The development of a differential for the improvement of traction control

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SYNOPSIS: An introduction to the function of Gleason's TORSEN differential including discussions of its major characteristics, design flexibilities, and effects on vehicle performance.

1 INTRODUCTION

Traction management… the ability to match available power to actual road conditions… is a concern shared by drivers and automotive engineers alike. With the Torsen differential, Gleason is meeting this challenge of improving traction management in both front and rear wheel drive vehicles, all-wheel drive vehicles, and in a variety of applications of the various drives for use in cars, trucks, military vehicles, construction and utility vehicles, and racing cars.

This paper explains the basic operating functions, various design alternatives, and the possibilities for improving traction management provided by the Torsen differential.

2 CHARACTERISTIC FUNCTIONS

The Torsen differential provides for the selection of an optimal compromise between the two primary functions of any differential, namely, transmitting power from a single power source to two drive axles (or shafts) and permitting independent rotation of the two driven axles (i.e., differentiation). This compromise enables an increase in the total amount of torque which can be conveyed by the drive axles under all traction conditions, without unduly restricting differentiation. Differentiation is necessary to accommodate different rotational speeds between drive axles due to vehicle turning situations and variations in tire rolling radii. These objectives are accomplished by associating the function of differentiation with a proportioning torque between drive axles. The significance of this important characteristic will be apparent from the following discussion, beginning with an explanation of torque transfers within a differential.

2.1 A general statement of differential torque transfers

One of the two above-mentioned primary differential functions, the transmission of power from a single drive shaft to the two driven axles is most closely associated with the objective of traction management (see Figure 1). Power, of course, is the product of torque and rotational speed. However, since it is possible to express vehicular traction as a reaction force acting at a given wheel radius, traction considerations related to the function of power transfer to the drive axles may be expressed in terms of torque alone.

Actually, two types of torque transfers may be identified in differentials. The first being the one primary function related to the transfer of torque from a single power source (engine) to the two drive axles. The second type is the transfer of torque between the drive axles. The two types of torque transfer are interrelated, and it is an important characteristic of the Torsen differential to control torque transfers between drive axles and thereby enhance the capacity of the differential to transfer an increased amount of torque to the drive axles collectively.

2.2 Comparison with open differential

The just-mentioned characteristic of the Torsen differential may be best appreciated in comparison with the inherent torque transfer characteristics of an "open" or conventional differential. The drive axles associated with an open differential are interconnected by a bevel gear set designed to divide equal torque between drive axles. This arrangement will not support any substantial torque difference between the drive axles and, as a consequence, offers very little resistance to differentiation. Virtually any attempt to deliver an increased amount of torque to one of the drive axles will result in rotation of the gear set as evidenced by differential rotation of the gear set as evidenced by differential rotation between drive axles. For example, if once of the drive wheels should lose traction, any attempt to deliver additional torque to the other drive wheel (having better traction) will result in undesirable 'spin up' of the wheel having poorer traction. The maximum amount of torque conveyed by the drive axles collectively is limited to approximately twice the amount of torque supported by the drive wheel having the least traction.

It is this type of problem which is most often identified with the need for improved traction management (see Figure 2). The Torsen differential addresses this need by providing for a torque proportioning characteristic between drive axles by interconnecting the drive axles with an Invex* gearing arrangement. This gearing is designed to support a predetermined ratio of torques between drive axles.

2.3 Invex gearing

Invex gearing in a Torsen differential includes a gear train arrangement comprised of two or more pairs of satellite gears (called 'element gears') in mesh with central helical gears (called 'side gears'). The pairs of element gears are interconnected with each other by means of spur tooth engagement. Figure 3 illustrates a typical Invex gear train for the Torsen differential. This particular arrangement consists of six element gears and two side gears. The number of element gears pairs used in a specific design is a function of overall torque capacity and space requirements.

The modified crossed axis helical gear mesh, element gear to side gear, is designed and processed to provide instantaneous elliptical contact for reduced tooth stress and increased tooth overlap engagement. In addition, gear tooth helix angle, pressure angle and tooth depth proportions are selected to further minimize stress and wear without sacrifice to function.

