Automotive hydraulics at Nissan Motor Company

Yuichi Sanada, Naohiko Inoue, Hirotugu Yamaguchi, and Kenro Takahashi
Nissan Motor Co., Ltd.

1. Introduction

In recent years, new advances have been achieved in hydraulic technology in line with the improvements seen in the dynamic performance, comfort and safety of vehicles. A major factor behind these advances is the appearance of a new approach to vehicle design premised on the application of electronic control. Electronic control technology makes it possible to break through the limitations on improvements in performance and functionality achievable by mechanical means, and thus allows dramatic advances to be obtained in overall vehicle performance. For instance, the application of electronic control to a power steering system allows the steering effort to be optimally matched to the operating conditions. An electronic automatic transmission delivers improved power performance and fuel economy while providing smooth gear changes free of shift shock. Still another new technology can be seen in the development of 4-wheel steering (4WS) systems, torque split 4WD systems and hydraulic active suspension systems based on the concept of active control over the dynamic performance of a vehicle.

Electronic control has become a key element of these advanced hydraulic systems and has given rise to a requirement for higher hydraulic performance. To meet this requirement, further advances have been pursued in hydraulic technology by improving the design and performance of hydraulic devices and systems.

This paper first describes the progress in hydraulic systems at Nissan Motor Co. and their present status today as a way of outlining the advances seen in vehicle performance and hydraulic technology in recent years. It then presents several new developments in hydraulic systems at Nissan, including the hydraulic active suspension system, torque split 4WD system and 4WS system, and discusses the present state of hydraulic technology. Finally, a general discussion is presented concerning several major issues in automotive hydraulics, such as the combination of integrated control and hydraulic systems, networking and application of intelligent capabilities to hydraulic devices, fuel economy improvement and energy-saving hydraulic systems and reduction of the noise and vibration caused by hydraulic systems.

2. Progress in Hydraulic System Development in Recent Years

The implementation of new hydraulic system technologies in the chassis and powertrain of Nissan vehicles in the 1980s is outlined in Table 1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Adjustable Shock Absorbers</th>
<th>Super Sonic Suspension</th>
<th>Hydraulic Active Suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>Three-Way Electronically Controlled Power Steering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1987</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1988</td>
<td>HiCAD-FW</td>
<td>HiCAD</td>
<td>HiCAD</td>
</tr>
<tr>
<td>1989</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Implementation of Electro-hydraulic Control Systems in Nissan Vehicles

Adjustable shock absorbers were adopted in 1981 which allowed three-way control over the damping rate so that drivers could adjust ride and handling properties to suit their personal preferences. In 1984, a new Supersonic Suspension system was developed that automatically adjusted the damping rate to the optimum level to match the driving conditions. Around that same time, an electronically controlled power steering system was commercialized that allowed a three-way selection of the desired steering effort and also controlled it to the optimum level according to the vehicle speed. An electronically controlled four-wheel anti-skid system was also implemented. These systems exemplify the vigorous efforts that were under way to incorporate in the chassis the electronic control technology that had already been implemented in the engine.

In 1985, Nissan became the first manufacturer in the world to develop a practical 4WS system for controlling the rear wheels. Called HICAS (High Capacity Actively controlled Suspension), the system was further upgraded to create HICAS-II in 1988 and Super HICAS in 1989.

That same year, Nissan was also the first manufacturer in the world to pioneer a practical hydraulic active suspension.

Similar progress was also being seen in the powertrain. Following the introduction of electronic control in Nissan automatic transmissions in the early 1970s, lock-up control was added in 1982 to obtain better fuel economy. In 1986, a system was developed that provided fully electronic control over a 4-speed automatic transmission, and the system was further upgraded in 1989 to create a 5-speed automatic transmission.

In the area of 4WD technology, a new system was developed in 1986 that featured a viscous coupling. Electronic control was incorporated in a 4WD system in 1989 with the development of an electronically controlled torque split 4WD system called the Nissan ATTESA E-TS, an acronym for Advanced Total Traction Engineering System for All terrains and Electronic Torque Split.

