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NEW COMPUTER-AIDED METHODS FOR PRELIMINARY ARCHITECTING AND SIZING OF AIRCRAFT HYDRAULIC SYSTEMS

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Abstract

Today's design of aircraft hydraulic systems is highly complex and can hardly be handled without software-based assistance. In this paper the concept and first realization of a computer-aided tool for preliminary architecting and sizing of aircraft hydraulic systems is described. First the general preliminary design process is discussed. The process is used for developing a tool concept. Second the model-based system design approach which is supported by knowledge-based methods is explained. Furthermore, it is shown how the general concept and modeling is realized in the ArOLab (Architecture Optimization Laboratory) tool. This includes the user interface, the computation methods and the key performance determination. Finally, the results are discussed and further goals are explained.

1. INTRODUCTION

Generally today's system design is often characterized by an increasing amount of functions, cost pressure and shorter development cycles. This is also the case in the design of aircraft hydraulic systems. The multiple interfaces to other aircraft systems like landing gear, engine, flight controls and the various operating conditions and failure cases result in a highly iterative process. Additionally, there are strict system requirements regarding operability, maintainability, mass and costs. The uncertainty of parameters and changes of requirements lead to the fact that this process has to be done in multiple loops. Thus a manual architecting, sizing and evaluation of different system architectures is time consuming and error-prone. These circumstances can result in a follow-up of unsuitable system solutions, which cause large design loops and therefore high development costs. Furthermore, the usage of a non-optimal system in the aircraft is very probable due to the lack of early and objective evaluation. Thus a computer-aided assistance even in the early design phases of aircraft hydraulic systems seems to be essential.

Today an Excel based tool is used for this task. This tool is based on a stationary approach for flow and pressure computation along the high and low pressure lines. Although this approach seems to be sufficient in computation time and accuracy the tool lacks quality regarding user interface, data exchange interfaces and modeling time. Especially changes in architecture design are time consuming and error-prone. Additionally, it does not supply the computation with uncertain parameters, which are often present in the preliminary design stage. In [1] the development of the hydraulic system design tool ICaRos is described. The tool, however, has a broader approach and its main focus is the design of flight control systems.

Hence, the concept and first realization of a computer-aided tool for preliminary architecting and sizing of aircraft hydraulic systems will be described in this paper. The tool named ArOLab (Architecture Optimization Laboratory) uses a model-based system design approach, which is supported by knowledge-based methods. ArOLab is inspired by the tool WissBaSys, developed at the Institute of Aircraft Systems Engineering of the Hamburg University of Technology for the preliminary design of aircraft high lift systems, in which these methods were implemented successfully [2].

2. GENERAL PRELIMINARY DESIGN PROCESS

In FIGURE 1 the general preliminary design process of aircraft hydraulic systems is depicted. The particular phases of the process are described briefly in the next paragraphs.

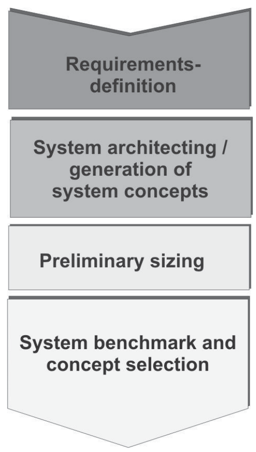

FIGURE 1: General pre-design process

2.1. Requirements Definition

The first phase describes the definition of system requirements. The requirements depend highly on factors like aircraft configuration, type of operation and general trends in system design. Most of the requirements result from flight control handling qualities. In this phase the preliminary number and type of hydraulic consumers are denoted and the corresponding data, if not already known from similar in-service aircraft, is gathered. The result is a list of system requirements.

2.2. System Architecting / Generation of System Concepts

During system architecting several concepts for the architecture of the hydraulic system are generated. For these concepts the number of individual systems, pumps and individual consumers are defined under various restrictions and influences shown in FIGURE 2. This definition is highly iterative and mainly based on the engineer's experience [3]. Often a basic system architecture is already induced due to safety requirements linked to flight control systems. The results of this procedure are several system concepts with all numbers and types of pumps chosen and the consumers allocated to the particular system. Additionally, data about pump and consumer locations are gathered in order to estimate the system's tube lengths. The system architectures and the handling qualities denoted in the requirements are used in the next step to pre-size the individual concepts.