2.4 Torque bias ratio

The maximum torque ratio which is supported by a particular differential design is termed 'bias ratio'. This term is expressed as the quotient of the torque in the higher axle divided by the torque in the lower torque axle in proportion to unity.

The provision of bias ratio significantly affects the operative connection between drive axles and represents a careful choice for controlling torque transfers between drive axles to achieve optimum traction. A '4:1' bias ratio design means that the Torsen differential is capable of delivering, to the drive wheel having better traction, four times the amount which can be supported by the lower traction wheel. In comparison with an open differential, this means that, under the same conditions, a '4:1' bias ratio differential is capable of delivering approximately two and one-half times more torque to the drive axles collectively than an open differential.

2.5 Comparison with other types of differentials

Other means are also known for modifying the operative connection between drive axles to provide for the transfer of additional torque to the drive axles collectively. For example, many limited-slip differentials provide for pre-loading friction clutches to oppose the transfer of torque between drive axles. This frictional pre-load represents a particular minimum magnitude of resistance which must be overcome to permit any relative rotation between drive axles which may interfere with the operation of anti-lock braking systems. Also, since frictional forces are continually active to resist differentiation, the friction clutches tend to wear, resulting in a deterioration of intended differential performance.

In contrast to a limited-slip's continuous magnitude of frictional resistance to differentiation, the torque biasing characteristic of the Torsen differential provides for a maximum ratio of torque distributions between drive axles. For instance, as the amount of torque being conveyed by the Torsen differential decreases, the amount of resistance to differentiation also decreases. That is, even though the bias ratio remains relatively constant, a proportional division of a lower magnitude of torque being conveyed by the differential results in a smaller torque difference between drive axles. In braking situations where little or no torque is being conveyed by the differential, a four to one apportionment of torque between drive axles amounts to little or no torque difference between drive axles. Thus, the Torsen differential will not support any appreciable torque 'wind-up' between drive axles during braking and so does not interfere with the operation of anti-lock braking systems.

Another known approach to modifying the operative connection between drive axles is to provide for resisting differentiation as a function of the speed difference between drive axles. It has long been appreciated that undesirable wheel slip is associated with very high rates of differentiation. Differentials have been designed using fluid shear friction, which respond to increased rates of differentiation by increasing fluid shear frictional resistance to differentiation. The obvious problem with such 'speed sensitive' differentials is that undesirable wheel slip has already occurred well in advance of its detection. Also, the fluid shear friction designs generally rely on the changes in fluid temperature associated with high differential shear rates to increase resistance to differentiation. However, similar temperature changes may be associated with extended periods of desirable differentiation, or may be influenced by changes in ambient temperature, so that resistance to differentiation may vary throughout ordinary conditions of vehicle use.

The bias ratio characteristic of the Torsen differential instantly reacts to unequal traction conditions by delivering an increased amount of torque to the drive wheel having better traction before the other drive wheel exceeds the limit of traction available to that wheel. The bias ratio characteristic also remains substantially constant over a wide range of torque conveyed by the differential, and is not sensitive to changes in ambient temperature or conditions of vehicle use.

3 STRUCTURE FOR ACHIEVING TORQUE BIAS

As previously stated, the torque biasing characteristic of the Torsen differential is achieved by interconnecting the drive axles with an Invex gearing configuration which selectively controls the generation of frictional torques within the differential. It is important to note that there are no intrinsic forces or pre-loads within the differentials which affect transfers of torque between drive axles. All of the forces which are controlled to produce frictional resistance between drive axles are derived from transfers of torque between a single drive source and the drive axles.

The characteristic of torque bias is achieved in a very simple way. It is well known that frictional forces are determined by the product of the coefficient of friction of a given surface and the normal force applied to that surface. Frictional torque, of course, is merely the application of that normal force at an effective frictional radius. All of the forces which are active within the differential are derivable from the torque which is being conveyed by the differential and the friction coefficients of surfaces within the differential. Therefore, all of the frictional forces which are generated within the differential, and all of the resulting resistant torques which oppose the transfer of torque between axles, are proportional to the torque being conveyed by the differential. Since the maximum difference in torque between drive axles which can be supported by friction is proportional to the combined torque of the drive axles, the maximum bias ratio remains constant with respect to changes in the combined drive axle torques.

