

## ELECTRICAL FLIGHT CONTROL TECHNOLOGIES FOR ROTORCRAFTS

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### Abstract

Fly-by-Wire technology is now taking the lead over hydro-mechanical flight control systems on Rotorcrafts.

Goodrich Actuation Systems, the European leader in Flight Controls, is proud to have participated in the development of a Fly-By-Wire (FBW) system which represents a significant technical innovation in the rotorcraft market. The first flight of Eurocopter's new European military helicopter, the NH90, has successfully been made with Goodrich Actuation Systems participation in the FBW technology for all electric flight controls on the aircraft.

The Full Authority Quadruplex FBW System presents many advantages for the Rotorcraft market. For the first time on a helicopter there are no mechanical links between the pilot controls and the main and tail rotor actuators. The FBW technology increases the manoeuvrability of the aircraft and also reduces the pilot's workload. It also enables manufacturers such as Eurocopter to significantly reduce the weight of the helicopter – thanks to simplified mechanical parts and fewer hydraulic units. Furthermore, the main rotor actuator, which makes use of Goodrich's Direct Drive Valve Technology, benefits from an increased level of redundancy and safety. The high reliability and safety performance of Goodrich's rotary valve have been demonstrated for more than 30 years and this technology is at the heart of Goodrich's DDV technology.

As a first application programme of Goodrich's FBW Main Rotor Actuator, the NH90 flight controls were designed and developed in partnership between Goodrich Actuation Systems' facility at Buc, France and Liebherr Aerospace of Lindenberg, Germany (the prime contractor for the Flight Controls of NH90). Goodrich is the design authority for the FBW Main Rotor Actuator (MRA). Liebherr Aerospace is the control electronic designer and manufacturer.

Goodrich Actuation Systems, as specialists in Flight Controls, has developed a range of technology options including a new electro-mechanical actuator design for flight controls in a "Direct Drive" Architecture. Consequently, Goodrich can offer the Rotorcraft market state of the art technology. Electro-mechanical technology gives several advantages such as lower maintenance, cost reduction and elimination of oil leakage. In addition, electrical technology allows the removal of all of the hydraulic systems. This architecture leads to weight and life cycle cost reductions at the system level.

Goodrich's expertise acquired in the development of innovative products, especially in full FBW (Fly-by-Wire) systems, DDV (Direct Drive Valve) and EMAs (Electro-mechanical Actuators) makes it well prepared for the future of the "more electric" rotorcraft.

### Introduction

On December 12<sup>th</sup> 2003, NH90 PT3 made its first flight in full Fly By Wire Mode at Eurocopter Marignane, with Goodrich Main Rotor Actuators onboard.

NH90 will be the first production rotorcraft equipped with a full Fly-By-Wire Flight Control System.

This milestone is a key event in the long lasting collaboration between Eurocopter and Goodrich in the field of Rotorcraft Flight Controls.

After reviewing the pioneering phases of this collaboration, this paper describes the main features of the NH90 Actuator contributing to this innovative control system.

The paper then gives an overview of the actuator technologies resulting from Goodrich's recent Research and Development that could benefit Rotorcraft in a near future.

## The Dauphin CDVE : Pioneering Rotorcraft Fly-By-Wire Flight Controls

Goodrich has been delivering hydraulic flight control equipment to Eurocopter for more than 40 years.

Building on this shared experience, Eurocopter, who launched the CDVE<sup>[1]</sup> R+D project in 1981, employed Goodrich (formerly SAMM) to develop the Flight Control System for the Dauphin Flight Demonstrator from 1985.

This Flight Control System involved a dual hydraulics, duplex control system architecture as shown in Fig. 1.

The actuators (see Fig. 2) featured 2 electrical inputs and one back-up mechanical input.

The Dauphin CDVE made its first flight in 1989. The subsequent test flights and system development [1] paved the way for the introduction of the NH90 Fly-By-Wire project launched in 1992.

