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QUADRIFOGLIO : A NEW PHILOSOPHY IN THE CONFIGURATION OF THE SERVO-CONTROLS FOR HELICOPTERS

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ABSTRACT

The purpose of this work is to illustrate the new philosophy followed for the configuration of the main rotor servo-control for the EH101 helicopter.
After a brief description of the solutions till now used (tandem and side-by-side) for the design of redundant servo-controls, either for helicopters or for fixed wing aircraft, and an analysis of the respective characteristics and deficiencies, there is the enunciation of the design requirements for the main rotor servo-control of the EH101, which led to the solution called "Quadrifoglio".
There is a description of such solution, consisting of the position of the cylinders as quadrilateral, connected two by two to each hydraulic system according to the diagonals of the quadrilateral itself, as well as the illustration of the main engineering solutions which allowed to obtain such configuration.
The description of the servo-control continues with the analysis of the servo-valves and the by-pass systems in case of hydraulic failures, jammings and lack of hydraulic pressure.
Then, there is a comparative analysis between side-by-side and "Quadrifoglio" solutions, analysis which includes all the technical aspects of the servo-control : from consideration on envelope and weight characteristics to an operating analysis up to a reliability analysis.
This allows to fully evaluate the reasons which let Magnaghi Oleodinamica trust in this new solution by submitting it, with success, for the EH101 helicopter.

In the last years, for the manufacture of servo-controls for primary flight surfaces, either for fixed wing aircraft or for helicopters, the concept of full redundancy of the operating capabilities became more and more universal.
Such redundancy assures the necessary reliability and safety levels for these control systems which, because of the continuous increase in the loads applied to the surfaces being controlled, represent the only possible way for flight control.
The present state-of-art shows various solutions for the structure of the control and feed-back section : from manual systems, having linear or rotary valves, equipped or not with anti-jamming devices to much complicated electro-hydraulic systems, with two or more servo-valves, with equipment for internal or external monitoring of the operating conditions for each control lane.
On the contrary, the structure of the power section, being bound to the existence of only two independent circuits of hydraulic supply,

nearly in most cases, can be led back to two alternative solutions :

- tandem
- side-by-side

These two definitions refer to the position of the two power elements which, for our applications, are linear and double effect actuators, in most cases fully or partially balanced.

"Tandem" solution (see fig. 1) foresees the position of the actuators along the same axis, connected between them by means of a common rod and other disparate systems as to the bodies; "side-by-side" solution (see fig. 2) foresees the actuators located "side-by-side" with the rods joined through a yoke and the bodies connected by means of different ways according to specific applications.
Both solutions became, time by time, the most suitable as to specific application and different requirements of the design specifications.
It is clear that, whenever there is a limited space as regards front envelope, and large space as to longitudinal (along load axis) envelope, "tandem" solution appears the best as to "side-by-side" solution which, on the contrary, is selected when space availability foresees conditions opposite to those previously mentioned.
Anyhow, one must not think that the selection between the two solutions may be the only possible on the ground of envelope and installation considerations.
The selection between the two solutions is conditioned by another parameter, i.e., their different behaviour in case of failure in one of the two hydraulic sections.

Either with one or with two hydraulic operating sections, as to "tandem" solution, the pressure line of loads applied through the controlled surface coincides with the pressure line of the reactions developed by the actuator(s); on the contrary, this does not happen for the "side-by-side" solution (see fig. 3).
From this, it comes that, while in case of failure, "tandem" solution shows the only problem of a power reduction depending on the non-operation of a section, "side-by-side" solution suffers, under this condition, all the effects connected to the arising of lateral loads on the operating actuator, loads which result in a drastic reduction in the operation time under such conditions.
Practically, a hydraulic failure of the "tandem" solution can be compared, with no doubt, to a normal operation; on the contrary, a hydraulic failure, depending on any other component of the supply circuit, becomes, in a short time, for the "side-by-side" solution, a typical induced failure.
Under these terms, this last consideration should be, alone, sufficient to make nearly unproposable "side-by-side" solution, but, already more than once, either for installation requirements, or for other reasons as, for instance, the best behaviour as to balistic survival, the designers were obliged to choose this solution by resorting to the most different technical and design solutions to obviate, or better to limit, such problem.

On drawing up the technical proposal for the main rotor servo-control of the Agusta-Westland EH101 helicopter, the Magnaghi Engineering staff, recently, was in the situation of selecting the architecture of the power stage.

The main requirements of the technical specification were :

- Max length at midstroke : 580 mm
- Total stroke : 145 mm
- Balanced actuators
- No reduction in life when operating with only one hydraulic section
- No maintenance requirement after operation with only one hydraulic section.

If an analysis is made for the first three requirements, it is easy to realize that, in this case, "tandem" solution should be rejected for envelope reasons. In fact, without considering the length of the glands and the eye ends for the connection of the fixed and movable structure, with a full stroke of 145 mm, the minimum length of a "tandem" throughly balanced servo-control, at mid-stroke, is :

$$L_{min} = 3.5 * \text{stroke} = 507.5 \text{ mm}$$

If we add to this dimension the lengths of the four glands (two at center for reliability reasons), which, at least, correspond each to the equivalent of a rod diameter and room necessary for the housing of the frame fittings and pistons, it is easy to state that the minimum length of a "tandem" actuator at mid-stroke could not have been less than 750 to 760 mm.
These considerations induced the designers to try to solve the problem of meeting the last two requirements by resorting a "side-by-side" solution.

