

COMPUTER-AIDED ENGINEERING FOR THE DESIGN OF FLIGHT CONTROL AND HYDRAULIC SYSTEMS

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Abstract

Generic, ready-to-use preliminary design methodologies for aircraft utility systems, made available by means of a Computer Aided Engineering (CAE) tool do not exist. An attempt is made to apply principles used in preliminary aircraft design to preliminary design of utility systems. This is demonstrated for the flight control and hydraulic system. The Computer-Aided Engineering tool consists of independent modules that build on each others results. For the programming of each of these modules it was necessary to thoroughly review the state of the art. This paper presents one module in more detail: the module for steady state calculation of hydraulic systems. This module provides key information for aircraft hydraulic system design. It is based on the Linear Theory Method with p - q -equations and supports the incorporation of aircraft-specific hydraulic components into the calculation.

Introduction

Flight control and hydraulic systems are just two examples of utility systems (also known as fundamental, basic or general systems) of an aircraft. Utility systems in modern civil transport aircraft have reached high technical and economic importance. Without them the aircraft would not even leave the ground. Utility systems together with avionic systems account for about one third of total aircraft production costs. Much knowledge and experience was gathered by manufacturers and suppliers during past decades in the preliminary design of aircraft systems. Nevertheless, it seems that for many utility systems, generic and generally accepted preliminary design methodologies do not exist - not to speak of Computer Aided Engineering (CAE) tools for these design activities.

This is very much in contrast to preliminary aircraft design. Text books and computer programs by *Roskam*⁽¹⁾⁽²⁾ and *Raymer*⁽³⁾⁽⁴⁾ are just two examples of an approach in preliminary aircraft design where generic methodologies are offered as printed medium and ready-to-use CAE tools.

Here, an attempt is made to apply principles used in preliminary aircraft design to preliminary design of utility systems. The aim is to progressively develop and detail a design from basic data. This basic data for aircraft utility system development results from preliminary aircraft design. Two utility systems - the flight control and hydraulic system - are used to demonstrate this approach. The paper starts with an overview of available modules, applied methods, and the appearance of the tool to the user. Detailed background information is given on the module for steady state calculation of hydraulic systems.

Modules, Methods, and CAE Tool Design

Preliminary design of aircraft utility systems is based on data obtained from preliminary aircraft design as given in the Aircraft Definition Note. The CAE tool does, for now, include calculations for design activities as shown in Figure 1. Supported are the preliminary design of flight control actuation systems (flight control law design is not included) and the layout of the aircraft hydraulic systems.

Modules

The tool includes so far modules as follows (Figure 1):

- 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 available 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.

Classification of CAE Tool

The CAE tool is conventionally programmed and can be classified as 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.

Design of flight control actuation systems

The design of actuation systems is based on maximum required actuator output performance. Actuator performance is the product of required deflection rate and required hinge moment at this deflection rate. The size of the available installation space for the flight control actuators is found from preliminary aircraft design data. The actuators have to be designed into this available installation space. In cases of hydraulic actuators, the valve has to be sized together with the controller gain according to dynamic performance requirements.

Hinge Moments. Maximum hinge moments of control surfaces are found from checking required maneuvers throughout the flight envelope⁽⁶⁾. 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 based on maneuvers given in FAR/JAR 25.349. Maximum rudder hinge moments generally occur for multi engine aircraft as a result of an engine failure as detailed in JAR 25.147. These maneuvers yield the angle of attack at the control surface and the required deflection angle of the control surface. Hinge moment derivatives can be estimated from *DATCOM*⁽⁶⁾ or *ESDU*⁽⁷⁾. Data from *DATCOM*-diagrams was incorporated into the computer program by means of cubic surface splines. Equations for spoiler hinge moments were developed from flat plate analysis and are matched to aircraft test data. **Figure 2** shows a screen shot of the CAE module for hinge moment calculation.

Deflection Rates. Following a rule of thumb⁽⁸⁾, a first estimate of a control surface deflection rate $\dot{\delta}$ is

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

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. In general, control surface deflection rates have to meet requirements due to aircraft

maneuverability, Pilot-In-the-loop Oscillations (PIO), autopilot commands, and commands generated to stabilize an unstable aircraft. For traditional civil transport category aircraft, only the first two requirements will have an impact on maximum deflection rates. The methods to calculate related maximum deflection rates are for

- o maneuverability requirements:
 - Elevator: MIL-STD-1797 "Effective Delay" from short-term pitch response, alternative C.
 - Aileron: roll performance from MIL-STD-1797 "Time to Achieve Bank Angle" or JAR 25: ACJ 25.147(e).
 - Rudder: MIL-STD-1797 yaw axis response to asymmetric thrust during takeoff run or JAR 25.149(e).
- o PIO requirements:
 - A new PIO criterion was proposed by *Duda*⁽⁹⁾ which takes account of actuator rate saturation. The criterion gives limits, drawn in a *Nichols* chart. For the systems under consideration, the onset point⁽⁹⁾ is calculated and compared with limits in the *Nichols* chart.