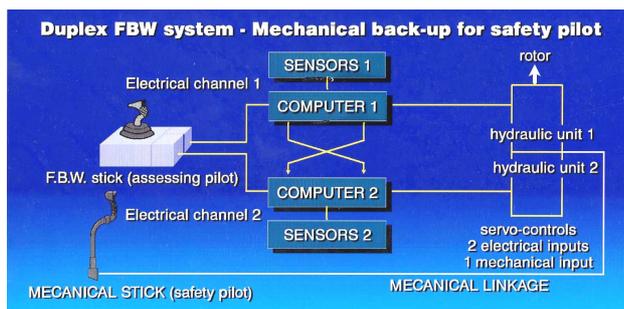


Fig. 1 Dauphin CDVE Flight Control System Architecture

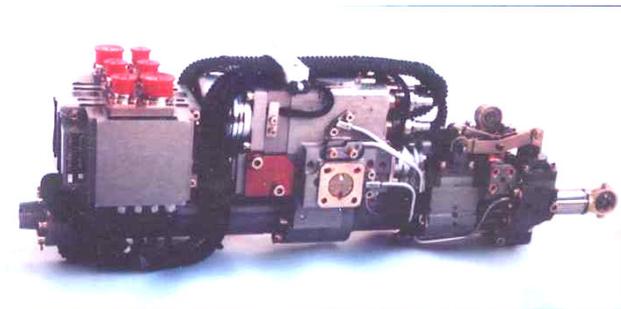


Fig. 2 Goodrich's Dauphin CDVE Actuator

## The NH90 Actuators

The description of the NH90 Flight Control System, led by Eurocopter Marignane, is provided in [2] and [3].

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<sup>[1]</sup> Standing for Comande De Vol Electrique i.e. Electrical Flight Controls

Goodrich Actuation Systems in cooperation with Liebherr Aerospace of Lindenberg, contributed to the development of the NH90 Servo Actuation System (SAS) at actuator and Actuator Control Computer (ACC) levels and is now delivering the Main Rotor Actuator in series production.

## Design drivers

Goodrich and Liebherr engineering effort was focused on devising solutions to meet the demanding safety specification set by Eurocopter for the SAS.

All the solutions proposed were then justified by the team, strongly relying on Goodrich's unique experience in Rotorcraft Flight Control Actuators.

While retaining the traditional dual hydraulics implemented by Goodrich on Dauphin and Super Puma, the NH90 actuators feature a quadruplex control architecture that complies with Eurocopter's system requirements.

After providing a general description of the Main Rotor Actuator, this section describes the key innovations that have made it possible to achieve the first NH90 FBW flight.

Although featuring different sizes, materials and general layouts, due to different performance, duty, space and interface requirements, the NH90 Main and Tail Rotor Actuators use the same overall architecture. This paper will therefore focus on the Main Rotor Actuator. Most of the details described hereafter also apply to the Tail Rotor Actuator.

## General description

The NH90 Main Rotor Actuator, shown on Fig. 3 is a fixed body full-Fly-By-Wire Actuator, consisting of :

- a tandem cylinder assembly, in which a single rod is actuated by two double acting unbalanced pistons, each supplied by a 207 bar hydraulic system, and
- a quadruplex Direct Drive Valve (DDV) assembly to control the application of hydraulic power to pistons.

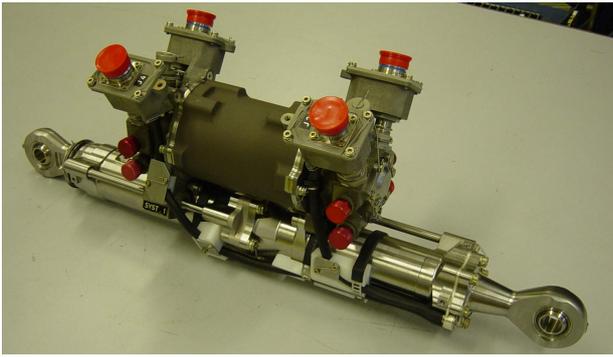


Fig. 3 NH90 Full Fly By Wire Main Rotor Actuator

By design, the two hydraulic systems are completely segregated.

The DDV assembly contains two rotary control valves driven by four electrical rotary DC-Permanent Magnet Torque Motors. Each of the two Actuator Control Computers (ACCs) control two torque motors.

The Actuator Control Architecture is shown in Fig. 4.

