Development of automotive hydraulics at Toyota

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ABSTRACT

The main characteristics of the hydraulics and pneumatics is that they are quite suited for the automobile. Electrohydraulic control technology has produced intelligent control and active safety of the automobile.

In recent years, various automotive hydraulic systems have been widely used. For example, for the power train, the electronic control automatic transmission, the device of driving systems of the engine cooling fan can be mentioned. The electronic control system for the automatic transmission is detailed. For the chassis, the 4-wheel power steering, the 4-wheel anti-lock brake, the semi active suspension, active suspension can be named. Full explanation is given to the suspension control.

Basic study of the automotive hydraulic system is advancing in the fields of system simulation and control, analysis of fluid flow, and tribology.

Key word : Automobile, Hydraulics, Pneumatics, Toyota

INTRODUCTION

In the history of the automotive development, hydraulic and pneumatic systems appeared at an early stage, and now have become indispensable to the basic functions of the automobile, that is, "drive, turn and stop".

Fig.1 shows the rate of applying leading systems such as power steering and automatic transmission to Toyota cars.

Such wide use is accounted for by their following characteristics which are quite suited for the automobile:

(1) They are small in size and high in output power.
(2) They make a quick response and have good control characteristics.
(3) The reliability of these devices is high.

In recent years with the development of car electronics, systems which have more advanced functions by use of electronic control techniques have been developed and made practical one after another: automatic transmissions, power steering electronic controls, active suspensions, four-wheel anti-lock brakes, traction controls, the devices for the control of the four-wheel driving force.
distribution, the integrated controls of power train
by use of the above devices, etc.

As a result, driving stability, driving safety, and
driving comfort have greatly advanced. The
automobiles which are safe, easy, and comfortable
to drive are being realized.

Even before when the shifting was
mechanically, the governor pressure modulated
with vehicle speed was acted upon the shift valve
opposite to the throttle pressure modulated with the
throttle opening. Then, according to the balance of
the forces generated the valve was switched and the
pressure acting to each of the clutches or brakes
were switched.

In ECT, the microcomputer has been introduced
and the running conditions are detected
electronically. The shift is obtained by controlling
the pressure acting to the shift valve with the shift
solenoid, which switches the valve and the
pressure acting to each clutch or brake. The
engagement of the lock-up clutch from low speed
gear and the selection of shift pattern such as
"power" and "economy" according to driver's taste
have become possible(Fig.2). Furthermore, the

Fig.1 Rate of applying hydraulic systems
to Toyota cars

Fig.2 Example of ECT shift schedule
integrated control with other control systems such as engine, suspension and auto drive etc. has become possible.

The system described below is the examples of evolution in the integrated control system and have been adopted since 1987 and well received.

[1] ENGINE-AT INTEGRATED CONTROL SYSTEM

Engine torque is reduced during shift to reduce shift shock and the heat load of clutches. Fig.3 shows the concept of this systems.

[2] CHASSIS-AT INTEGRATED CONTROL SYSTEM

Unexpected down shift is inhibited during cornering driving condition by introducing steering signal to ECT.

In 1989, Toyota has developed a new four-speed AT called A341E for luxury passenger car and obtained a large improvement in shift quality and quietness at the same time. Thus, achieving the highest level of compatibility between the improvement in fuel economy and drivability. The control system that achieves silky-smooth and anti-aging shift quality has been established. To control shift transient characteristics freely, a new linear solenoid valve has been developed(Fig.4). It is installed for the transmission clutch and lock-up clutch hydraulic control.

The size and weight of an electromagnetic portion to generate appropriate loads with large values of current were reduced by means of FEM magnetic field analysis. The frictional resistance of the sliding unit was also reduced substantially by supporting the spool shaft with bearings. Excellent response characteristics and a major reduction of hysteresis have been realized.

Fig.5 shows the clutch hydraulic pressure control system. The linear solenoid valve output pressure is used as the signal pressure to vary the accumulator back pressure by means of the control valve. This system has adequate fail safe functions against electronic failures. Only one solenoid valve is sufficient to control all accumulators. The actual control will be described next, using up-shift as an example.
Basically, the engine torque is reduced during the inertia phase. The accumulator back pressure is setup as an optimum value according to the type of shift and input torque etc. Finally, at the end part of the inertia phase, the pressure is reduced. Furthermore, the clutch pressure is corrected according to the deviation of the actual rotation speed of input shaft from the target values. The initiation of clutch pressure feedback control is delayed from that of the engine torque control to avoid interference of each control. The rate of resuming the engine torque is followed by the input speed change rate to prevent prolonged shift times. The proper constants for the feedback control are selected to optimize the stability and the response with the aid of a newly developed simulation program. The example of the shift transient characteristics is shown in Fig.6.

