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EH101 HELICOPTER FOLDING SYSTEM

by

D. TURATI, A. ZECCHIN

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Davide Turati - Andrea Zecchin

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1. ABSTRACT

The EH101 helicopter, jointly developed by Agusta of Italy and Westland of U.K., has been designed to replace existing shipborne ASW helicopters. The requirement to stow the EH101 inside the mother ship in adverse environmental conditions has led to the development of a fully automatic and autonomous system to fold both the main rotor blades and the tail. The system is composed by an electronic management unit which controls 15 highly reliable electro-mechanical actuators, and is interfaced with various other aircraft sub-systems. The system has been extensively tested on ground rigs and on prototype helicopters both on ground and aboard ships, also in high wind and rough sea conditions.

2. SYSTEM REQUIREMENTS

The EH101 Integrated Development Program (IDP) was born from the Italian and British Navies requirement for a replacement of the licence made Sikorsky SH-3D - Sea King ASW helicopters, as well as from a worldwide marketing survey which pointed out the possibility of fulfilling, with different variants of the same basic aircraft, the roles of civil passenger and military troop and material transport. In particular, the naval requirement addressed an air vehicle with a substantial increase over the Sea King (a 9000 kg class helicopter) in terms of mission fit and time on station, leading to a Maximum Take-Off Weight (MTOW) of 14.300 kg, while retaining the capability of being recovered in the same class of ships as its predecessor, that is into a box of 16.0 x 5.5 x 5.2 meters (length x width x heigth).

The EH101 had to be able to take-off from and land on such small navy vessels (e.g. frigates and destroyers) in a harsh operating environment of 45 knots winds from any direction, high sea states and temperature limits from -40 to +50 C°. This environment requires a high degree of automation in the preparation of the helicopter for launch and in its stowage into the ship's hangar, in order to minimise or even eliminate the need for the presence of personnel on the deck.

In order to achieve this the ship must be fitted with specific equipment for the automatic manoeuvre from and to the hangar, such as the McTaggart-Scott deck handling system for the Royal Navy and the HHRSD (Helicopter Hauldown and Rapid Securing Device) for the Canadian Navy, and the

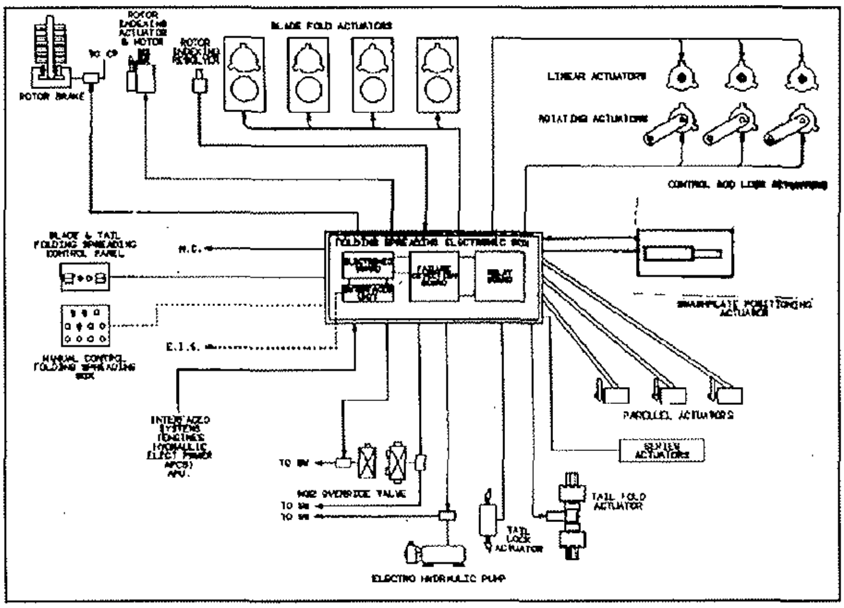

Fig. 1 Folding system schematic

helicopter must be fitted with an autonomous and highly automated blade and tail folding system.
Another driving requirement for the EH101 was the overall reliability and maintainability of the helicopter in general, and of the folding system in particular, having in mind the well-known reliability problems of hydraulic folding systems (See Ref. 1).