The Magnaghi staff weighed and designed many manufacturing and technological solutions to produce the components subject to anomalous loads in case of hydraulic failure, but what was developed, besides making the manufacture of the servo-control complicated, did not give the requested full warranty of meeting the prescribed requirements.
For this reason, the Magnaghi people continued looking for alternative solutions till they got the idea of "Quadrifoglio" : the proposed and winning solution for the EH101 helicopter.
Posteriorly, this solution appears to be the easiest and most intuitive to solve the problem of a load asimmetry in case of failure between "side-by-side" actuators.
It foresees the use of four actuators as quadrilateral, connected two by two, and consisting of the two systems according to the diagonals of the quadrilateral itself.
The four cylinders are connected together and to the structure through a yoke which embodies the eye end for the connection to the structure; in the same way, the four pistons are bound together and to the movable elements to be controlled (see fig. 4).

The name "Quadrifoglio" of this servo-control derives from the front shape of these yokes.
To have positioned the power components of each system according to the diagonals of a quadrilateral let that, under each working condition, the pressure line of the applied loads was coincident with the resultant of the servo-control opposite reactions, by eliminating, in this way, the problems existing for "side-by-side" solution.
Besides, it was possible to draw near the cylinders the structure connection, without moving from the load pressure line, as, on this line, are no longer the outgoing backrods.

This peculiarity led to the realization of a servo-control having, at mid-stroke, a length of 495 mm only, with considerable advantages as to installation, and with the possibility of containing the relevant weights within specification limits (of course, four cylinders should result, linear dimensions and performances being equal, heavier than two).

From a schematic point of view, this type of architecture solved, in a very simple way, the problem outlined many times, of the reaction balance, but it required considerable efforts to succeed in determining all the suitable manufacturing solutions and make it functional, reliable and comparable, as to weight, to the "side-by-side" solution.
The problem existing for obtaining a complete parallelism between two "side-by-side" actuators are doubled if the actuators become four; the distribution of the pressurized oil, along distances equivalent in the two directions, and without excessive pressure drops, with four actuators, involves the development of systems for hydraulic connection between the actuators of each independent circuit; the two yokes must be structurally designed in such a way as to drive, along a unique center axis, the forces developed by the four actuators and, at the same time, they must be easily manufactured and have limited weight and envelope.

The servo-control, designed by Magnaghi (see figg. 5/6/7) should solve these problems.
As regards the power section, it consists of four cylinders (identic two by two), at blind end on one side and embodying a gland on the other side.
This allows to obtain, on the blind side of the cylinder, an external cylindrical centering area which, on inserting, for two cylinders in the yoke for the connection to the fixed structure and for the others two in an intermediate collecting yoke, creates a guide sufficient for the positionning of the four elements with parallel axes.
In addition, the blind end allowed to keep the drive diameter under the outside diameter of the cylinder itself, by locking it to the yoke by means of a ring nut having a very small diameter.
With this locking solution it was possible to have, on both yokes, on the quadrilateral sides, a small ring nut and a large one adjacent by keeping, in this way, at minimum the center distance among the four actuators.
Besides limiting the front envelope of the servo-control, this limitation of the center distance allowed to obtain a shape of yokes, which makes them as elements having an even resistance capable of withstanding the applied stresses without being very heavy and complicated as to manufacture.
These elements are forgings in stainless steel, type 15-5PH, which are machined under extremely fine dimensional tolerances and with a shape in the cylinders shrinking-on area suitable for assuring their exact positioning.

The hydraulic connections between the actuators of the same circuit are obtained by means of ducts inside the cylinders and pipes which insert, perpendicularly to the longitudinal axis, close to the connection yokes. Such pipes accomplish the double function of hydraulic connection and broaching (axial relative positioning) of the actuators but without being subjected to lateral loads or generating lateral loads on the cylinders.

The above allows to illustrate the solutions followed to assure, as to power section, the compliance with the specification requirements for the "Quadrifoglio" servo-control we proposed for the EH101 helicopter. However, we think it is worth saying some words also in the description of the servovalves, fitted to this servo-control which, too, show some original ideas as to the by-pass system in case of failure of a circuit and for the monitoring of this condition.

These units are two assemblies independent from the hydraulic actuators but connected to them by means of a threaded fitting. They have a body in aluminium alloy (in order to limit weight) and are fitted to the two upper actuators, one opposite to the other so as to give their input in the mean area of the actuators themselves, where the input/feed back and summing levers are located (the servo-control is mechanical input type).
They consist of two flow control valves one for the by-pass of the actuator chambers connected to it, the other for distributing the pressurized fluid (see fig. 8).
The by-pass valve, which foresees a hydraulic precession such as not to supply the valve till the by-pass condition is eliminated, is moved and kept under normal operating condition whenever is a supply pressure and the valve does not show any failure.
In this condition, a micro-switch is changed-over so as to signal the proper operation of the complete system.

The flow control valve consists of two concentric pistons : the outer piston acts like a flow control valve, while the inner piston is for re-positioning, under by-pass conditions, the by-pass valve in case of jamming of the outer piston.
A system of springs produces the thrust load value required for the operation of this system, while, being by-pass occurred, this condition is signalled by means of the same micro-switch and constantly kept till the servo-control hydraulic supply is de-pressurized; this gets the by-pass valve to come to by-pass condition.

As already told, before conceiving the "Quadrifoglio" servo-control, the Magnaghi staff designed a "side-by-side" solution optimized in compliance with the requirements of the EH101 specification.
By virtue of the above, it is now possible, through a comparative analysis between the two proposed and developed solutions, to show what are the reasons which led to select the "Quadrifoglio" servo-control.
In particular, the main parameters for this selection are :

- Dimensions
- Weight
- Life under emergency condition
- Reliability
- Safety

We analyze below these characteristics for the two Magnaghi configurations of the servo-control for the EH101 main rotor.