These developments are illustrative of the vigorous R&D activities that were under way in the 1980s to implement new control techniques in the chassis and powertrain. Those techniques made full use of electronic and hydraulic control and enabled vehicles to demonstrate levels of performance that had been unobtainable with traditional mechanical approaches. The aim of those control techniques was to enable people to enjoy greater pleasure, comfort and peace of mind when operating vehicles. This positive commitment to incorporate electronic control technology in vehicles has been a common characteristic of all automobile manufacturers in Japan.

3. Recent Developments in Hydraulic Systems at Nissan

Active control systems have been implemented in automobiles in recent years to obtain higher performance and improved vehicle dynamics. It has become essential for hydraulic systems to support these advanced automotive control systems. This section describes Nissan's hydraulic active suspension, new 4WS system and torque split 4WD system, which employ the company's latest electro-hydraulic control technology, and discusses the technical requirements of automotive hydraulic systems.

3.1 Active Suspension System

Nissan has developed a hydraulic active suspension that can control vehicle movement freely and continuously. This control capability makes it possible to provide higher levels of ride comfort than conventional suspension systems. The major features of this system include (1) active bouncing control by a skyhook damper, (2) a frequency-sensitive
damping mechanism, and (3) active control over roll, dive, and squat.

- **Hydraulic System Construction**
  The hydraulic circuit of the system is diagrammed in Fig.1. This hydraulic system uses an oil pump and four pressure control valves to produce hydraulic pressure that negates external forces acting on the vehicle. The system assures practical levels of energy consumption and control response. The task of suppressing unsprung vibrations is shared among the sub-accumulators and pressure control valves. This works to reduce the amount of hydraulic energy needed and eases the response requirement of the control valves. The task of maintaining the vehicle height when the engine is not running is accomplished by a simple construction using a main check valve and a pilot-controlled check valve. The two valves are incorporated in a multi-valve unit. A simple and highly efficient fail-safe system has been designed using a single cutoff valve in combination with the flow resistance of the check valve built into control valve unit.

- **System Components**
  (1) **Oil Pumps**
  Figure 2 shows the internal hydraulic circuit of the pump assembly along with its discharge rate characteristics. Two plunger pumps having different discharge rates are employed and two solenoid valves are used to switch between the two pumps, thereby controlling the discharge rate of the hydraulic system to one of three available modes. This makes it possible to select the discharge rate matching the vehicle and driving conditions, which works to improve fuel efficiency.

(2) **Pressure Control Valves**

The construction of the pressure control valves is illustrated in Fig.3. Pressure control valves are provided at all four wheels and function to control the hydraulic pressure of the actuators. Pilot-type proportional electromagnetic pressure reducing valves are used, which provide sufficient response for active control of bounce, roll, dive and squat.
(3) Actuators

The actuators consist of a hydraulic power cylinder, sub-accumulator and damping valve. Because auxiliary coil springs are also used in the system, the hydraulic energy required by the system has been reduced.

(4) Controller

The controller consists of two high-speed 16-bit microprocessors that provide the fast computation cycle times needed to suppress transient vehicle motion. Computations are carried out in cycles of several milliseconds. This controller supports four control operating: acceleration control (Fig.4), oil pump control, vehicle height control, and the fail-safe function.

- Characteristics of Hydraulic System

The dynamic characteristics of the hydraulic system are the system frequency response (Fig.5) and the damping force characteristics (Fig.6). The system frequency response indicates the responsiveness required for active control of bounce, roll, dive and squat. The damping force characteristics show the frequency-sensitive damping force needed to assure good ride comfort. Since these two dynamic characteristics are closely related, they must be tuned to the optimum level to provide the respective performance required of the system.

- Vehicle Performance

A vehicle mounted with the active suspension (Infinity Q45) and several other vehicles equipped with conventional suspensions are compared in Fig.7 in terms of their roll rates and root mean squares of vertical acceleration. The data indicate that the active suspension can provide both a flat attitude and a smooth, comfortable ride.

![Fig.3 Pressure Control Valve](image)

![Fig.4 Acceleration Control](image)

![Fig.5 System Frequency Response](image)

![Fig.6 Damping Force Characteristics](image)

![Fig.7 Vehicle Performance](image)
3.2 Four Wheel Steering System (4WS)

Nissan has developed a new 4WS system, Super HICAS, featuring phase reversal control over the rear wheels to achieve a significant improvement in vehicle response and stability. The concept of the resulting vehicle behavior is illustrated in Fig.8. This behavior would make it easy for a driver to keep the vehicle on the target path.