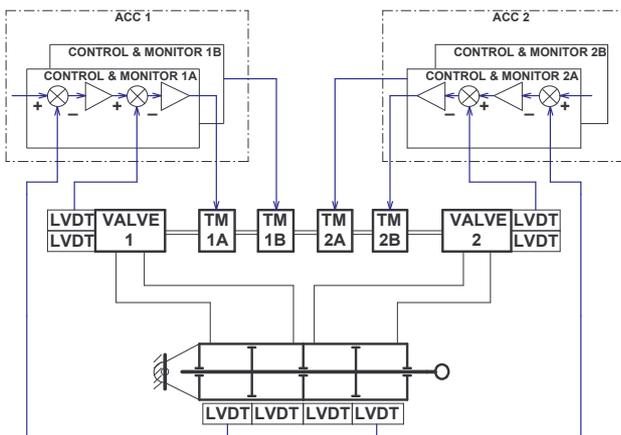


Fig. 4 :NH90 Main & Tail Rotor Actuators control architecture

Both rotary valves are of a double rotary valve type to provide an anti-jamming function. In case of seizing of one of the two primary spools, the secondary valve rotates to maintain controlled operation of the DDV shaft, and to provide a degraded level of flow control to the affected system.

A quadruplex inner control loop controls the position of the rotary valve. Each valve position is fed back by two LVDT's which are each mechanically connected to the rotary spool by a lever.

The quadruplex outer control loop controls the actuator position. A quadruplex LVDT, connected to the piston rod, feeds the actuator rod position signal back to the ACCs.

Each motor rotor is connected to a common shaft by a mechanical anti-jamming clutch. Thus detection of a motor mechanical failure or hardover requires only monitoring of the motor current and no additional switching logic is needed.

The highest possible level of electrical segregation is provided in the actuator design. There are no flying leads or exposed wires.

To minimise the sensitivity of the actuator to fire, the length of the wires is minimised. The external cables are all protected by a metallic braid and are tightly fixed on the actuator. The wires terminate at four segregated electrical connectors; one per ACC lane.

### Direct Drive Valve (DDV)

Generalities. The DDV assembly consists of two rotary control valves which are controlled by four torque motors.

Four LVDTs, connected to levers rotating with the valves, measure the angular position of each rotary valve and feed it back to the ACCs.

Each rotary control valve is connected to one of the hydraulic circuits in order to control the flow to each cylinder of the tandem actuator.

The two rotary control valves are totally hydraulically segregated. They are mechanically connected together by a common shaft to synchronise the motion of the two valves thus preventing force fighting between the two actuator cylinders.

The DDV assembly is bolted to the ram assembly with two bolts on the ram lower cylinder and two bolts on the ram upper cylinder.

This attachment, hydraulic connection design, and electrical connection design, allow easy replacement of the DDV assembly.

Valve blocks. The 2 valve blocks that are flanged at each end of the Torque Motor Assembly, are identical.

They use Goodrich's patented rotary valve design, which is well proven through decades of in-flight service on many Eurocopter rotorcraft (Puma, Twin Engine Squirrel, Dauphin and Super Puma families, ...)

Rotary Valve The main components of Goodrich's rotary valves are shown on Fig. 5.



Fig. 5 : Goodrich Rotary Valve Components

The principle of the hydraulic distribution is described by the drawing in Fig. 6. Proportional opening of the valve's distribution nozzles is obtained by a rotary motion of the valve, instead of a linear motion as in traditional hydraulic valves and servovalves.

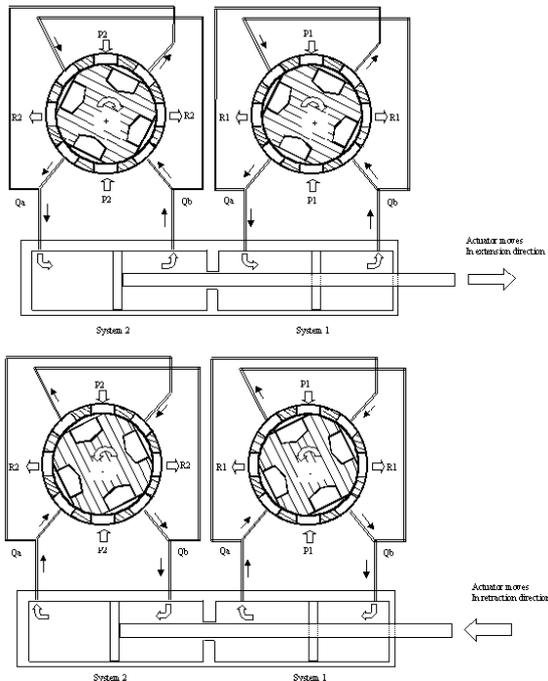


Fig. 6 Hydraulic distribution with Rotary Valves

Two principal criteria led to the selection of rotary valves for NH90.