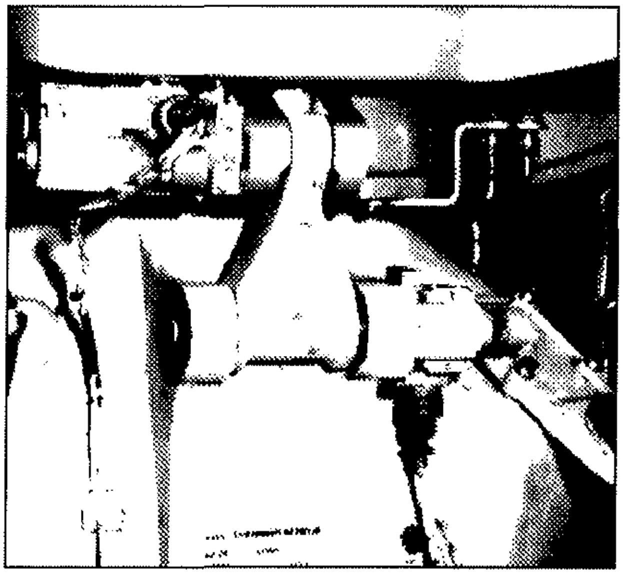

Fig. 2 Pitch lock system

3. GENERAL DESCRIPTION

The EH101 is a five bladed main rotor (see Figure 6), four bladed tail rotor helicopter. The blade and tail folding system is composed essentially by electro-mechanical actuators, powered by the 115 VAC electrical system, which can be fed either by the APU mounted generator or by the main generator installed on accessory gear box. External electrical power supply may be used too. Hydraulic power is only requested for flight controls positioning during the folding cycle and can be taken either from the utility hydraulic system, which can be fed on ground by an AC electro-hydraulic pump in case of engine shut off condition or by the N°2 flight controls hydraulic system powered by the pump installed on accessory gear box. The accessory gearbox can be driven, without rotors turning, by engine N°1 in accessory drive mode. This allows the folding system to be completely autonomous and to operate even in case of a single power source failure. The system is normally fully automatic with manual override in case of electric motor(s) failure. Anyway, the choice of all electrical actuators grants a higher reliability compared to the usual hydraulic systems.
The system is physically comprised of the following components (see Figure 1), which will be then described in detail in Section 5:

- Folding control panel, in the cockpit
- Folding Management Unit (**FMU**), installed on the ceiling of the main cabin under the main gearbox;
- Rotor Indexing Actuator (**RIA**), installed on main gearbox;
- Flight Control Positioner Actuator (**FCPA**), installed behind the mixing unit which combines the collective and cyclic flight control inputs;
- Pitch Lock Rotating Actuators (**PLRA**), installed on upper case of the main gearbox, as shown in Figure 2;
- Pitch Lock Linear Actuators (**PLLA**), installed on fixed swashplate, as shown in Figure 2;
- Slip ring, installed in the master shaft;
- Blade Fold Actuators (**BFA**), installed one for each of the five blades, between the inboard and outboard tension link, as shown in Figure 3;

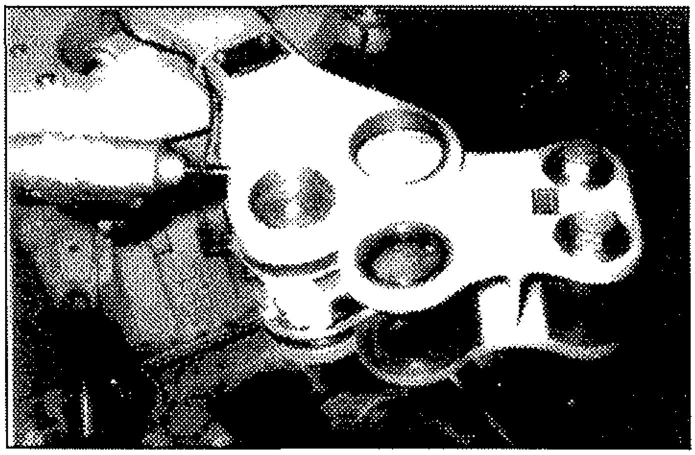

Fig. 3 Folding tension link

- Tail Lock Actuator (**TLA**), installed on rear fuselage, as shown in Figure 4;
- Tail Fold Actuator (**TFA**), installed on rear fuselage, as shown in Figure 4.

