

Direct Drive Valve (DDV) hydraulic actuator for helicopter FBW

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By adapting Direct Drive Valve (DDV) hydraulic actuator to the helicopter Fly-by-Wire (FBW) actuation, the system can be simplified with the advantages of high reliability and of weight, size, cost reduction of the components.

We have studied DDV hydraulic actuators for helicopter FBW since 1989, and in 1993, we developed DDV actuator installed in the first FBW experimental helicopter in Japan.

This time, DDV hydraulic actuator with triple electrical and dual hydraulic redundancy has been developed under Advanced Technology Institute of Commuter-Helicopter (ATIC). This actuator is going to be installed in the ATIC demonstrator helicopter for flight test in 1999.

This paper describes the lessons learned through the development of these DDV hydraulic actuators. One of the most important problems of DDV actuator is the confirmation of jam proof capability. At first, problems and solutions are discussed at the development of rotary motor and rotary valve DDV hydraulic actuator that has chip shearing capability. Then the other DDV actuator of jam proof type is discussed mainly on its design and performance obtained. In the event of jam, DDV actuator of this type generally degrades in threshold and response, for additional force is needed to drive the valve spool against the nonlinear force of the detent spring that hold the inner sleeve. Although simple control law that has no change from normal mode to jamming mode is applied, required performance could be obtained. The actuator revealed the performance, from the pilot simulation, enough to be installed in the flight control system of the helicopter FBW.

1. INTRODUCTION

Most of the present helicopter flight control systems are composed of mechanical linkage which directly transmit the operation of the pilot to the hydraulic actuator that controls the rotor blades. Recently the requirements for the helicopter application has been getting more and more multipurpose and sophisticated. As to the flight control system, the realization of the FBW system instead of the conventional mechanical linkage system is longed for its flexible controllability.⁽¹⁾ And for the FBW Electro-Hydraulic actuator, DDV actuator can provide simple system architecture with the following advantages over the Electric Hydraulic Servo Valve(EHSV) actuator such as high reliability, reduction of weight, size, cost of the components.

DDV actuators are today installed in some of the fixed wing aircraft. Various types of DDV actuators have already developed. A classification

of DDV is that of the type of the motor and the valve. At first, we worked on the DDV actuator composed of rotary motor and rotary valve.

2. DEVELOPMENT OF ROTARY MOTOR AND ROTARY VALVE DDV HYDRAULIC ACTUATOR

2.1 ROTARY MOTOR AND ROTARY VALVE DDV

(1) Design of DDV

A study of FBW helicopter by the modified BK117 helicopter was started by Kawasaki Heavy Industries, LTD at 1989. And we worked on the development of DDV actuator for the tail rotor flight control actuation system.

Figure 1 is the configuration of the DDV developed. In order to get enough force to acquire chip shearing capability, gap winding type rotary motor with six coils radially arranged was selected.

In the event of jam, the spool of the valve can not be driven and the actuator becomes out of

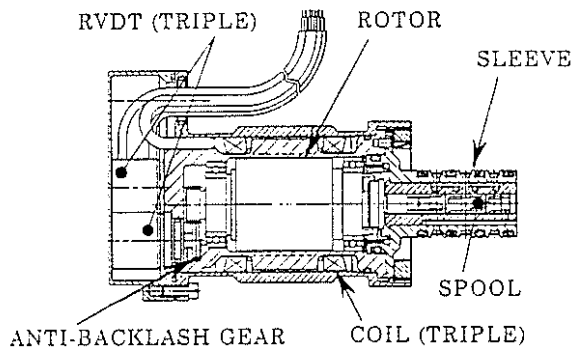


Figure 1 The configuration of rotary motor / rotary valve DDV

control, which may cause a catastrophic failure. Chip shearing capability is the ability to shear off the chip materials and prevent from jamming. Normal brushless motors are slot winding type whose output torque is likely to be saturated with the increase of the current because of the saturated nature of the magnetic flux density. On the other hand, the output torque of gap winding type motor is not likely to be saturated and high torque can be obtained provided for a short time in which the motor will not be damaged.

The flow ports of the valve are arranged in an axial direction so that the diameter of the spool becomes small, which leads to an increased chip shearing force. The coils of the motor are arranged free from electromagnetic cross channel coupling and completely separated from oil. The force due to the hydraulic pressure that applied to the valve is balanced to prevent the spool from binding by the deformation of the sleeve.

