HELICOPTER HYDRAULIC SYSTEM

(Design, Component Selection, Modular Construction, Integration & Testing)

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1. INTRODUCTION

Hydraulic fluid power is widely used in air-borne applications specifically to operate the flight controls and landing-gear systems due to its compact size, high response rates, high load holding capabilities and excellent power to weight ratio. Modern helicopters are no exceptions in this regard due to the adaptation of advanced rotor systems calling for higher control loads, fast response requirements and use of retractable landing gear systems. This paper provides the salient features of the hydraulic systems used in helicopters based on literature survey and experience gained during the development of a recent origin helicopters.

Helicopters under 3000 kg all-up weight category using conventional articulated rotors could be manually controlled since the rotor control loads will be well within the handling capability of pilot. However, to reduce the pilot's workload, hydraulic boosters are used in such helicopters with lower fluid pressure for their operation. Helicopters above 3000 kg all-up weight category using modern rotor concepts like semi-rigid or rigid rotors will result in control loads beyond pilot's handling capability and positively calls for fully powered flight control system. Requirement of high response characteristics under high operating load conditions needed for the flight control operations has resulted in extensive use of hydraulic systems in helicopters.

Helicopters with all up weight in excess of 3000 Kg and fitted with high response rotor system, the rotor loads are beyond the pilot's handling capability & hydraulic power is invariably used to operate the flight controls.

2. SYSTEM TRADEOFFS

System tradeoffs need to be made to clearly define the number of systems required for the helicopter including certain primary parameters to be finalized considering overall requirements of the helicopter reliability & survivability. To achieve this use of multiple hydraulic systems has emerged. With the decision to use two hydraulic systems, there are two available options to the designer. First option is to design each system capable of handling the entire spectrum of control loads and use one system as the main system keeping the other system as a standby system. The standby system gets activated automatically in the event of failure of main system. Second option is to design each hydraulic system capable of handling the control loads for minimum basic flying and both system together cater for the entire flight spectrum in which case failure of any one system will ensure minimum basic flying capability. The second option provides better reliability due to the fact that both systems will be operating at all times and is also lower in weight. As per the emerging new civil airworthiness requirements, in addition to dual hydraulic systems, one electrical back up system is also need to be provided for the flight control system of helicopter. This third system can also be used for the flight control system preflight checks.

Landing gear retraction / extension, wheel brake, deck lock harpoon, rescue winch and sonar winch are some of the other systems of the helicopter, which are operated using hydraulic power. In the helicopters using a primary & standby hydraulic systems for flight control operation, the standby hydraulic system may be used for these utility services with a safety device to divert the hydraulic power to controls in the event of primary hydraulic system failure. However, such diversion of hydraulic power to the utility services from standby system will reduce reliability of flight control system due to the presence of many other operating equipment. Helicopters adopting continuously operating dual hydraulic system for flight controls invariably demand the additional utility hydraulic system to operate all the utility services.

3. SELECTION OF SYSTEM PRESSURE, FLOW RATES & OPERATING FLUID

After defining hydraulic system configuration, next step is to define the primary parameters of each of the systems like system fluid pressure, maximum fluid flow rate and the hydraulic fluid that need to be used.

3.1 Selection of Fluid Pressure

For a defined power level, a lower system pressure will increase the size of equipments. On the other hand high system fluid pressure will call for increased wall thickness in the equipments. Hence, selected system pressure has a bearing on the hydraulic system weight & size, while meeting the required power levels. It is interesting to note that the hydraulic system weight for a defined power level will considerably lower for operating fluid pressure between 3000 psi and 4000 psi. Hence, it is preferable to develop the hydraulic system for fluid pressure range 3000 to 4000 psi and to have the advantage of weight & size reduction. Use of standard fluid pressure 3000 or 4000 psi will also provide the advantage of using many already developed hydraulic equipments and reducing the development cost & time.