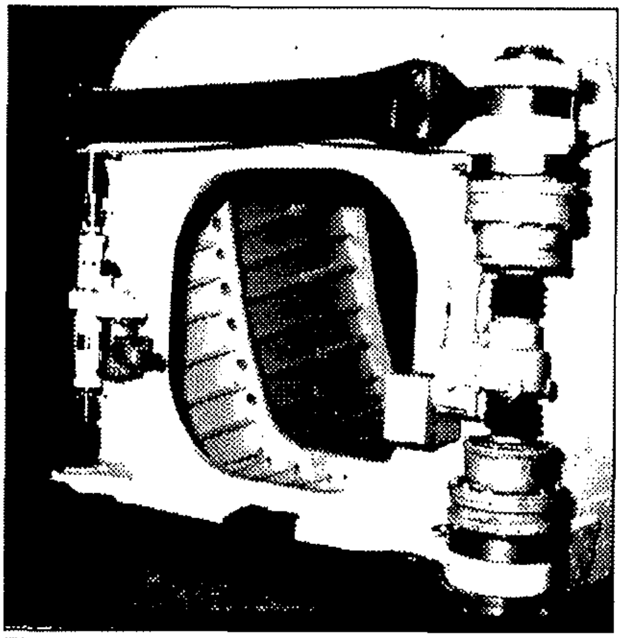

Fig. 4 Tail lock & fold actuators

It should be noted that although blade N° 1 (the master blade) does not fold, it is equipped with the same blade fold actuator like the other four, to maintain rotor dynamic balance and to allow it to be folded manually for maintenance purpose only.
The necessary resolvers and end-of-stroke microswitches are integrated in the appropriate components.
Although physically part of the main rotor head, the inboard/outboard tension link assemblies are an essential part of the system, in that they guarantee the appropriate relative positioning of the blades.
The blade flap and lag stops are another fundamental element of the system since they positively restrain the blades from undesired movements; because of this importance, their description is included in Section 5 as well.
In addition, the system is interfaced with the Automatic Flight Control System actuators (**AFCS**) and with the helicopter's Electronic Instrument System (**EIS**), which prompts the crew on necessary actions, provides them with a visualisation of the progress of the operation and informs of any malfunction in *individual system components (See Figure 5 for an example of the folding display).*

The system may be functionally split in two main parts: main rotor blades and tail cone. Each of the two parts can be operated separately so that it is possible to fold either the main rotor blades or the tail or both concurrently.

4. GEOMETRY AND FOLDING SEQUENCE

The blade folding geometry foresees a master blade positioned aft along the centerline and approximately level, the two blades next to the master folded backwards along the master and approximately parallel to it, and the other two blades folded underneath the previous ones, with an inclination of 14° downwards. In order to accomplish this, the following four main operations have to be performed:

- Swashplate positioning,
- Swashplate locking,
- Master blade alignment,
- Blade folding.

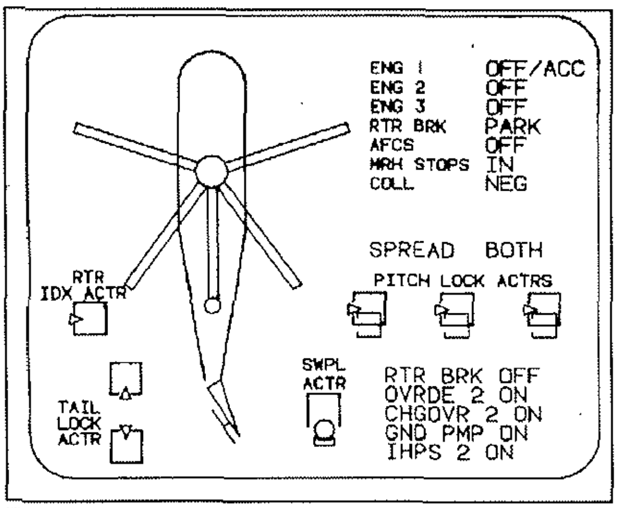

Fig. 5 EIS folding display (example)

The tail folding geometry foresees a forwards and downwards movement, for which it is necessary to perform the two main operations:

- Tail unlocking,
- Tail folding.

To start the operations, after normal engine and rotor shut down procedure, the pilot is asked to switch **ON** the folding system, to select section of helicopter that needs to be folded (MRH and/or TAIL; both for this description), to set the switch to **FOLD**, and at the end to push the collective down. At this point the folding sequences starts.

At first the RIA pulls out its splined shaft to engage the gear of the main gearbox *but it still does not align the* master blade. The rotor cannot rotate because the electromagnetic brake inside the RIA. At the same time the FMU pressurizes the hydraulic system.