In addition to providing a geared interconnection between drive axles which permits the usual opposite relative rotation between the drive axles, the gearing also distributes forces which may be generated to resist differentiation over a large number of different surfaces within the differential. The surfaces over which the Invex gearing distributes forces are designed with different coefficients of friction, and the Invex gearing is designed to distribute different loads between the surfaces. Collectively, the surfaces and the gearing are designed to distribute wear evenly over the surfaces and to control the overall amount of friction within the differential needed to achieve a desired bias ratio.

3.1 Major components of the Torsen differential

The twenty-one components which make up the differential are shown in Figure 4. All components of the Invex gear system are contained within the housing. Input power usually is transmitted to the housing by way of a ring gear (crown wheel) bolted to the housing itself. Trunnions are adapted to receive bearings by which the housing is rotatively supported and retained within the axle carrier assembly. These trunnions also receive the respective axle ends which are splined to the side gears within the housing.

Each side gear meshes with element gears arranged at intervals about the periphery of the associated side gears; tangent to, and in engagement with, the pitch surfaces of the side gears. Each of these element gears is formed with a helical middle portion and spur gear end portion. Each side gear meshes with the middle portion of these associated element gears. At the same time, the integral spur gear portion of each element gear meshes with the spur portion of its adjacent element gear. Element gears are shaft mounted by means of their associated journal pins. The number of element gears and associated hardware may vary. However, the usual arrangement has three sets of element gear pairs arranged at 120 degree intervals as illustrated by Figure 3. It is this arrangement of Invex gearing that provides for (a) connecting the drive axles for opposite directions of relative rotation with respect to the differential housing and, (b) controlling the transfer of torque between drive axles.

Completing the hardware complement are thrust washers used between each end of each side gear, between side gears and the housing. Selection of thrust washers is important in determining the operating characteristics for each application. Proprietary Gleason models permit selection of components with a high degree of accuracy with respect to vehicle characteristics.

3.2 A mathematical representation of the Torsen differential

This section of the paper provides a mathematical representation of the basic frictional relationships within a Torsen differential which are responsible for achieving the bias characteristic between drive axles. The mathematical representation assumes that the direction of torque transfer through the differential is from a vehicle's engine to the drive axles. Figure 4 may be again referred to for identifying differential components mentioned in this section. However, specific forces and torques which are mentioned in this section are illustrated in Figure 5 in association with a schematic depiction of key differential components.

Engine torque applied to the ring gear (T_{rg}) is substantially equal in magnitude to the sum of reaction torques which are developed at each drive axle (T_1, T_2). The engine torque is transferred to the drive axles through (a) the differential housing which supports the ring gear and (b) the Invex gearing which is carried within the housing and interconnects the drive axles for equal but opposite directions of relative rotation with respect to the housing.

Thus, in addition to transferring torque from the differential housing to the drive axles, the Invex gearing also provides a rotational interconnection between drive axles which may be understood to function as a gear train for transferring torque between drive axles. Gear trains, of course, develop various reactions at gear meshes and mounting surfaces which generate friction opposing rotation of the train in proportion to the torque being carried by the train. Since all of the engine torque which is transferred to the drive axles is carried by the Invex gearing, reaction torque which opposes rotation of the Invex gearing is proportional to the engine torque which is transferred to the drive wheels. Thus, the transfer of torque between drive axles is also resisted in proportion to the transfer of torque between the engine and drive axles.

This feature enables the Torsen differential to support a torque imbalance between drive axles which contributes to the total amount of torque which can be transferred from the engine to the drive axles when the amount of torque which can be supported in one of the drive axles is limited by available traction. The major frictional interfaces which are responsible for supporting a torque difference between drive axles are listed below along with parenthetically enclosed symbols representing the coefficients of friction of the respective interfaces.

Side gear to element gear Invex gear meshes (μ_1)
Element gear faces to differential housing (μ_2)

Side gear face to side gear face (μ_3)
Side gear face to differential housing (μ_4)

Typically, the largest reaction forces within the differential are side gear thrust forces (F_{a1}, F_{a2}) resulting from normal tooth loads (F_1, F_2) acting at the side gear to element gear Invex tooth meshes. The reaction forces are related to the normal tooth loads according to the following equation:

$$F_{a1}, F_{a2} = (F_1, F_2) \times \cos ø \times \sin ß$$

where ' ø' is the tooth normal pressure angle and ' ß' is the side gear helix angle.