Actuator Design. Actuator design for conventional linear hydraulic actuators basically yields the actuator piston diameter, lever arm, and stroke. **Figure 3** shows a screen shot of the CAE module which calculates actuator dimensions from input parameters and draws the actuator in its critical position in relation to the available installation space.

Valve sizing and determination of controller gain. The valve is sized⁽⁵⁾ from maximum deflection rate and hinge moment requirements. Finally, the controller gain for the actuator control loop is determined⁽⁵⁾ from dynamic requirements as given in SAE ARP1281 and MIL-F-9490D.

Flight Control Configuration

The maneuverability of the aircraft during normal operation and failure cases depends on the allocation of hydraulic systems and signal sources (i.e. flight control computers or control cables) to the flight control actuators⁽⁵⁾. A computer module has been written which calculates the expected value of the maneuverability about roll and pitch axes for a proposed design. Rudder actuation of fully powered systems is usually simple enough to necessitate the need for computer aided allocation of hydraulic systems.

Aircraft Hydraulic System Design

The design of an aircraft's hydraulic system is based on an optimized flight control configuration (see above). A structured approach to preliminary aircraft hydraulic system design was developed⁽¹⁰⁾ and considers

- o an optimized load distribution,
- o routing of pipes,
- o definition of auxiliary hydraulic power and safety devices,
- o preliminary pipe diameter sizing.

The preliminary system generated in this way needs to be further checked and optimized. For a first check of pump and pipe sizing at all possible failure conditions and during normal operation, a steady state calculation (see below) is better suited than a dynamic simulation because of reduced input data requirements.

Design Evaluation

As in aircraft design, solutions are evaluated by means of their cost effectiveness. For this purpose, a method to calculate the Direct Operating Costs (DOC) for aircraft utility systems was developed⁽¹¹⁾.

Programming

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.

A conventionally programmed CAE tool seemed to be most beneficial for the direct implementation of selected design methodologies. Another approach could start from an expert system shell. *Rockwell International* made an approach in such a way⁽¹²⁾.

Steady State Calculation of Fluid Power Systems

The CAE tool includes a module for the steady state calculations of fluid power systems. The module calculates pressure and flow in each node and pressure losses in every component of the system. Valve positions can be set or alternatively calculated. The operation of main and auxiliary power sources can be calculated depending on actuator speed and load requirements. For

the design evaluation of aircraft hydraulic systems, this information needs not only be generated for a single point of operation but for a list of normal and failure conditions. Considering the amount of data, it is evident that a single steady state value of flow or pressure is more meaningful than a full time history.

State of the Art

Most hydraulic computer packages solve a set of differential equations describing the hydraulic system in question. These packages can calculate the steady state conditions from a ramp input or a series of small step inputs. Unfortunately, more calculation time is required compared to a direct steady state solution⁽¹³⁾. The main disadvantage for the user, however, is the fact that more input data is required.

Computer Programs. Examples of simulation packages used in aircraft fluid system design (with emphasis on the aircraft hydraulic system) are:

- o HYTRAN developed at McDonnell Douglas in cooperation with the Air Force Aero Propulsion Laboratory⁽¹⁴⁾. HYTRAN was subsequently also used and enhanced by other aircraft manufacturers.
- o EASY5 developed at Boeing. EASY5 is a general purpose simulation tool⁽¹⁵⁾. Available is a library with special aircraft hydraulic components;
- o FLOWMASTER initially developed at the British Hydromechanics Research Association. A general purpose hydraulic package. Available is also a general fluid power module for steady state analysis⁽¹⁶⁾. However, aircraft hydraulics are not specifically considered. FLOWMASTER is used in the aircraft industry⁽¹⁷⁾. Airbus uses FLOWMASTER mainly for water distribution and fuel system simulation⁽¹⁸⁾.

Methods. The CAE module for the steady state calculation of hydraulic systems applies the **Linear Theory Method** with *p-q*-equations to solve a set of nonlinear equations. Other frequently applied methods are the *Hardy Cross Method*⁽¹⁹⁾ and the *Newton-Raphson Method*⁽²⁰⁾. The Linear Theory Method was first⁽²¹⁾ introduced by *McIlroy*⁽²²⁾ in 1949. He based his algorithm on ΔQ -equations (linearized equations based on the difference between estimated and corrected flows in a component). Later computer programs were written based on *Q*-equations⁽²³⁾ (linearized equations of flows in components) and *p*-equations⁽²⁴⁾⁽²⁵⁾ (linearized equation of nodal pressures). All these computer programs merely deal with fluid distribution systems in contrast to fluid power systems.