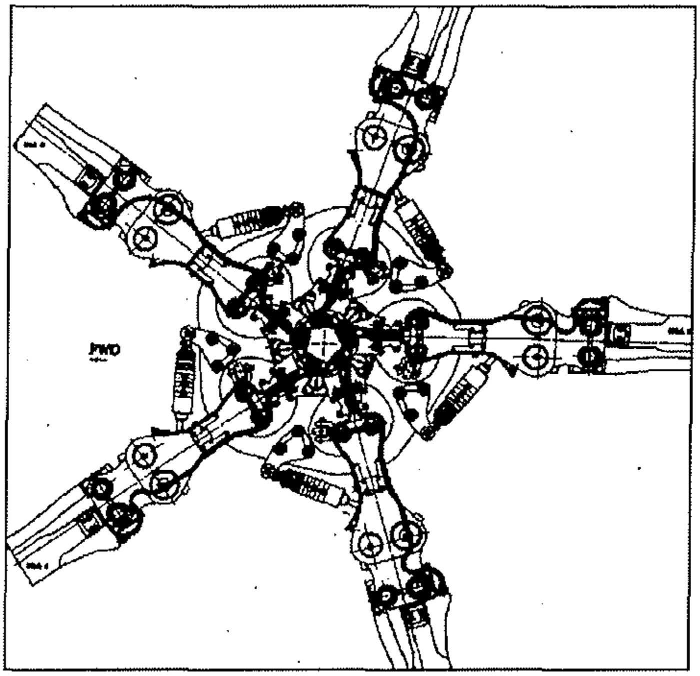

Fig. 6 Main rotor head

As soon as the hydraulic system is pressurized, a check list appears on one of the cockpit CRT's, which displays **COLLECTIVE NEG** to prompt the pilot to push the collective lever down into the negative collective position, which is the only manual action required during the folding sequence. Measures are taken by the FMU to prevent the need for pilot action on the collective trim switch during this operation. The cyclic stick is automatically centered because of the geometry of the mixing unit (at low collective position correspond low cyclic movements).

This action has the effect of preparing the flight controls for the next step and to operate a Negative Collective Microswitch which sends a signal to the FMU.

Once this is accomplished the FMU outputs a signal to drive the FCPA (mounted aft of the mechanical mixing unit) to push against its interface to the mixing unit and subsequently to move it forward to a predetermined position. This action accurately positions the swashplate and maintains locked the flight controls. During these operations, the FMU also manages the AFCS parallel actuators connected to the control runs in order to maintain positive contact between the FCPA and the mixing unit. Subsequently, the FMU commands the three Pitch Lock Rotary Actuators to position vertically the pitch lock levers inside the brackets of the fixed swashplate.

In this condition, the pins of the three Pitch Lock Linear Actuators, on the fixed swashplate, are driven to full extend position. Due to the tolerance of the entire subsystem, it is expected that perhaps the PLLAs cannot carry-on their entire stroke; for this reason, the FMU, at a well identified step, removes hydraulic pressure: the relative freedom given to the swashplate allows the proper insertion of the PLLA pins. In this way, at the end of the operation, the fixed swashplate results to be strongly locked to the upper case of the main gearbox.

At this point the *FMU will power the Rotor Indexing Motor (RIM) to align the master* blade. *Signals* regarding the main rotor shaft position are sent to the FMU by the resolver inside the slip ring. From the position signal the FMU defines if the rotation sense has to be clockwise or counter clockwise in order that the maximum excursion for the rotor is always less than 180 degrees. 90 degrees before reaching the folding position, the four blade fold actuators are powered to the fold sense. The rotor head will reach the folding position always within a well defined time from the start of the four blades. The FMU is able to

take under control this condition which warrants the impossibility of contact between blades and helicopter structure. As soon as the intermediate blade (blade N° 2, starboard side) has completely folded (at this point the main rotor head is already positioned), the tail folding sequence is activated. At the first the FMU powers the Tail Lock Actuator to full retracted position so to leave the tail free to rotate. After that, the Tail Fold Actuator is powered till the end of stroke of the tail is reached.
In the lower hinge shaft of the tail, there is a resolver which reads the position of the tail. As during rotation of the tail, the blades N° 3 and N° 4 are still moving, in order to avoid contact between tail cone and blade N° 3, the FMU will check that the blade N° 3 had reached its folded position before that the tail reaches a well defined angle. It is worth noting that due to the inclination of the tail folding hinge, the tail itself folds forwards and downwards, bringing the top of the tail rotor disk below the main rotor hub height and thus avoiding the need for individual tail rotor indexing.
At the end of the sequence the space envelope occupied by the EH101 is 15.85 x 5.3 x 5.2 meters (length x width x heigth). This can be compared with the 14.57 x 4.95 x 4.81 folded dimensions of the Sea King helicopter.
All the folding operations are performed within a time of 160 sec. If only blades are selected to fold, the total time becomes about 145 sec; 60 sec for folding of the tail only. The Sea King model in service with the Marina Militare Italiana (**MMI**) in comparison, takes about 115 sec for blades folding (tail folding is manual), but this time excludes the blade pitch lock phase which has to be performed manually by the pilot with the use of the cyclic stick; this phase usually takes no less than 30 seconds but may take considerably longer.

5. DESCRIPTION OF SYSTEM COMPONENTS

BLADE FLAP/LAG STOPS

The blade flap-lag stops in their present configuration consist of a spigot installed on the rotor hub, a sliding limiter, a spring, a series of masses and a limiter support installed on the tension link, as Figure 7 shows. Inside the support, at a well defined N_r when the rotor is decelerating from flight to ground idle, the spring force prevails over the centrifugal force of the masses, moving the sliding limiter to engage the spigot which, when the rotor comes to rest, provides positive limitation of blade movement before starting of the folding operations.

