TECHNICAL PERSPECTIVE

Left-Right Torque Vectoring Technology as the Core of Super All Wheel Control (S-AWC)

Kaoru SAWASE* Yuichi USHIRODA* Takami MIURA*

Abstract

The Super All Wheel Control (S-AWC) system is an integrated vehicle dynamics control system that maximally exploits the capability of all four tires in a balanced manner to realize predictable handling and high marginal performance. A direct yaw moment control technology that effects left-right torque vectoring (this technology forms the core of S-AWC system) can control cornering maneuvers as desired during acceleration, steady-state driving, and deceleration. Various left-right torque vectoring mechanisms have been proposed for the direct yaw moment control technology. These mechanisms are identical in terms of theoretical efficiency, but each has distinct characteristics owing to the employed elemental technology. It is conceivable that various left-right torque vectoring systems will emerge as various elemental technologies are improved.

Key words: *Torque Split, Four Wheel Drive (4WD), Vehicle Dynamics, Integrated Control*

1. Introduction

All Wheel Control (AWC) is a Mitsubishi Motors Corporation (MMC) four-wheel dynamic control philosophy for maximally exploiting the capability of all four tires of a vehicle in a balanced manner to realize predictable handling and high marginal performance, which in turn yield the driving pleasure and utmost safety that MMC sees as fundamental in producing vehicles. As shown in **Fig. 1**, the AWC philosophy is put into practice by means of three forms of control.

The first form of control is control over the four tires' vertical loading, by means of which each tire is kept in firm contact with the road surface for consistently maximal grip. The vehicle's basic specifications and its body and suspension technologies are exploited for this purpose.

The second form of control is control over the four tires' slip ratios and slip angles (control that is effected over the respective slip ratios and slip angles of the four tires such that the longitudinal force and lateral force produced by each of the four tires are maximized in a balanced manner). An Anti-lock Braking System (ABS), a Traction Control (TCL) system, and steering-system control technologies are exploited for this purpose.

The third form of control is control over the four tires' force assignment (control that is effected over the distribution of longitudinal forces and lateral forces among the four tires such that the tires are uniformly loaded for well-balanced utilization). Powertrain and braking-system control technologies are exploited for this purpose.

In line with this development philosophy, MMC in 1987 equipped the Mitsubishi GALANT with a center-differential-type full-time four-wheel drive (4WD) system (this system incorporated a viscous coupling unit), a four-wheel steering system, four-wheel independent suspension, and a four-wheel ABS (these systems were highly advanced for the time), thereby dramatically improving dynamic performance(1). MMC has since realized various other technologies including a trace-control function that controls engine output for stable cornering(2) and an electronically controlled center-differential-type full-time 4WD system that controls the front/rear torque distribution for heightened traction performance and cornering performance(3).

Notably, in 1996 MMC led the industry by equipping the world's first production vehicle with an Active Yaw