These reaction forces are opposed by the respective frictional interfaces associated with the end faces of the side gears and result in the generation of frictional torques (T_{f3}, T_{f4}) which oppose side gear rotation. These frictional torques are related to the reaction forces according to the following equation:

$$T_{f3}, T_{f4} = (F_{a1}, F_{a2}) \times (R_3, R_4) \times (\mu_1, \mu_2)$$

Where ' R_3' and 'R_4' are the effective friction radii at the respective side gear interfaces.

Frictional torques (T_{f5}, T_{f6}) are developed at the respective interfaces between the element gears and differential housing. These frictional torques are also developed as a result of reaction forces at the side gear to element gear meshes, but the reaction forces being considered here are those which are directed along the respective axes of the element gears. These reaction forces (F_{b1}, F_{b2}) are related to the normal tooth loads according to the following equation:

$$F_{b1}, F_{b2} = (F_1, F_2) \times \cos ø \times \cos ß$$

The above-mentioned frictional torques (T_{f5}, T_{f6}) are related to the reaction forces (F_{b1}, F_{b2}) according to the following equation:

$$T_{f5}, T_{f6} = (F_{b1}, F_{b2}) \times (R_5, R_6) \times (\mu_5, \mu_6)$$

Where 'R_5 and R_6' are effective friction radii at the respective element gear to housing interfaces.

In addition to the frictional torques developed at the Invex gearing mounting surfaces, sliding contact between the side gears and element gears at the respective Invex gear meshes also produces frictional torques which contribute to supporting a torque division between drive axles. The respective friction forces at the Invex gear meshes may be represented as:

$$Fc, Fd = (F_1, F_2) \times \mu_1$$

The resulting frictional torques (T_{f1}, T_{f2}) opposed to side gear rotation is related to mesh friction as follows:

$$T_{f1}, T_{f2} = (F_c, F_d) \times R \times \sin ø \times \sin ß$$

where 'R' is the pitch radius of the respective side gears.

Therefore, the maximum difference torque which can be supported between drive axles is related to each of the above-equated frictional torques as follows:

$$T_1 - T_2 = T_{f1} + T_{f2} + T_{f3} + T_{f4} + (R / R_c) \times (T_{f5} + T_{f6})$$

where 'R_c' is the pitch radius of the combination gears.

Letting the torque difference between drive axles ($T_1 - T_2$) be represented by ' T_d ', it follows that:

$$T_1 = (T_{rg} + T_d) / 2, \text{ and}$$
$$T_2 = (T_{rg} - T_d) / 2$$

From this, the maximum ratio of torque which can be supported between drive axles (i.e., bias ratio) is expressed by the following proportion:

$$\textit{torque bias} = T_1 / T_2 : 1$$

An alternative way of referring to drive axle torque distributions is by the term 'percent locking'. This term may be mathematically expressed as follows:

$$\textit{percent locking} = (T_d / T_{rg}) \times 100$$

Figure 6 shows the relationship between torque bias and percent locking over a range of comparable values of each.

4 DESIGN FLEXIBILITIES

The Torsen design provides several options for adjusting bias ratio to different operating conditions. First, it is possible to increase or diminish bias ratio. Second, it is possible to achieve significantly different bias ratios between opposite directions of relative drive axle rotation. Third, it is possible to achieve different bias ratios between vehicle operating conditions of driving and coasting. Each of these options is discussed under a separate heading below.

4.1 Overall bias control

The Torsen differential may be designed with different bias ratios ranging from approximately '2.5:1' to '6:1' or higher. This may be accomplished by varying the side gear helix angles, or by altering the friction characteristics for the primary components. An increase in helix angle increases the thrust component of the side meshes along the axis of the side gears so that smaller portions of the loads communicated by the side gear meshes are related to rotation of the side gears. In addition, the higher thrust component along the axis of the side gears increases frictional resistance at the end faces of the side gears which opposes side gear rotation and thereby further contributes to an increase in bias ratio.