FOLDING MANAGEMENT UNIT

Is the intelligent heart of the fold/spread control system managing all the operative sequences and their status. The unit is essentially divided into three areas comprising three main control boards as follows:

- Electronic folding computing/processing board
- Power relay board
- Fault detection board

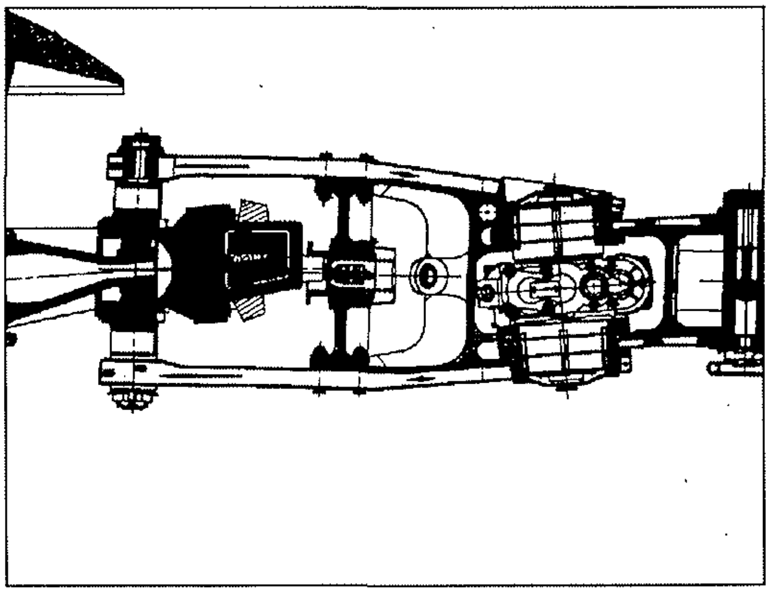

Fig. 7 Blade flap/lag locks

The FMU receives electrical inputs from the following interfaced systems:

- Engines;
- Rotor brake;
- Hydraulic systems;
- Electrical power systems;
- Undercarriage (Weight on wheels switch);
- AFCS (parallel and series actuators);
- Electronic Instrument System (EIS);
- Sensor Interface Unit for Master Caution generation as required.

The FMU processes the status of the above interfaced system and activated interlocks to prevent:

- Starting of N° 1 engine if in MAIN drive;
- Starting of N° 2 engine;
- Starting of N° 3 engine.

Subsequently the FMU selects and powers the motors and actuators in the correct sequence for fold/spread operations as selected on the FOLD/SPREAD control panel. The sequential inputs to the various sub systems will only proceed to the next stage if the FMU receives the enabling status at the correct time for each stage, otherwise it will send a Master Caution generation signal to the Aircraft Management System. Throughout a Fold/Spread operation an interface unit to the EIS provides crew monitoring of the course of events via a dedicated screen on the Power System Display. The display (Figure 5 shows an intermediate phase of a spreading cycle) indicates the individual stage of operation currently being undertaken (indexing, blade fold), the status of all the subsystems involved, and is provided with a symbology to advise the pilot, in case of failure, of the item failed and whether the folding sequence can continue for the remaining items. This last feature is in line with the general philosophy of the EH101 management system which monitors all the subsystems and also logs all the failure and maintenance events for subsequent action by ground personnel.
A dedicated connector is provided to connect the MFU to a Manual Control Box to allow manual control over the various operations of the Fold Spread System in the event of the automatic system malfunctioning. During a manually controlled operation the EIS display could be still available.

ROTOR INDEXING ACTUATOR

The RIA is inclusive of:

- Rotor Indexing Motor with the function, when engaged, of positioning in azimuth the main rotor. It has the double possibility of CW or CCW rotation so that the maximum excursion it is requested to ingenerate on the rotor is never more then 180 degrees;
- Linear Actuator with the purpose of engaging or disengaging the splined shaft of the Rotor Indexing Motor.

PITCH LOCK ACTUATOR SYSTEM

As already said in Para 3, the Pitch Lock Actuator System includes Pitch Lock Rotating Actuators and Pitch Lock Linear Actuators:

- The PLRA is composed by three identical items installed around the upper case of the Main Gear Box, approximately 120 degrees apart. Each of them includes an arm which can be rotated around its axis towards the position **LOCK** or **UNLOCK** positions (referred to the swashplate). Each actuator is equipped with begin of stroke and end of stroke microswitches;

- The PLLA is composed by three identical items installed on the stationary swashplate (one Linear for each Rotating). When the PLLA is in its proper position the PLRA can lock the swashplate by inserting its pivot in the proper site under action of the linear motor. The linear motor has double polarity, extend or retract, and the travel of the pivot operates a begin of stroke, an insertion begun and end of stroke microswitches.