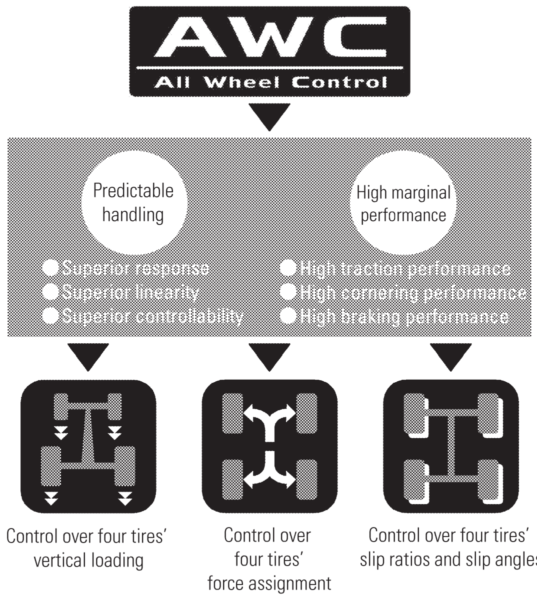


Fig. 1 AWC philosophy

* Drivetrain Engineering Dept., Development Engineering Office

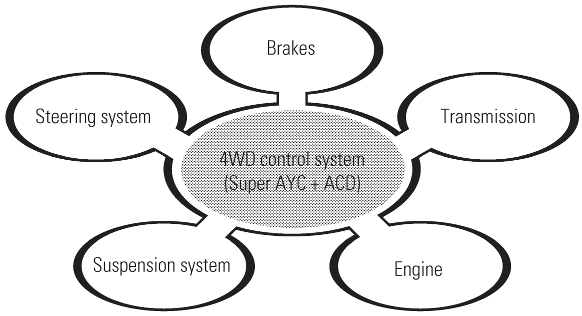


Fig. 2 S-AWC concept

Control (AYC) system that controlled the vehicle's yaw moment by vectoring torque between the left and right wheels in accordance with a totally new concept. Thanks to the appearance of this technology, it became possible for the first time for the load distribution among a vehicle's four tires to be controlled during all vehicle operation. As a result, cornering could be controlled as desired(4). Since then, MMC has continuously worked on to turn the AWC philosophy into reality by refining and evolving AYC hardware and software and by developing integrated control arrangements that control not only the AYC system but also a center differential, an ABS, and other items. The ultimate embodiment of the AWC philosophy is the S-AWC system, a 4WD-based integrated vehicle dynamics control system that MMC unveiled in the Mitsubishi Concept-X vehicle at the 2005 Tokyo Motor Show. As with earlier embodiments of the AWC philosophy, AYC plays a central role in this system.

Left-right torque vectoring technologies exemplified by MMC's AYC systems are, owing to flexibility they realize in cornering control, a focus of great interest in Europe and North America. In recent years, various left-right torque vectoring mechanisms providing the same function as MMC's AYC systems have been proposed(5)(6). Most of these mechanisms are based on an arrangement in which a differential is combined with planetary gears and two or more clutches or brakes. Their operation and distinct characteristics are difficult to intuitively ascertain.

The remainder of this paper, then, gives an overview of the S-AWC system and describes the benefits of the direct yaw moment control yielded by this system's left-right torque vectoring technology. It also describes, using the velocity diagram method(7) (a method used in analysis of the shift control of automatic transmissions), the respective characteristics of various mechanisms that realize left-right torque vectoring. Plus, it discusses possible future developments.

2. The S-AWC system

Various vehicle dynamics control technologies have been developed since the 1980s. From the viewpoint of active safety (safety that it intended to reduce the likelihood of accidents), the main purpose of these technologies has been to stabilize the vehicle by erecting functional barriers that make it difficult for the vehicle to exceed its performance limits. Control over the braking system has been used as the primary means of advancing the practical implementation of the system. In relatively recent years, arrangements have emerged in which control over the braking system is supplemented by control over the steering system for seamless enhancement of driving stability from normal driving conditions right up to the vehicle's performance limits.

Unfortunately, placing the braking system at the heart of integrated control creates a conflict with the driver's desire to exploit the vehicle's running capability (one of the three fundamental vehicle capabilities, the others of which are turning and stopping). Such an arrangement thus represents a handicap with respect to driving pleasure.

On the other hand, a 4WD system offers certain major advantages as the basis of a dynamics control arrangement. By transmitting torque to all four wheels, a 4WD system gives better running stability than a two-wheel drive system. And if a 4WD system's distribution of torque to the wheels is appropriately controlled, enhancement of cornering performance is possible. Notably, cornering control effected by means of a 4WD system brings great merits. It does not conflict with the driver's acceleration and deceleration operations, meaning that it can be exploited not only near the vehicle's performance limits but also in normal driving conditions.

Consequently, MMC focused on the aforementioned merits of 4WD-based control in development of its AYC systems and in development of an Active Center Differential (ACD)(8). As shown in **Fig. 2**, MMC used 4WD control as the core of the S-AWC integrated vehicle dynamics control system.

Fig. 3 shows the configuration of the S-AWC system in the Mitsubishi Concept-X. This system is based on 4WD control effected by a combination of a Super AYC system and an ACD. It also incorporates an Active Brake Control system, an Active Steering System, and a Roll Control Suspension system. Integrated control of all system elements ensures that the vehicle gives predictable handling and high marginal performance even when it is operating near its performance limits and with all four tires slipping.

3. Direct yaw moment control yielded by left-right torque vectoring

When control over the distribution of torque to a vehicle's four wheels is considered, the typical approach is to focus on the proportions of torque to be transmitted to the respective wheels and then work out a mechanism and control logic to realize those proportions. With this approach, however, decreases in engine torque (including engine braking force) toward zero are accompanied by decreases toward zero in the potential for control over the vehicle's dynamics. And during constant-speed driving, no control effect can be obtained. Further, appropriate distribution of torque when the engine torque is high requires an unduly large