- Dimensions :

  A) "Side-by-side"

- Length at mid-stroke	:	580 mm
- Front width	:	220 mm
- Front height	:	198.3 mm

B) "Quadrifoglio"

- Length at mid-stroke : 495 mm
- Front width : 195 mm
- Front height : 177 mm

NOTE : As to height, we considered the envelope of servovalves cylinders assembly plus the feedback lever, for, as to installation, there were no space problems on the side of the input lever.

In this case, numbers talk alone. All dimensions are lower in case of the "Quadrifoglio" servo-control, therefore, the advantages obtained with it can be easily realized.
Anyhow, it is important to outline, above all, the saving in the length at mid-stroke. As already pointed out, the solutions with "side-by-side" actuators are applied just to reduce this envelope which causes, on the helicopters and for the main rotors, many problems connected to the configuration of the main gear box.
In addition, in this case, it was possible to manufacture some stout, but at the same time light,supports for the servo-controls, by just taking advantage of the very small length at mid-stroke.
The choice of the "Quadrifoglio" servo-control allowed a saving in weight,for the aircraft structure, of about 500 gr. for each servo-control.

- Weight :

A) "Side-by-side" : 16 Kg

B) "Quadrifoglio" : 16.7 Kg.

In this case, if we consider the data pertaining to each servo-control, the advantage for the "side-by-side" solution is evident.
But, taking into account the saving in weight as to the support structure, this gap becomes very small and quite negligeable.

- Life under emergency conditions :

A) "Side-by-side" : 10% of total life

B) "Quadrifoglio" : no limit to total life

This peculiarity, which is the intrinsic reason for the creation of the "Quadrifoglio" servo-control, constitutes, practically, the winning element for such solution.
In spite of the design efforts and the solutions applied for "side-by-side" configuration, considering the load conditions called out in the specification as regards the emergency operating cycles we did not think possible to declare a life of our "side-by-side" servo-control under these conditions higher than 10% of total life. This as stress condition, of some components, such as, for instance, the glands, reach limits such as to reduce operating reliability below acceptable limits.

- Reliability :

A) "Side-by-side"

- Logistic reliability $< 250\ 10^{-6}$ F/hr
- Mission reliability $< 150\ 10^{-6}$ F/hr

B) "Quadrifoglio"

- Logistic reliability $< 260\ 10^{-6}$ F/hr
- Mission reliability $< 90\ 10^{-6}$ F/hr

These parameters, very important either for commercial or for military use of the helicopter, show that, if the greatest quantity of the "Quadrifoglio" components make their logistic reliability worse (that correlative to the unscheduled maintainability) its architecture, by limiting stresses under any operating condition, assures better results as to mission reliability.

- Safety :

A) "Side-by-side" $< 0.2\ 10^{-6}$ F/hr

B) "Quadrifoglio $< 0.1\ 10^{-6}$ F/hr

These data were calculated, considering as prejudicial to flight safety, the following failure modes :

- impossibility to generate an input control;
- impossibility to generate output movements ;
- no correlation between input and output.

Fig. 9 shows the two fault trees for the two configurations for an analysis at the first failure.

As you can see, the big advantage of the "Quadrifoglio" servo-control is not to consider a single failure which can cause no-correlation between input and output.
This depends on the fact, for example, that, on the "side-by-side" servocontrol, we were obliged to use only one feedback lever in order not to increase the mismatch effects connected to failure and normal mode, and deformations, due to failure operation, can become, for the "side-by-side" servo-control, so high as to provoke a lack in correlation between input and output.
Besides these parameters, which can be synthesized in numerical data in our analysis, we have not to undervalue other parameters which, on the contrary, can not be easily quantified and synthesized, but not less important.

For instance, maintainability is undoubtedly better for "Quadrifoglio". It is enough to think of how many monitoring difficulties and check of failure modes would be necessary because of life limit of the "side-by-side" servo-control under these conditions. This would give rise to a continuous monitoring during operation and considerable care for people involved in maintenance as regards the warranty of reliability and flight safety in opposition to operational economy and availability of helicopters.