FLIGHT CONTROL POSITIONER ACTUATOR

The FCPA is a linear actuator mounted aft of the flight controls mechanical mixing unit. When powered, it engages and pushes forward the moveable mixer stop and consequently moves the flight controls to the predetermined position.

TAIL FOLD ACTUATOR

The TFA consists of a rotating actuator driven by an electric motor, and of a couple of geared hinges which provide motion to the movable tail unit. The external case of each hinge is secured by a frontal spline to a fixed arm in the rear fuselage, and is retained by a Vee band clamp. A splined pinion engages the tail unit's arm. The input shafts are mechanically connected and are driven by the motor through a reduction unit. The motor is hard mounted to the frame of the rear fuselage through removable bolts.

TAIL LOCK ACTUATOR

The TLA consists of a linear actuator powered by an electrical motor, and a couple of pins which fit, at the end of actuator stroke, the holes located on the coupling beams of both the rear fuselage and the tail unit. The TLA is hard mounted onto the frame of the rear fuselage by removable bolts.

SLIP RING

It is the electrical interface between the main rotor head and the main gearbox. The slip ring is also carrying the Azimuth Position Transducer (resolver). It is installed inside the main rotor mast.

BLADE FOLD ACTUATOR

The blade fold actuator consists basically of two actuators (one rotary for blade folding/spreading and one linear for the actuation of the locking pins), one electrical motor, an epicyclic gear train to transfer the motion from one actuator to the other and two interlock devices.
The blade fold actuator has been designed on a modular concept for easy of repair and maintenance. It consists of the following seven modules:

- one housing containing the

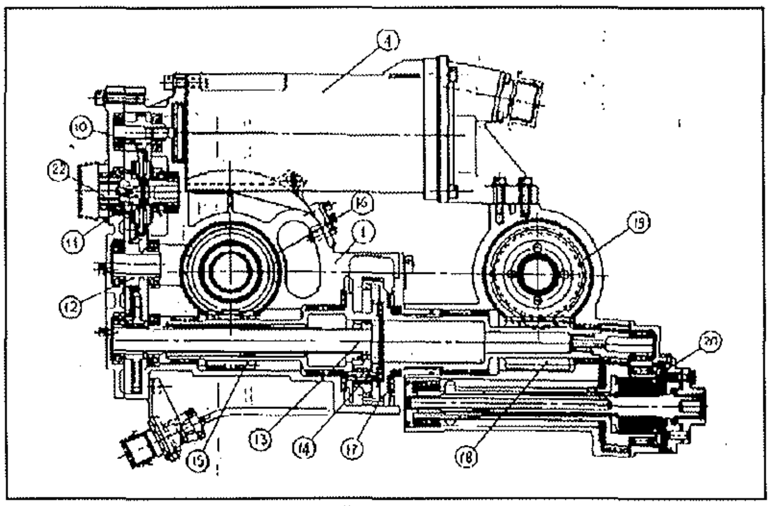

Fig. 8 Blade fold actuator #1

gearing mechanism, the interlock devices and the mechanical stop (1);
- two rotary actuators (2);
- two linear pins (3);
- one electric motor (4);
- one flag indicator (21).