The hydraulic system construction is shown in Fig.9. The system consists of a pressure control valve for driving a hydraulic cylinder, a cutoff valve for the fail-safe system, a hydraulic cylinder for steering the rear wheels and other components.

- System Components
  1. Pressure Control Valve

The pressure control valve (Fig.10) is of the open center type. It is constructed of a solenoid that generates force in proportion to the current applied from the controller, a spool valve that narrows the passage according to the force level and outputs hydraulic pressure into the left and right cylinder ports, and a reactive force piston that transmits reactive force to the spool valve in accordance with the cylinder port pressure level. This direct acting control valve provides a sufficiently high level of response and has made it possible to achieve a highly reliable hydraulic system. The response characteristics obtained in tests on this hydraulic system are shown in Fig.11.
The mechanism for steering the rear wheels is designed to turn the wheels directly around the kingpin axis of the multi-link rear suspension. Centering springs are built into the hydraulic cylinder to maintain a neutral rear wheel steer angle and also to maintain the angle against external forces. A maximum steering angle of about one degree can be obtained with hydraulic cylinder travel of about 3 mm.

(3) Controller

The controller consists of input ports for the steering wheel angle, vehicle speed pulses and fail-safe system inputs, an 8-bit CPU, a digital-analog converter, a watchdog timer circuit for monitoring microprocessor operations, an output current drive circuit and various output ports. It also incorporates a function for detecting problems in the sensors, wiring harness and controller, as well as functions for processing fail-safe commands and outputting warnings when irregularities are detected.

3.3 Four Wheel Drive System (4WD)

Nissan has developed an electronically controlled torque split 4WD system (ATTESA E-TS) with hydraulic control for regulating the engagement pressure of a wet multi-plate clutch by means of a proportional pressure reducing valve. The configuration of the system is shown in Fig. 12. By varying the hydraulic pressure applied to the multi-plate clutch, the torque split to the front and rear wheels can be controlled continuously from a rear-wheel-drive mode (0:100) to a rigid 4WD mode (50:50).

- Hydraulic System Construction

The on-board hydraulic system consists of the hydraulic unit (Fig. 13), a reservoir tank, piping and a clutch cylinder built into the transfer unit. A motor-driven pump, accumulator, pressure control valve and other major hydraulic components have been integrated into the hydraulic unit for improved mountability and reliability. To reduce energy
consumption, the motor-driven pump has been designed to operate intermittently within the range of the hysteresis characteristic of the pressure switch.

- Characteristics of Hydraulic System

A basic technical subject that must be addressed when applying a hydraulic control system to a car is how to achieve an optimum balance of system performance characteristics over a wide temperature range. The low-temperature response of the system is particularly important. However, the response and stability characteristics required of the pressure control valve are incompatible. Figure 1.4 shows the optimized response and stability of the hydraulic system, where $\Delta T$ is the step response delay of the control pressure and $R_s$ is the surge rate of the control pressure, representing the stability of the system. In tuning the system to the best characteristics, choke orifice diameter and the pre-pressure must be selected so as to match the performance desired of the hydraulic system.

3.4 Technical Requirements of Automotive Hydraulic Systems

(1) Hydraulic characteristics must be tuned to the best level for meeting each requirement of the system. This means that engineers must know how the parameters of each hydraulic component are related.

(2) An optimum balance of hydraulic system performance characteristics must be achieved over a wide temperature range.

(3) A hydraulic system must incorporate a fail-safe function to satisfy the requirement for high reliability, which is essential in hydraulic systems.


4.1 Automotive Technological Trends and Future Hydraulic Systems

The forgoing sections have described the progress seen in automotive technologies through the pursuit of improvements in vehicle dynamic performance and comfort. This progress can be charted as a transition from mechanical to passive control and then onto active control. The focus of development work has already shifted from passive to active control, and the latter will continue to take on increased importance in automotive engineering in the coming years.

As active control continues to advance, how will hydraulic systems change? Moreover what impact will progress in other technologies have on hydraulic systems? An outline of the interrelationships between automotive and hydraulic technologies is given in Fig.15. Higher levels of response and accuracy have been obtained through the development of the active suspension and torque split 4WD system.