Firstly, the direct use of a rotary motion make rotary valves convenient for Direct Drive by an electric motor.

Secondly, they have demonstrated a very high robustness to jamming in-service which is key given the demanding safety requirements for the NH90: Since their first application in 1962, Goodrich rotary valves have flown for nearly 160 million Flight Hours on helicopters without any jam, which demonstrates

a jam failure rate of better than  $6,5 \times 10^{-9}$  per Flight Hour per valve.

It was therefore straightforward to demonstrate that the double jamming of a rotary valve and of its anti-jamming back-up is extremely improbable, which even allowed Eurocopter to specify a simplification of the anti-jamming test and a relaxation of its check interval for the EC225 and NH90.

Each of the 4 Torque Motors is sized in order to deliver a maximum torque of 1.05 Nm, which exceeds the maximum 0.9 Nm chip shear torque measured by Goodrich during the valve contamination test program.

After 3 motor failures, the DDV is therefore still able to provide a 170 N (38 lbs) chip shear force at the distribution nozzle. In normal operation (with 4 motors active), this chip shear capability rises to 680 N (152 lbs), which far exceeds the 50 lbs minimum requirement set for valve certification.

#### Torque Motor Assembly

The Torque Motor assembly consists of following components:

The torque motor assembly casing which is made of cast aluminium and is fixed to the valve blocks. This housing holds the attachments between the ram cylinder assembly and the motor distributor assembly.

The torque motor stator casings: Each Torque Motor assembly includes 2 torque motor casings, each containing two encapsulated Torque Motors stators.

The DDV Shaft: The common DDV shaft links the two rotary valves, and holds the 4 Torque Motors' permanent magnets and the mechanical clutch device.

The Torque Motor Clutch device. In case of one motor jamming, a threshold spring relieves the shaft from driving the failed motor. The increase of torque resulting from the fight against the spring clutch is detected automatically by the current monitoring during an ACC Pre-Flight Built-In Test.

#### Quad LVDT

Due to the quadruplex nature of the NH90 Flight Control Systems, each actuator rod position is measured by 4 LVDT signals. Due to the upper deck environment, Goodrich decided to equip the Main Rotor Actuator with a Quadruplex LVDT (Quad LVDT).

The Quad LVDT integrates four segregated LVDTs that measure the rod position. Each LVDT signal is fed back to one ACC channel, where it is compared

with the actuator electrical position demand to calculate the rotary valve position demand.

The Quad LVDT housing is attached by a flange to the lower ram cylinder. The four LVDT rods are connected to the piston rod by means of a triple load pathed ball bearing arrangement. This arrangement was necessary to make the probability of complete loss of the actuator rod position extremely improbable, as the resultant effect is classified as catastrophic. General views of the Quad LVDT (without the moving part) fitted with the actuator bottom eye-end are shown on Fig.7.

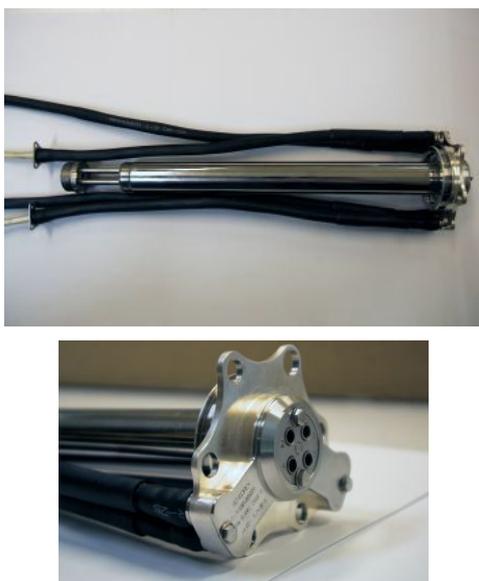


Fig. 7 : NH90 MRA LVDT Quad

#### Further Developments in Goodrich in the field of Electrical Actuators

The NH90 is now flying in full Fly-By-Wire Mode and the production actuators are completing their qualification.