3.2 Computation of Fluid Flow Rates

Second step is to arrive at the fluid flow rate requirements for each of the hydraulic systems used in the helicopter, which is specific to the helicopter under consideration. This step needs certain forecast about the sub-systems that are likely to operate together at a given point of time. Let us assume that all the flight control actuators work simultaneously and these flight control actuators are supported by two hydraulic systems 1 & 2. From the rotor design we obtain the maximum control loads that need to be operated by each of the actuators. Since two hydraulic systems are feeding power to each of the flight control actuators having two operating cylinders, it can be assumed that each cylinder will hold 75% of maximum control load and both the hydraulic systems together will provide 150% of the maximum control load. This philosophy is preferred to arrive at a lower weight of the actuators compared to 200% maximum load holding capability. However, it is essential to ensure that 75% of the maximum control load would be adequate to perform all the basic flying capability of the helicopter under consideration to ensure flight safety, in the event of one hydraulic system failure condition. Once the maximum actuator ram load per hydraulic system has been arrived for each of the servo actuators, the piston annular area can be easily computed using the defined operating fluid pressure. Then by using the operation rate of controls (it is considered that pilot can move the control stick end to end in one second in absence of any specific data), we could easily arrive at the fluid flow rate. No load speed of the actuators (normally 150% of maximum operating speed by the pilots) should also be taken into account while computing the system fluid flow rate since it has an indirect relation to the actuating speed under loaded condition. For the fluid flow rate thus arrived, we need to add the estimated internal fluid leakage rate including pump case drain leak rate to arrive at the pumping capacity of the hydraulic pump. Similar analysis has to be made to arrive at the fluid flow rate for the utility hydraulic system considering all utility services, which operate simultaneously.

3.3 Selection of Hydraulic Fluid

Suitable hydraulic fluid is selected considering functional requirements, operating environment and operating temperature limitations. Careful consideration has to be imparted for the fluid properties like viscosity, pour point, lubrication ability, oxidation resistance, rust & corrosion protection etc.

Mainly three types of hydraulic fluids are used in aerospace applications. Mil-H-5606 is a mineral based hydraulic fluid which is very much suitable for hydraulic systems working under operating temperature range -40 to +107°C with a maximum temperature range of -54 to +135°C defined for hydraulic systems conforming to Mil-H-5440G, Type II systems. Mil-H-83282 is a fire resistant synthetic hydraulic fluid, suitable for hydraulic systems working at temperatures beyond +100°C and in fire susceptible areas but this fluid becomes highly viscous below -20°C. Skydral is the other hydraulic fluid, which is mainly used, in commercial civil aircrafts.

4. PRELIMINARY DESIGN

Preliminary design shall include identification of specific type of equipments and hydraulic lines, which will become part of the system. It is essential to make a detailed study of the airframe under consideration, to arrive proper interfaces & mountings and efforts to be made to suit available hydraulic equipments to a maximum possible extent as a part of the preliminary design. Any hydraulic system shall have Hydraulic Pump to generate fluid flow, Fluid Reservoir to store & circulate fluid, High Pressure Relief Valve to release any high fluid pressure, Fluid Filter to keep the fluid clean, Pressure Sensor to indicate fluid pressure and Hydraulic Lines to connect various hydraulic equipments. Hence, they should be defined.

Apart from above basic equipments, other equipments need to be added based on requirements. Each of the equipments has to be clearly specified so that the equipment is as simple as possible without compromising the performance requirements. As a part of preliminary design, it is essential to prepare a Failure Mode & Effects Analysis (FMEA) to evaluate the system and to incorporate required modifications to avoid many problems during detailed design & qualification. Preparation of a hydraulic line layout is essential as a part of preliminary design to look into any probable problems during detail design phase and to optimize the line routing.

5. SYSTEM PRESSURE CONTROL

5.1 Pressure Relief Valve

This is a safety equipment and essential to be fitted in any hydraulic system between the high-pressure side and reservoir. The preset opening pressure will be 110% of the normal operating system pressure in case of fixed delivery hydraulic pumps and 125% of the nominal operating system pressure in case of variable delivery hydraulic pumps. The maximum flow rate of this valve shall be equivalent that of maximum flow rate of the system. If flow rate is in excess of 10 lpm, two stage valves are used to bring down unit size & weight.