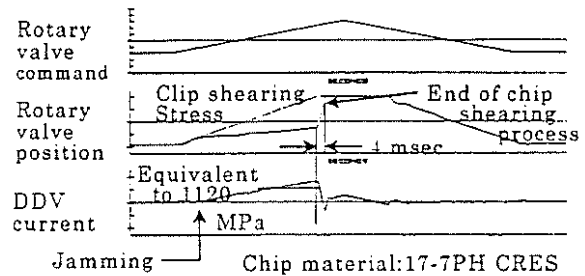
Three Rotary Variable Differential Transformers (RVDTs) are equipped for position feedback of the valve, each of which is coupled with the rotor via anti-backlash gear coupling to be free from backlash.

To reduce resonant peak gain in the frequency response caused by the coupling of the flow force and the rotor inertia, electrical damping is used.

(2) Test results of the chip shearing capability

The tests on the chip shearing capability were conducted in two phases, one on the chip shearing, the other on the jamming detection. The test result of the chip shearing is shown in Figure 2. Some representative chip metals are set at the metering

orifice of the valve, and the generated shearing stresses and the time for the chip shearing were measured. The shearing stress was 1360MPa maximum for 17-7PH corrosion resistant steel. The chip shearing time is likely to be longer as the chip metal is ductile, 13.5msec maximum for bronze.

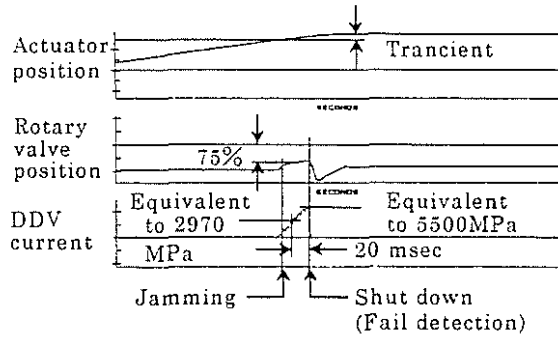


Chip material	Test result	
	Shearing stress (MPa)	Shearing time (msec)
17-7PH CRES (spring wire)	1120~1360	3.8~4.1
2024-T3 AL	310~320	5.2~5.6
SUS304 CRES (safety wire)	440~530	8.5~10.0
C1201W-0 bronze	180~220	11.0~13.5

Figure2 The test result of Chip shearing

So, we assumed that the required shearing stress should be 1800Mpa at minimum by taking the other tough metals into consideration, and the chip shearing time should be 20 msec at maximum. We judged that most of all chips can be sheared off provided the above condition, and for fear of the exceptional failure, the jamming is detected after 20 msec and the hydraulic system is shut down.

Figure 3 is the test result of jamming detection. The valve spool is stuck artificially. The generated equivalent shearing forces and the transient were measured. The equivalent shearing stress was more than 2900Mpa in every case. The transient at the chip shearing is considered within that of the test result.



Valve jamming position & command type	Actuator cylinder trancient (mm)	Shearing force(N)/stress(MPa)
75%open		
Rectangular	2.5	102~189 / 2960~5480
Triangle	2.1	106~187 / 3660~5410
25%open		
Rectangular	1.3	92 ~133 / 8030~1150
Triangle	1.0	101~133 / 8790~1150

Figure3 The test result of Jamming detection

2.2 ROTARY MOTOR AND ROTARY VALVE DDV ACTUATOR

Figure 4 is the appearance of the hydraulic actuator on which the DDV mentioned above is mounted and the Actuator Control Computer(ACC). The redundancy of this actuator is hydraulic single and electrical triple, two fail operative. To obtain fail detection ability after one failure, ACC is self monitored by the use of two Digital Signal Processor(DSP) for each channel.