4.2 Bias ratio between opposite directions of differentiation

The Torsen differential can also be designed so that different bias ratios are associated with different directions of differentiation between drive axles. That is, this design permits one drive axle to support a larger proportion of total drive torque than the other. The interaction of forces within the differential which give rise to this design characteristic are very complex. However, it may be generally explained that such different bias ratios are obtained by relatively raising the coefficient of friction which is effective between the end face of one side gear and the differential housing. This tends to increase resistance to the rotation of the drive axle associated with the one side gear with respect to the other drive axle.

This feature may be particularly advantageous in 'center box ' applications where the Torsen differential is used to interconnect drive shafts to the front and rear drive axles with a single power source. In this application, it is possible to set different limits to the maximum proportions of torque which can be unequally divided between the front and rear drive axles. Since division of torque is automatically achieved by the Torsen differential in proportion to available traction, a separate 'torque splitter' is not required. In fact, such a predetermined torque split may detract from the designed torque biasing operation.

4.3 Bias ratios between drive and coast modes

It is also an important design freedom to provide for different effective bias ratios between vehicle driving and coasting modes. Since the Torsen differential is designed to have little or no effect on vehicle performance unless torque is being transferred by the differential, it should be understood that what is meant by the coasting mode is actually vehicle deceleration caused by engine braking. This mode is most evident with standard shift vehicles engaged in down shifting.

Invex gearing also makes possible this important design alternative (see Figure 7). The side gears within the differential are designed with the same hand of helix angle. When engine power is applied to the differential (i.e., drive mode), both side gears are thrust against the same end of the differential housing. Alternatively, when the engine is used to brake the drive wheels (i.e., coast mode), the side gears are thrust against the opposite end of the housing. This feature provides an opportunity to vary frictional characteristics between opposite ends of the housing to vary bias ratios between the opposite directions of power transfer through the differential.

The possibilities for independently varying bias ratios between the two directions of power transfer enables the differential to be designed with one bias ratio to compensate for undesirable steering effects associated with down shifting and a second bias ratio which is selected for most other purposes.

5 TORSEN DIFFERENTIAL PERFORMANCE

The Torsen design makes important contributions to vehicle performance, especially with respect to the concerns of traction management. These contributions may be better understood with respect to familiar vehicle operating conditions which give rise to problems of traction management.

5.1 Vehicle travel on straight roads

On smooth, dry, straight road surfaces, with no apparent traction management, Torsen differential performance is virtually undetectable from that of an open differential.

However, on slippery road surfaces where one of the drive wheels does not have adequate traction to support at least one-half of the applied engine torque to the differential housing, the Torsen differential delivers an increased amount of the applied torque to the drive wheel having better traction. The amount of additional torque which can be delivered to the wheel having better traction is limited only by the bias ratio or the amount of traction available to that wheel. Of course, it is never possible to deliver more torque to the drive wheels than the torque which combined traction of the drive wheels will support. However, a Torsen differential designed with an appropriate bias ratio assures that, for most vehicle operating conditions, the vehicle can deliver all of the torque which combined traction of the drive wheels will support.

5.2 Vehicle travel through turns

In turning situations, the outside wheels of a vehicle travel over more distance than the inside wheels. Accordingly, the inside and outside drive wheels must rotate at slightly different speeds (i.e., differentiate) to maintain rolling traction with the road. A torque division between drive axles at the bias ratio is a precondition for differentiation under all circumstances of operation. Essentially, in order for one drive wheel to rotate faster than the other, the drive wheel having greater resistance to rotation slows with respect to the differential case and transfers torque to the other wheel contributing to its faster rotation. The Torsen differential resists transfers of torque between drive wheels in proportion to the torque applied to the differential housing, and this results in a larger proportion of the applied torque being delivered to the slower rotating drive wheel. Therefore, bias ratio should be selected to provide the maximum traction advantage that will still allow both drive wheels to deliver significant portions of engine torque in turns.