Background of Linear Theory Method

The hydraulic module in the CAE tool applies the Linear Theory Method and is based on p - q -equations. For the formulation of p - q equations, pressures p in the nodes are taken as the basic unknown parameters together with the unknown external nodal flows q . The node flow continuity relationship is applied to all J nodes of the system.

$$\sum Q_x + q_j = 0, \quad \text{for all nodes } j = 1, \dots, J. \quad (2)$$

The pressure loss in a component x can be calculated from the hydraulic resistance R_x

$$p_i - p_j = R_x \cdot Q_x^n. \quad (3)$$

The exponent is usually set to $n = 2$. Equation (2) can now be rewritten

$$\sum \left(\frac{p_i - p_j}{R_x} \right)^{\frac{1}{n}} + q_j = 0, \quad \text{for all nodes } j = 1, \dots, J \quad (4)$$

and linearized

$$\sum - C'_x (p_i - p_j) = q_j, \quad \text{for all nodes } j = 1, \dots, J \quad (5)$$

with the modified conductance

$$C'_x = \frac{|p_i - p_j|^{\frac{1}{n} - 1}}{R_x^{\frac{1}{n}}}. \quad (6)$$

In this way the nonlinear system of equations (4) was transformed into a linear system of equations (5). Note however, that this was only possible by introducing the modified conductance C'_x which depends on unknown pressures p . Hence, an iterative solution is required with initial estimated pressures. The iteration also takes care of resistances R_x which depend on Reynolds Number and hence internal flows Q . Note furthermore, that equation (5) is not suited for a direct numerical solution because unknown pressures and unknown external nodal flows are present on the left hand side as well as on the right hand side of the equation. Equation (5) needs to be rearranged which can be systematically done⁽²⁴⁾ and programmed. During the iteration, cases of overcorrection can occur. In order to avoid them a damping factor for the modified conductances K_C is introduced (t indicates the number of the present iteration)

$${}^{(t+1)}C'_x = (1 - K_C) \cdot {}^{(t)}C'_x + K_C \cdot {}^{(t)}C'_x. \quad (7)$$

Comparison of Methods

The Linear Theory Method with p - q equations was compared⁽²⁷⁾ with other methods - the Hardy Cross Method⁽¹⁹⁾ and the Newton-Raphson Method⁽²⁰⁾. The main practical advantages are:

- o Convergence problems have not been observed.
- o There is no need for manual input of initial values for the iteration because any practical set of initial pressures will converge.
- o Nodes may have an unknown pressure and an unknown external flow as long as the "Rules for Solvability of Pipe Networks"⁽²¹⁾ are met.
- o The method may be programmed relatively straight forward.

Implementation of Valves

Implementation of Check Valves, Pressure Relief Valves, and Priority Valves. The steady state characteristics of the valves are entered into the program in form of Δp - Q -diagrams. Additionally, the opening pressure is required. For a pressure differential greater than opening pressure, the valve is treated like a normal hydraulic resistor. In the other case, the modified conductance C' is set to zero.

Implementation of Pressure Maintaining Valves. Pressure maintaining valves change their hydraulic resistance depending on a pressure differential $\Delta p_{1,2}$ between two points in the system. Their purpose in aircraft hydraulic systems is to protect a part of the system (e.g. for primary flight control) and ensure that the system pressure will not unduly drop. For this purpose, the consumption of a secondary component can be limited depending on the measured pressure differential $\Delta p_{1,2}$. This is done by insertion of a variable resistor. Pressure maintaining valves are calculated in the program by defining a resistor with variable pressure loss coefficient

$$\zeta = f(\Delta p_{1,2}). \quad (8)$$

Implementation of Four-Way Servo Valves. A servo valve can be modelled from four variable hydraulic resistors in bridge connection. These four variable hydraulic resistors are automatically generated by the CAE module upon insertion of a servo valve and are set according to the selected valve opening. Aircraft hydraulic systems can be tested by demanding certain motor speeds and piston velocities at given loads. In order to deal with these cases, the hydraulic module is able to iteratively determine the required valve setting. The first iteration starts at maximum valve opening. If the resulting actuator speed is less than required, no practical solution is possible. Otherwise, the valve setting will automatically be reduced to achieve the demanded actuator speed.