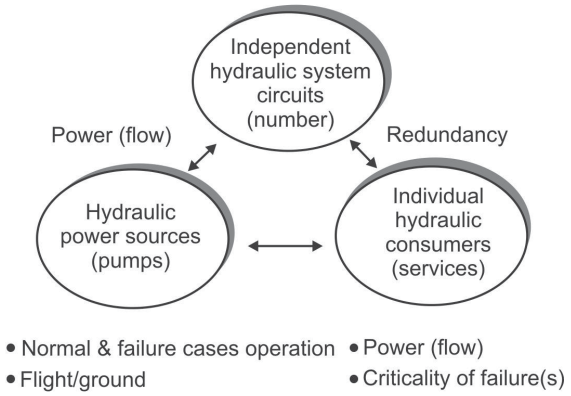

FIGURE 2: Considerations to system architecting [3]

2.3. Preliminary System Sizing

The main goal of system preliminary sizing or pre-sizing is the calculation of key performance parameters for the developed concepts. These are the basis of an objective evaluation and the selection of the best concept. A secondary objective is the creation of a data fundament for further analysis in later development phases, like dynamic or thermal simulations. The sizing process is mainly based on the adherence to consumer differential pressure and fluid velocity limits.

Today a static approach is used for preliminary sizing of aircraft hydraulic systems. For this approach the pipe lengths and handling qualities have to be extracted from the system concepts and the general requirements. These values can be used to determine the flow of all consumers in all flight cases at the available pump speeds. Knowing the demanded consumer flow it is possible to calculate the flow through every pipe for high and low pressure of an individual system by summing from the consumers to the pump, like shown in FIGURE 3. This is typically done straight-forward based on the branch-type design of aircraft hydraulic systems.

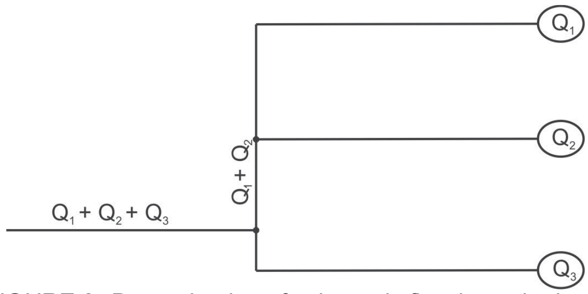

FIGURE 3: Determination of volumetric flow in each pipe

If the flow through the pipes is determined a first sizing of pipes and pumps can be conducted. Starting with all pipes at the minimum available diameter the diameters are increased until the fluid velocity in every pipe for all operating points of the system is within particular limits. Also the size of the pump can be determined. Knowing the maximum flow, the pump speed and assuming the value of the pump's internal leakage, the minimum required pump displacement can be calculated.

The system pre-sizing by consumer flows can be used to perform the second design step based on the minimum differential pressure of the consumers. Beginning at the pump the particular pressure losses of all pipes leading to a consumer are calculated for every flight all possible failure cases of the system. By subtracting the pressure losses from the nominal pump outlet pressure, the pressure at the consumer port can be derived. The same can be done for the low pressure lines starting at the reservoir assuming a constant reservoir pressure. The individual pressure losses of the pipe are determined regarding the pressure loss of the tube itself and the singular losses of e.g. elbows. The effect of singular losses is estimated per meter tube length [4]. The friction factor λ is determined via the Reynolds number regarding the temperature and pressure dependence of the fluid. With the pipe length l, the tube diameter d and the fluid velocity v it is possible to determine the stationary pressure loss of every tube for every operating point. By subtracting the pressure at high and low pressure port of the particular consumer, as depicted in FIGURE 4, the available differential pressure can be calculated.

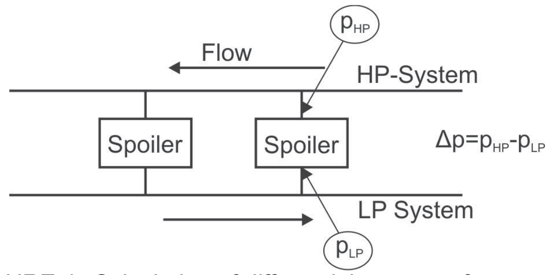

FIGURE 4: Calculation of differential pressure for consumers [4]

If the differential pressure is under a certain minimum the tubes guiding to the consumer have to be resized. Which and how many tubes have to be enlarged to meet the limitations has to be determined by the engineer [5]. Since the temperature of the fluid has a major influence on the pressure loss, the system has to be checked at the minimum nominal performance temperature. If this second sizing step is done the system is fully pre-sized. On the basis of the pre-sized system the key performance parameters of the system can be calculated. This data is used in the next phase to evaluate the pre-designed system concepts and select the best concept.

