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Computer Aided Engineering for the Design of Flight Control and Hydraulic Systems

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ABSTRACT

A Computer Aided Engineering (CAE) tool has been developed for the design of flight control and hydraulic systems. The CAE tool consists of independent modules that build on each others results. For the programing of each of these modules it was necessary to thoroughly review the state-of-the-art. This paper presents a structured design procedure for hydraulic systems of transport category aircraft aiming at maximum performance at minimum weight (and cost). Reference is made to CAE modules written to support a substantial part of this design procedure. The module for the steady state calculation of hydraulic systems is further detailed.

INTRODUCTION

The purpose of this paper is to outline a design procedure for hydraulic systems of transport category aircraft. It will be shown in which way the classical design approach could be extended and supported by computer usage.

Hydraulic systems fly for decades on different types of aircraft. Much has been published on different, single aspects of aircraft hydraulic systems. Nevertheless, the aspect of system integration (as seen from an aircraft manufacturer's perspective) has received relatively little attention - not to speak of computer tools to support these integration activities.

At Rockwell International a concept was developed for computer-aided aircraft utility system design [1]. The idea includes a case-based reasoning expert system which was applied and tested for aircraft hydraulic system design. It seems however, that the concept lacks support of many small questions which an engineer is concerned with in his everyday routine. General Dynamics has developed a tool that integrates simulation of aircraft flight dynamics and simulation of hydraulic systems [2]. The initial design and sizing process, however, is not supported by the tool.

Moir and Seabridge summarize the "Classical Design Procedure for Hydraulic Systems" [3]:

"*When the nominal system pressure is chosen ... the designer must allocate some realistic pressure drop which can be achieved in full flow conditions form pump outlet to reservoir. This is usually about 20% to 25% of nominal pressure ... The aerodynamic loads and flight control laws will determine the piston area and rate of movement. The designer must then decide which actuators will be required to act simultaneously and at what speed they will move. The sum of these will give the maximum flow rate demanded of the system ... If an allowable pressure drop of 25% has been selected throughout the system, this may now be further divided between pressure pipes, return pipes and components ... Once pipe length, flow rates and permissible pressure drops are known, pipe diameters can be calculated using the expressions governing friction flow in pipes ... Theoretical sizes will be modified by the need to use standard pipe ranges.*"

The design procedure of hydraulic aircraft systems as classically applied falls short in some important aspects:

1.) The allocation of hydraulic systems to the flight control actuators should be done more systematically in order to optimize the maneuverability of the aircraft in failure cases.

2.) Required control surface deflection rates should be calculated from flight dynamics (instead of using "rule of thumb deflection rates"). Design rates should be limited to necessary minimum rates for normal operation and failure cases, because deflection rates directly influence the size of hydraulic components.

3.) Pipe and actuator sizing should be done in relation to each other for weight optimization.

4.) The complete hydraulic system should be modelled and calculated by means of a steady state analysis well ahead of building the "iron bird" test rig.

These tasks will be approached and included in a straight forward design procedure suitable for practical every day use. The theoretical background of above aspects numbered 3.) and 4.) will be discussed in more detail below.

DESIGN PROCEDURE FOR TRANSPORT CATEGORY AIRCRAFT HYDRAULIC SYSTEMS

DESIGN GOALS - During the design phase of an aircraft, usually several alternative hydraulic systems will be considered. A preliminary design will be made for each alternative, leading to an economic evaluation, followed by the selection of the most economic and favorable candidate.

The economic evaluation can be based on the Direct Operating Costs (DOC) of a hydraulic system [4]. It can be shown that DOC of hydraulic systems for transport category aircraft are predominantly caused by system weight and Direct Maintenance Costs (DMC). Each accounts for more than one third of the total hydraulic system DOC. The system price is of further importance. Energy efficiency, in comparison, is of minor importance and accounts only for about 1% of hydraulic system DOC. Besides Direct Operation Costs (DOC) also Non Recurring Costs (NRC) - particularly development costs - should obviously be kept low. This can be achieved by a simple straight forward design based on well known and proven technology. Such a simple design will also help to lower DMC.

Design goals stated above should be kept in mind when working on details of the hydraulic system. 13 design steps will be outlined in subsequent sub-chapters. Computer modules have been written for design steps whenever necessary.

HYDRAULIC CONSUMERS - **STEP 1**: Determine the hydraulic consumers together with the level of required reliability.

The majority of aircraft in use today need hydraulic power for a number of tasks. Many functions to be performed affect the safe operation of the aircraft. Failure conditions will have effects of different severity.

When starting the design of a new hydraulic system, the engineer should start with determining the functions to be performed by the hydraulic system. Simultaneously, the effects of a failure condition should be classified according to the severity of the following criteria:

a) The reduction of safety margins related to perfomance, handling qualities, structure and system operation.

b) An increase in workload above the level normally required of the flight crew.

c) Discomfort, injury or death to occupants.