The following discussion considers four issues that are thought to be important for hydraulic systems
within the context of the future progress expected in automotive technologies.

4.2 Combination of Integrated Control and Hydraulic Systems

Automotive control is continually progressing from discrete control to integrated control. The dynamic performance of a vehicle is determined by the longitudinal and lateral forces acting on the tires. These forces are interrelated and their total magnitude is determined by the tire-road surface coefficient of friction and the load. Consequently, achieving optimized control over 4WS, 4WD, ABS and other systems on an individual basis does not necessarily result in optimal control over the entire vehicle as a whole.

Solving this type of problem requires the application of integrated control. Simply gathering together individual systems that have been optimized will not create the best hydraulic system for a vehicle. Problems related to space, weight, cost and fuel economy are likely to appear. The type of hydraulic system integration that is thought to be necessary is outlined in Fig.16. European manufacturers have already gained considerable experience with integrated hydraulic systems.

Nevertheless, to meet the requirements of the coming age of active control and integrated control, it will be necessary to construct new types of integrated hydraulic systems and to achieve new innovations in component technologies.

4.3 Networking and Application of Intelligent Capabilities to Hydraulic Devices

Implementing integrated control systems in vehicles involves a problem of in-vehicle information networking as well as integrated software issues. What kind of impact will the construction of an in-vehicle information network have on hydraulic systems?

At present, automotive engineers are groping for an answer to this question. One point which is clear is that the hydraulic devices making up hydraulic systems must also be incorporated in the information network. Considerable progress has already been seen in the application of intelligent capabilities to general hydraulic devices outside of the automotive field.

One concept of an intelligent hydraulic system for the automobile is illustrated in Fig.17.
It seems certain that vigorous R&D programs will be mounted to resolve these issues since the application of intelligent capabilities can result in the following benefits:

1. Dramatic improvements in hydraulic device performance, including enhanced accuracy and response,
2. Greater ability to compensate for changes in characteristics or environmental changes through the use of a state variable feedback system, and
3. Improvement in reliability because it is possible to provide self-diagnostic functions.

Achieving intelligent capabilities will require further progress in sensors, semiconductors, and other electronic technologies. At the same time, it will also require the formation of design concepts for hydraulic devices that are premised on use of intelligent functions.

4.4 Fuel Economy Improvement and Energy-Saving Hydraulic Systems

The power level required by different electro-hydraulic control systems is shown in Fig.18. It is seen that the new systems which have appeared recently tend to have higher output levels, which means a corresponding increase in power consumption. For instance, Nissan's hydraulic active suspension consumes around 2 kW of power, and a 4WS system can use up to 1 kW of power.

Since these power consumption levels of hydraulic systems present fuel economy problems, suitable tradeoffs must be made with performance. One major issue for future work is the question of how to hold down energy consumption while achieving high control efficiency. Solutions to this issue will require the development of energy-minimizing control techniques. As for hydraulic systems, attention should be directed to these issues:

1. Development of hydraulic energy management systems
2. Development of more efficient pumps and pump control systems, and
3. Development of hydraulic devices with little internal leakage.

4.5 Reducing Noise and Vibration Caused by Hydraulic Systems

The trend in the interior noise level of cars in recent years is shown in Fig.19. It is seen that the passenger compartment has become quieter every year. This trend has increased the importance of
reducing the noise and vibration levels of on-board hydraulic systems.

In order to achieve sufficiently low noise and vibration levels, it will be necessary not only to develop quieter-operating components but also to improve the noise and vibration characteristics of the entire hydraulic system. This will require the use of highly accurate computer aided analysis.

These are "new" issues in automotive hydraulic devices. They are typical of the most critical concerns that must be addressed if active control technology is to continue to find increased use in production models.

5. Conclusion

This paper has described Nissan's hydraulic technologies with specific focus on those already at the mass production level. It has also presented a consideration of future issues in automotive hydraulic technology.

This description of the R&D work being carried out at Nissan has served to outline recent trends in automotive hydraulic technologies in Japan. It has indicated that automotive hydraulic technologies are on the verge of achieving new breakthroughs. While hydraulics has a long history of use in the automobile, the era of technological innovation now under way is presenting automotive engineers with exciting new challenges. These signs point the way toward major improvements in the years ahead that will transform the automobile into an even more wonderful means of mobility.

References