a vehicle is the torque as a function of the slip. The power transfer is derived basically from the shear forces generated between the plates and the fluid.

In the following, reference is made initially only to fluid friction, given a design-specified interval between the plates (gap width).

In accordance with the shear stress conditins between two disks rotating at different speeds, there is a torque which, for the characteristics assumed in the following

$\Delta\omega$ = 0.661/s Differential speed
ν = 0.1 m^2/s Viscosity of silicone
r_a = 0.0056 m Outside diameter
r_i = 0.025 m Inside diameter of plates
s = 0.000212 m Gap width
ρ = 970 kg/m^3 Density of silicone

and given the simplified shear stress formula:

$$T = 2\pi \int_{r_i}^{r_a} \tau r^2 dr \; ; \; \tau = r \cdot \omega \cdot \mu / s \; ; \; \mu = \nu \cdot \rho \qquad (7.1)$$

and

$$T = \frac{\pi \omega \cdot \nu \cdot \rho}{2 s} \cdot r_a^4 \left[1 - \left(\frac{r_i}{r_a}\right)\right]^4 \qquad (7.2)$$

according to the relation (7.2) for a plate pair, there results, after multiplication by n = 63 working surfaces for five viscosities from 50,000 to 250,000 cSt (= mm^2/s), a linear family of curves in Fig. 7.1. The intrinsic viscosity is not taken into account. (This could easily be obtained by inclusion of the exponential law $\tau = \alpha * \dot{\gamma}^{\beta}$. α and β are constants which are obtained in accordance with the molecular weight and the material properties. β is between 1 and 1/4 in the case of siloxanes.)

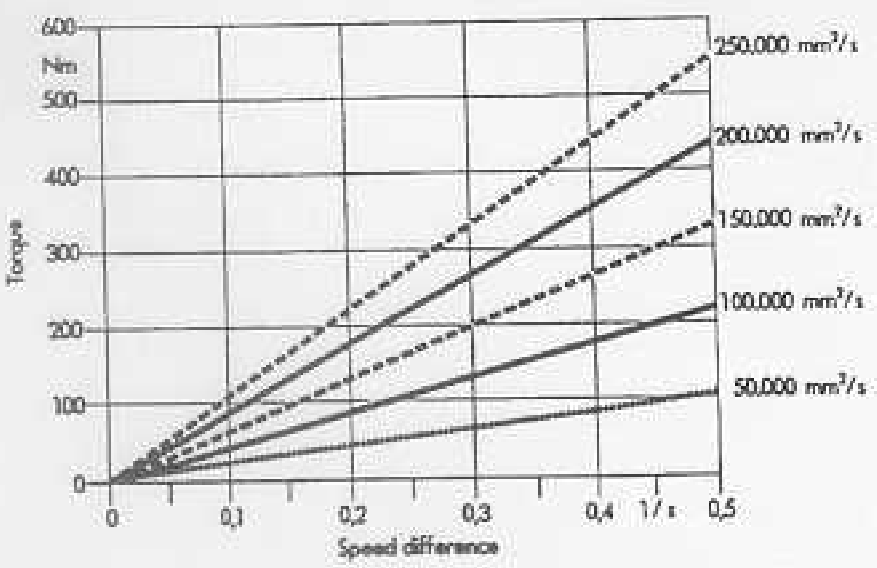

Fig. 7.1 Torque as a function of slip speed for design-specified gap between plates of 0.21 mm and for different viscosities according to relation (7.2)

Of interest is the influence of gap width s according to relation (7.2): s is in the denominator.