With application of ACJ No 1 to JAR 25.1309 [5] failure effects can then be classified into:

o catastrophic effect,
o hazardous effect,
o major effect,
o minor effect.

Table 1 lists some typical hydraulic consumers. The effects of a failure condition and hence the classification of the failure effect depends on the specific system design and the aircraft in question. Table 1 provides some guidance for the classification of failure effects as required for the hydraulic system design. The information on primary flight control is related to a flight control system of a typical fully powered transport category aircraft (i.e. an aircraft without manual reversion). Many other functions can be carried out by aircraft hydraulic systems. Table 1 lists those hydraulic functions that are generally found on modern transport category aircraft.

A relationship between the severity of the effects and the probability of a failure condition (i.e. the reliability objective) is specified in ACJ No 1 to JAR 25.1309 [5] (**Figure 1**). For design purposes a reliability objective of 10^{-3} 1/FH (FH = flight hour) should be used for minor failure effect.

REQUIRED NUMBER OF HYDRAULIC SYSTEMS - **STEP 2**: Determine the number of required central hydraulic systems.

For the layout of the hydraulic system the number of independent hydraulic systems has to be found. This can be achieved by looking at the most severe safety requirement. Considering the reliability of a hydraulic system (as used for preliminary design) with 10^{-4} 1/FH some general conclusions can be drawn for fully powered flight control systems as listed in **Table 2.**

In summary: Hydraulically fully powered flight control systems need at least three hydraulic systems (compare with Boeing 757, 767 and Airbus A300, A310, A320, A330, A340). In contrast, flight controls with mechanical reversion can be designed with just two hydraulic systems (a typical case is the Fokker 100). This is in agreement with MIL-H-5440 [6] which specifies (Chapter 3.2) that "*The hydraulic systems shall be configured such that failure of any two fluid systems ... which cause loss of fluid or pressure will not result in complete loss of flight control.*"

The number of central hydraulic systems should be reduced if the number of systems is only required by very few consumers. If for example only a minor number of consumers require three hydraulic systems, introduction of three central hydraulic systems may not be the best solution. Instead, it could be thought of applying electric power either directly via Electro- Mechanical Actuators (EMA), or converted to hydraulic power by means of one of various Integrated Actuator Package (IAP) designs. [7] includes an overview on IAP design principles.

HINGE MOMENTS - **STEP 3**: Calculate maximum aerodynamic hinge moments for control surfaces.

Maximum hinge moments of control surfaces are found from checking required maneuvers throughout the whole flight envelope. The maximum elevator hinge moment is calculated for large civil transport category aircraft from requirements given in FAR/JAR 25.255. Maximum aileron hinge moments are calculated from maneuvers given in FAR/JAR 25.349. Maximum rudder hinge moments generally occur for multi engine aircraft as a result of an engine failure just after takeoff. Hinge moment derivatives can be estimated from *DATCOM* [8] or *ESDU* [9]. The algorithms for these calculations together with equations for spoiler hinge moments are given in [10]. A CAE module has been written for the calculation of maximum control surface hinge moments.

MAXIMUM DEFLECTION RATES - **STEP 4**: Calculate maximum required deflection rates for control surfaces.

Following a rule of thumb [7], a first estimate of a control surface deflection rate $\dot{\delta}$ is

$$\dot{\delta} = \frac{\delta_{max}}{\Delta t} \quad \text{with} \ \Delta t = 1 \ s \ . \qquad (1)$$

δ_{max} is the deflection angle to move the control surface from the neutral position to full hard over. However, it should be aimed for higher accuracy than available from a rule of thumb. Required control surface deflection rates should therefore be calculated from flying qualities as defined in MIL-F-8785C [11] or MIL-STD-1797 [12]. [10] describes the approach to deflection rate calculations from these sources. In addition, deflection rates have to be high enough to avoid Pilot-In-the-loop Oscillations (PIO). This approach generally yields lower deflection rates than EQ (1).

NOMINAL PRESSURE - **STEP 5**: Choose the nominal pressure for the hydraulic system.

Basically there is not much choice. Systems have become standardized at 3000psi (206 bar) [13]. Few aircraft apply systems with 4000 psi (275 bar) as for example the MRCA Tornado. Many studies have been undertaken by industry to raise the standard working pressure. Pressure targets have varied from 5000 psi (344 bar) to 8000 psi (551 bar), and all resulting system claim to show reduced system component mass an volume. A detailed study would show that the optimu pressure will differ for every aircraft design. This i obviously impractical and would preclude the commo use of well-proven components and test equipment. Test have been undertaken with variable pressure systems [14] Variable pressure systems can reduce heat rejection an energy consumption.