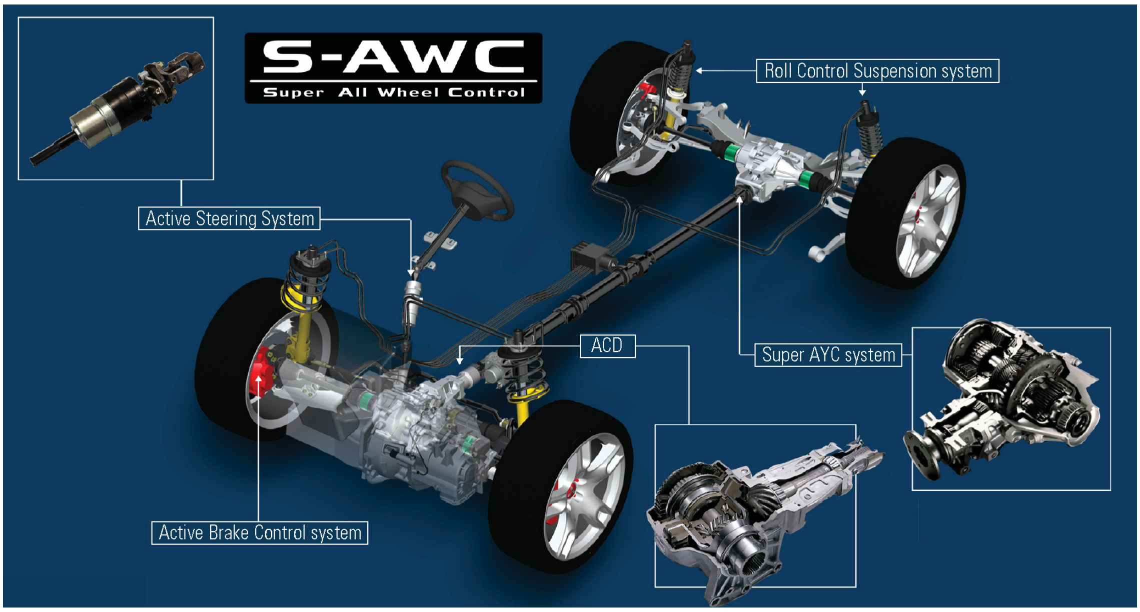


Fig. 3 S-AWC system configuration

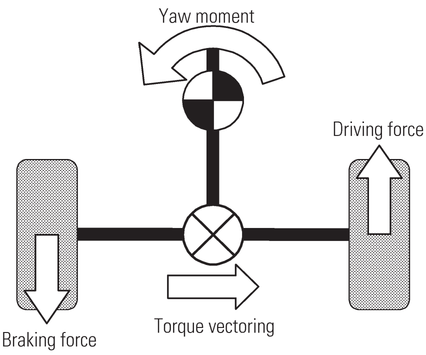


Fig. 4 Left-right torque vectoring concept

mechanism since the torque designated as a control object is large.

In light of the aforementioned factors, MMC realized that the ideal mechanism to enable cornering to be controlled as desired was one capable of controlling the yaw moment (in other words, a mechanism capable of controlling torque differences between wheels, not one that controlled the torque distribution). Based on this realization, MMC devised the concept of left-right torque vectoring and put the concept into practice with an AYC differential.

As shown in **Fig. 4**, the left-right torque vectoring concept involves vectoring torque between the left and right wheels such that braking force is generated on one side and driving force of the same magnitude is generated on the other. Consequently, it is possible to directly control the yaw moment as desired at any time without the control being dependent upon the level of engine torque and without their being any conflict between the control and the driver's acceleration and deceleration operations.

When left-right torque vectoring is implemented on the rear wheels of a 4WD vehicle, it yields two main benefits. One is enhancement of cornering performance by means of tire load equalization between the left and right rear wheels. The other is enhancement of cornering performance by means of tire load equalization between the front and rear wheels as a result of direct yaw moment control.

An example of tire load equalization between the left and right rear wheels is shown in **Fig. 5**. While the vehicle is cornering, a load vectoring between the left and right wheels causes the loading on the cornering inside tire to decrease and the loading on the cornering outside tire to increase. Thus, a difference is created between the left and right wheels in terms of capacity to vector force to the road surface. At the same time, however, the differential mechanism located between the left and right wheels' respective drive shafts distributes torque uniformly (discounting the effects of transient conditions and mechanism friction) to the left and right wheels. If the torque increases, therefore, the cornering inside tire, whose capability has decreased, reaches its grip limit and starts to slip, meaning that no further improvement in dynamic performance can be obtained (**Fig. 5 (a)**). By controlling the torque transmitted to the left and right wheels such that it is optimally apportioned, it is possible increase the load margin relative to the tire capability, thereby improving cornering performance (**Fig. 5 (b)**). **Fig. 6** shows the results of a simulation conducted for verification of the rear cornering force margin relative to the torque difference between the left and right rear wheels. As the left-right torque difference increases, the cornering force margin increases up to a certain point. Any excessive torque vectoring reduces the benefit. As shown, however, the slope is extremely gentle in the vicinity of the optimal