2.4. System Benchmark and Concept Selection

In this phase the pre-sized concepts are evaluated by criteria, which are mainly derived from the requirements list. These criteria can be system mass, power consumption, fluid amount, first costs, direct maintenance costs and operational interruptions. The type of benchmark can vary, but it is clear that a pre-sizing of the system concepts is needed for an objective evaluation. The more data of the concepts can be generated in early design phases the more dependable is the evaluation process. This reduces the risk of selecting an unsuitable concept.

3. GENERAL CONCEPT OF AROLAB

Based on the described process the desired structure of ArOLab is defined. Additionally, the tool should comply with several general approaches which are described in the next paragraphs.

3.1. Model-based System Design

One major objective of ArOLab is the model-based pre-design of aircraft hydraulic systems. While in later design phases the model-based approach is used widely and by various engineering disciplines, the pre-design is often done manually or with the assistance of a spread-sheet program. Due to the various components and functions of aircraft hydraulic systems the usage of model-based methods seems to be promising even in early system design phases.

The goal of this approach is the generation of an overall system model out of particular component models. These component models can be used for different system concepts, which reduces time for modeling and parameter definition. The system models should use a stationary computation approach for flow and pressure as this is implemented successfully in the Excel-based tool used today. Additionally a model for key performance parameters like masses, reliability or costs is necessary. This should be based on the particular component models and combined to an overall system key performance determination.

3.2. Knowledge-based Methods

Another general approach is the usage of knowledge-based methods in component and system modeling. The goal is to bring the engineers experience into the modeling and sizing process. Especially in preliminary sizing this approach seems to be promising since many parameters are uncertain or completely unknown. The knowledge can be used for parameter estimation and making sizing decisions even in the high degree of uncertainty in early design phases. This can be achieved by a strict separation of parameters and constraints. Constraints can represent physical relations, sizing algorithms or heuristic sizing rules between different parameters. It should be possible to implement these constraints into the component and system modeling in order to achieve fast and efficient sizing. Additionally, the parameter uncertainty itself should be modeled. It should be possible to bring the engineer’s parameter knowledge even if it is uncertain into the component and system modeling. Therefore modeling techniques which allow the computation with parameter intervals should be chosen.

3.3. Toolchain Integration

Another general objective of ArOLab is to be part of an integrated toolchain for hydraulic system design. Thus different interfaces to other tools are required in order to prevent time consuming and error-prone remodeling and re-entry of data. The manual data input should be minimized. Therefore an import function for component and parameter data is needed. Additionally, a system model export is aimed. The system model structure and its sized and chosen parameters should be exported for detailed simulations with different tools in later design phases.

3.4. User interface

In order to handle the numerous components of aircraft hydraulic systems a clear user interface is favourable. The architecture and its components have to be visualized. Quick changes in design and parameters shall be possible. The results of the system computation and the sizing process needs to be post-processed and depicted. Furthermore, a visualization of the systems key performance should be possible.

In FIGURE 5 the target structure of the ArOLab preliminary design tool is shown. The interfaces consist out of the import of requirements data, the architecture input of the user, the key performance computation and the system model export. The tool itself is mainly grouped into the objects modeling library, computation function, sizing function and calculation of system values.

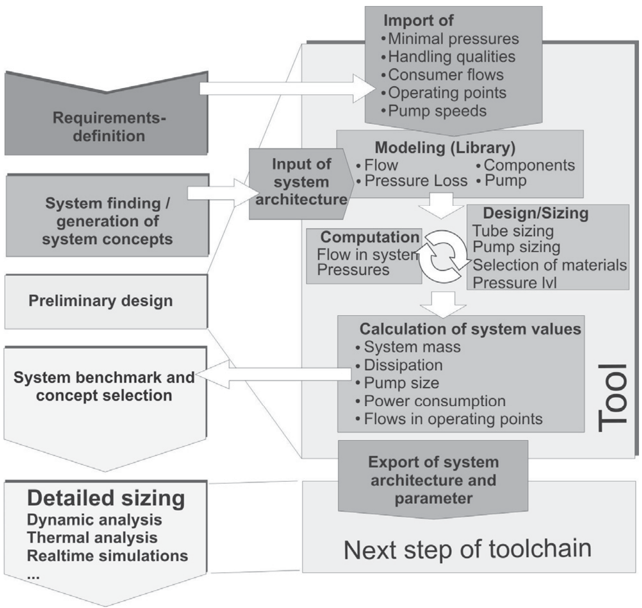

FIGURE 5: Target structure of a hydraulic system pre-design tool

During the project, different tools were examined in order to derive calculation methods that are adequate for the tasks of the new ArOLab tool. The tool WissBaSys which is used for the preliminary transmission design of aircraft high-lift systems offers due to its stationary computation approach, its generic buildup and the interfaces for data import and model export, a promising basis for ArOLab. In the next section the general approach of ArOLab is shown.