PRELIMINARY FLOW RATES AND PRESSUR FACTOR - **STEP 6**: Calculate the flow rates of th consumers. Determine an optimum pressure factor k_p fo each consumer.

Flow rates Q can be calculated without knowledge o actuator installation details. Maximum design hing moments or hydraulic motor torque *T* is required as inpu parameter together with the maximum required deflectio rate ω

$$Q_{eff} = \frac{T \cdot \omega}{p_0 \cdot k_p \cdot \eta} \qquad (2)$$

ω maximum design deflection rate from STEP 4;
T maximum design hinge moment or hydrauli motor torque from STEP 3;
p_0 system pressure from STEP 5;
k_p pressure loss factor, (see below: "Optimizing th Pressure Loss Factor"), $k_p = \Delta p_c / p_0$;
η efficiency of actuator-valve combination.

ALLOCATION OF HYDRAULIC SYSTEMS **STEP 7**: Determine a suitable allocation of hydrauli systems to primary flight control actuators fro maneuverability requirements during normal operatio and failure cases.

The maneuverability of the aircraft during norm operation and failure cases depends on the allocation o hydraulic systems and signal sources (i.e. flight contr computers or control cables) to the flight control actuator [10]. A computer module has been written whic calculates the expected value of the maneuverabilit about roll and pitch axes for a proposed design. Rudde actuation of fully powered systems is usually simpl enough to elevate the need for computer aided allocatio of hydraulic systems. Often each rudder actuator i connected to one central hydraulic system.

In addition to the expected maneuverability values, cumulative distribution function can be plotted for proposed design and can be compared with fligh dynamic requirements. **Figure 2** shows such a cumulativ distribution function for roll control due to the allocatio of hydraulic systems and flight control computers t ailerons and spoilers based on equations in [10]. Thes results were obtained with data taken from the Airbu A320 as an example. The cumulative distribution functio shows the probability of a failure resulting in a roll rat wer or equal than indicated.

Many combinations of hydraulic system allocations to e actuators can be checked with this computerised pproach in a short period which enables the engineer to ptimize the design.

LOAD DISTRIBUTION - **STEP 8**: Distribute the ydraulic load suitably over the central hydraulic systems y allocating the remaining consumers to the hydraulic ystems.

The remaining consumers are listed in Table 1 as ose for secondary flight controls, utility functions, and ackup functions. Keep in mind that secondary flight ontrols and landing gear require by far the highest flows. specially if their simultaneous actuation during takeoff r approach phase is required, this will most probably etermine the layout of the hydraulic system. (If STEP 8 oes not yield a suitable hydraulic load distribution, go ack to STEP 7).

ROUTING OF PIPES - **STEP 9**: Check the mplications of STEP 7 and STEP 8 to the routing of ydraulic pipes.

- o The segregation between circuits should be such as to minimise the risk of a single occurrence causing multiple failures of circuits or power supplies of the system concerned. Groups of hydraulic pipes should be so segregated as to prevent damage to the main and alternative systems and power supplies. (See ACJ No 6 to JAR 25.1309) [5].
- o Ensure a design that uses only the necessary amount of hydraulic pipe length. This will save system weight, cost and maintenance effort.
- o To minimise the consequences of a mid air collision, try to reduce the number of central hydraulic systems being present in the extremities of the aircraft like, e.g. the wing tips.
- o Consult ARP 994 [15] Chapter 5.5 "Damage Protection" for further design criteria.

Go back to STEP 7 if the design does not fulfill the quirements, especially if the necessary segregation of ydraulic pipes for different hydraulic systems seems not be adequate.

AUXILIARY HYDRAULIC POWER AND SAFETY EVICES - **STEP 10**: Extend the preliminary design with e definition of the auxiliary hydraulic power generation. dd safety devices (check valves, relief valves, shut off alves, hydraulic fuses) to the hydraulic system as far as cessary.

All main hydraulic power on board an aircraft stems om the engines. In order not to waste energy by necessary energy conversions (AIR 4543) [16], main draulic power should come, as far as feasible, from mps coupled to the accessory gearbox of the engines. r auxiliary power this is different. Auxiliary power is quired if main hydraulic power fails. This means that either the engine quits its service or the engine driven pump (EDP) fails.

The reliability of a central hydraulic system, as taken for preliminary design (10^{-4} 1/FH), can in general only be achieved with an auxiliary power source. Another reason for an auxiliary power source installed besides the EDP is for system pressurisation on the ground. There are various sources for auxiliary hydraulic power. AIR 744 [17] gives a general systematic summary. Auxiliary power sources could be applied as follows (listed in the order of importance for hydraulic systems):

- o electric motor driven pump, EMDP;
- o power transfer unit, PTU (ARP 1280) [18];
- o ram air turbine, RAT;
- o accumulator, ACC;
- o air-driven pump (powered by the bleed air system of the aircraft) (Lockheed C-5A, (AIR 1899) [19]; Boeing 747 [20]);
- o APU-driven pump (Fairchild A-10A, (AIR1899));
- o Emergency Power Unit - driven pump (powered by solid or liquid propellant gas generators) (General Dynamics F16, (AIR 1899)).