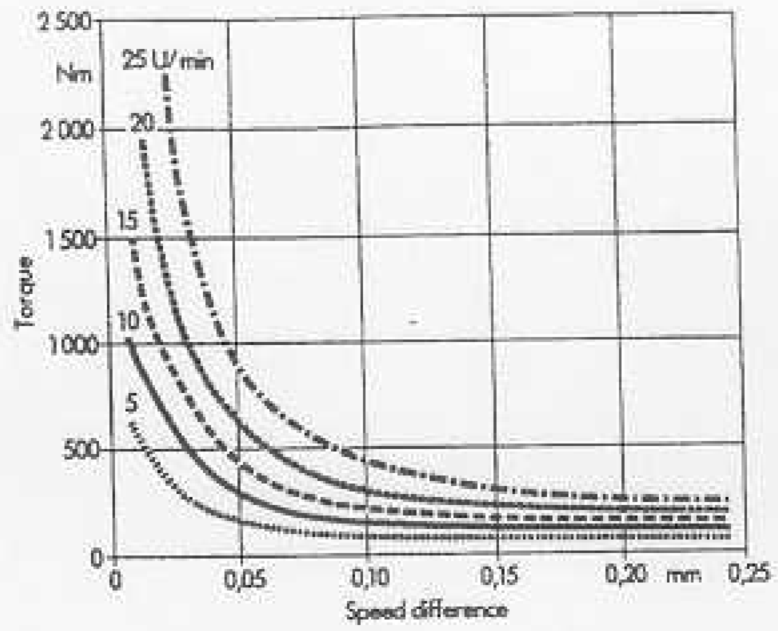

Fig. 7.2 Torque of a plate pair as a function of gap width

The relationship between torque and gap width s shown in Fig. 7.2 makes it clear that the torque rises sharply in the case of gap widths less than 0.1 mm. At this point it is already possible to identify one component of the torque progression (hump); if some plates come very close to each other, this means that the shearing moment is greatly increased for these plate pairs.

This coming-close together of the plates simultaneously signifies a moving-away-from-each-other for the other neighboring plate pairs.

7.2 PRESSURE CHARACTERISTICS ON THE MODEL

– On the single-disk hand model it is possible to present the pressure conditions of the system of two disks rotating at different speeds. This differs from the coupling in that on the model one of the two disks is stationary (housing bottom), while in operation the coupling rotates together with the housing plates and only when "activated" does a differential speed start the shear friction in the fluid and thus the dissipation.

It was stated in Section 6 that in narrow gaps only frictional forces have to be taken into account; inertial forces can be neglected.

By attaching transparent riser tubes on four radii from the edge to the center it was possible even with a small shear rate of $\dot{\gamma} \approx 12.0$ 1/s (where $\dot{\gamma} \approx r * \omega / s$ and r=0.004 m, ω = 0.3 1/s, s = 0.001 m) and with polydimethylsiloxane AK 30 000 to establish a compressive-stress distribution, rising toward the center of the disk, which also corresponds to the theoretical considerations in this section through Equation 7. 6.