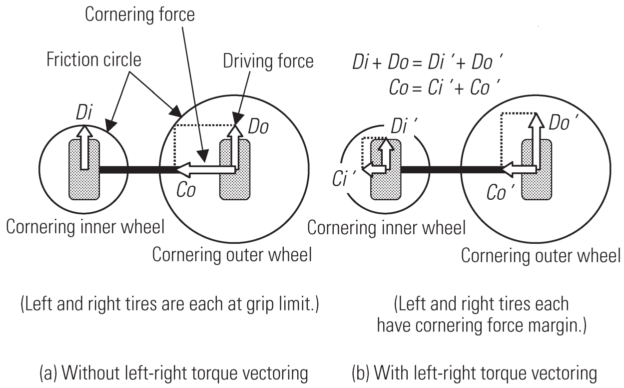


Fig. 5 Tire load equalization between left and right rear wheels

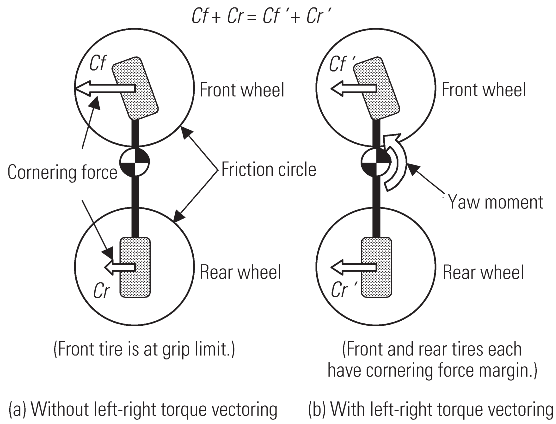


Fig. 7 Tire load equalization between front and rear wheels

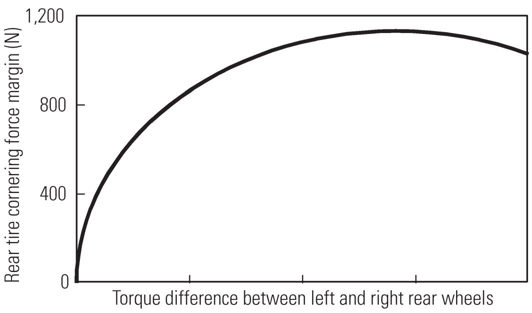


Fig. 6 Cornering force margin of rear tire

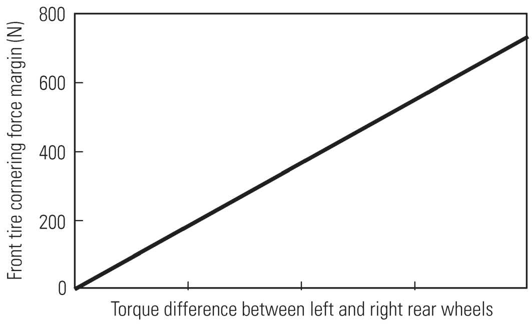


Fig. 8 Cornering force margin of front tire

value, meaning that an ample benefit can be obtained even if the optimal value is not determined with strict precision.

An example of tire load equalization between the front and rear wheels is shown in **Fig. 7**. **Fig. 7 (a)** indicates understeer where further cornering is not possible. Here, the capability of the front tire is being maximally employed but there is a margin of capability in the rear tire. If the cornering force of only the rear wheel were increased, the moment (yaw moment) balance about the center of gravity would break down such that cornering could not be continued. Notwithstanding the margin in the rear tire, therefore, the capability of the rear tire cannot be more greatly exploited. By imposing a yaw moment by means of a left-right torque vectoring, it is possible to increase the cornering force of the rear tire and reduce the cornering force of the front tire by the same magnitude with no breakdown in the moment balance about the center of gravity such that the load margin of the front tire is increased and cornering performance is improved (**Fig. 7 (b)**). **Fig. 8** shows the results of a simulation conducted for verification of the front tire cornering force margin relative to the torque difference between the left and right rear wheels. As shown, increases in the left-right torque difference are accompanied by increases in the front tire cornering force margin.