Flow control devices should be added as safety features. Their purpose is to prevent the entire central hydraulic system to fail in case of a local failure. Applied flow control devices are:

- o check valve;
- o pressure relieve valve;
- o motor-operated valve, shut off valve (SOV), (applied e.g. on Boeing 747);
- o hydraulic fuse [21];
- o hydraulic circuit breaker [22].

Furthermore, flow control devices protect primary flight control consumers against excessive pressure drop caused by consumers with high flow demands. Applied are:

- o priority valve;
- o pressure maintaining valve.

SYSTEM RECONFIGURATION AND REQUIRED DEFLECTION RATES IN FAILURE CASES, SIZING OF PUMPS - **STEP 11**: Decide from the system reconfiguration logic based on STEP 7 which actuators will be required to act simultaneously. Determine the control surface deflection rates in failure cases. Establish the pump size from hydraulic load analysis.

Relevant failure scenarios have to be checked for hydraulic system design. This has to be done for all relevant failure states, for all flight phases, and for main consumption patterns. In addition, required deflection rates in failure cases have to be established.

Single failure and double failure cases should be generated from combinations of events as follows:

- o failures of EDP,
- o failure of auxiliary power generation,
- o total system failure (e.g. due to rupture of hydraulic lines)
- o failures of an engine.

All flight phases should be checked with emphasis on takeoff and approach (low engine rpm). Consumption patterns should include separate as well as simultaneous operation of high flow consumers as far as necessary.

Required flight control deflection rates can be calculated for failure cases in much the same way as maximum required deflection rates for normal conditions as given in STEP 4 - only the required flying quality level might be different. MIL-H-5440H [6] specifies: "*Fixed wing aircraft shall maintain level one (1) flying qualities of MIL-F-8785 with one fluid system failure (including the power source) and level three (3) flying qualities ... with two fluid system failures*". Table III of MIL-F-8785C [11] adapted to civil aviation asks for level 2 flying qualities after minor failures and level 3 after major failures.

For each failure scenario, the sum of required consumer fluid flows has to be compared with available pump flow rates. (Note: EDP output depends on engine rpm). The most demanding combination of required and available flow rate will size the pumps. In some cases, it may be found that the maximum flow demand is of very short duration involving very small volumes of oil. Here, sizing a pump to meet this demand may not be justified. An accumulator can be used to augment the flow available, but care must be taken. In a situation where the flow demanded will exceed the pump capabilities the system pressure is controlled by the accumulator, not the pump. This case will influence the circuit pressure drop calculation if the necessary pressure across the actuator piston is to be maintained. The frequency of maximum demand must also be known, and time must be available for the pump to recharge the accumulator.

PRELIMINARY PIPE DIAMETER SIZING - **STEP 12**: Track the maximum flows in the various tubes for normal operation and failure cases with established deflection rates as obtained from STEP 4 and STEP 11. Determine the maximum flow rate for each tube among all failure scenarios. Preliminarily size the tubes from allocated pressure drops and minimum operating temperatures.

Historically pipe sizing was done from average fluid velocity limitations. The MIL-H-5440D rule of thumb was 15 feet per second (4.57 m/s). ARP 994 [15] reports of aircraft with 25 ... 30 feet per second (7.62 m/s ... 9.14 m/s).

At *Airbus* different maximum average fluid velocities for different lines are used:

o high pressure lines:	10 ... 12 m/s,
o return lines:	6 ... 8 m/s,
o suction lines:	2 ... 3 m/s.

Recent practice (MIL-H-5440H, Chapter 3.6.6 [6]) is to size the inner tube diameter d from several considerations:

- allowable pressure drop at minimum required operating temperatures,
- pressure surges caused by high fluid velocity and fast response valves,
- back pressure in return lines,
- pump inlet pressure.

The allowable pressure drop that has to be allocated to a tube (from pump to consumer) can be calculated from the pressure loss factor k_p (see below):

$$\Delta p_t = (1-k_p) \cdot p_0 \quad . \tag{3}$$

Δp_t is the sum of pressure losses in the tubes to and from a consumer and has to be further distributed between supply and return pipes. For sizing the lines of commercial transport airplanes, typical minimum operating temperatures have to be considered [15]:

- minimum fluid cold start capability: -54 °C,
- minimum fluid temperature for rated pump suction flow: -29 °C,
- minimum fluid temperature for full system performance: 10 °C.