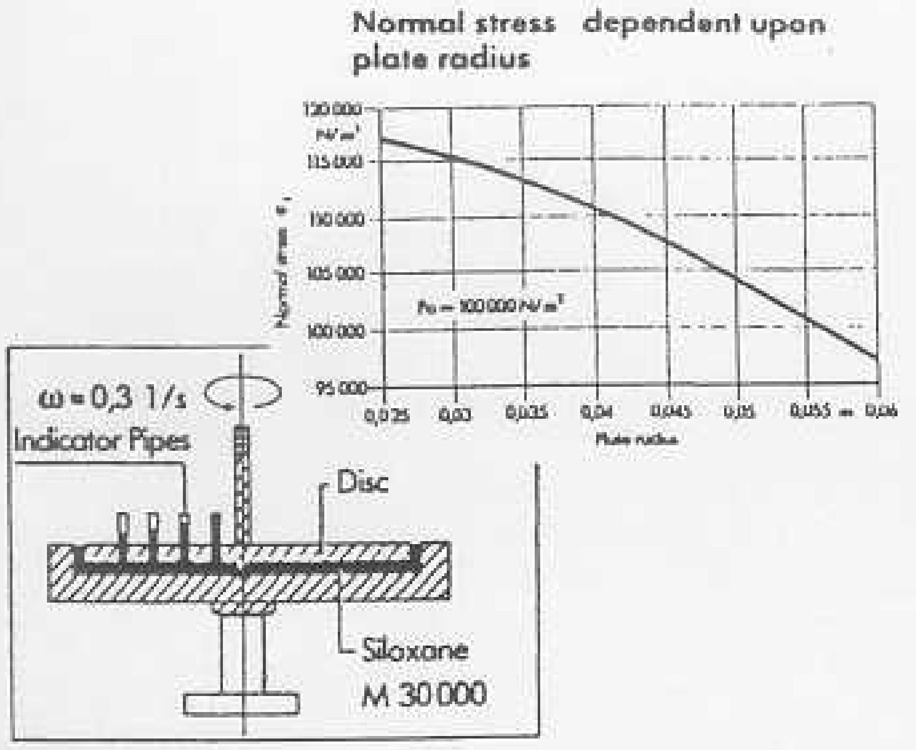

Fig. 7.3 Diagram of pressure distribution in riser tubes on hand model

This experiment indicates that siloxane of the aforementioned viscosity has visco-elastic properties and is a non-Newtonian fluid under the test conditions.

7.3 AXIAL FORCE - In deriving the normal stresses, it has already been established that the rotating disks build up normal stresses in the z direction (axially) which tend to thrust the disks away from each other.

By integration of the normal stresses over the area, one obtains the direction and magnitude of the thrusting-away force F.

$$F = -2\pi \int_0^{r_a} r \cdot \sigma_{zz}\, dr \qquad (7.3)$$

The relation for the compressive stresses derived from the normal-stress difference is better suited for arriving at the axial force F by integration:

$$F = -2\pi \int_{r_i}^{r_a} p \cdot r \cdot dr \qquad (7.4)$$

After integration

$$\boxed{F = \pi p_a r_a^2 \left[1 - \left(\frac{r_i}{r_a}\right)^2\right] - \frac{\pi}{4} r_a^4 \omega^2 \left[1 - \left(\frac{r_i}{r_a}\right)^2\right]^2 \left[\frac{\rho \cdot \nu_1}{s^2}\right]} \qquad (7.5)$$

With the values:

$\Delta\omega$ = 0.66 1/s Differential speed
ν = 0.1 m²/s Viscosity of silicone
r_a = 0.0056 m Outside radius
r_i = 0.025 m Inside radius of plates
s = 0.000212 m Gap width
ρ = 970 kg/m³ Density of silicone

F results as 854 N, a considerable axial force.

V = Vl + Vs

When the coupling is filled, the two states - cold and after heating - are described by the variables

t_1 = Initial filling temperature
γ_1 = Expansion coefficient at t_1
t_2 = Temperature after dissipative heating
γ_2 = Expansion coefficient at t_2

$C_L = \frac{V_L}{V}$ Air proportion at filling.

With Equation (7.6) it is possible to express the compression (volume) ratio of the air bubble at temperatures t_1 and t_2 for:

$$\frac{p_{(t_2)}}{p_{(t_1)}} = \frac{t_2 + 273.15}{t_1 + 273.15} \cdot \frac{1 + \gamma_1 \cdot t_1}{(1 + \gamma_2 \cdot t_2) - \frac{1}{C_L} \cdot (\gamma_2 \cdot t_2 - \gamma_1 \cdot t_1)} \qquad (7.6)$$

7.4 LIMIT TEMPERATURE - Equation (7.6) has a pole point where the denominator tends toward zero:

From this the limit temperature t_{Limit} is derived:

If one simplifies $\gamma_2 \approx \gamma_1$ and $C_L \ll 1$, then $1/(1-C_L) \approx 1+C_L$ and

$$t_{Limit} = (1+C_L) \cdot \left\{t_1 + \frac{C_L}{\gamma_1}\right\} \qquad (7.7)$$

The principle of the coupling is geared to a torque increase which is to be obtained after operating for a while with slip. As is to be explained later, the precondition for progression is the rise of the system pressure in the housing, which goes hand in hand with the rise in temperature. Theoretically, an immediate rise in the pressure (even under minimal heating) would be advantageous. If operated, for example in sand, the second driven axle would cut in quickly. This desirable characeristic could be achieved by filling the visco coupling without a proportion of air. However, this cannot be allowed for the following reason: According to Fig. 7.6, even with slight exceeding of the ambient temperature, the system pressure would rise so sharply that the coupling housing would explode or the seals or the housing cover would be forced out. Consequently, 8 % - 10 % air is currently used as a safety "cushion".