In 1991, a compact and high performance five-speed AT called A350E was developed. A five-speed AT meets a need for improvement in fuel economy and in power performance. But ordinarily the weight and the size increase is inevitable. We have developed a five speed AT with the same gear train as a conventional four speed AT(A340E) by means of the industry's first modern control theory aided shift technique. Namely it produces five gear ratios by combining gear ratios of two gear units connected in series. One of the technical problems in this construction is to shift each gear of two gear units synchronously in opposite directions. Fig.7 shows the hydraulic pressure control circuit. Each shift...
Fig. 8 Two clutches cooperative control system

valve and hydraulic pressure acting to the brakes of each unit (B0 and B2) can be controlled independently. Speed sensors of the sun gear members of each unit are used to sense shifting progression of each unit. The concept of the control will be described next using 2-3 up shift as an example.

Basically, the pressures of each brake are controlled according to shifting progression of each unit. But it is a system in which the front and rear unit interact with each other dynamically, so appropriate control can not be ensured by constructing two independent feedback systems. Therefore modern control theory is applied. This is appropriate for the control of a system with multiple inputs and outputs. Furthermore, the compensators for the delays of electric-hydraulic systems were introduced for stabilization (Fig. 8). Consequently, favorable shift transient characteristics are derived. This system is confirmed to be robust for the dispersion and aging in hydraulic pressure, engine torque and clutch friction coefficient by simulation and various laboratory tests.

In conclusion, we traced the development of the pressure control system by discussing representative AT's. The electronic-pressure control supported the down sizing and improvement of performance of the sensor, actuator and electronic control unit. The integrated control supported by the evolution of information transportation action technique will be progressed further.

2. CHASSIS

Chassis technologies have been upgraded mainly in the mechanical, hydraulic and pneumatic categories. Especially in recent years, these are widely equipped to the production vehicles due to the extraordinary improvement of the electronic technologies such as sensors, actuators or microprocessors. These systems have been evolved from passive systems to semi-active systems with the functions of variable characteristics, and moreover, active systems that are based on the real-time feedback controls. Fig. 9 shows the development of chassis controls.

[1] ELECTRONIC SUSPENSION CONTROL

The aim of electronically controlled suspension is the control of vehicle vertical motions using the electronic control components to improve the ride comfort, vehicle maneuverability and stability.
Fig. 9 Development of chassis controls

1) SEMI-ACTIVE SUSPENSION

Semi-active suspension is the system that makes optimal control of damper and pneumatic spring characteristics according to the driving and road conditions.

Fig. 10 shows the concept of semi-active suspension.

Toyota has developed at first a damping force control system called "TEMS(Toyota Electronic Modulated Suspension)" in 1983. Next, they developed a damping force, pneumatic spring and vehicle height control system called "Toyota Electronic Modulated Air Suspension", and improved damping force control system called "Piezo-TEMS" in 1989.

TEM5 is damper control system with switchable absorbers whose characteristics are changed automatically according to driver's maneuvers. In usual conditions, soft damper setting is selected for better ride comfort. And when it comes to sense the driver's wishes from steering, braking or accelerating pedal signals, damper setting is selected firm at a moment to improve handling maneuverability. The damper characteristics are changed by opening and closing the two or three orifices in the rotary valve, which is integrated with the control rod and driven by the suspension control actuator.

Toyota Electronic Modulated Air Suspension is adopted in luxury models. Enough air volume equal to a very low spring coefficient can ensure a supreme soft ride comfort, compared to the coil suspended vehicle. While on the other hand, this system also achieves the maneuverability and stability including small attitude change by decreasing the air volume and selecting firm damper state, if necessary.

Piezo-TEMS has been developed for damper control against individual irregularities of road surfaces. Fig. 11 shows sectional view of Piezo-
TEMs shock absorber. Piezo-sensor placed in the absorber rod generates electrons in proportion to damping force and it can be used for the judgement of road surface conditions. Piezo-actuator generates forces by the deformation of Piezo-Stack and drives the control valve of damper according to switching algorithms.

2) ACTIVE SUSPENSION

An active suspension system has some external energy source in the system, and it continuously and actively supplies or discharges the energy through the actuators according to a state feedback control algorithm. This systems enables progressive control of ride comfort, vehicle attitude, controllability and stability.

Toyota has developed an active controlled suspension system using hydro-pneumatics in 1989. Fig.12 and Fig.13 show configuration of this system.

The system is a combination of hydraulics with electronics. It is an integrated system consisting of sensors to detect the vehicle’s motion, hydro-pneumatic cylinders in place of shock absorbers, solenoid valves to control the linear hydraulic pressure control valves.

Fig.14 shows the pump configuration for active suspension. It is a kind of tandem pump; small one for power steering and four wheel steering system and big one for active system.

This pump is of a swash plate, axial piston type which provides optimal fluid flow by using a pressure sensing control valve. Further, in order to improve the quietness in the vehicle system, the pulsation of the pump pressure was reduced and this pump has been realized for automobile use.
In addition, vertical acceleration sensors are used to realize an optimal vibration system called the skyhook system to further improve the vehicle's ride.