SYSTEM CHECK - **STEP 13**: Perform steady state calculation and check the system for pressure surges.

Experience has shown that the combined simulation of the aircraft's hydraulic systems with their high number of parts and possible interactions by way of power transfer units should be kept as simple as possible. A steady state calculation can reduce the complexity in comparison to a dynamic simulation. A computer program named ICaroS has been written to perform tasks such as:

- Check the systems for functional integrity.
- Check the pressure drop in pipes at maximum flow velocities and minimum temperatures against allocated values from STEP 12.
- Check the interaction of the pressure drops in the pipes with actuator performance and pump characteristics.
- Check the pump input pressure against the minimum allowable pressure.

In addition, the system should be checked for pressure surges. FAR 25, Volume III, Transmittal 1, Amendment 25-23 specifies that transient pressures shall not exceed 125% of the design operating pressure [15]. For an abrupt closure of a valve the pressure rise in the system depends on the original fluid velocity v

$$\Delta p = v \cdot \sqrt{K \cdot \rho} \tag{4}$$

where K is the fluid bulk modulus and ρ is the fluid density. As can be seen from EQ (4), the higher the chosen average fluid velocities are, the more is the system prone to experience pressure surges.

BACKGROUND AND IMPLEMENTATION

OPTIMISING THE PRESSURE LOSS FACTOR - The pressure loss factor is defined as the ratio of available pressure at hydraulic consumers to the nominal system pressure: $k_p = \Delta p_c / p_0$. Different optimum values for k_p are proposed in the literature. ARP 994 (Chapter 4.1.2) [15] proposes $k_p = 0{,}66$. *Moir and Seabridge* [3] give $k_p = 0.75 \dots 0.8$. *Airbus Industrie* specifies e.g. $k_p = 0.82$ [23] and $k_p = 0.84$ [24] for flight control actuators at maximum flow.

ARP 994 [15] indicates that there is not just one optimum pressure loss factor: "*It is even possible to let the pressure differential across the actuator be a variable in the solution and obtain a truly minimum-weight system for long lines where an increase in allowable tubing pressure drop can provide more weight saving than needs to be added for the slightly larger actuator sizes.*"

Let us assume that the mass of linear actuators m_a , motors m_m , tubes m_t , and pumps m_p can be calculated from mass models based on statistics and component parameters [25] like required tube length l , required inner tube diameter d , piston area A , piston stroke s , and theoretical pump or motor displacement V_{th} at given constant system pressure p_0 (in general 3000 psi):

$$\begin{aligned} m_p &= f(V_{th}) \\ m_t &= f(d, l) \\ m_a &= f(A, s) \quad \text{(linear actuator)} \\ m_a &= f(V_{th}) \quad \text{(motor)} \quad . \end{aligned} \tag{5}$$

For maximum required actuator torque T and maximum deflection rate ω, system pressure p_0 , efficiency of the actuator-valve combination η (see EQ(2)), fluid density ρ, fluid kinematic viscosity ν, tube length l, the theoretical required inner tube diameter d depends on the pressure loss factor k_p and flow condition (laminar or turbulent flow). For turbulent flow

$$\begin{aligned} d &= k_t \cdot \sqrt[5]{\frac{1}{k_p^2 - k_p^3}} \\ k_t &= \sqrt[5]{\frac{8 \cdot \lambda \cdot l \cdot \rho \cdot T^2 \cdot \omega^2}{\pi^2 \cdot p_0^3 \cdot \eta}} \quad . \end{aligned} \tag{6}$$

This gives a minimum theoretical tube diameter d for a pressure loss factor $k_p = 0.66$. For laminar flow

$$\begin{aligned} d &= k_l \cdot \sqrt[4]{\frac{1}{k_p - k_p^2}} \\ k_l &= \sqrt[4]{\frac{128 \cdot \nu \cdot \rho \cdot T \cdot \omega \cdot l}{\pi \cdot p_0^2 \cdot \eta}} \end{aligned} \tag{7}$$

This gives a minimum theoretical diameter d for a pressure loss factor $k_p = 0.5$. EQ(6) and EQ(7) are plotted in **Figure** 3. It can be seen that for laminar as well as for turbulent flow there is a relatively wide range of k_p-values that yield close to optimum tube diameters. In practice, pipe design will be done for turbulent flow.

The optimum pressure loss factor k_p obviously depends not only on tube diameter d and hence tube mass m_t , but also on the actuator mass m_a , and pump mass m_p . For n tubes, connecting m different actuators in a hydraulic system to one or more pumps, the m different pressure loss factors $k_{p,j}$ can be obtained form minimising the total mass

$$m = \sum_{i=1}^{n} m_{t,i} + \sum_{j=1}^{m} m_{a,j} + m_p \tag{8}$$

or can be estimated form

$$k_p = 1 - (1 - k_{p,opt}) \cdot \frac{\sum m_t}{m} \tag{9}$$

where $k_{p,opt}$ has to be set to the optimum value (for turbulent flow) of 0.66 .