5.2 Pressure Regulating Valve

Pressure regulators (mainly pressure reducing valves) are used to step down system pressure for use in specific sub-system. Pressure reducers may include relief valves for protection of sub-system in the event of regulator failure.

6. SYSTEM DESIGN

System design will be a mile stone activity in which the system requirements and configuration will be clearly defined. A typical helicopter requirement is taken as an example to describe this stage of design.

6.1 Hydraulic Equipments

This chapter throws some light on the hydraulic equipments and the means by which they have been achieved in a typical Helicopter Hydraulic Systems.

6.1.1 Hydraulic Pump

A few types of hydraulic pumps along with their construction details and operational features are explained here for information.

Gear Pumps & Gerotar Pumps are available only in fixed delivery types. As a result, power will be draining through pressure relief valve when the operating systems are not in use or being used partially. They are suitable only for low-pressure (upto 500 psi) applications. Vane pumps are complex in their design and bigger in size. As a result they are not popular in aerospace applications. Radial Piston Pumps are also not used in aerospace applications since they are bigger in size and weighs more than an equivalent axial piston pump.

The most popular hydraulic pumps in the aerospace applications are the variable delivery axial piston pumps due to their simple construction, smaller size and low weight against a defined hydraulic power output. The power drain is absolutely minimum in these pumps due to the existence of automatic outlet pressure compensator as a part of this pump. These pumps have minimum internal fluid leakage and collected back to the reservoir through pump case drain.

If the pump is driven at a lower RPM, the size of the pump will increase and the pressure pulses in the pump pressure line will also be significant. On the other hand if the pump is run at a very high RPM, the wear of the pump will be prominent and calls for frequent maintenance of the pump. Hence, based on the literatures collected on the proven pumps, it is preferable to drive these pumps around 6000 RPM. In a typical helicopter application, these pumps are driven by gearbox.

System compatibility tests on pump must be conducted as early as possible in the hardware development period. Care should also be taken that none of helicopter vibrating frequencies are closer to pulsating frequency of the pump and pump pulsating frequency shall not impart any resonance on the other helicopter systems.

6.1.2 Fluid Reservoir

Reservoirs store fluid (working fluid & fluid from sub-system differential volumes), provide room for thermal expansion / contraction and cater for calculated external leakage at dynamic seals during system operation. Mainly fluid reservoirs can be grouped into two varieties. One, vented to atmosphere, and other not vented to atmosphere. Reservoirs, which are vented to atmosphere, cannot provide pressurized fluid at the suction port of the hydraulic pump and cause cavitation problems in the suction lines of high performance hydraulic pumps. To avoid this problem, generally the reservoirs are closed in their construction and the fluid stored in the reservoir is pressurized up to 50 psi by means of spring load or compressed air or by the high-pressure fluid of the hydraulic system itself. If the reservoir fluid is self-pressurized by the high-pressure fluid of the system with the help of a differential piston then such reservoirs are called as bootstrap reservoirs. If there is no forced fluid cooling system, the reservoir shall have adequate cooling fins built around it to continuously cool the fluid.

The first aspect that needs to be defined in a reservoir is its fluid capacity. Use of closed loop hydraulic system involving bootstrap type of reservoirs are permitted to have reservoir fluid capacity equivalent to 10% of the maximum fluid flow rate of the system.

As the quantity of fluid reduces in the reservoir, cooling of the hydraulic system will become more critical. Hence, as a first step, use of variable delivery hydraulic pump is a must to reduce the power drain, when the system is being used at low power levels. As a next step, it is preferable to have fins on the reservoir to dissipate the heat to surroundings. If the above two measures are found inadequate to keep the oil temperature within the permissible level, it is essential to have an oil cooling facility.