From the aforementioned points, it can be seen that increasing the left-right torque difference between the rear wheels causes the respective cornering force margins of the front and rear wheels to increase up to a certain point such that the vehicle's cornering performance improves. It can also be seen that increases in the yaw moment yielded by the left-right torque difference between the rear wheels are accompanied by increases in the front tire cornering force margin such that the vehicle's turnability improves. The benefits can be obtained not only during acceleration but also during steady-state driving and during deceleration.

To maximize the benefits, a torque vectoring mechanism such as the AYC differential (a mechanism capable of controlling the left-right torque difference regardless of whether the vehicle is accelerating, moving at a constant speed, or decelerating) is clearly desirable.

4. Analysis of torque vectoring mechanism

The AYC differential and other torque vectoring mechanisms are combinations of multiple gears and clutches, so their operation and distinct characteristics are difficult to understand. MMC employs the velocity diagram method as before, which is also used for analysis of the shift mechanisms of automatic transmissions, as an effective analysis tool for visually ascertaining the operation of such complex mechanisms. With the

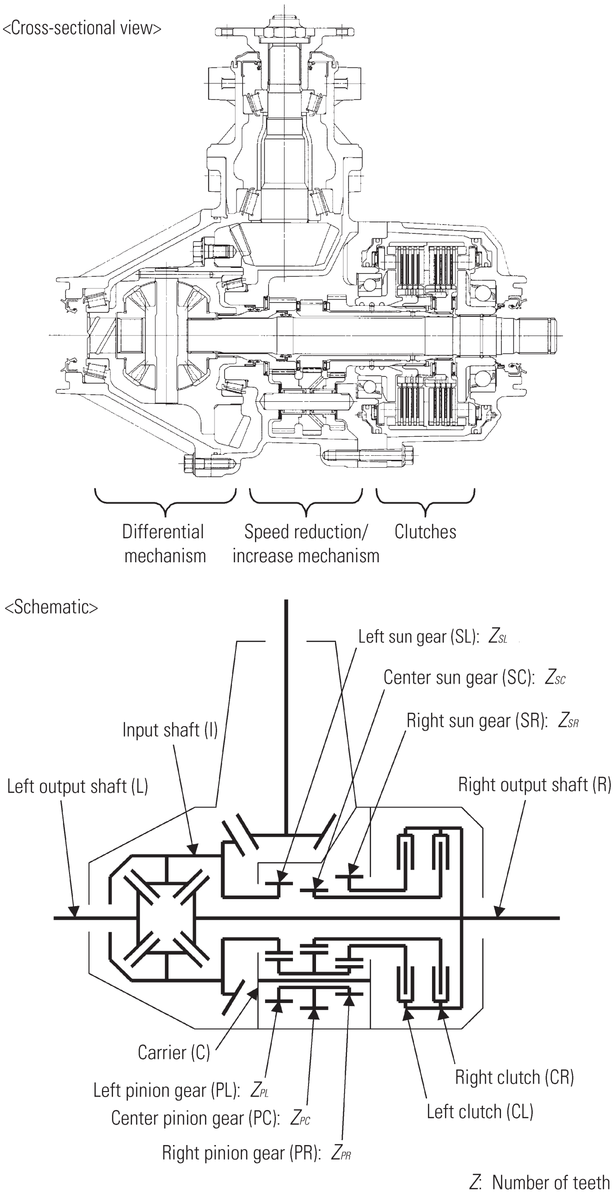


Fig. 9 Structure of AYC differential

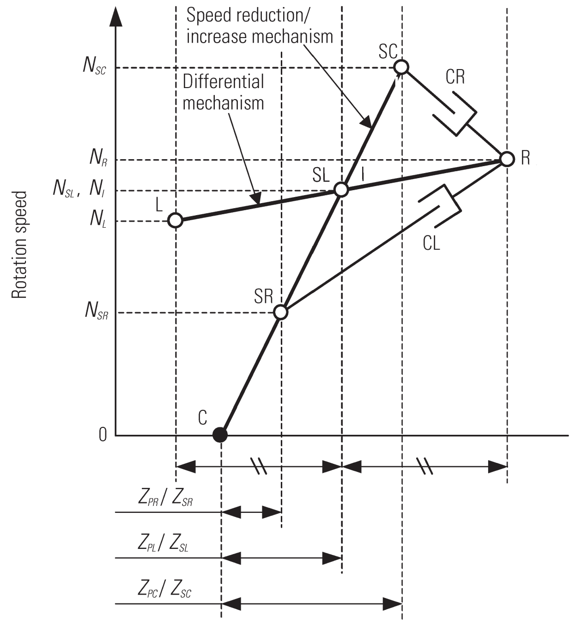
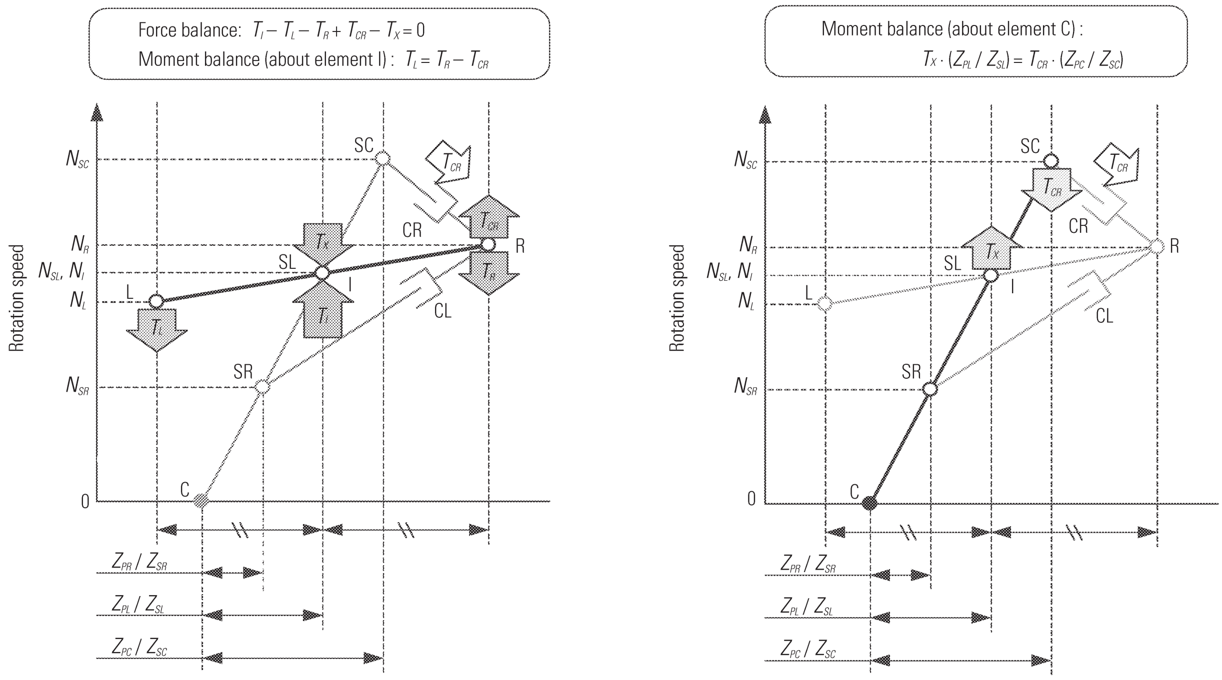


Fig. 10 Velocity diagram of AYC differential

velocity diagram method, a single gear set is represented by a single straight line; the rotation speed of each rotating element positioned on a straight line can be visually ascertained. In the text hereafter, expansion of this technique for application to a left-right torque vectoring mechanism is explained with reference to the AYC differential.