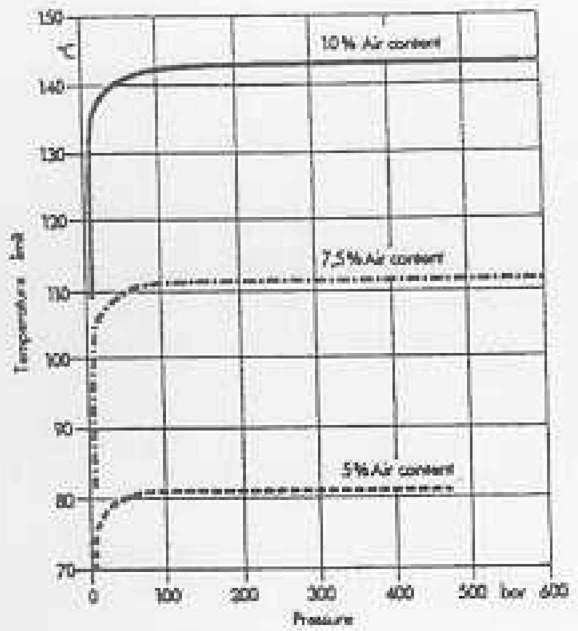

Fig. 7. 4 Limit temperature as a function of air proportion

From Fig. 7. 4 it can be derived that each proportion of air c_l is assigned a limit temperature at which the pressure rise goes toward ∞.

The visco coupling is so designed that it can withstand a maximum pressure of 100 bar. To protect it from bursting at allowable temperatures around 100° C, it is necessary to provide an air proportion c_l of at least 7%.

8. CONCLUSIONS

The visco coupling, integrated into the driveline of a four-wheel-drive vehicle in place of an interaxle differential, has been analyzed by thorough tests and experiments. The unusual torque-rpm behavior (humping) has been investigated while varying the following parameters:

- Temperature (of fluid)
- System pressure
- Percentage of air
- Structure and plate surface.