4. SELECTION OF USER INTERFACE, MODELING AND COMPUTATION APPROACH

The modeling and computation in ArOLab can be grouped into the system and component modeling and the key performance determination. The data derived in the computation can be used for the actual sizing process of tubes and pumps. Also a determination and visualization of the concept's performance data is possible.

Since the stationary computation of flow and pressure in hydraulic system pre-design were applied successfully in the Excel-based tool, this approach is also implemented in ArOLab. This computation method seems to be fast and accurate enough for a preliminary design and reduces the complexity of the system model and the effort for data input in comparison to e.g. dynamic models [1][4].

One of the main points in the requirements for ArOLab was to build a suitable user interface, which is described in the next section.

4.1. User Interface

In order to handle the numerous components of aircraft hydraulic systems a suitable user interface with an architecture visualization, a graphical component library and a structured visualization of sizing and computation results was created. The user interface is shown in FIGURE 6.

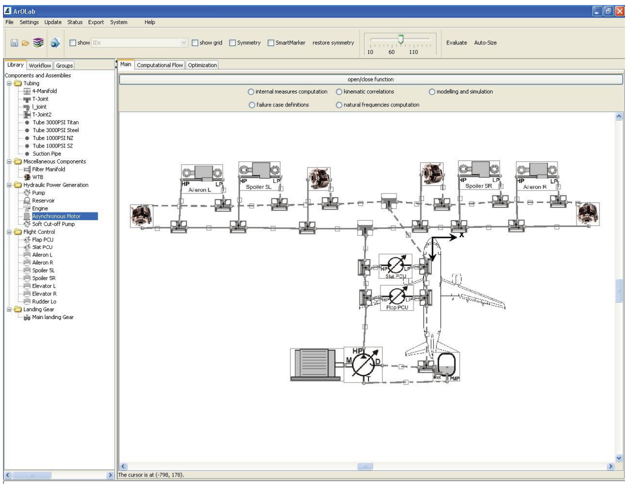

FIGURE 6: User interface of ArOLab

A graphic component model library is arranged on the left side of the tool's window. Here, component models can be created, grouped into model folders, filled with parameters and equations as well as visualized by referring component pictures. The library is the main area for component modeling, which can be used for building up different architecture concepts. The workspace of ArOLab is depicted on the right side. In this area the system model can be created by placing and connecting component models out of the library into the workspace via a drag-and-drop function. The models are visualized by the referred pictures. Thus a structured and self-explanatory graphical architecture representation is possible. Changes in modeling and parameters can be undertaken in the particular component dialog shown in FIGURE 7 for the example of a tube component.

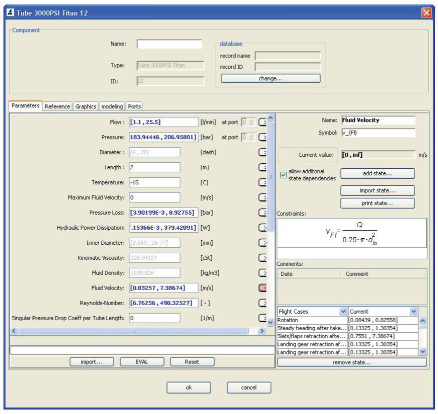

FIGURE 7: Component dialog in ArOLab

Inside the dialog it is also possible to visualize computation results in diagrams, like shown in FIGURE 8. In this example the flow at a pump's outlet port is shown on the y-axis and the system states are at the x-axis. Additionally, it is possible to export the chart into a pdf-file.