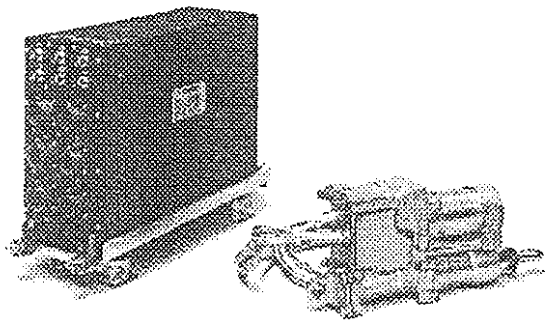


Figure 4 DDV actuator and ACC equipped on the BK117 FBW Experimental Helicopter in 1993

This actuator revealed remarkable performance, the frequency response was 9.5Hz at 45 degree phase lag, the threshold was 0.03% per full stroke. In 1993, this actuator was installed in BK117 FBW experimental helicopter, and flight test was performed with no problem.

3. DEVELOPMENT OF JAM PROOF DDV HYDRAULIC ACTUATOR

A study of FBW flight control system has been proceeded at Advanced Technology Institute of Commuter-Helicopter(ATIC) since 1994, and we have worked on the development of actuator for helicopter FBW actuation system. To meet the requirement for minimization of weight and cost, we selected DDV actuator, and the type of DDV was considered.

Table 1 shows the comparison of some aspects classified by the type of the motor and the valve. Further consideration for the determination of the design of the actuator will be discussed in chapter 3.1 and 3.2.

Table 1 Comparison of DDV by the Motor/Valve type

	Motor/Valve			Remark
	Rotary/ Rotary	Rotary/ Linear	Linear/ Linear	
Output force	△	○	△	Rotary/Linear type can take gearing
Configuration	○	○	○	Rotary/Linear type cannot be coupled in line
Weight	○	○	○	Equivalent
Cost	△	○	○	Rotary/Rotary type cost much for jam proof DDV

3.1 CONSIDERATION ON JAM PROOF CAPABILITY

In the field of military fixed wing aircraft, chip shearing force of DDV is considered to be adequate at the level of 40kgf to 100kgf for keeping flight reliability. On the other hand, flight control actuator of the helicopter requires higher reliability, for the operation becomes impossible if any of the

four axes, pitch, roll, collective pitch, and yaw axis, becomes out of control. No standard of the chip shearing force required for the helicopter exists. As for the actuator of helicopter flight control developed recently, jam proof valves that bypass the cylinder ports of the piston of jamming channel are mostly adopted to helicopters of relatively middle or large scale, for example CH-47J, SH-60J, UH-60J, and BK117 in Japan.

The loss of actuator control by the jamming of the valve has never been reported in Japan. But to acquire jam proof capability is an important problem. We judged that for the actuator of helicopter actuation system, jam proof type DDV actuator is adequate for its high reliability, and the design in detail was considered.

One solution in order to give jam proof capability is to use two independent separate valves and motors for each of the two hydraulic systems. But we determined to select the DDV of jam bypass type for its small size and low cost. The jam bypass type DDV is composed of dual sleeve. Inner sleeve is normally held at the neutral position by the detention spring. In the event of jam, inner sleeve is driven against the load of the detent spring, and the path to bypass the cylinder ports is formed, which enables the free control by the other hydraulic system. In the event of jam, the motor must provide adequate torque to control the valve against the load of the springs. The preload of the detention springs was determined to 10kgf from the viewpoint of preventing the drive of inner sleeve by the weak binding with the spool or by the shock applied.

3.2 CONSIDERATION ON THE MOTOR AND THE VALVE

(1) Type of the motor and the valve

To give jam proof capability to rotary motor and rotary valve type DDV actuator, its structure is likely to be complex. Despite the merit that the coupling of rotary motor and rotary valve can be direct and free from backlash, we determined to select DDV composed of rotary motor and linear valve for its comparatively simple configuration and for cost reduction. As for the type of the motor, linear motor was also considered, but for its difficulty to hold the armature against the unstable reluctance torque, rotary motor was selected.

For the DDV of rotary motor and linear

valve, the mechanism to transform the rotary motion of the motor to linear motion of the valve is required. Several types of coupling were compared from the viewpoint of realizing smooth motion with less backlash and friction, the mechanism of simple direct coupling shown in Fig 5(2) was selected.