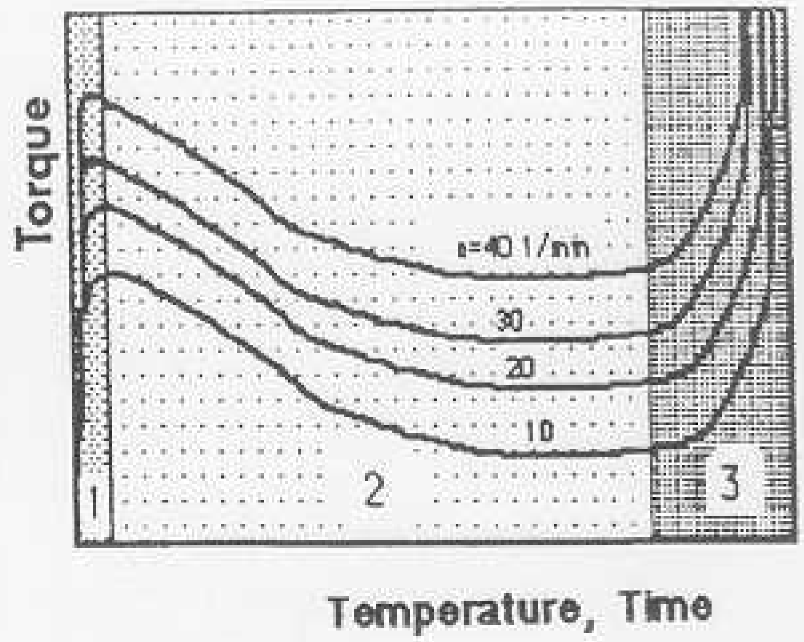

Fig. 8.1 Schematic characteristics of visco coupling

8.1 (VISCOUS) SHEAR RANGE (1 AND 2) - Studies of the flow and pressure conditions of transparent basic models provided pointers to the torque-transfer mechanisms. In the initial range at low slip speeds and with brief loading with correspondingly low heat generation, the plates produce only a shearing torque which, due to the intrinsic viscosity, yields a degressive curve versus the shear rate (rotational speed) and versus time.

8.2 FRICTION RANGE - The heat generated by friction causes a rise in pressure in the sealed housing. The gradient of this rise in pressure is determined by the inclusion of a specific proportion of air. This system pressure, resulting from dissipation, acts in the friction phase as an "hydraulic clamping force" on some plate pairs which have sufficient silicone oil in their gaps (pressure pairs). The other pairs, which are in close contact with each other and pass into mixed friction due to the clamping, become "friction pairs".

Apart from the pressure due to heat generation, visco-elastic normal-stress differences also build up within the flat layer flow between the plates. These normal-stress differences tend (as compressive stresses) to force the plates apart.Compared with the system pressure, these are smaller by a power of ten, but result in the same effect as the latter: The friction pairs are transferred into a state of mixed friction. This results in the torque rise which is so desired for the propulsion of the vehicle.

(The pressure can also be mechanically applied from outside. This suggests the idea of installing a torque-controlled pressure device).

It is demonstrated that the air bubble inclusion determines the limit temperature.

Silicone oil exhibits good suitability for the desired torque-rpm bahavior with regard to thermal stability and its expansion behavior. Due to its intrinsic viscosity and the limited lubrication capability, it is not entirely the ideal fluid for the operation of the visco coupling.

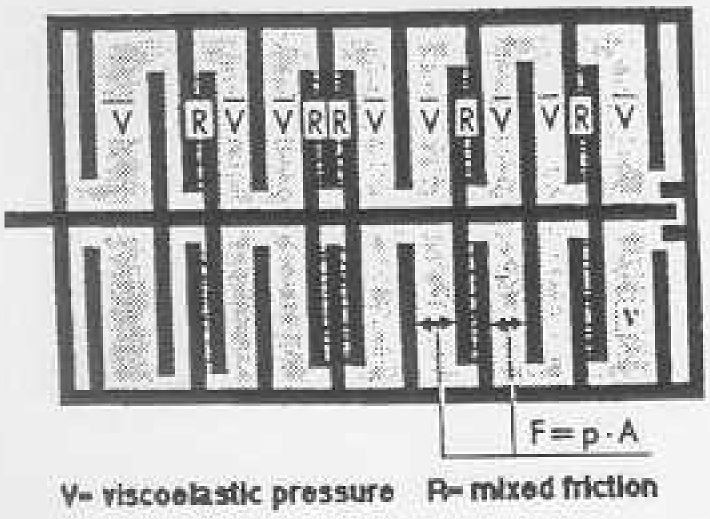

Fig. 8.2 Schematic distribution of friction (R) and pressure (V) pairs

Basically, the visco coupling consists of two fundamentally different operational systems. One is characterized by viscous shear, the other by mixed friction, similar to a conventional axial coupling, but with "automatic, internal, hydraulic clamping".

<u>Procedure</u>

The APPLE™ Macintosh personal computer was used to prepare the present text, the figures, the calculations and corresponding graphics.

Software: Text------ ------ APPLE™, Mac Write
Figures --------- APPLE™, Mac Paint
Calculations----- MICROSOFT™, Multiplan
" ---- SOFTWARE ARTS™, TK!Solver
Graphics--------- MICROSOFT™, Chart+
" ---- SOFTWARE ARTS™, TK!Solver

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