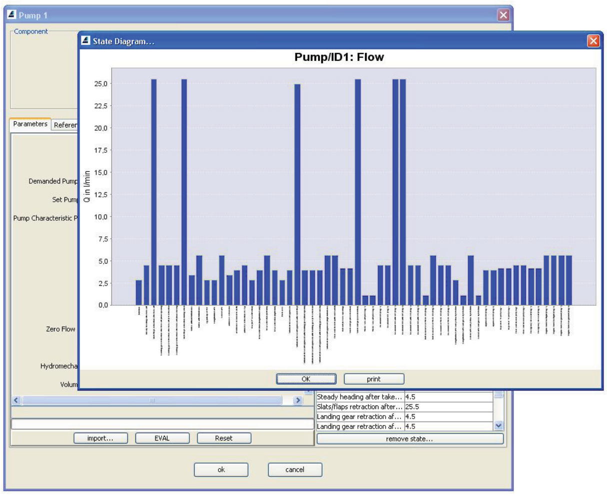

FIGURE 8: Example of a diagram created in ArOLab

Furthermore, there are features like different graphical representation of high and low pressure tubes, direct indicating by coloured markers if specific constraints are not met and the direct visualization of system parameters for a fast sizing and error detection.

4.2. Component Modeling and Computation

The component modeling consists of the internal parameter computation and the modeling of transmission behavior. The internal computation uses constraint propagation techniques, which are described briefly in the next paragraph.

4.2.1. Constraint propagation

A constraint describes the dependencies and restrictions between objects [6]. In ArOLab these objects are the different parameters of a component. The connection of all constraints is the constraint net. The target in the design process is to meet all restrictions in such a way that the constraint net is satisfied [7]. The method of constraint propagation used in ArOLab has not the goal to find a solution for the constraint problem but reduces the solution space of the involved parameters. This is done by using interval constraint satisfaction methods, in which only the upper and lower bounds are checked for consistence, e.g. the possible upper and lower bound for the tube diameter. The bounds are checked with the help of interval arithmetic. The constraint propagation is very suitable for problems with many uncertain parameters and strong dependencies due to its fast reduction of solution space. The usage of interval arithmetic offers the possibility to work with uncertain knowledge. The constraint propagation is based on algorithms used in WissBaSys [2][8].

4.2.2. Tube Modeling

The stationary flow transmission behaviour of a tube with the two Ports *0* and *1* is defined by the continuity equation

(1) $$\sum Q_i = 0.$$

It is defined, that the flow into a component is positive and out of a component is negative. The pressure transmission behaviour can be determined with

(2) $$p_0 - p_1 = p_l \cdot sgn(Q_0)$$

where p_0 and p_1 are the pressures at the particular ports, Q_0 is the flow at Port *0* and p_l is the pressure loss along the pipe. The pressure loss is computed internally in the component. The basis for the pressure loss calculation is the determined flow *Q* through the tube and the calculation of fluid velocity with

(3) $$v = \frac{Q}{0.25 \cdot \pi \cdot d_{in}^2}$$

whereas d_{in} is the internal diameter of the tube. Furthermore, the viscosity *ν* and density *ρ* of a hydraulic fluid is determined by analytic equations. Thus the density and viscosity of the fluid is known for temperatures between -15 and 100 degrees Celsius and pressures between 1 and 350 bar.

Also the Reynolds number for pressure loss calculation is determined with

(4) $$Re = \frac{v \cdot d_{in}}{\nu}.$$

The Reynolds number is used for friction factor calculation for laminar and turbulent flow through the tube,

(5) $$\lambda_{lam} = \frac{64}{Re},$$

(6) $$\lambda_{turb} = 0.3164 \cdot Re^{-0.25}.$$

It has to be noticed that the Reynolds number in aircraft hydraulic system tubes are normally small enough to neglect the tube's surface roughness. To model a continuous transition between laminar and turbulent flow the approach

(7) $$\lambda = \lambda_{lam} \cdot (1 - \alpha) + \alpha \cdot \lambda_{turb}$$

described by [9] is used. The factor *α*, which becomes zero for laminar flow and one for turbulent flow can be determined with

(8) $$\alpha = exp(-exp(0.0033 \cdot Re - 8.75)).$$

Thus the linear pressure drop of a general tube can be calculated with

(9) $$p_l = \frac{\rho}{2} \cdot v^2 \cdot \left(\lambda \cdot \frac{l}{d_{in}} + \zeta\right)$$

whereas *l* is the constant length of the tube and *ζ* is the factor describing the resistance of singular pressure losses. The factor is derived from experiments and given as statistical data per meter tube length depending on the application area.