The following are future improvement items to upgrade the fundamental vehicle functions;
(1) Ride comfort at high frequency
(2) Acceptable sales price per performance level
(3) Adequate power consumption and acceptable running cost

![Variable capacity piston pump of active suspension](image)

Fig.14 Variable capacity piston pump of active suspension

[2] ELECTRONIC STEERING CONTROL

The electronic control system has been applied to improve the vehicle maneuverability, stability and the controllability at the critical level of driving safety.

Four wheel steering is being energetically studied and developed especially in Japan. The system of rear wheel steering added to front wheel steering is to make the turning radius small and to improve the steering response to lateral acceleration.

The Toyota active four wheel steering(4WS) system, using a yaw velocity feedback control for the first time in the world for mass production cars, has been introduced in the 1991. Fig.15 shows the system configuration of active 4WS. This system is capable of detecting vehicle running conditions with various sensors and controlling the rear wheel steering angle by means of a hydraulic copying valve type rear wheel steering actuator.

The yaw velocity feedback control using a newly developed yaw velocity sensor not only provides stability during high-speed traveling but also counteracts deflection caused by external disturbances such as crosswinds and slippery roads by automatically steering rear wheel in the direction that stabilizes the vehicle.

![System of active 4WS](image)

Fig.15 System of active 4WS
The rear wheel steering actuator is capable of steering the rear wheel mechanically by 5° in the opposite direction of front wheels at low speeds, also contributing to improvement of vehicle maneuverability in a low speed range.

Hydraulic control block is for supplying hydraulic pressures to the power steering(PS) gear box and rear wheel steering actuator.

[3] INTEGRATED CHASSIS CONTROL

Chassis control system based on electronics are developed almost exclusively for each function of suspension, steering, braking and traction.

The integrated control system is developed for two main targets.

1) The realization of improved performance by integrating and harmonizing various functions that cannot be obtained by independent control.
2) The pursuit of cost/performance for the entire vehicle by using the same signals and signal processing and the same hardware, i.e., actuators, power sources, sensors, computers etc.

The integrated control system which was applied in 1991 consists of active suspension(A-SUS), active four wheel steering(4WS), anti-lock brake(ABS) and traction control system(TRC). Fig.16 shows the system configuration.

BASIC RESEARCH FOR AUTOMOTIVE HYDRAULICS

Toyota Central Research & Development Laboratories, Inc., a member of Toyota group, is doing basic research in the field of system dynamics and control, fluid mechanics and tribology.

In the field of system dynamics, the simulation of dynamics of the hydraulic system is being carried on by using the impedance method or the method of characteristics.

The ways to reduce noise and vibration are being made clear through the analyses of pressure pulsation, fluid transient, and self-excited vibration. For example, the analysis of pressure pulsation caused by pump flow ripple in each part of the power steering system, the analysis of pressure transer characteristics in the clutch hydraulic system, the analysis of self-excited vibration in the power steering system, the analysis of self-excited vibration in the hydraulic driving system of the engine cooling fan, the analysis of the pressure pulsation when the anti-lock brake is working, the analysis of the characteristics of Piezo actuator type semiactive suspension, etc. are being made.

Regarding system control, application of the fuzzy control and modern control theory is being studied.

In the field of fluid mechanics, numerical analysis of flow is being made by the boundary element method and the finite difference method, and flow in the hydraulic devices is being measured by flow visualization. Design considering flow has become possible by computer-aided engineering(CAE), which use numerical method verified by experiment. In addition, the analysis of flow in the torque converter of the automatic transmission, and the
designing of the torque converter blade profile, the analysis of high viscous flow in the viscous coupling, the analysis of flow in the hydraulic control valve, etc. are being conducted.

In the field of tribology, study is being made of the reliability and endurance of the component which become a subject of discussion with recent advances in down-sizing, lightening, and high pressure-rising. On the other hand, evaluation of the characteristics of frictional material for wet type clutch and working oil is being conducted.

CONCLUSION

The circumstances around the automobile are getting more and more unfavorable. As is well known, warming of the earth, the destruction of forests by acid rain and that of the ozone layer by chlorofluorocarbons(CFCs) as well as local air pollution are being discussed all over the world.

The major problems the automobile has to solve regarding environment are fuel economy and exhaust emission cleanup. Under the slogan "the automobile friendly to man and the earth", Toyota is making every effort to develop new technology.

Regarding the automotive hydraulic and pneumatic systems, the development of techniques to make high efficiency and lightening compatible with low vibration-noise and low cost, is urgently needed. Improvement of system components and materials including working fluid is also necessary. Moreover, simplification and integration of systems on the basis of the optimum designs have to be promoted.

Further development of hydraulic and pneumatic systems is required to make them continue to be indispensable to the automobile.

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