In case of bootstrap reservoir, seal friction and life expectancy are of primary considerations. Other aspects of the reservoir, which need to be defined, are fluid level indicator, good air-bleeding provision, hydraulic port inter-faces and mounting interface. In pressurized reservoirs (including bootstrap type) where fluid is stored under pressure, it is also essential to provide an over-board relief valve to expel excessive fluid in the event of thermal expansion and to limit reservoir fluid pressure with in design limits.

6.1.3 Filtration & Fluid Filters

Filters are used in the hydraulic system to continuously filter the fluid and reduce fluid contamination, which occur from external sources and internal generation. If the entire fluid passes through the filter, then such filters are called as full flow filters. On the other hand if a portion of the flow is diverted across the filter installed through a parallel circuit, such filters are defined as by-pass filters. In the aerospace applications only full flow filters are used. Further, it is common to use more than one filter in a hydraulic circuit. For example use of one pressure line filter and a return line filter is a standard practice. In addition to two main filters, last chance filters are also used just before the fluid enters certain critical equipments like servo valves.

Adequate filtration is essential for satisfactory operation of the hydraulic system. Mil-F-8815 covers the detail requirements for filter housings and filter elements and NAS-1638 defines fluid contamination levels. It is necessary to have automatic shut-off valves as a part of the filter assembly, so that minimum amount of fluid is lost during changing filter element.

Differential pressure indicators are required in order to signal when the element is loaded with contamination and needs replacement. Thermal lockouts are used to keep the differential pressure indicators from operating below a specified fluid temperature. The interactions of the relief valve, thermal lockout, differential pressure indicator and filter element clean-dirty differential pressure characteristics are inter-related and highly important while selecting a suitable filter unit. In a typical helicopter application, 15-micron filter with out by-pass is used for pressure line filtration and 5-micron filter with by-pass is used for return line filtration.

6.1.4 Accumulator

Accumulators are used for energy storage and / or for pressure pulsation attenuation. They can be of the piston or bladder type to separate gas-fluid separation. Seal & bladder leakage and its control are the basic accumulator problems. In most of the high-pressure applications, piston type accumulators are commonly used.

The evolution of high response pumps has almost eliminated use of accumulators as a pressure pulsation attenuator. During this phase of design, if it is noticed that the pump pressure ripples as felt at the flight control servo actuators are negligible, use of accumulator as a part of hydraulic system is not required. Avoiding use of gas charged accumulator is very good since such accumulators may ingress the charged gas into the hydraulic system when its seal fails and it will be extremely difficult to detect this failure. With this, accumulators find place only as emergency back-up system. Accumulator sizing & selection are a function of temperature range under which the accumulator is likely to be used. The fluid volume available at minimum pressure and minimum operating temperature should obviously meet the sub-system operating energy requirements. Being pressurized units, the accumulators used in tactical helicopters shall be designed to retain their integrity when exposed to gunfire as a safety requirement.

6.1.5 Servo Valves

Servo valve is a directional control valve that may be infinitely positioned to provide control of both the quantity and direction of fluid flow. A servo valve coupled with the proper feedback sensing devices provides very accurate control of position, velocity or acceleration of an actuator.

6.1.6 Hydraulic Actuators

The major function of a hydraulic actuator is to convert hydraulic power into mechanical power. Linear actuators are called as cylinders or jacks and generally move end to end. Rotary actuators are called motors. If the actuator is associated with position or load control then they are termed as servo actuators or servomotors.

Since hydraulic servo actuators is a vital component used to operate various systems in an aircraft, specifically the flight control system with its interface to fly-by-wire & fly-by-light technologies, actuators themselves make a major topic for discussion in aerospace field. Hence, more emphasis is not imparted on actuators in this paper.

6.1.7 Other Hydraulic Equipments

High pressure relief valve is used as a safety equipment to off-load fluid from high pressure line to reservoir in case of increase in the fluid pressure beyond 125% of nominal system operating pressure.

Check Valve is used to avoid control the fluid flow in a defined direction. For example, if no check valve is provided in the pump pressure line, the pump may function as a motor during the system interface with ground hydraulic power source during system checks.