Implementation of Energy Converting Components

Fluid distribution networks, for which the basic methods - Hardy Cross, Newton Raphson, and Linear Theory - were developed, need to deal only with a limited number of different types of components. In addition to various resistances, simple pumps and check valves can directly be built into equation (5)⁽²¹⁾. For fluid power systems however, energy converting components are more important than simple resistances. Therefore, the hydraulics module of the CAE tool models the energy converting components separately from the rest of the network and merely manages the interface to these components with the remaining system. This will be demonstrated for some selected components.

Implementation of Pumps. Five different pump models are considered:

- 1.) pumps with constant overall efficiency;
- 2.) pumps with variable overall efficiency depending on the pressure increase over the pump, Δp , and pump speed n calculated from $\eta = f(\Delta p, n)$;
- 3.) pumps described by Δp - Q -diagrams;
- 4.) *Bavendiek*-modelled⁽²⁸⁾ pumps with the efficiency depending further on oil viscosity ν and swashplate setting α :
 $\eta = f(n, \Delta p, \nu, \alpha)$;
- 5.) pressure regulated pumps.

Figure 4a shows a pump in a simple network. The pump is connected on both sides to a pipe. Let us assume that node 1 and 4 are linked to a reservoir. Hence, the pressure in node 1 and node 4 are known, however, the external flows are unknown. The pump is now taken off the system and considered separately. Two separate networks emerge with two new boundary nodes. For pump models 1.) through 4.), these new nodes are taken as having unknown pressure. Assuming no external leakages, effective outlet flow must equal effective inlet flow: $q_3 = -q_2$ (Figure 4b). For each iterative step during network calculation, a procedure as follows is initiated:

- 1.) calculate a new pump efficiency η depending on the pump model;
- 2.) calculate an effective pump flow Q_{eff} from pump efficiency, pump displacement, and pump rotational speed (for the first iteration an efficiency will be assumed);
- 3.) set external flows on new boundary nodes: q_2 and q_3 ;
- 4.) calculate Δp for the next calculation of pump efficiency;
- 5.) perform the next iteration step.

For pressure regulated pumps, p_3 and q_2 in Figure 4b are considered to be known with $q_2 = -Q_{eff}$. Accordingly, the calculation procedure changes slightly. Q_{eff} and pump outflow pressure p_3 taken from the last two iterations are averaged. This introduces damping to the iteration and ensures a stable solution.

Implementation of Hydraulic Motors. Three different motor models are considered:

- 1.) motors with constant efficiency;
- 2.) motors with variable efficiency depending on pressure drop Δp and motor speed n : $\eta = f(\Delta p, n)$;
- 3.) *Bavendiek*-modelled⁽²⁸⁾ motors with efficiency depending further on oil viscosity ν and swashplate setting α :
 $\eta = f(n, \Delta p, \nu, \alpha)$.

Again, this component is calculated separately from the rest of the network. At motor outlet, the external flow q_3 of boundary node 3 and at motor inlet pressure p_2 are considered to be known. For each iterative step during network calculation, a procedure as follows is initiated:

- 1.) calculate a new motor overall efficiency η depending on the motor model;
- 2.) calculate an average outlet pressure p_3 from the last two iterations; calculate motor inlet pressure p_2 from outlet pressure and required differential pressure Δp due to motor loading;
- 3.) set $q_3 = -q_2$ and effective flow $Q_{eff} = q_3$;
- 4.) calculate motor speed n from effective flow Q_{eff} , motor displacement, and volumetric efficiency;
- 5.) calculate required differential pressure Δp (used in step 1.) from hydromechanical efficiency, effective torque, and geometric displacement;
- 6.) perform next iteration step to obtain new values for inlet flow q_2 and outlet pressure p_3 .

The calculation of linear actuators follows the same principles as given for the hydraulic motor.

Implementation of Power Transfer Units (PTU). Power transfer units are used to transfer hydraulic power from one hydraulic system into another hydraulic system in case of a fault in one system. The exchange of hydraulic fluid is not permitted. Therefore, energy is transferred mechanically via a shaft which connects two hydraulic devices. Several PTU designs and constellations may be distinguished for the calculation:

- o Fixed displacement PTU: The PTU is made up of two standard fixed displacement pump/motor units mounted back to back:
 - unidirectional PTU: power transfer only in one direction,
 - bidirectional PTU: power transfer in either direction.

- o Variable displacement PTU: The PTU can maintain the same pressure in the faulty system as in the working system, and have that be possible in both directions:
 - the variable displacement unit is in the faulty system (pump),
 - the variable displacement unit is in the working system (motor).