However, even in turning situations, the Torsen differential enhances traction management. Since torque is already distributed in increased proportion to the inside drive wheel, it is exceedingly unlikely that the outside drive wheel will ever exceed available traction and 'spin up'. Alternatively, should the torque of the inside wheel exceed available traction in a turn, it is equally unlikely for this wheel to 'spin up' since such a 'spin up' would still require a difference in traction between drive wheels which exceeds the bias ratio. Ordinarily, when the inside wheel exceeds available traction, differentiation ceases and torque is divided in more even proportion between drive axles determined by the maximum torque that can be sustained by the inside drive wheel. Thus, in all directions of travel, the Torsen differential will resist 'spin up' of either drive wheel by instantly dividing torque between drive axles in proportions up to the bias ratio to match prevailing traction conditions.

6 CENTER BOX APPLICATION

Although the differential has been described with respect to its use between drive axles, it should be understood that analogous performance can be expected from use of the differential as an operative connection between drive shafts to the front and rear axles. For example, traction management is enhanced in such 'center box' applications by assuring that more of the traction of the front and rear drive wheels is available for use.

7 CONCLUSION

The Torsen differential exhibits a torque biasing characteristic which matches available engine power to changing traction conditions. In particular, Invex gearing provides special design opportunities to match different biasing characteristics with different vehicle applications and conditions of use to best accommodate traction consideration in each instance. Gleason's applied engineering can provide optimal Torsen differential designs to meet a wide variety of traction management requirements.

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* Invex is a Gleason trademark applied to torsen differential components.