Solenoid Valve can be used in each of the sub-system in multi-system configuration to isolate defined sub-system.

Reservoir Low Fluid Indicator, is a part of reservoir to indicate low fluid level when falls below a predetermined volume.

Pressure Transducer is used to continuously measure the system pressure and indicate the same in the cockpit.

Pressure Switch is used to provide a low-pressure warning in the cockpit when the system pressure drops below a defined level.

Temperature Switch can be used to check the temperature of fluid returning to reservoir & provide a high temperature warning in the cockpit when the fluid temperature goes above a defined level.

Quick Disconnect Couplings are used in places where fluid connections are disturbed frequently and to isolate certain sub-systems. This will avoid air ingress to the system during servicing and eliminates use of any tools for connection / dis-connection.

6.2 Hydraulic Lines

Hydraulic lines form a part of hydraulic system and inter-connect various hydraulic equipments. Both rigid pipelines and flexible hoses are used as hydraulic lines based on the requirements. Flexible hoses are used where hydraulic port of the equipment has a relative movement w.r.t. structure or associated hydraulic equipment.

Defining hydraulic line sizes to inter-connect various hydraulic equipments is an important task. As a thumb rule, the fluid velocity in the high pressure lines carrying fluid under pressure above 2000 psi shall be limited to 5 m/sec and in the low pressure lines carrying fluid below 100 psi shall be limited to 3 m/sec. Where as the fluid velocity in the pump suction lines should not exceed 1 m/sec.

Titanium alloy tubes are used for the high & low-pressure lines due to its low density, higher fatigue life and better flexibility. Flexible hoses used in aerospace applications are made of PTFE inner core tube reinforced externally by stainless steel or Kevlar braid as necessary. Interface connections between the hydraulic equipments and hydraulic lines need to be clearly defined. Hoses, quick disconnects and swivels are heavy & expensive. Hence, a balanced combination between tubes & hoses will workout as the best solution.

6.3 Integration of Hydraulic Components

Once the required hydraulic components are decided, the next task is to integrate them with at most care for achieving simple installation, low maintenance, reduced weight, space optimization and least number of hydraulic lines. Interface for ground & service hydraulic connections could be provided by quick disconnects couplings for ease of handling and to avoid air & dust ingression to the system during servicing & maintenance.

7. DETAIL DESIGN

In this chapter, certain design aspects, which need to be considered during detailed design phase, are explained as a guideline.

7.1 Strength Consideration

All the hydraulic system components including their attachment linkages and mounting provisions shall be designed so as to meet the most critical combination of loads. Adequate safety margins shall be provided as a part of design to ensure safety and life of components.

Hydraulic system design fluid pressures (operating pressure, proof pressure and burst pressure) shall be determined based on the guidelines provided in Mil-H-5440 standard. The actuating cylinders and other components including interconnecting lines & fittings if subjected to acceleration loads as experienced during most adverse flight condition, shall not deform or malfunction. They shall be adequately tested to prove such conditions.

7.2 Temperature Consideration

At high temperatures, low fluid viscosity can cause internal leakage and slippage in pumps, actuators and valves. Compressibility of a fluid increases with pressure & temperature and result in loss of volume output of pumps. In control systems, compression of fluid provides a mass-spring condition that limit system response. The designer shall consider the temperature distribution within the helicopter, in order to achieve judicious placement of hydraulic system plumbing and components in cooler regions. In many applications, normal heat losses from lines and components are adequate to maintain hydraulic system temperatures within design limits, thus use of heat exchangers is unnecessary.

Permitted temperature variations shall not lead to malfunctioning of the system or cause excessive stress. Hence consideration must be given during design to cater for expected temperature variations to avoid binding, sticking or malfunctioning of components.

7.3 Installation Consideration

It is very much necessary to impart adequate thinking well in advance for proper installation and support of hydraulic units & lines to avoid installation problems substantially at the drawing making stage.