All four PTU variants are considered in the programming of the hydraulic module. Again, also the PTU is calculated separately from the rest of the network. The principle way to calculate a PTU is explained using a variable displacement PTU with a variable displacement pump (Figure 5). External flows q_1 , q_2 , q_3 , and nodal pressure p_4 are considered to be known. p_1 , p_2 , p_3 , and q_4 are obtained from network calculation. The procedure is this:

- 1.) calculate pump and motor efficiencies,
- 2.) a) p^*_1 is the average from p_1 taken from the last two iterations,
b) pump outlet pressure p_4 is set equal to p^*_1 (this is the control goal of the PTU),
- 3.) a) q^*_4 is the average from q_4 taken from the last two iterations,
b) $q_3 = -q^*_4$,
c) pump flow $Q_P = q_3$,
- 4.) a) motor flow Q_M is calculated from geometric (i.e. theoretical) displacements V_{th} and volumetric efficiencies η_{vol} of motor (M) and pump (P):

$$Q_M = Q_P \cdot \frac{V_{th,M}}{V_{th,P}} \cdot \frac{1}{\eta_{vol,M} \cdot \eta_{vol,P}}$$

- f) external flows can be set: $-q_1 = q_2 = Q_M$,
- 5.) a) $\Delta p_P = p_4 - p_3$ with p_4 from step 2.)b) and p_3 from network calculation,
b) Δp^*_P is the average from the last two iterations,
c) $\Delta p_M = p_1 - p_2$ with p_1 and p_2 from network calculation,
d) Δp^*_M is the average from the last two iterations,
e) the variable displacement of the pump is calculated (required for step 4.)a) during next iteration):

$$V_{th,P} = V_{th,M} \cdot \frac{\Delta p_M}{\Delta p_P} \cdot \eta_{hm,M} \cdot \eta_{hm,P}$$

with η_{hm} being the hydromechanical efficiency,

- 6.) speed n for step 1.) and torque M for output are calculated,
- 7.) perform next iteration which yields new values for p_1 , p_2 , p_3 , and q_4 .

User Interface of Hydraulic Module

The hydraulic module can be used in batch operation with input files describing the hydraulic system. In addition, a graphical user interface is available as presented in Figure 6.

Conclusion

This paper has presented a Computer-Aided Engineering (CAE) tool for the design of flight control and hydraulic systems. Details were given on the module for the steady state analysis of aircraft hydraulic systems. Steady state calculations appear useful for preliminary hydraulic system design. Analysis tools specifically for the steady state calculation of aircraft hydraulic systems seem not to exist. The presented analysis tool tries to fill this gap. It is based on the Linear Theory Method with p - q -equations. Energy converting hydraulic components and aircraft-specific components were successfully incorporated into the Linear Theory Method.

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Appendix

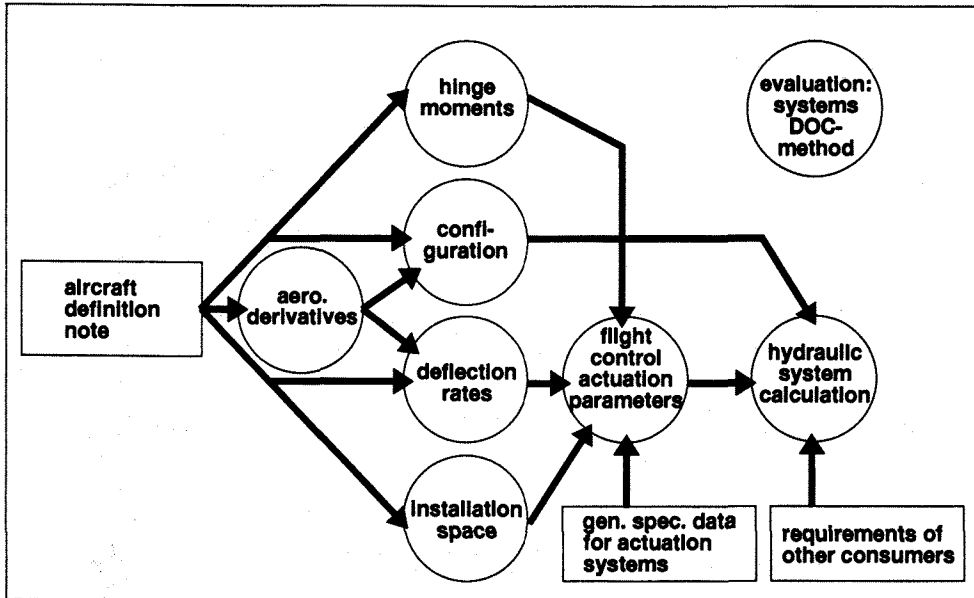


FIGURE 1 - Modules of CAE tool for the design of flight control and hydraulic systems