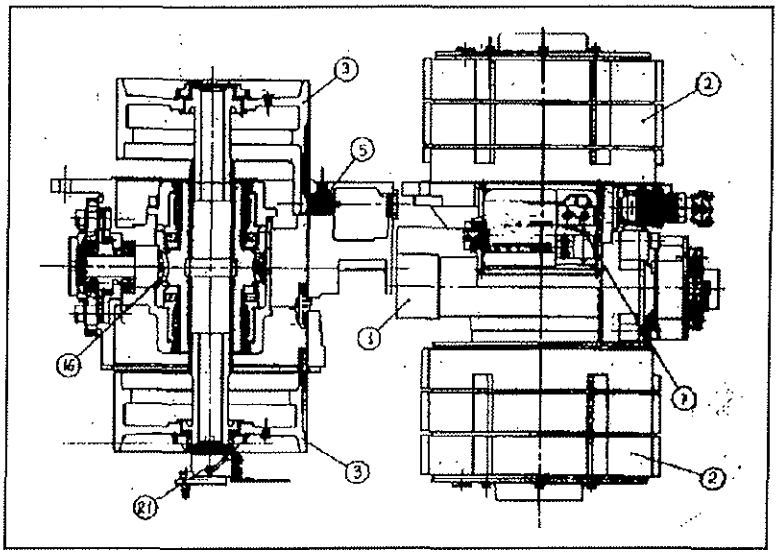

Fig. 9 Blade fold actuator #2

Each module, with the exception of the housing, can be removed and installed on the helicopter without the removal of the other modules.
The gear train comprises three stages of spur gears, an epicyclic differential gear and two worm/wheel gears. The differential gear, whose function is to transfer the motion either to the pins or to the rotary actuators, has the sun gear (13) connected to the motor, the planet carrier (14) connected to the linear pins and the outer gear (17) connected to the rotary actuators.
As it will be explained later, depending upon the operating phase, the electric motor drives either the planet carrier or the outer ring gear. A further reduction is obtained downstream the differential gearing by means of two worm/wheel gears, one driving the linear pins and the other driving the rotary actuators.
The actuators (2) which fold and spread the blade are geared epicyclic rotary actuators consisting of a sun gear, driving compound planet gears meshed with a fixed ring gear connected to the blade and two ring gears connected to the tension link. The actuators planetary gear train provides the function of torque amplification and speed reduction. A large reduction ratio is achieved by having similar but slightly different ratios of planet teeth or ring gears teeth for the inner and outer sections.
The blade fold actuator also includes two microswitches, one (5) which signals the extension of the locking pins and the other, adjustable, related to the angular position of the blade. The microswitches are of the sealed type.
Additionally there are two interlock devices, one (8) actuated by the rotary actuators and the other (9) actuated by the locking pins. The first one allows the movement of the locking pins only when the blades are in the fully spread position, while the second one prevents any movement of the rotary actuators unless the pins are fully retracted. The equipment operation, starting from the spread position, is as follows (make reference to Figures 8 through 11 for identification of numbered items).

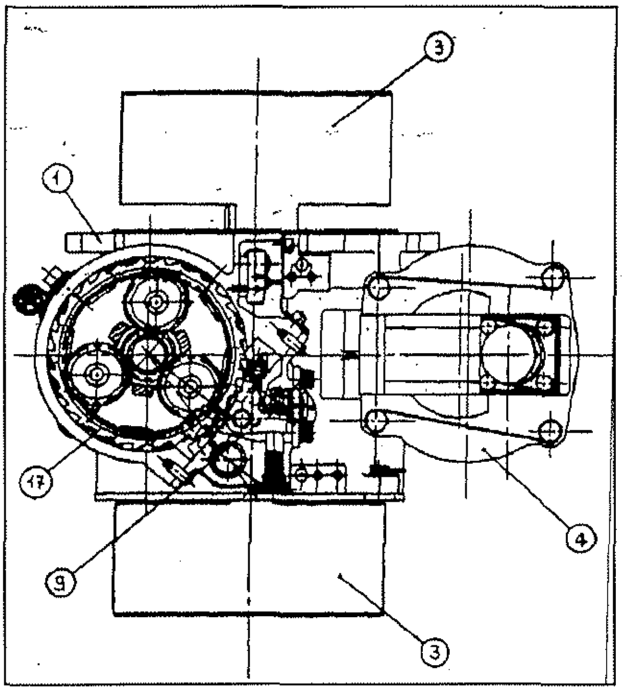

Fig. 10 Blade fold actuator #3

In the spread position the locking pins (3) are in the extended position, the microswitch (5) is actuated, the interlock (8) of the pins is disengaged and the interlock (9) of the rotary actuators is engaged.