STEADY STATE CALCULATION OF HYDRAULIC POWER SYSTEMS - Computer programs for the steady state calculation of fluid <u>power</u> systems are rare in comparison to programs for the steady state calculation of fluid <u>distribution</u> systems. FLOWMASTER [23] is an example of a program that also handles fluid <u>power</u> systems but lacks support of some important aircraft components like power transfer units. Therefore, a computer program named ICaroS (<u>I</u>nteractive <u>Ca</u>lculation of <u>H</u>ydr<u>a</u>ulic P<u>o</u>wer <u>S</u>ystems) was written especially for the steady state calculation of aircraft hydraulic systems.

ICaroS is based on the "Linear-Theory-Method" also known as "Finite-Element-Method" and solves p-q-Equations (node equations expressed in terms of unknown pressure p and external flows q) iteratively by Gauss elimination [24]:

$$\sum_{x=1}^{k} Q_x + q_j = 0 , \tag{10}$$

$$\text{for all nodes } j = 1, \dots, J$$

with Q_x the internal flows in k adjacent pipes. This yields a set of $M + N = J$ equations for N nodes in the system and M unknown external flows. Q_x can be substituted by introducing the hydraulic resistance R_x

$$\sum_{x=1}^{k} \left(\frac{p_i - p_j}{R_x} \right)^{\frac{1}{n}} + q_j = 0, \qquad (11)$$

$$\text{for all nodes } j = 1, \ldots, J \quad .$$

Usually it is chosen $n = 2$. EQ (11) can be linearized to give

$$\sum_{x=1}^{k} C_x' \, (p_i - p_j) + q_j = 0, \qquad (12)$$

$$\text{for all nodes } j = 1, \ldots, J$$

with C'_x being the linearized hydraulic conductance. The inclusion of hydraulic component other than resistance requires further considerations and will not be discussed here.

IMPLEMENTATION - The CAE tool includes so far modules as follows (**Figure 4**):

- o calculation of hinge moments,
- o calculation of required surface deflection rates,
- o evaluation of flight control configurations in terms of their offered maneuverability under standard and failure conditions,
- o calculation of required installation space for flight control actuation systems,
- o calculation of static and dynamic design parameters for flight control actuation systems
- o steady state calculation of hydraulic systems
- o calculation of the economic implications of a system configuration by means of a Direct Operating Cost (DOC) method tailored to aircraft systems.

The CAE tool is conventionally programed and can be classified as a decision support system. It allows the systems engineer to work closely with the computer when it comes to

- o retrieving information,
- o calculating system characteristics,
- o designing alternative solutions,
- o selecting a suitable solution among considered alternatives.

An up to date programming concept ensures the development of a user friendly and comfortable product: Hardware independent programming is based on ANSI C. A User Interface Management System (UIMS) facilitates the programming of an interactive Graphical User Interface (GUI). An incorporated hypertext system provides the user with technical information to his problems in a context sensitive way. An incorporated plot program helps to visualize the results. The independent program modules exchange information via a common, universal data base.

CONCLUSION

This paper has presented a structured approach to the design of hydraulic systems for transport category aircraft. Some design activities need to handle large data quantities and/or ask for high computing power. For these design activities computer modules have been written forming together a CAE tool for hydraulic system design of transport category aircraft.

A computer-aided design process allows a detailed check of various aspects of the proposed system. Therefore, the number of required modifications on the test rig will be substantially reduced in comparison to a less evaluated design.

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APPENDIX

Table 1: Typical functions of hydraulic systems and generalized classification of failure effects for loss of control of hydraulic function.

HYDRAULIC FUNCTION GROUP	HYDRAULIC FUNCTION	FAILURE MODE *	GENERALIZED FAILURE EFFECT CLASSIFICATION
primary flight control	rudder actuation	loss of rudder control associated with an engine failure at take off	catastrophic
	elevator actuation	loss of control of one elevator	major
	aileron actuation	loss of control of one aileron	minor
	spoiler actuation	loss of control of one spoiler	minor
	trimmable horizontal stabilizer (THS) actuation	loss of control of the THS surface	major
	elevator actuation	loss of all elevators	catastrophic
	aileron and spoiler actuation	loss of roll control	hazardous
	elevator and THS actuation	loss of pitch control	catastrophic
	aileron, spoiler and rudder actuation	loss of yaw and roll control	catastrophic
secondary flight control	flap control	loss of flap control	minor
	slat control	loss of slat control	minor
utility functions	landing gear retraction and extension	loss of control	minor
	landing gear door operation	loss of control	minor
	wheel braking	loss of control	major
	nosewheel steering	loss of control	minor
	cargo door operation	loss of control	minor
backup functions	electrical supply by means of a generator coupled to a hydraulic motor	loss of control	minor

* This Tabel considers only the failure condition "loss of control" as the important information towards safety requirements for hydraulic systems.