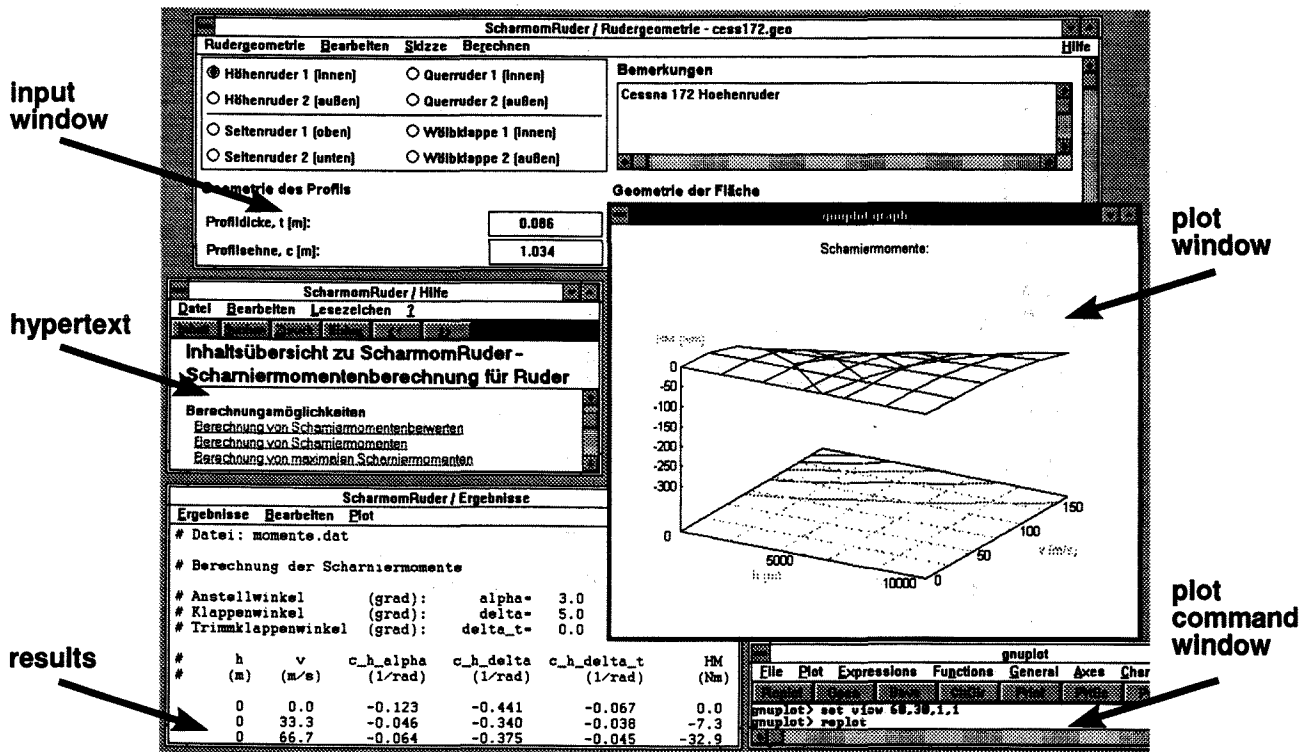


FIGURE 2 - Screen Copy of Module for the Calculation of Hinge Moments

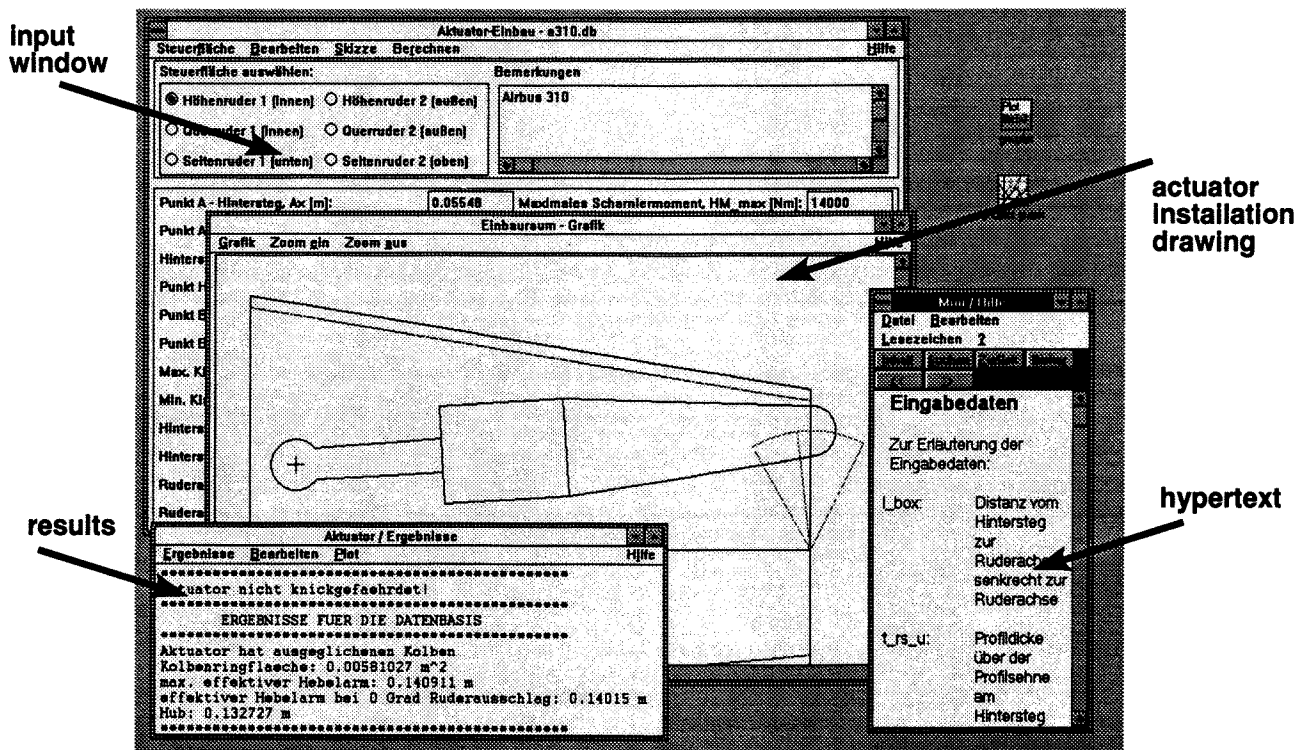