4.2.3. Pump Modeling

The pump component model has three ports, which represent pump inlet, outlet and case drain port. For each port the parameter of flow and pressure are defined. The flow at the pump's outlet Q_{out} which is determined during system computation is used for pump sizing. With the equation

(10) $$V = \frac{Q_{out}}{n \cdot \eta_{vol}}$$

it is possible to calculate the demanded pump displacement *V* for each flight case with the outlet flow Q_{out}, the pump speed *n* and the volumetric efficiency η_{vol}. The maximum demanded displacement can be used for pump sizing. This is done by setting the maximum pump displacement V_{Set} to a chosen value larger than the demanded displacement.

Depending on the demanded flow for the specific flight cases the pressure at the outlet port may vary due to the pump's flow – pressure characteristic. For an engine driven pump the outlet pressure can normally be modeled by a linear decline of outlet pressure for increasing flow. However, this approach does not take the dependency of pump speed and flow into account. Since a characteristic line of demanded pump displacement and outlet pressure does not depend on the pump speed, the demanded and set pump displacement is chosen to model the outlet pressure in ArOLab. With the equation

(11) $$p_{out} = p_{zero} - k \cdot \frac{V}{V_{set}}$$

the pump outlet pressure p_{out} can be calculated with the demanded displacement *V*, the maximum displacement V_{set}, an characteristic factor *k* and the zero flow pressure p_{zero}. The factor *k* describes the decline of outlet pressure from zero to maximum flow. This equation is only valid if the set displacement is larger than the demanded displacement.

With the help of inlet and outlet pressure the load pressure of the pump can be derived with

(12) $$p_{load} = p_{out} - p_{in}.$$

The load pressure can be used to determine the demanded torque *M* with the hydro-mechanical efficiency η_{hm} and the demanded displacement *V* by

(13) $$M = \frac{V \cdot p_{load}}{2\pi \cdot \eta_{hm}}.$$

Also it is possible to calculate the shaft power of the pump P_w with

(14) $$P_w = 2\pi \cdot n \cdot M.$$

The dissipation P_l can be determined by

(15) $P_l = P_w - p_{load} \cdot Q_{out}.$

The pump's inlet flow Q_{in} can be calculated with

(16) $Q_{in} = \frac{Q_{out}}{\eta_{vol}}$

and depends on the demanded outlet flow Q_{out} and the volumetric efficiency η_{vol}. Both, the hydro-mechanical efficiency η_{hm} and the volumetric efficiency η_{vol}, are considered to be constant. The internal leakage flow of the pump is calculated by

(17) $Q_{leak} = Q_{in} - Q_{out},$

which is also the equation for the case drain port flow. The hydraulic system's pressure level of 3000 or 5000 psi can be adapted by changing the parameter of nominal pressure at zero flow p_{zero} and the specific pressure drop factor k in (11).

4.2.4. Consumer Modeling

The consumer components build the foundation of the flow computation in the system. The consumers include components like spoiler, aileron, main landing gear and rudder actuators. They can be classified into two groups, the consumers for which the demanded flow is defined directly, like flap/slat PCU motors or main landing gear actuator, and the consumers for which the flow is determined via the deflection rate and a flow factor.

The consumer components have two ports for high and low pressure line connection at which the port parameter of flow and pressure are set. The flow and leakage are defined for every particular flight case. The differential pressure Δp of a consumer is calculated by

(18) $\Delta p = p_{HP} - p_{LP}$

with the pressures p_{HP} at high and p_{LP} at low pressure port. If this pressure is under a certain minimum it is necessary to increase the tube diameters of the lines guiding to the consumer. For the system's flow calculation the flow values

(19) $Q_{HP} = Q + Q_{leak},$

(20) $Q_{LP} = -Q - Q_{leak}$

with the demanded consumer flow Q and the leakage flow Q_{leak} are used at the ports. While in some components the demanded flow is part of the handling qualities, in many flight control actuators the demanded deflection rate is given as a requirement. The deflection rate can be used to calculate with

(21) $Q = k_{flow} \cdot \dot{\delta}$

the demanded consumer flow Q. The flow factor k_{flow} represents the actuators lever arm and size. The demanded deflection rates are normally defined for every flight case. This linear approach between deflection rate and flow makes simplifications like assuming a constant lever arm, but seems to be sufficient for preliminary system sizing.

4.3. System Modeling and Computation

For hydraulic system modeling a stationary flow of the fluid is assumed. The demanded consumer flows and the pressures at pump outlet and reservoir can be treated as constants in a specific operating point. Due to the branch-type network design of aircraft hydraulic systems the flow through each component can be calculated by a simple linear equation system. The differential pressure at the consumers can be determined by summing the pressure losses in each tube guiding to the consumer and subtracting them from the constant pump outlet and reservoir pressure.