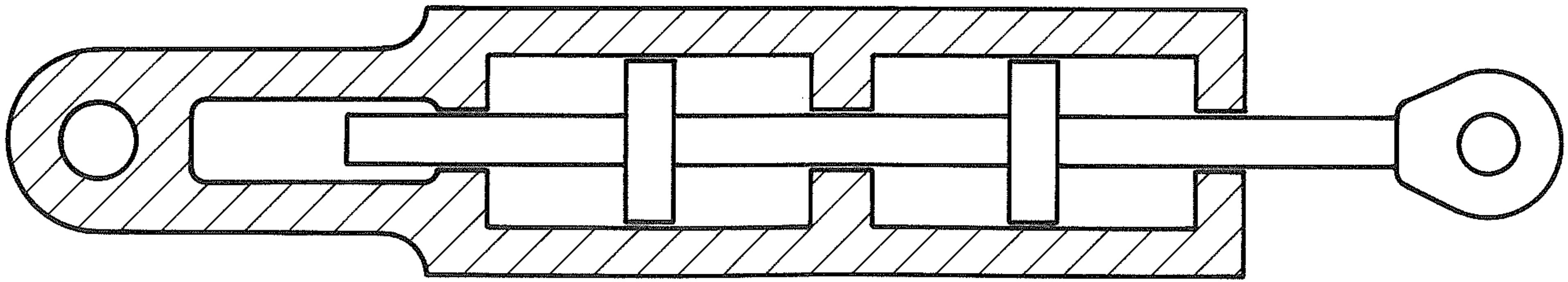


Fig. 1

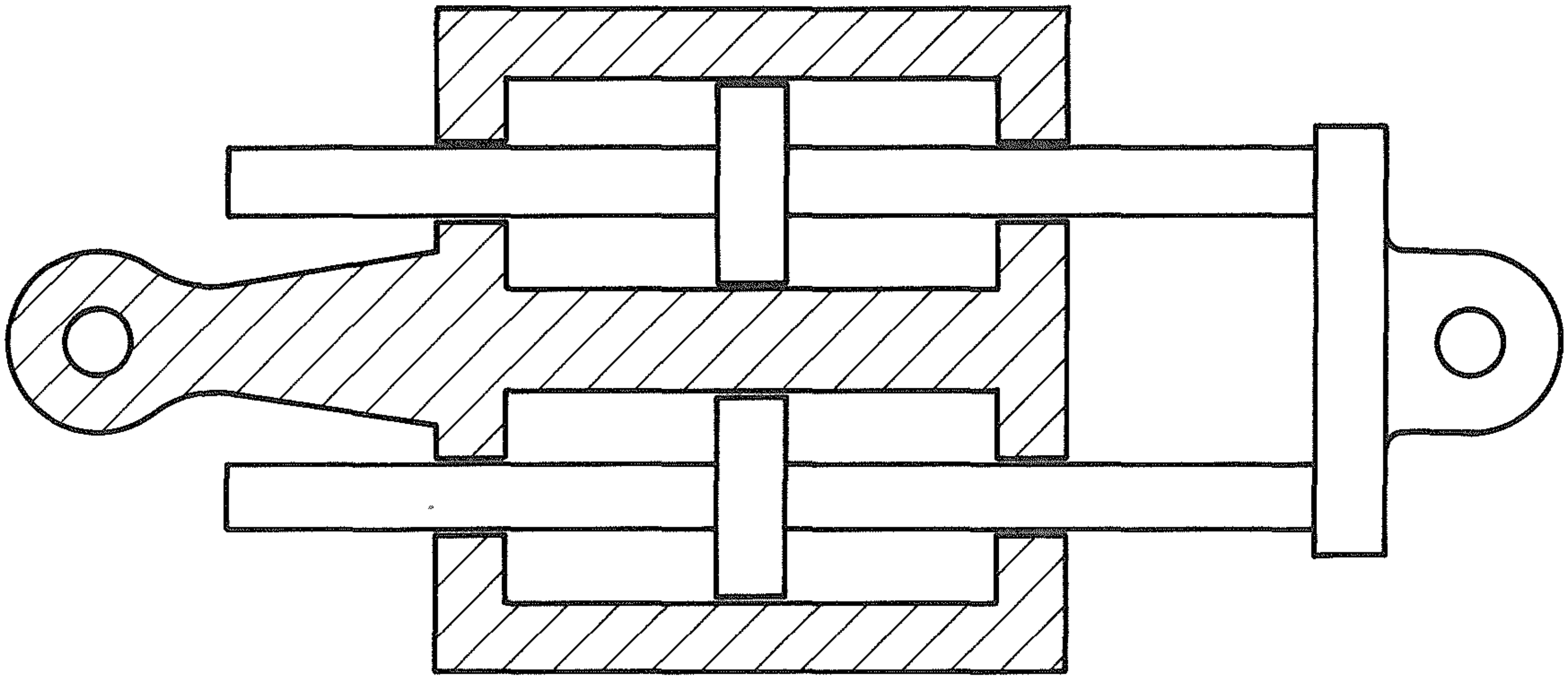


Fig. 2

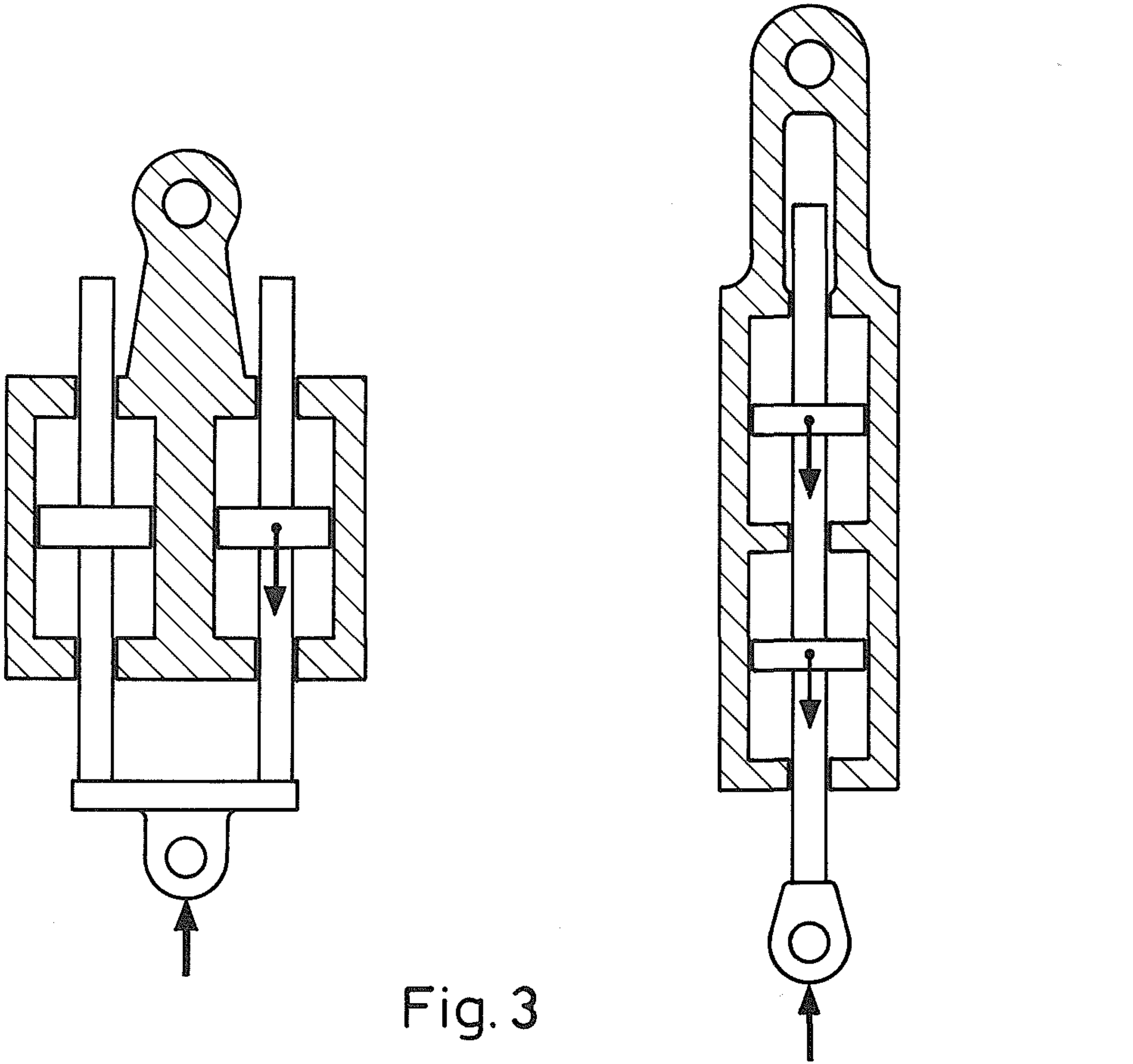


Fig. 3

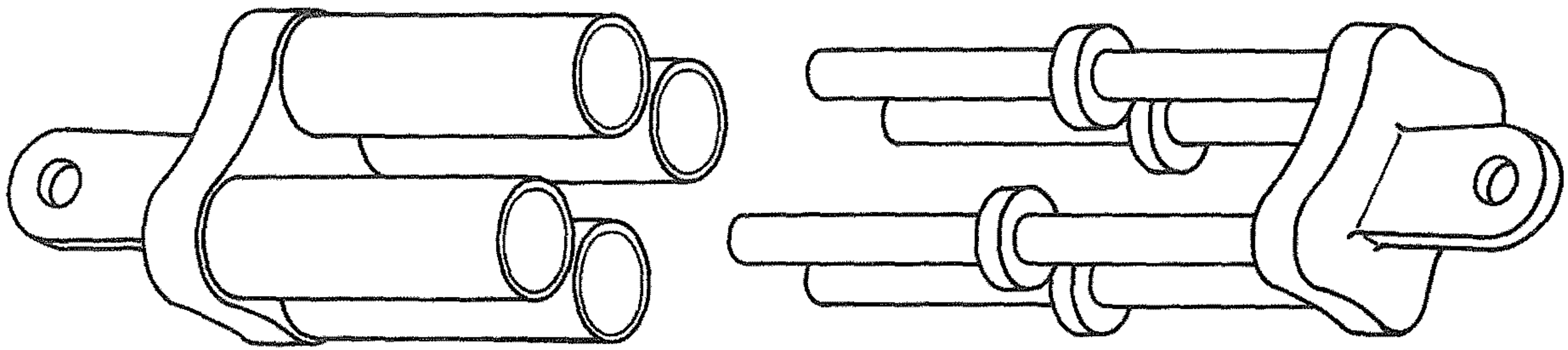