The AYC differential consists of a differential mechanism, a speed reduction/increase mechanism, and two clutches (**Fig. 9**). The differential mechanism has three elements and two degrees of freedom. In the velocity diagram in **Fig. 10**, the AYC differential is represented by the straight line that has the input shaft I positioned in the middle and the left output shaft L and right output shaft R equidistantly positioned on the respective sides. The vertical axis of the diagram indicates rotation speeds, and the relative positions (higher or lower) of items in the lateral axis indicate opposite directions of rotation. The elements can each move only upward or downward in accordance with their respective rotation conditions. They retain their straight-line relationship. Note that the diagram corresponds to leftward cornering. The speed reduction/increase mechanism consists of three sun gears, three pinion gears (these turn as one body), and a carrier C, which holds the sun gears and pinion gears. The carrier C is held in position, so the speed reduction/increase mechanism has four elements and one degree of freedom. In light of the relationships between the gear ratios, the diagram shows the right sun gear SR, left sun gear SL, and center sun gear SC positioned in that order from left to right along the straight line that begins at the carrier C. The two gear mechanisms (the differential mechanism and speed reduction/increase mechanism) are linked by the differential mechanism's input shaft I and the speed reduction/increase mechanism's left sun gear SL. The left clutch CL is located between the differential mechanism's right output shaft R and the speed reduction/increase mechanism's right sun gear SR. The right clutch CR is located between the differential mechanism's right output shaft R and the speed reduction/increase mechanism's center sun gear SC.