While in the Excel-based tool a recursive algorithm for solving flow and pressure equations in each line is used in ArOLab a linear equation system is generated once and then solved parallel for each flight case, component and port parameter.

4.3.1. Generation of Equation Systems

The system modeling is done via connection of component models. The component modeling can be grouped into an internal computation, mainly described in the previous sections, and a transmission behavior between the component's ports which is relevant for the generation of the system computation function. Due to the generic structure of ArOLab the internal computations and the transmission behavior can be chosen freely by the engineer. In the case of aircraft hydraulic systems the transmission variables or port parameters are flow and pressure. For each distribution component the sum of all flows at the ports and the demanded internal flows is zero. The flow at a port is positive if it is directed into the component and negative if it is directed out of the component. Assuming a vector q, which lists the port parameters of flow at all component ports,

(22) $q = \begin{bmatrix} Q_0 & Q_1 & Q_2 & \ldots & Q_n \end{bmatrix}^T,$

and the vector b, which lists all flows which are not part of the port parameters like the demanded flows at the particular component ports,

(23) $b = \begin{bmatrix} Q_{dem,0} & Q_{dem,1} & Q_{dem,2} & \ldots & Q_{dem,n} \end{bmatrix}^T,$

and a matrix A, which describes the continuity equations between the port parameters, the equation

(24) $A \cdot q = b$

can be determined. The same can be done for the pressure calculation regarding the vector p of the port parameter pressure for all components,

(25) $p = \begin{bmatrix} p_0 & p_1 & p_2 & \ldots & p_n \end{bmatrix}^T,$

and a vector $d(q)$

(26) $d(q) = \begin{bmatrix} p_{l,01} \cdot sgn(Q_0) & p_{l,12} \cdot sgn(Q_1) & \ldots & p_{l,nn+1} \cdot sgn(Q_n) \end{bmatrix}^T$

of all pressure losses between two ports and the vector h,

(27) $h = \begin{bmatrix} p_{ext,0} & \ldots & p_{ext,n} \end{bmatrix}^T,$

of all external pressure levels, like reservoir or pump pressure. The vector $d(q)$ depends on the flow distribution in (24). Equivalent to (24) an equation system with a Matrix B which denotes the connections between the port parameters can be found describing the pressure distribution in the hydraulic system by

(28) $B \cdot p = d(q) + h.$

4.3.2. Solving of Equation Systems

Regarding the flow dependency of the pressure distribution, the flow computation has to be undertaken prior to the pressure calculation. By multiplying the equation (24) with the inverted Matrix A^{-1}, the flow at every port can be determined with

(29) $$q = A^{-1} \cdot b.$$

Usually using a gaussian elimination instead of inverting the matrix *A* would be more effective, but since this method offers the possibility to calculate the equations for all port parameters symbolically and then solve the equations for every port parameter and every state parallel the overall system computation time is reduced.

After solving the flow equation system and calculating the pressure losses for each tube in the component models with (9) the pressure computation is started. For this the same method of inverting the connection matrix *B*, solving the equation system

(30) $$p = B^{-1} \cdot (d(q) + h)$$

symbolically and parallel computing for every port parameter and state is used. In practical use these methods fit efficiently into the modeling framework of ArOLab, comply with the use of interval arithmetic and uncertain knowledge and are efficient considering computation time.

4.3.3. Implementation of Flight Cases

The preliminary design of aircraft hydraulic systems has to cope with a complex set of handling qualities, requirements, failure cases and other constraints. This results in many flight cases or system states which have to be considered for system sizing. Therefore, it is possible to define global system states in ArOLab. These states offer the possibility to implement state depended parameters and thus model e.g. the different demanded deflection rates of a consumer for each flight case. The constraints or equations between these parameters are independent of the states. Thus a modelling, which regards all different flight cases in one equation, is possible. A sizing or key performance determination is possible on basis of e.g. a minimum or maximum value in one of the flight cases. In FIGURE 9 the state dialog is depicted. It is also possible to import a set of system states from an Excel file

FIGURE 9: State dialog in ArOLab

4.4. System Sizing

The system sizing is based on the pressure and flow computation. The pump sizing depends mainly on the required flow calculated in the flow computation and the pump speed which may be variable in case of engine driven pumps. With (10) a sizing of the pump displacement is possible, but regarding (11) it must be noted that the pump outlet pressure may decline in high demanded flow states.