The hydraulic lines must be installed behind other removable equipments. Reservoir filling, filter elements and ground support interfaces shall be easily reachable through quick access doors. Reservoir fluid level indicators and filter clog indicators shall be easily seen through transparent panels. All separable connections shall be relatively accessible easily since they are employed to permit component removal and / or removal of lines to have access to other equipments.

8. CONTAMINATION CONTROL

Contaminant in hydraulic system is defined as a foreign material in hydraulic fluid that has deleterious or adverse effect on fluid's intended performance as a component in the hydraulic system. The sources of contamination in hydraulic systems can be divided into three general categories i.e. Built-in contamination, Ingressed contamination & Internally generated contamination. Overall contamination in Aerospace Hydraulic Systems shall not exceed NAS 1638 Class-8 contamination level and the system must function satisfactorily up to NAS 1638 Class-10 during emergency. Even with a good awareness on prevention and control of contamination level in hydraulic systems, it is established that 70% of hydraulic system failures are due to fluid contamination.

9. CARTRIDGE VALVES

Cartridge valves provide several advantages over conventional valves but they need to be used with special interface manifolds. Several valves can be integrated on to a single manifold to greatly reduce system weight by avoiding inter-connecting external lines and fittings. Advantages of cartridge valves are Greater system design flexibility, Smaller package size & weight, Improved efficiency & reliability, Higher pressure capability, Faster cycle times, Elimination of external leakage, Lower installed cost, Better performance & control, Reduced maintenance, Greater contamination tolerance, Lower noise levels and Reduction of internal leakage. In aerospace hydraulic system applications these valves play a major role.

10. HYDRAULIC SYSTEM TESTING

10.1 Ground Tests

The ground tests are divided into two major groups. The tests that are done on a dedicated ground test rig are grouped under hydraulic system rig tests and the tests that are done on the helicopter are grouped under helicopter ground tests or pre-flight tests. These tests are for proving the system function, performance, proper integration of system on helicopter, failure mode analysis and endurance.

10.2 Hydraulic System Flight Tests

The primary objective of the flight test program is to confirm the theoretical analysis and ground test results. Load holding capability, system operating characteristics, ambient & fluid temperature effects, cockpit indications and performance in the total flight or mission envelope shall be evaluated. Flight control functions associated with dual hydraulic systems shall be evaluated in a series of flights with both the hydraulic system operating and with each one of the hydraulic system energized condition to establish one hydraulic system operating capability. The pressure, temperature, position and vibration transducer readouts shall be recorded and analyzed. The evaluation shall be conducted in accordance with a detailed flight test procedure developed prior to initiation of flight test program as per Mil-T-5522. The flights shall include flight conditions leading to service ceiling, cruise altitude, maximum speed, maximum banking and all other critical flight modes.

The utility hydraulic system flight tests shall be similar to the control hydraulic system flight tests and all utility functions used during flight shall be evaluated, like landing gear, brake, winch and any other function. In addition, any emergency back-up functions and manual release functions shall also be evaluated related to the specific performance requirements.

11. HYDRAULIC SYSTEM TROUBLE SHOOTING

It is essential to have a logical approach to hydraulic system trouble shooting with fundamental consideration to control of flow, pressure and direction. It is essential to know the functioning of equipments used, characteristics of the system and capabilities of the system. The hydraulic schematic with all details should be available as a ready reckoner. The ability to trouble shoot in a specific system is usually acquired with experience. Cause & effect trouble-shooting guide can be developed. Down time can be minimized by constant system maintenance, use of clean fluid, changing of the filters in time, cleaning strainers periodically and keeping all connections airtight. Safety has to be taken care during maintenance. For this it is essential to develop a start-up and shutdown procedures.

12. CONCLUSION

With the above details and concepts, a hydraulics designer could be in a position to get an overall picture of the tasks involved in the development of air-borne hydraulic system. The above design concepts have been implemented and proved in Advanced Light Helicopter (ALH), which is designed, developed, manufactured & tested by Hindustan Aeronautics Limited (HAL), India. HAL has already launched series production of ALH for Military applications.