The clutch elements each transmit torque from the faster-turning side to the slower-turning side. In the situation shown in **Fig. 10**, with the right clutch CR engaged, torque is transmitted from the center sun gear SC to the right output shaft R such that the torque at the right output shaft is increased. With the left clutch CL engaged, conversely, torque is transmitted from the right output shaft R to the right sun gear SR such that torque at the right output shaft R decreases. It can be seen, then, that if the rotation speed of the right output shaft R is between that of the center sun gear SC and that of the right sun gear SR, torque vectoring is possible toward either side (left or right). With the AYC differential, then, the driving conditions in which torque



(a) Forces acting upon differential mechanism

(b) Forces acting upon speed reduction/increase mechanism

Fig. 11 Force balance during torque vectoring

vectoring is possible are determined by the respective rotation speeds of the center sun gear SC and right sun gear SR, making the gear ratio settings of the speed reduction/increase mechanism crucial with respect to the AYC differential's performance.

The text hereafter describes the torque acting upon each element during torque vectoring. With the velocity diagram method, the straight line corresponding to a gear set is treated as a single lever and the torque at each element is expressed as a vertically acting force(s). It is possible to deduce the torque at each element from the balance of the upward and/or downward direction(s)s of the force(s) acting on each element and the balance of moments. By way of example, engage the right clutch CR in a torque vectoring from the left output shaft L to the right output shaft R in a situation where torque T_I is being applied to the differential mechanism's input shaft I (**Fig. 11**). The torque transmitted by the right clutch CR (this torque is designated T_{CR}) acts upon the right output shaft R in the direction that increases the speed of rotation (upward in the diagram) and upon the center sun gear SC in the direction that reduces the speed of rotation (downward in the diagram). In the speed reduction/increase mechanism, torque T_{CR} acting upon the center sun gear SC is opposed by torque T_X, which acts upon the left sun gear SL such that the moments about the C element balance. Since the left sun gear SL is linked to the differential mechanism's input shaft I, the reaction force caused by T_X acts upon the differential mechanism's input shaft I. At this time, the reaction forces acting upon the left and right output shafts L and R (in other words, the left and right shafts' respective torques T_L and T_R) can be deduced from the balance of forces in the differential mechanism and the balance of moments as follows.

$$T_L = T_I/2 - (Z_{PC}/Z_{SC}) / (Z_{PL}/Z_{SL}) / 2 \cdot T_{CR}$$
$$T_R = T_I/2 - (Z_{PC}/Z_{SC}) / (Z_{PL}/Z_{SL}) / 2 \cdot T_{CR} + T_{CR}$$

where
Z: Number of gear teeth

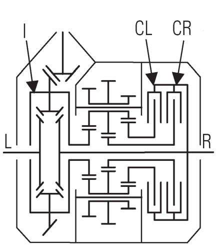
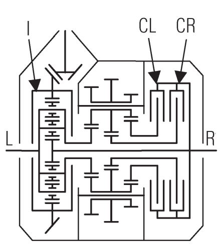
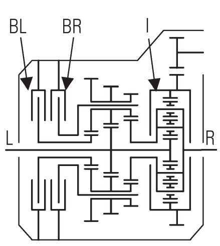
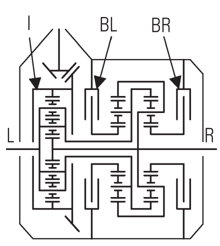
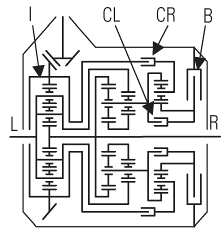
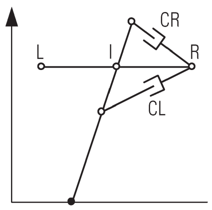
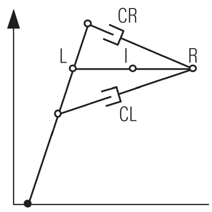
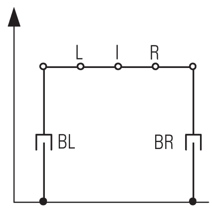
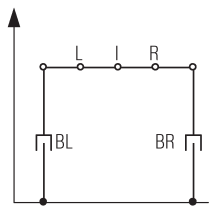
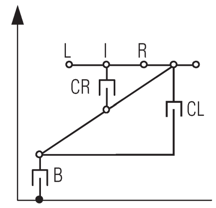
In this way, the velocity diagram method enables the respective rotation speeds of individual elements to be visually ascertained and facilitates deduction of the relationships between the acting torques. Since the velocity diagram method gives a straight-line representation of a gear set, it is possible for gear sets with different structures to be represented in the same way as each other. Once a given mechanism has been expressed in the form of a velocity diagram, therefore, it is easy to find structural variations. It can be seen, then, that the velocity diagram method can be applied not only to shift analysis with automatic transmissions but also to analysis of complex torque distribution mechanisms. Plus, the velocity diagram method is a valuable tool for devising new structures.