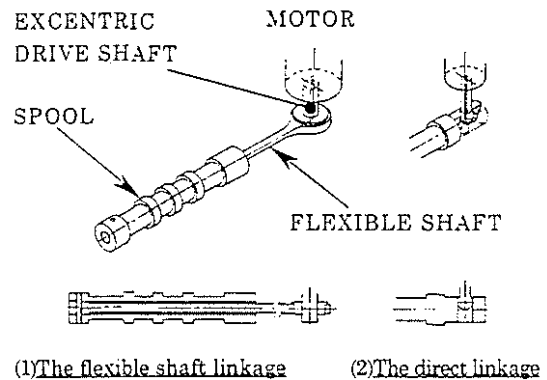


Figure 5 The types of linkage of rotary motor and linear valve

(2) Design of the motor

As mentioned in chapter 2.1, the motor of gap winding type can provide high torque for a short time. However in case continuous torque is required, it is not superior in efficiency. To get continuous torque efficiently, we selected troidal winding type as shown in Figure 6(2). Slot winding type is also efficient but like force motor, it requires method such as mechanical springs to stably hold the rotor against its reluctance torque, which is not the case with troidal winding type.

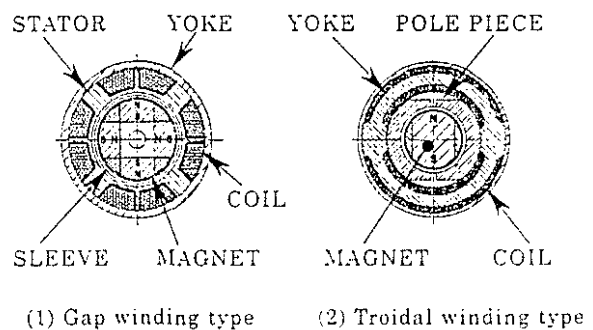
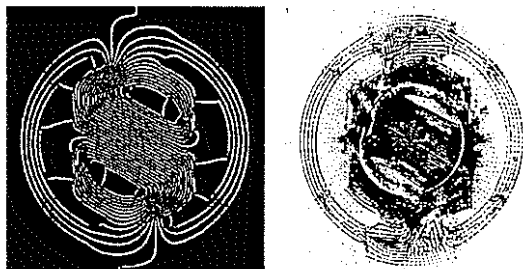


Figure 6 The types of rotary motor

To design troidal winding motor, we used simulation tool of finite element analysis of electromagnetic field.⁽²⁾ The example of the analyses is shown in Figure 7. By the use of the numerical analysis, the shape and dimensions of each components were determined to give adequate characteristics of the reluctance torque, and of saturation of magnetic field to realize high performance and less power consumption.



The stream lines of magnetic force

The distribution of flux density

Figure 7 The example of magnetic field calculated

3.3 DESIGN OF JAM PROOF DDV ACTUATOR

The DDV actuator for the ATIC FBW demonstrator helicopter was designed under the consideration mentioned above. The actuator is a parallel actuator which has the redundancy of electrically triple and hydraulically dual. Fig. 3 is the appearance and Fig. 9 is the schematic view of the structure of the actuator.