FIGURE 3 - Screen Copy of Module for the Calculation of Actuator Parameters

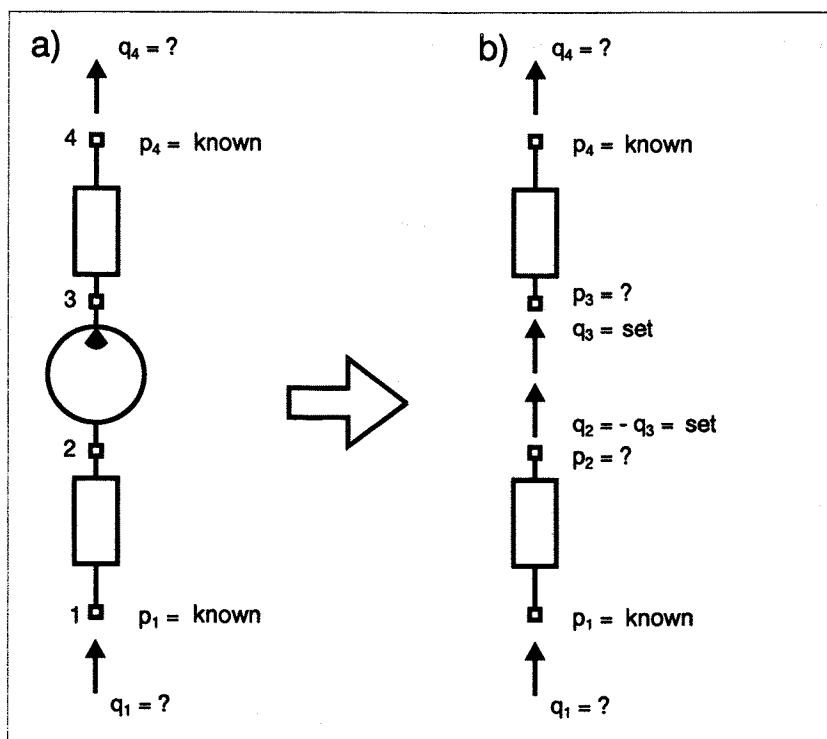


FIGURE 4 - Pump Cut Off a Simple Network for Separate Calculation