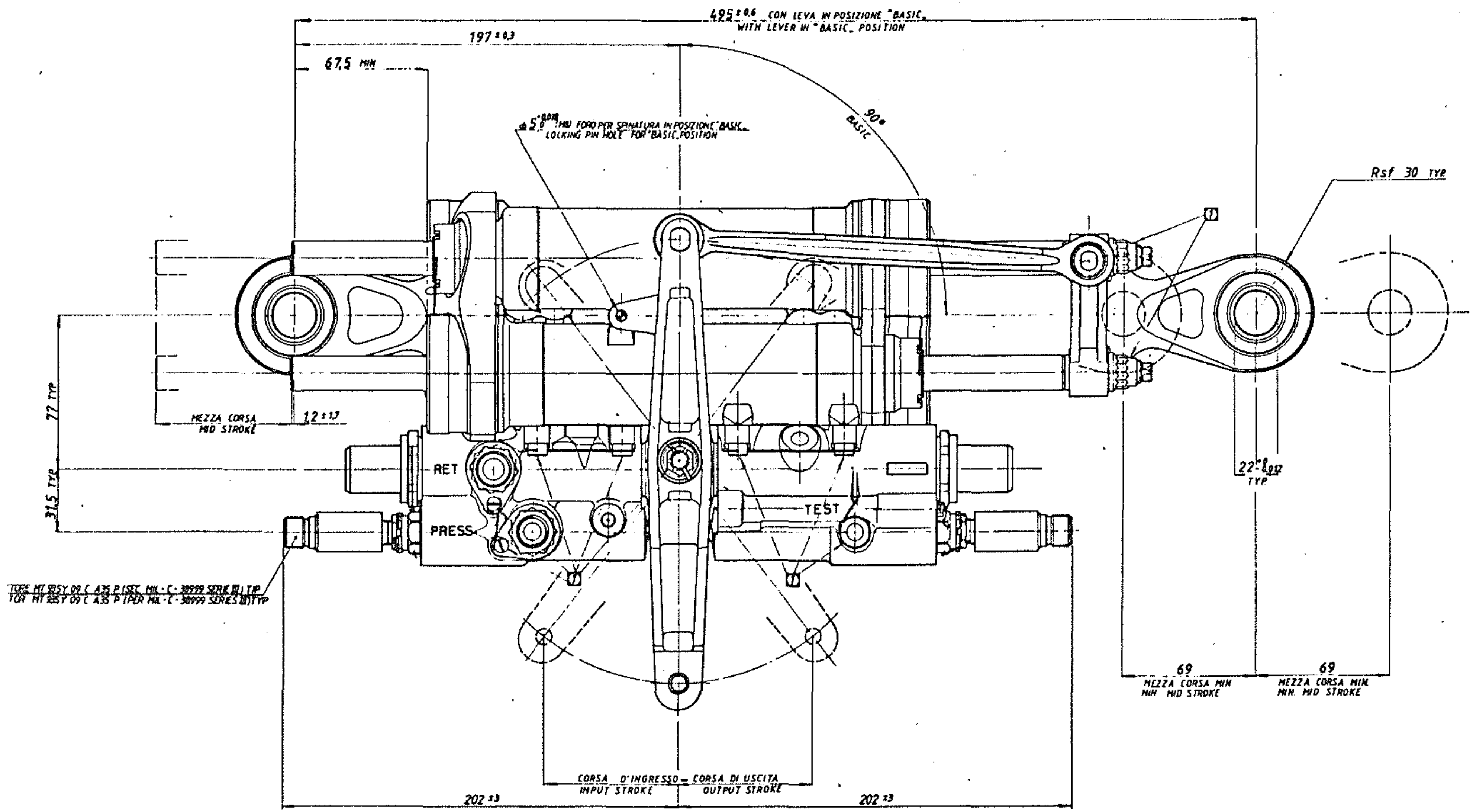
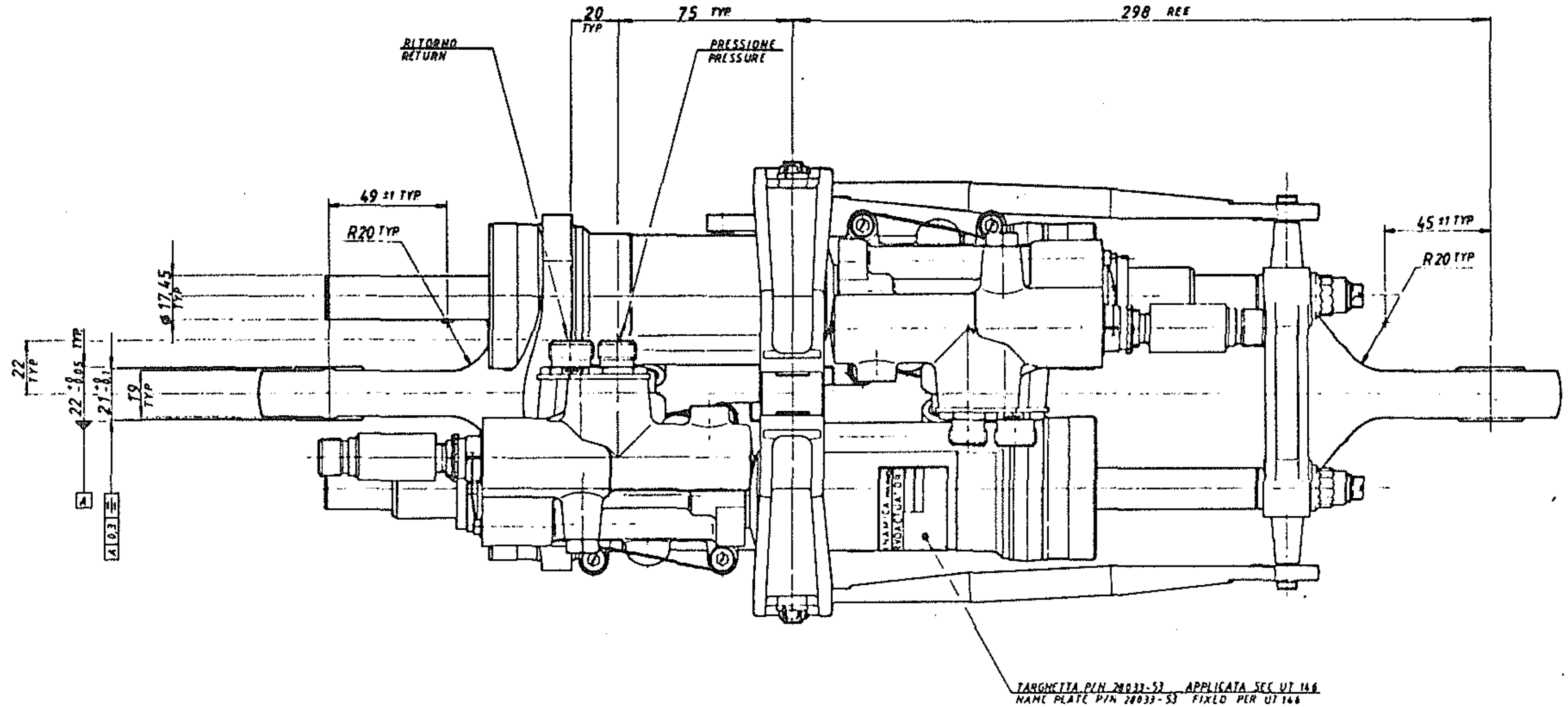


Fig. 4



CON LEVA IN POSIZIONE "BASIC"
WITH LEVER IN "BASIC" POSITION
197 ±0.3
67.5 MIN
90° BASIC
LOCKING PIN HOLE FOR "BASIC" POSITION
Rsf 30 TYP
MEZZA CORSA
MID STROKE
77 TYP
31.5 TYP
RET
PRESS
TEST
TYP
69
MEZZA CORSA MIN
MIN MID STROKE
69
MEZZA CORSA MIN
MIN MID STROKE
CORSA D'INGRESSO = CORSA DI USCITA
INPUT STROKE
OUTPUT STROKE
202 ±3
202 ±3