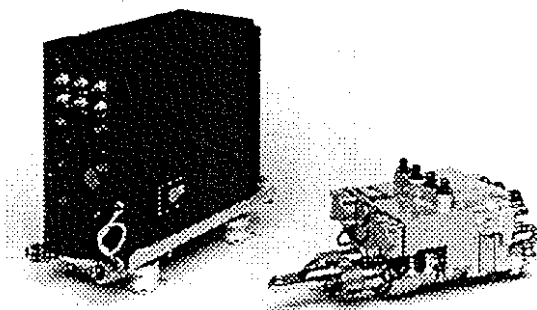


Figure 8 DDV actuator and ACC for the ATIC FBW Demonstrator Helicopter

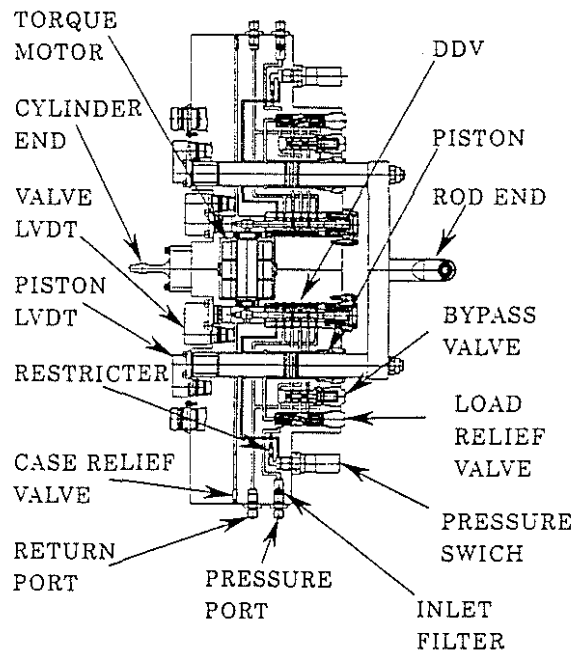


Figure 9 The schematic view of jam proof type rotary motor / linear valve DDV actuator

In order to meet the requirement of parallel cylinder, DDV is located at the center of the actuator surrounded by the two manifolds which compose rip stop structure of two independent hydraulic systems

Linear Variable Differential Transformers (LVDTs) are mounted for the position feedback of DDVs and pistons. Bypass valve is mounted to bypass the cylinder ports of the piston in case hydraulic system is shut down. Load relief valve functions to protect the components from being damaged by the excessive load that may be caused by any stick of the linkage to which the ram of the actuator is connected.

The timing of the open of the control orifices of two DDVs is tuned to be mechanically synchronized so that the dead band of the total output force of each piston may not be caused by the mismatch.

The feedback signals of the LVDTs are also tuned among channels so that the fighting of current that leads to the increased power consumption may be little. The motor current is controlled with Pulse Width Modulation (PWM) for the reduction of the power consumption.

The jamming of the valve is detected by the pressure switch and the signal of jamming is sent to the pilot.

By the use of the jam proof type DDV, flight control is obtained even in an event of jam.

Figure 10 is the block diagram of the actuator control. Minor loop is formed for the DDV control to improve total response. For the determination of the servo loop compensation, control parameters are researched by software simulations and finally tuned using the actual actuator. When electrically failed, the failed channel is shut down, with no change of control law of the other channel.

Four actuators are installed for the actuation of pitch, roll, collective pitch, and yaw axes. The Flight Control Computers(FCCs) send command signals that are determined from the operational signal of the side stick or other sensors to the Actuator Control Computers (ACCs). The ACC controls the actuator according to the command by the use of the feedback signals of the LVDTs.

3.5 TEST RESULTS OF DDV PERFORMANCE

The test results of the DDV performance is shown in Table 2. In an event of jam, the spool must be driven against the nonlinear force of the detent spring, which lead to the degradation of the threshold and response. The DDV obtained required performance by the preliminary considerations mentioned above.

The internal leakage is little, which is one of the advantages over EHSV that has more leakage due to its structure.

Table 2 The DDV performance

	Normal	Hydraulic one fail	Jamming
Rated flow	1,200 cm ³ /min		
Internal leakage	17~24 cm ³ /min		
Frequency response @ 90deg phase lag	77Hz	77Hz	43Hz
Threshold	0.2%	0.1%	1.1%
Hysteresis	1.3%	1.6%	4.4%
Linearity	3.1%	2.6%	—
Symmetry	2.6%	2.6%	—