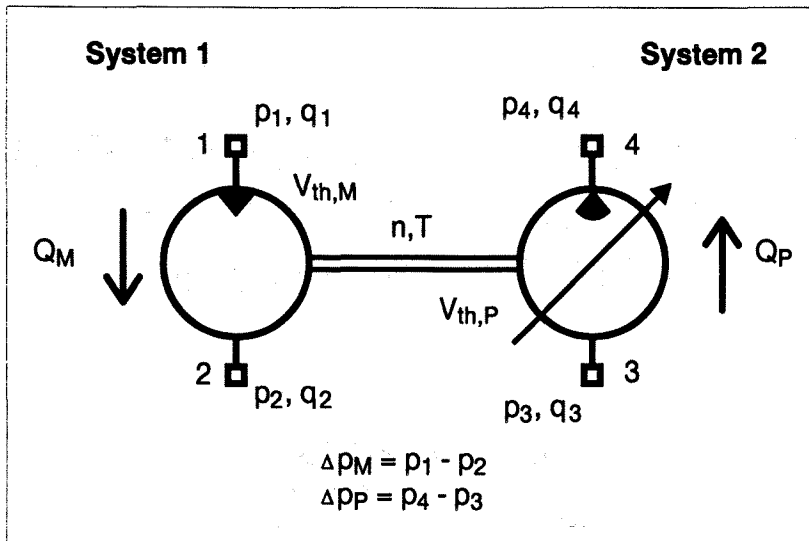


FIGURE 5 - Variable Displacement PTU Nomenclature

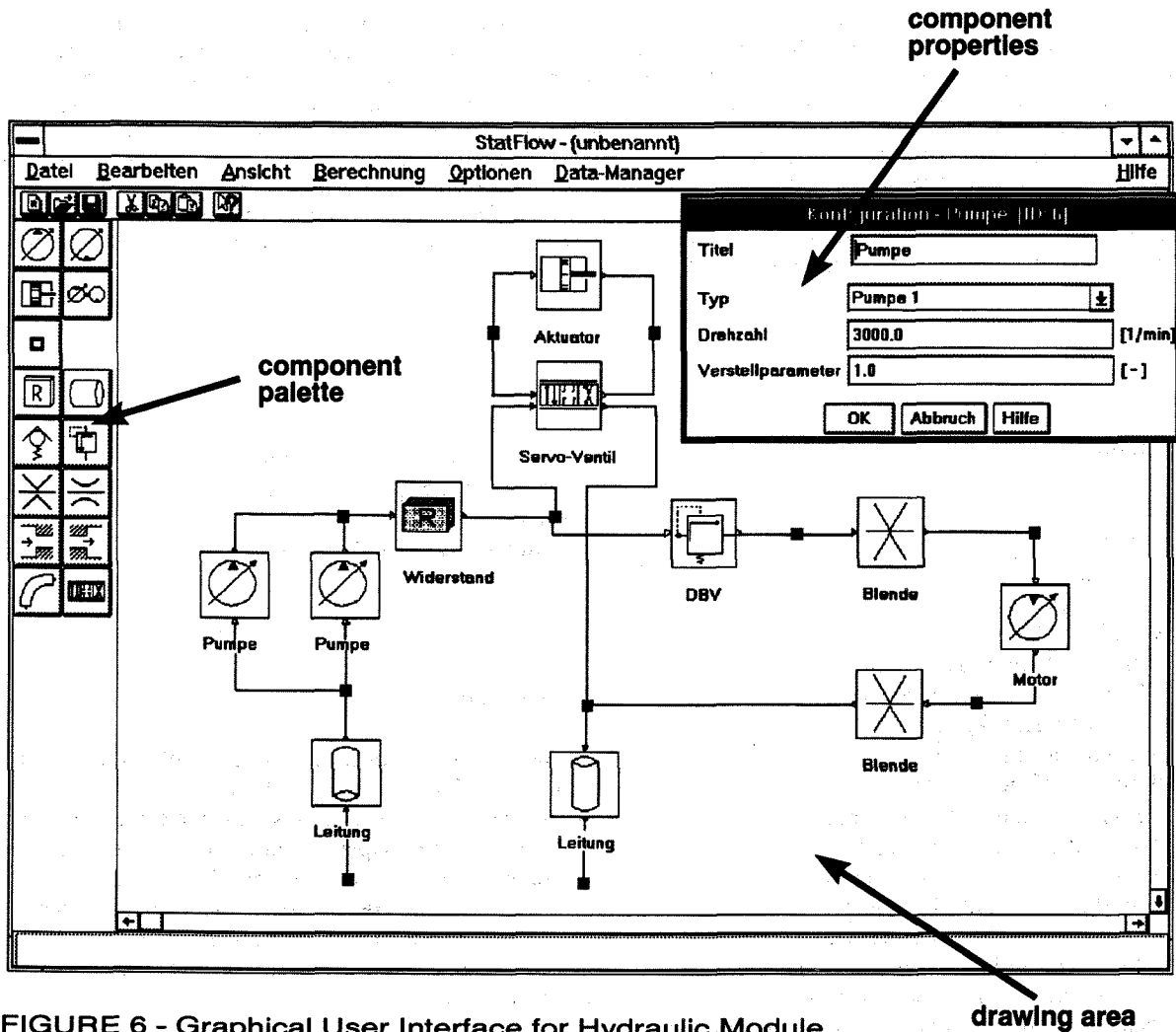


FIGURE 6 - Graphical User Interface for Hydraulic Module