Besides supporting Eurocopter during the Entry Into Service of this innovative Flight Control System, Goodrich is maintaining their Research and Development effort in the field of rotorcraft actuators.

The next sections provide two examples of the most recent Goodrich Actuation Systems developments that could be applied to Helicopters in a near future.

#### Goodrich Direct Drive Valve: A further step towards DDV integration

Building on the 'know-how' gained not only on the NH90 development, but also on the Rafale Steering Wheel and Formula 1 racing car applications, Goodrich has continued developing its Direct Drive Valve concept.

Goodrich recently patented a new technology of Direct Drive servo valves exceeding the capabilities of conventional Electro Hydraulic Servo Valves in terms of internal flow consumption, pre-flight testability, sensitivity to fluid pollution and vibrations, chip shear performance and simplicity of design.

To completely optimise the technology, cost, reliability and performance, Goodrich has developed its own low cost torque motor and rotary transducer, and its own compact electronic drive.

The Direct Drive Valve layout is shown Fig. 8.

Goodrich DDV is now qualified and will fly in 2004 on an AIRBUS A320 spoiler actuator.

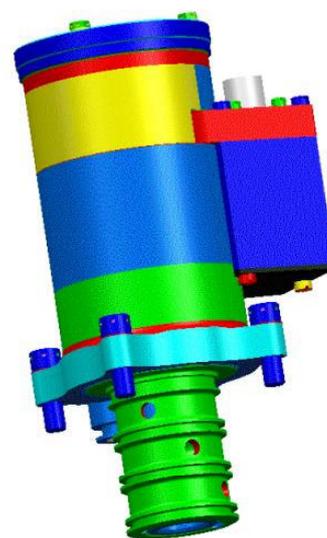


Fig. 8 : Goodrich Direct Drive Valve

The Direct Drive Valve SVD2001 is designed and qualified for ambient air temperature ranging from -55°C to +90°C and for a civil aircraft environment: temperature, vibration, waterproofness, altitude... It features EMI/RFI and lightning protection and is qualified in compliance with RTCA/DO160D and ABD0100C.

Future rotorcraft FBW control systems, including NH90 could benefit from the improvements brought by Goodrich through its original DDV concept in terms of simplification and integration.

### Goodrich Electro Mechanical Actuators: Towards Power by Wire on helicopters?

In parallel to its strong experience in the field of hydraulics, during the last decades Goodrich Actuation Systems has been developing their know-how in electromechanical actuation, initially for the Train Active Transversal Suspension System (for the high speed train/TGV projects) and subsequently for missile thrust vector control programmes.



Fig. 9 : Goodrich TVC ElectroMechanical Actuator

Goodrich's Electro-Mechanical Actuator (EMA) design (Fig. 9) is based on a direct drive concept with a brushless DC motor driving a satellite roller screw. This "no gear" concept is key to delivering high performance (no backlash, high stiffness, high bandwidth) at low weight, low cost and high reliability. An electronic vector torque control is implemented in order to optimise the power delivery, velocity and actuator position accuracy.

The use of a hollow shaft brushless DC motor results in a more compact design. As the motor directly drives the nut of the satellite roller screw, there is no gear transmission producing a smaller overall weight. With no unbalanced mass, the actuator is more resistant to shock and vibration. The direct drive architecture results in lower inertia and improved stiffness allowing higher speeds.

Actuators have been recently developed and qualified by Goodrich for a Thrust Vector Control Application with a maximum power of more than 40 kW and with a very high dynamic response.

Goodrich is ready to use their established knowledge of helicopter actuation to develop an Electromechanical Actuator from this EMA technology which is capable of meeting the Rotorcraft Flight Control performance and safety requirements.

One of the major challenges is then to decrease the overall cost, and especially the maintenance cost.

### Conclusion

Twenty years after its first application on a Dauphin demonstrator by Eurocopter and Goodrich, Fly by Wire technology has provided significant performance, reliability and weight advantages to the NH90 helicopter. The technologies and architectures selected for the NH90 have proved successful and are progressing to series production.

The Direct Drive Valve technology and the quadruplex control architecture developed by Goodrich and its partners for NH90 provide enabling technologies for the future application of FBW in the helicopter market.

Goodrich continues to develop Direct Drive Valve and Electromechanical Actuator technologies to support future rotorcraft flight control systems. These technologies are ready for full scale demonstration for rotorcraft applications.

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