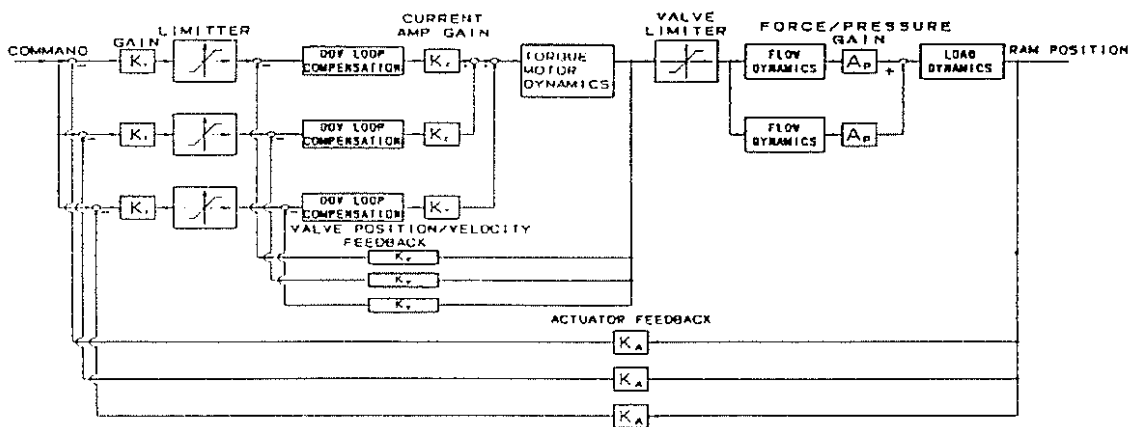


Figure 10 The block diagram of actuator control

3.6 TEST RESULTS OF ACTUATOR PERFORMANCE

The test results of the actuator performance is shown in Table 3, and Figure 11,12. The test condition of the load for the actuator is equivalent to that of the linkage to which the actuator will be connected.

Table 3 The actuator performance

	Normal	Hydraulic one fail	Jamming
Stroke(mm)	±23.8		
Maximum velocity (mm/sec)	94~95	91~99	91~99
Frequency response @ 45deg phase lag	9 Hz	9 Hz	7 Hz
Threshold	0.05%	0.02%	0.08%
Hysteresis	0.10%	0.14%	0.28%
Linearity	0.15%	0.18%	0.39%

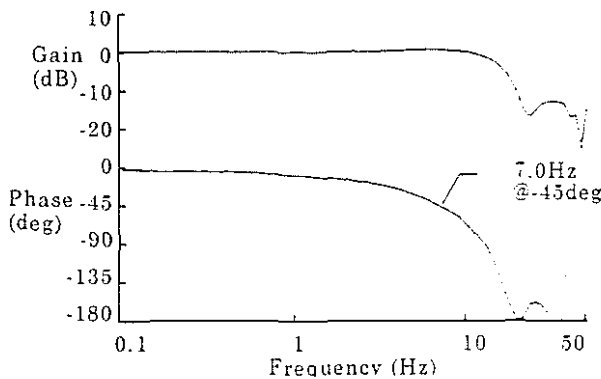


Figure 11 The frequency response of the actuator at jamming condition

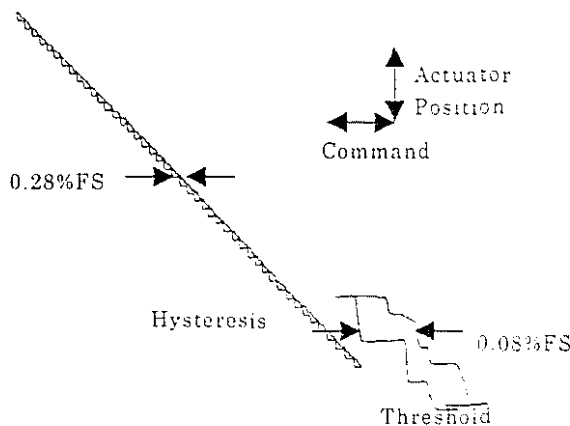


Figure 12 The Threshold and the Hysteresis of the actuator at jamming condition

By obtaining good DDV performance at jamming, actuator also showed good performance, the threshold was 0.08% per full stroke, the frequency response was 7 Hz at 45 degree phase lag. From the pilot simulation, this actuator revealed the performance enough to be installed in the flight control system of the helicopter FBW.

4 CONCLUDING REMARKS

Through the development, The prospect to realize the reliable jam proof DDV actuator could be obtained. The flight test of the ATIC demonstrator helicopter in which this actuator is installed is programmed. Many fruits of the technologies for flight safety are expected.

5 ACKNOWLEDGMENT

The development of jam proof DDV actuator was proceeded as the study of actuation system among the studies of basic technologies of the commuter- helicopter for the next generation. The authors appreciate those concerned for the precious aid and advice.

6 REFERENCES

- (1) T.Tomio, M.Ishida et al
" Testing for Design Validation of the BK117 FBW Experimental Helicopter"
, AIAA/AHS/ASEE Aerospace Design Conference, 1993.
- (2) T. Fuke et al
" Analysis of the magnetic field for the torque motor of the Direct Drive Valve actuator"
, 34th Japanese aircraft symposium, 1997.