Table 2: Typical required number of hydraulic systems for the actuation of single control surfaces or groups of control surfaces.

NUMBER OF REQUIRED HYDRAULIC SYSTEMS ...	... FOR ACTUATION * OF ...
3	all rudders
3	all elevators
2	one elevator
2	THS
2	all ailerons and spoilers
1	one aileron
1	one spoiler

* This table considers only the number of hydraulic systems required for actuation of single control surfaces and groups of control surfaces. In some cases additional actuators connected to other hydraulic system might be used to prevent uncontrolled movement of a surface in case of loss of control of the first hydraulic system and actuator.

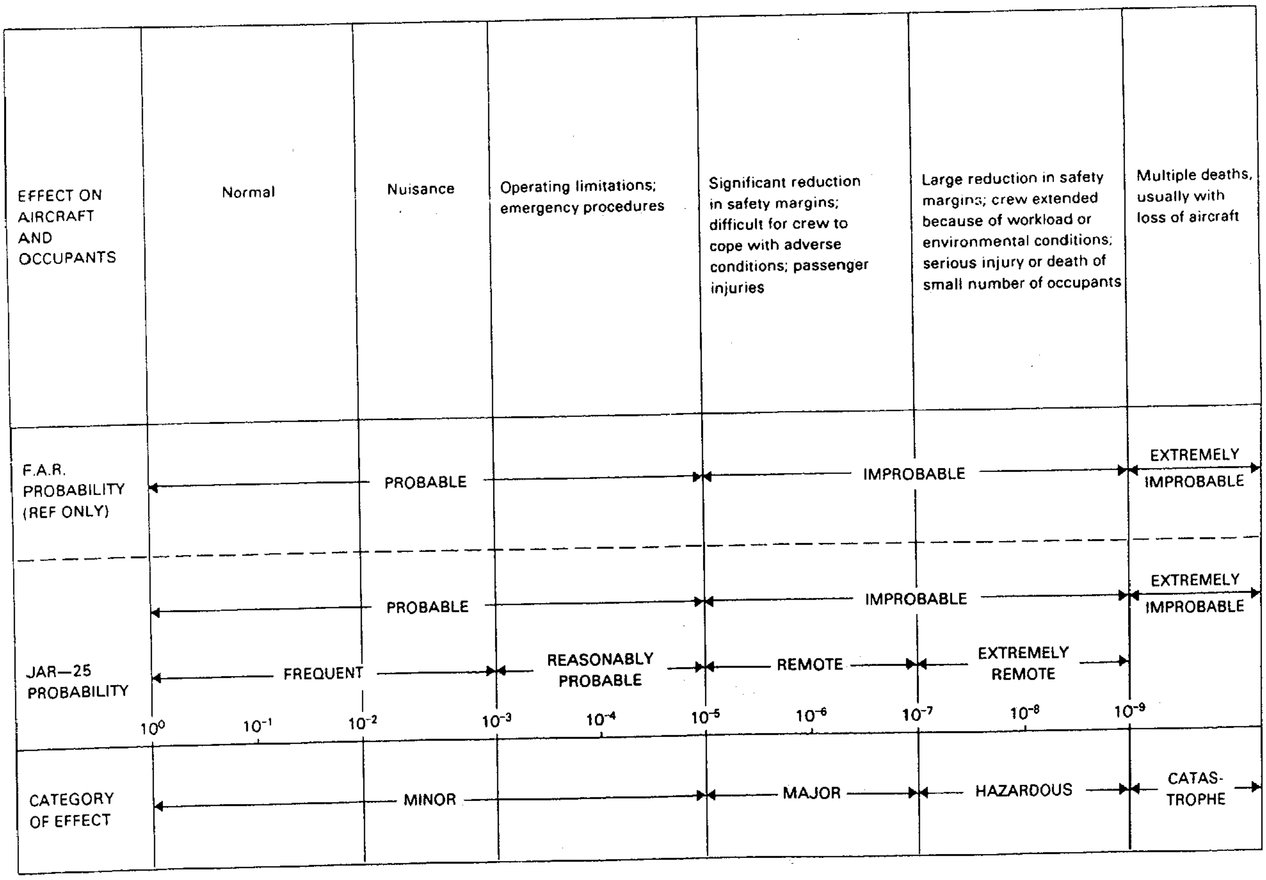

Figure 1: Relationship between severity of effect and required probability of failure condition [5]