5. Distinct characteristics of various torque vectoring systems

The respective characteristics of the AYC differential and other torque vectoring systems that have the same type of functionality are shown in the form of velocity diagrams in **Table 1**. ② in **Table 1** is the Super AYC as the core of the S-AWC.

Assuming (a) the driving conditions in which torque

Table 1 Comparison of various left-right torque vectoring systems

System	① MITSUBISHI AYC	② MITSUBISHI Super AYC [9]	③ HONDA ATTS [10]	④ MAGNA MDT-II [5]	④ RICARDO Torque Vectoring Differential [6]
Schematic	 CL: Controlled for torque vectoring to left shaft CR: Controlled for torque vectoring to right shaft	 CL: Controlled for torque vectoring to left shaft CR: Controlled for torque vectoring to right shaft	 BL: Controlled for torque vectoring to right shaft BR: Controlled for torque vectoring to left shaft	 BL: Controlled for torque vectoring to right shaft BR: Controlled for torque vectoring to left shaft	 CL: Engaged for torque vectoring to left shaft CR: Engaged for torque vectoring to right shaft B: Controls vectored torque
Velocity diagram					
Clutch capacity	Large	Medium	Small	Small	Small
Clutch speed difference	Small	Medium	Large	Large	Large
Energy losses	Small	Small	Small	Small	Small
Controllability	High	High	Middle	Middle	Low

vectoring is possible are the same for all of the systems and (b) the magnitude of the creatable left-right torque difference is the same for all of the systems, the energy losses resulting from torque vectoring are the same with all of the systems. In other words, the theoretical system efficiency is the same for all torque vectoring mechanisms that use clutches or brakes regardless of structure; the merits and demerits of each system in practice are determined by the effects of the elemental technology whose employment is dictated by the structure.

An illustration: The AYC differential requires greater clutch capacity than the other systems shown in **Table 1**, but it also has merits. The differences in rotation speeds in its clutches are the smallest, meaning that its clutch clearances can be made small for superior control response without creating any cause for concern about clutch drag. With systems that use brakes (for example, systems ③, ④, and ⑤ in **Table 1**), on the other hand, it is possible to make the brake capacity small and the physical dimensions concomitantly compact but a number of measures to enhance the elemental technologies are needed. For example, large differences in speeds of rotation necessitate measures to prevent drag, and enhancements in control precision are needed to enable large left-right torque differences with small control inputs.

Even though they have the same theoretical efficiency, then, systems that use clutches and systems that use brakes each have distinct merits and demerits. As the elemental technologies are refined, various systems are likely to be implemented.

If advances are made in efficiency improvements and cost reductions with new elemental technologies, left-right torque vectoring systems employing electric motors or hydraulic pumps (rather than clutches or brakes) as actuators may emerge. Notably, a system employing an electric motor would offer advantages in terms of controllability and efficiency since it could use a single electric motor to effect left-right torque vectoring and to lock the left and right drive shafts together. A number of basic structures have already been proposed. Provided electric vehicles and hybrid electric vehicles become more widespread, higher power supply voltages are adopted, and inverters are made more compact and less costly, the day when an electric-motor-based torque vectoring system is realized may not be far away.

6. Summary

Using AYC left-right torque vectoring technology, MMC added high cornering control potential to 4WD control. By doing so, MMC heightened vehicle dynamics control from a dimension in which 4WD gave a good balance of traction performance and cornering performance to a dimension in which cornering performance and turnability are vastly enhanced. The technology forms the core of the S-AWC system – an integrated vehicle dynamics control system that offers a superlative drive.

Although various similar technologies are likely to be implemented, MMC intends to continue basing its efforts on AYC, supplementing its extensive know-how with new ideas in pursuit of ever-higher levels of driving pleasure and utmost safety.

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Kaoru SAWASE


Yuichi USHIRODA


Takami MIURA