Fig.5



20 TYP
75 TYP
298 REF
RITORNO
RETURN
PRESSIONE
PRESSURE
49 ±1 TYP
R20 TYP
45 ±1 TYP
R20 TYP
Ø 17,45 TYP
22 TYP
19 TYP
TARGHETTA P/N 28033-53 APPLICATA SEC UT 146
NAME PLATE P/N 28033-53 FIXED PER UT 146

Fig.6

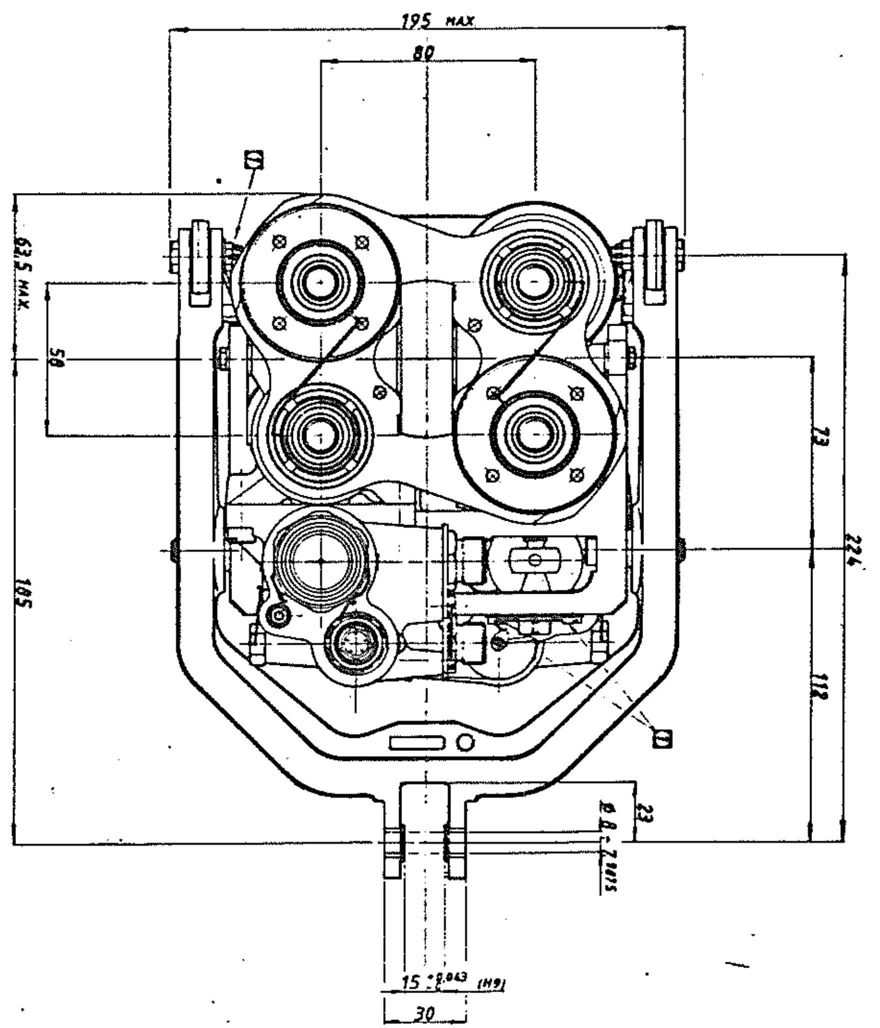


Fig.7