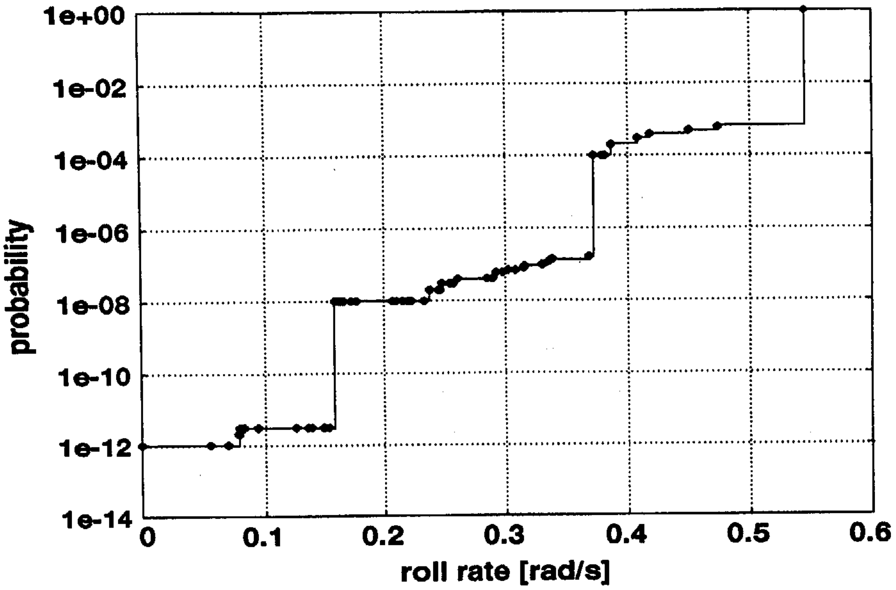

Figure 2: Cumulative distribution function for roll control. Results based on Airbus A320 input data.

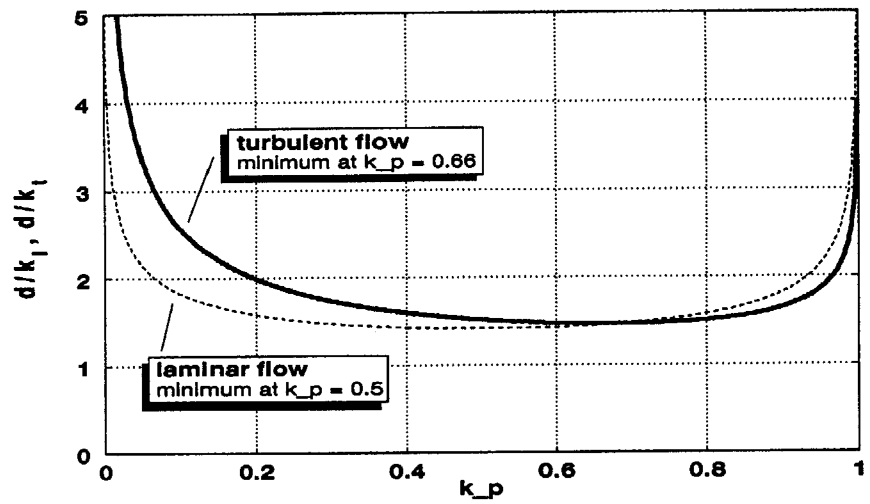

Figure 3: Dimensionless tube diameter versus pressure loss factor

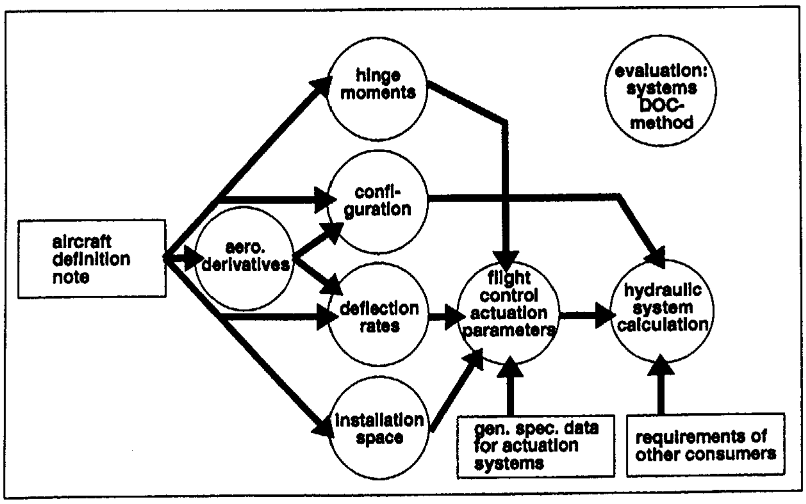

Figure 4: Modules of CAE-tool for the design of flight control and hydraulic systems