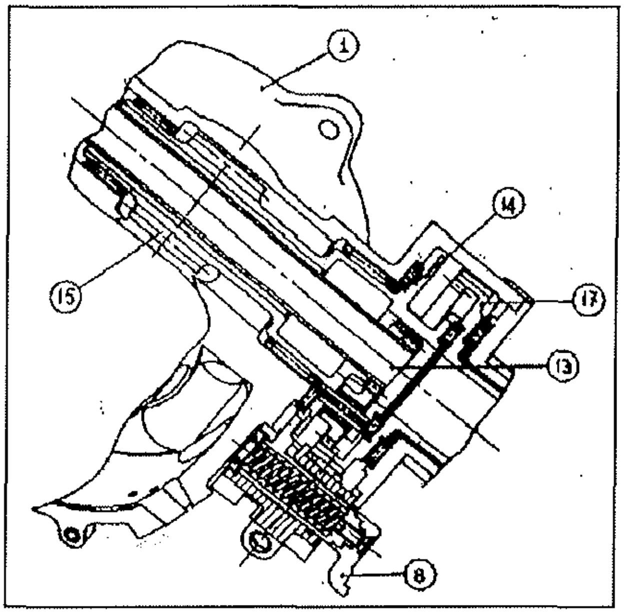

Fig. 11 Blade fold actuator #4

The first operation of the folding sequence is the retraction of the locking pins. This is achieved by driving the pins from the motor (4) through the gears (10) (11) (12) (13) (14) (15) (16). The worm (15) is driven trough the planet carrier (14) of the differential gear which has its outer gear (17) locked by the interlock mechanism (9) and therefore cannot rotate until the interlock is released. The retraction of the pins (3) continues until they come in contact with each other. At this stage, when the pins are fully retracted, the interlock (9) is released and the folding of the blade starts. During this phase the outer ring (17) of the differential gearing is free to rotate while the planet carrier (14) is mechanically locked by the interlock (8). The rotary actuators (3) are driven by the motor through the gear train (10) (11) (12) (13) (14) (17) (18) (19).
As soon as the rotary actuators start, the interlock mechanism (8) of the pins is activated through a cam integral with one of the rotary actuators and therefore the locking pins (3) are positively held in the retracted position.
When the folding position is reached, the end stroke microswitch (7) is actuated and the motor is stopped by the FMU. Simultaneously the electromagnetic brake of the motor is engaged. The equipment is also provided with an emergency mechanical stop (20) whose function is to prevent overrunning of the blade beyond the folded position in case of failure of the microswitch (7) or of the associated circuitry.
The spreading operation starts with the actuation of the rotary actuators which are driven through the differential gearing whose planet carrier (14) is positively locked by the interlock (8).
When the fully spread position is reached, the blade is stopped by a mechanical stop provided in the aircraft structure, the cam of the rotary actuator releases the interlock (8) and the pins start to extend driven through the planet carrier (14). At the same time the interlock (9) of the rotary actuators is engaged by the pins. As soon as the pins are fully extended, the microswitch (5) is actuated and the electric motor is stopped through the FMU.
Additionally a flag (21) actuated by one of the two locking pins provides a visual indication of the full engagement of the pins by switching its color from red to green.
The equipment can be manually actuated in case of failure of the power supply, through a splined input (22) in the first stage of the gear reducer. The equipment is sealed and grease lubricated for life.
The maximum time required for a folding or spreading operation over the angle of 142.5°, inclusive of the time required to retract or extend the locking pins, is 90 seconds.

6. SYSTEM DEVELOPMENT

After successful testing of the individual electro-mechanical components, the first trials of the complete system were performed on the EH101 Ground Test Vehicle (**GTV**) in 1989. The tests were conducted with a development control box, and the different control inputs were given manually. This allowed to refine the overall timing of the folding sequence and to proof check and improve all the steps in the folding logic. One problem that arose from those early tests was not related to the folding system itself but to the

lead-lag stops in the main rotor head which were of a conventional spring-loaded pendulum type and which did not engage properly under the rotor braking phase. This lead to an activity into identifying potential substitutes, such as pressurised lag dampers or different mechanical devices, in order to perform this essential function.
Meanwhile, the folding system was then installed on the MMI prototype and tested on ground, although using external AC power, in 1990, while in June 1991 the first folding operations on a ship were performed, operating on the Royal Navy (**RN**) Norfolk frigate, by the PP5 prototype fitted with the completely autonomous system, that is to say inclusive of the APU, APU generator and electro-hydraulic pump to supply AC current and hydraulic power.
Further trials were performed in October 1991 on the MMI carrier Garibaldi, while the first trials in high wind and rough sea conditions were performed in December 1992 by PP5 on the Iron Duke Type 23 RN frigate, where also the McTaggart-Scott deck handling system was extensively tested, showing the need for further refinement of the design of the interface with the helicopter landing gear. Fully automatic operation, in accordance with the description given in Section 4, has been achieved. It is interesting to note that, in order to clear the folding system for those trials, the PP6 prototype in Italy performed a series of fold/spread cycles with simulated wind from the down wash of a CH-47 hovering at very low height in the vicinity: relative wind measurement by ground personnel in the vicinity of the main rotor-tail area was used as a feedback and for correlation with the other recorded data (blade and tail displacements, stresses).
In June 1993 the newly designed flap-lag stops, as described in Section 5, were tested on the GTV and over 100 start-stop cycles were completed successfully without a single missed engagement-disengagement.
The next steps towards full qualification of the system will be:

- the execution of 100 folding-spreading cycles during the performance of the dynamic systems Type Test which has already been started using the GTV as test article;
- the completion of individual components qualification by the suppliers through exhaustive environmental and duty cycle testing.

Furthermore, within the frame of the Maturity Program which will take place during the next years with the aim of enhancing the overall reliability of the EH101, 3000 folding/spreading cycles on the complete system will be performed.

7. CONCLUSIONS

The EH101 automatic blade and tail folding system is entering its final qualification phase: the concept, after some design refinements, has proved to be capable of working properly also in the adverse conditions it will have to face during its operational life, to be easily operated by the pilot, due to its fully automatic management, and to require no intervention at all by ground personnel. The individual components are being qualified, and the complete system is currently flying and operating on two prototypes and is installed on the GTV for type test qualification purpose, and for future maturity testing.

8. REFERENCES

1. C.V. Toner, SH-60B Seahawk automatic blade fold system, AHS National Specialists' Meeting "Rotor System Design", Paper III-2, October 1980.