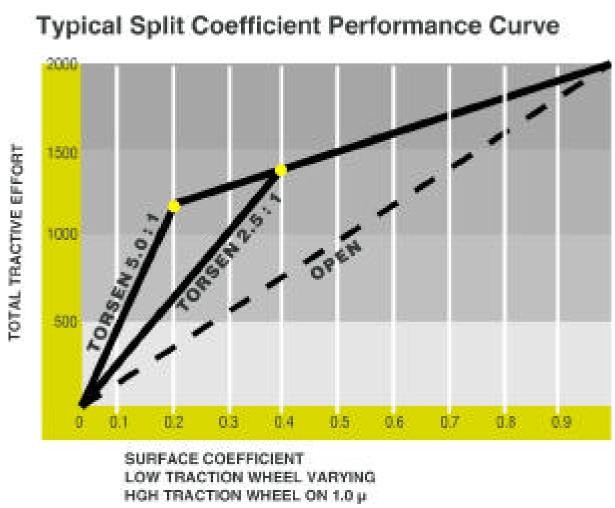

Fig.2 - Comparison with open differential

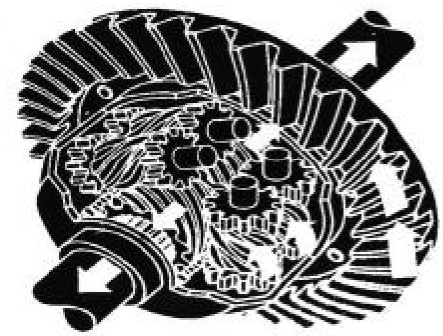

Fig. 1 Power flow

Fig. 3 Invex gear train

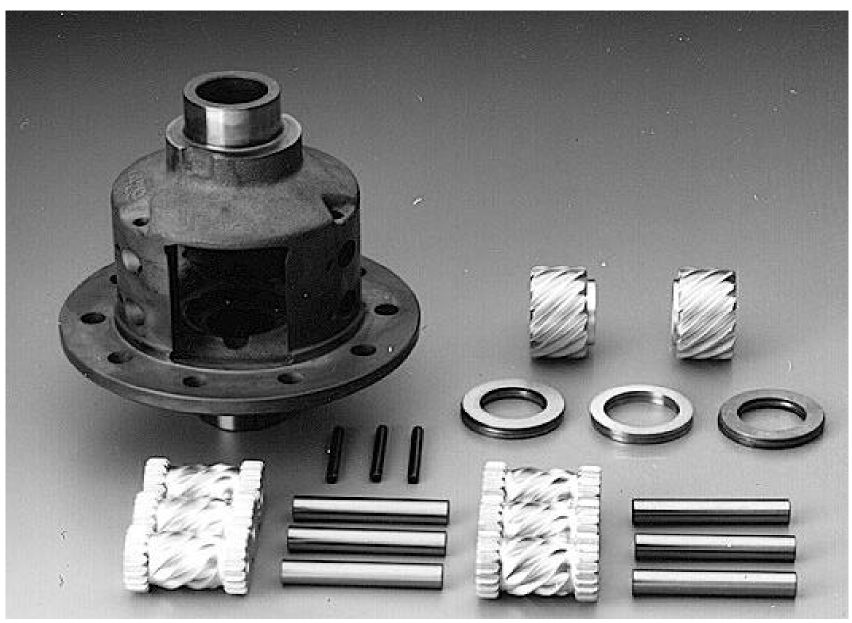

Fig. 4 Components of the Torsen differential

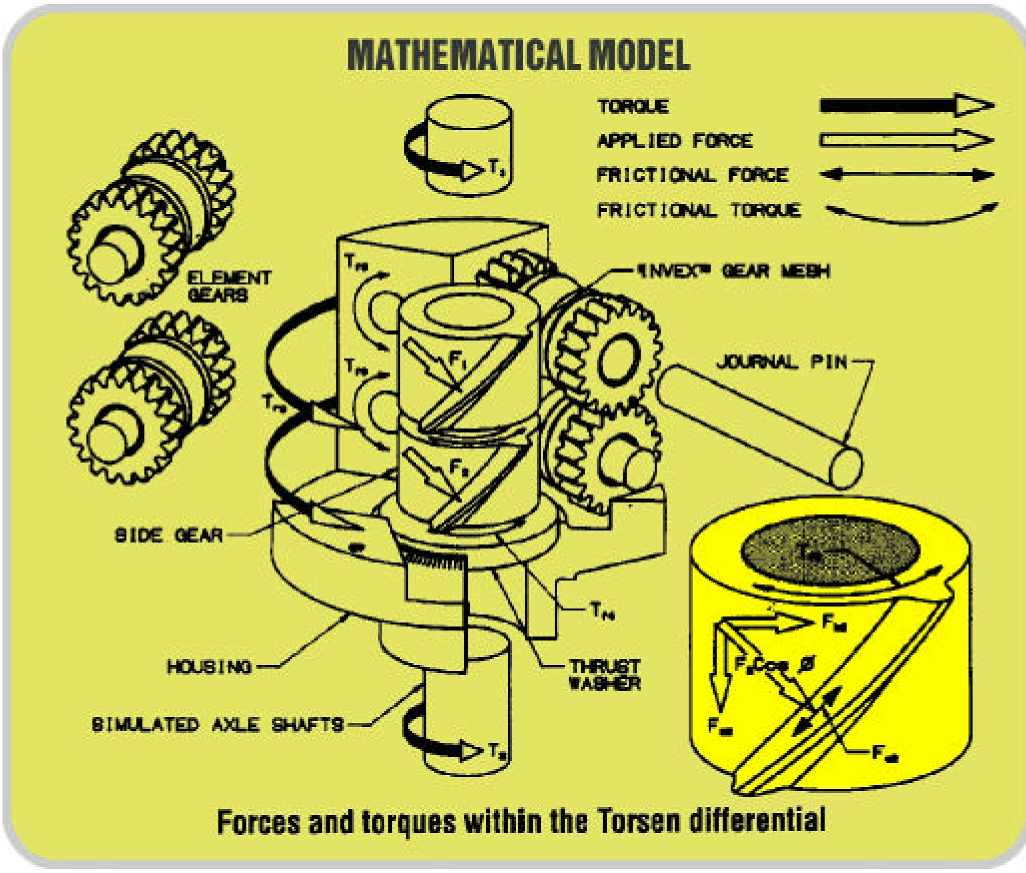

Fig. 5 Forces and torques within the Torsen differential

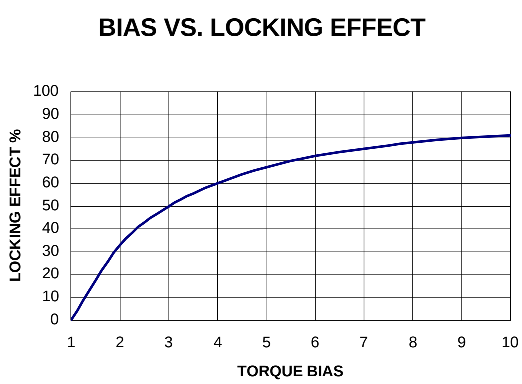

Fig. 6 Torque bias versus locking