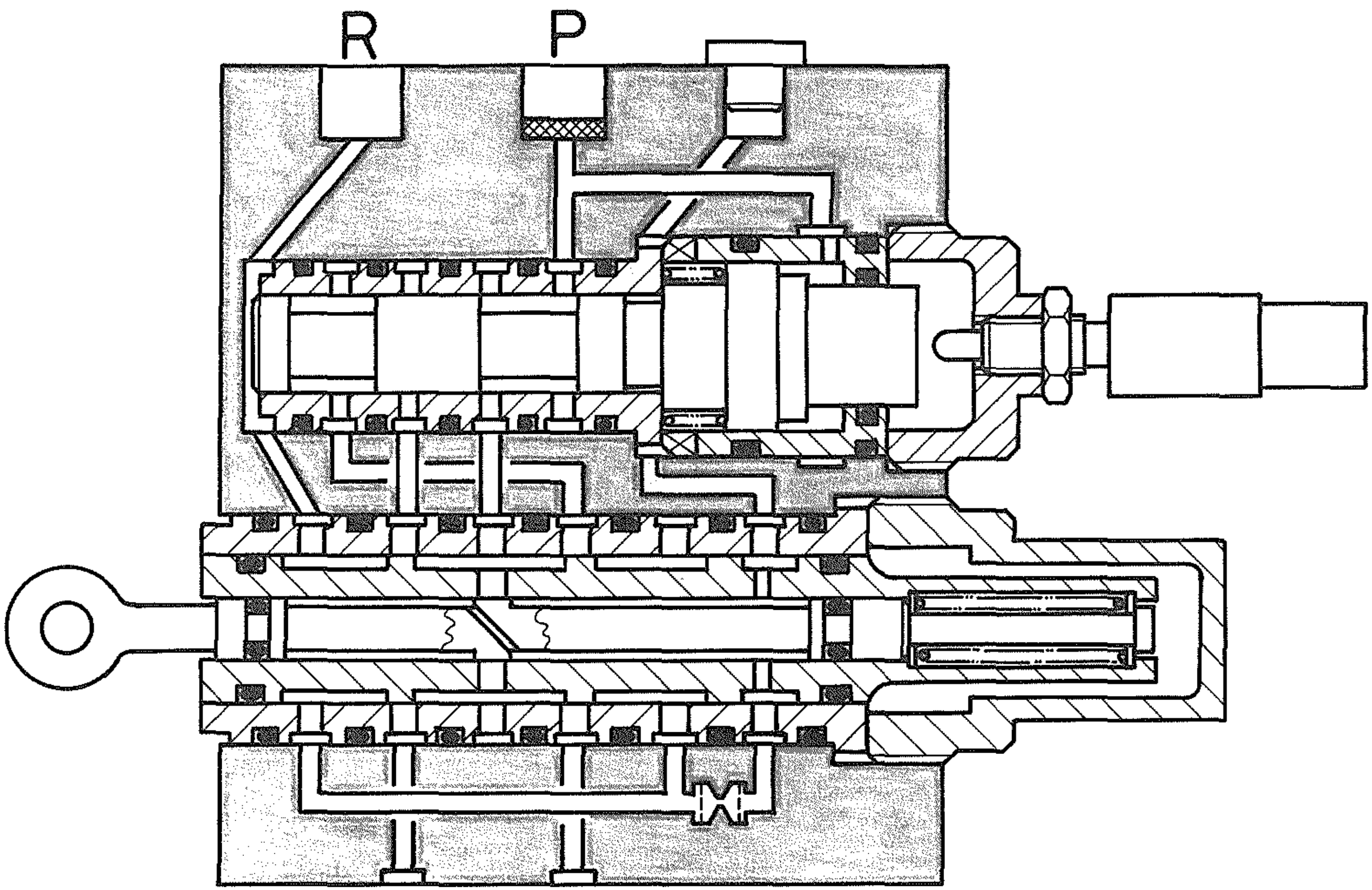
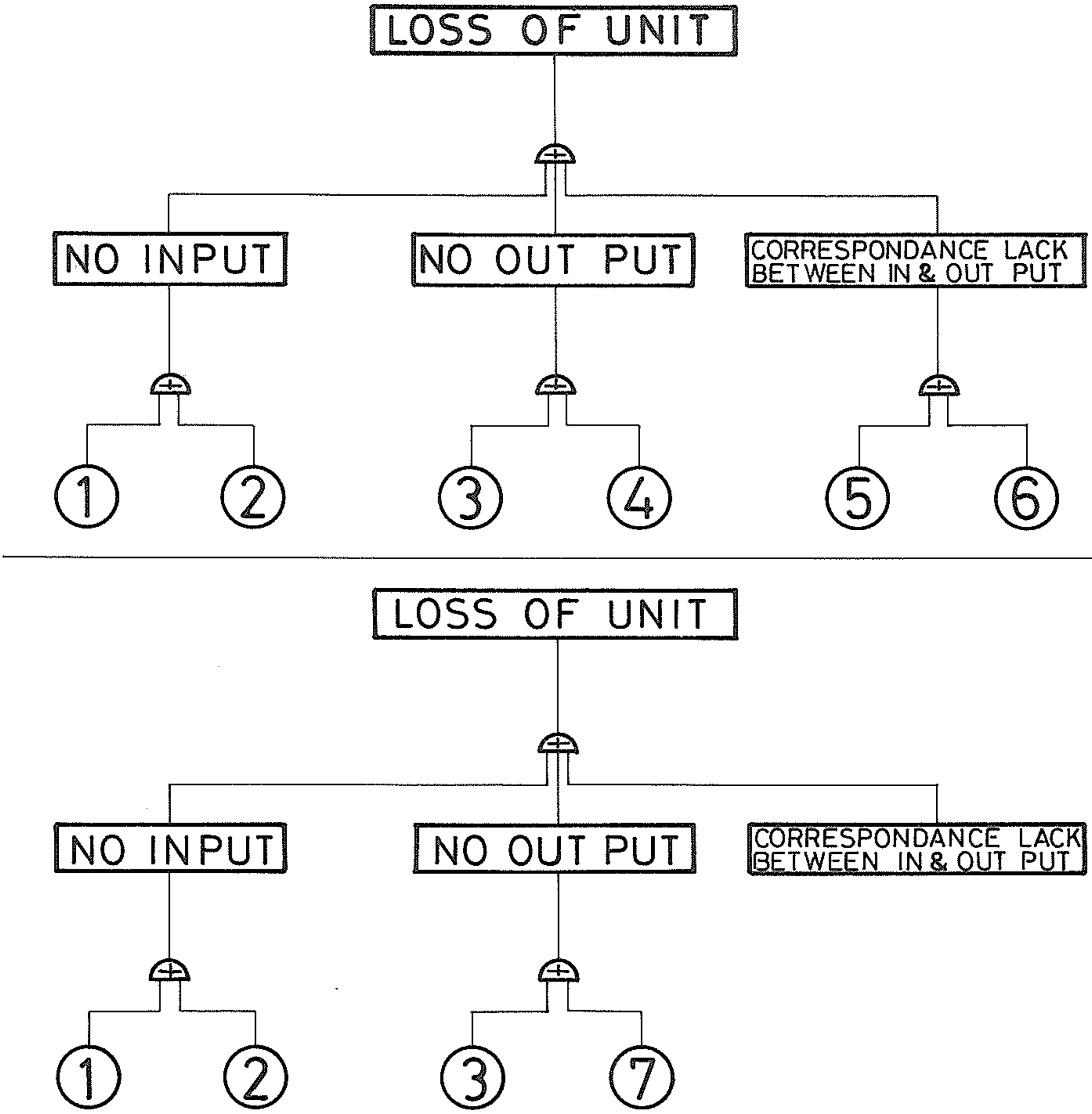


Fig. 8



1 - Rupture of input lever

2 - Rupture of summing lever

3 - Rupture of earth end

4 - Rupture of manifold

5 - Rupture of rod

6 - Rupture of feed-back lever

7 - Rupture of rod end

Fig. 9