The tube sizing is based on two requirements. First the fluid velocity in a tube must not exceed certain limits for high and low pressure lines. This results directly in a reduction of possible tube diameters. This requirement is used for an automatic-sizing function which uses a combination of a tube data table with finite values and the constraint propagation denoted in section 4.2.1. Thus the first sizing of all tubes is automatically done by this function in ArOLab.

The second sizing is based on the minimum consumer differential pressures. For all flight cases certain limits of differential pressure depending on the consumer type must be ensured. If the differential pressure between high and low pressure line falls below this limit the tube diameters of the tube guiding to the consumer must be enlarged in order to reduce pressure losses in the pipes. Since this criterion can not be used to size directly particular tubes, the engineer itself has to do this task. In future an optimization function is planed for a complete auto-sizing of the system regarding both criterions.

4.5. Key Performance Determination

If the system is completely sized, the determination of key performance parameters, which can be used for evaluation of different system concepts, has to be undertaken. In this section the overall mass and overall dissipation calculation and its implementation in ArOLab is explained.

The mass of a hydraulic power generation and distribution system can be grouped into the mass of the components and the mass of the tubes. The tube mass can further be grouped into the tube dry mass, the mass of clamps and fittings and the mass of the fluid inside the tube. The component masses are given by internal component parameters and are defined by the engineer itself.

The tube masses depend on the length of the tube and its diameter. Depending on the diameter it is possible to compute factors which describe the particular mass per length. These factors are available in the form of tables. With the particular diameter chosen for a tube, the dry tube mass per length k_{dry} can be extracted from the table and thus the mass can be calculated with

(31) $$m_{dry} = l \cdot k_{dry}.$$

Next the fitting mass is calculated. The statistic fitting mass factor k_{fit} which describes the fitting mass per length and for different tube sizes is used in (32) to estimate the overall fitting mass of a tube.

(32) $$m_{fit} = l \cdot k_{fit}.$$

For the clamp mass calculation statistic data for the number of clamps per tube meter n_{cl} and the mass of one clamp for the particular tube diameter m_{cl1} is used. Thus the mass can be calculated by

(33) $$m_{cl} = l \cdot n_{cl} \cdot m_{cl1}.$$

So it is possible to determine the overall mass of dry tube, fittings and clamp for a tube with a specific length and diameter with

(34) $m_t = m_{dry} + m_{fit} + m_{cl}.$

The mass of the fluid is also computed with the help of a factor k_{fl}, which can be derived from the fluid density and the specific tube cross section for every diameter. So the mass of the fluid in a tube is determined by

(35) $m_{fl} = l \cdot k_{fl}.$

The tube and fluid mass calculation is also capable of working with length and diameter intervals to comply with the uncertain knowledge in preliminary design.

For the calculation of the overall system mass in ArOLab a global parameter function is used. In this function the summing of all single masses is implemented. This computation regards the component masses $m_{c,i}$, the masses of the tube, fittings and clamps $m_{t,i}$ and the masses of the fluid $m_{fl,i}$ with the equation

(36) $m_{sys} = \sum m_{t,i} + \sum m_{fl,i} + \sum m_{c,i}.$

In (9) the calculation of the particular pressure loss is described. Together with the flow through the tube a determination of the dissipation in each line for each flight case is possible. Also a global parameter is used to sum up all single dissipations in tubes and pumps. So the overall dissipation can be calculated as the sum of the dissipation in pumps $P_{lp,i}$, tubes $P_{lt,i}$ and other components $P_{lc,i}$ with

(37) $P_l = \sum P_{lp,i} + \sum P_{lt,i} + \sum P_{lc,i}.$

This value can be used for calculating the dissipation per system surface and thus to compare different system concepts according to their possible heat load.

5. CONCLUSIONS AND OUTLOOK

It was made clear that the numerous components and functions of aircraft hydraulic systems and its preliminary design process can only be handled efficiently with computer-aided assistance. Due to increased functionality the tools currently in use need to be improved. Therefore, the preliminary design process was analyzed and requirements for a hydraulic system architecting and sizing tool were defined. On basis of these requirements the tool ArOLab was developed, which uses a model-based system design approach, which is supported by knowledge-based methods and a suitable user interface for architecture visualization. The general user interface of ArOLab was explained and the methods for component modeling were described on basis of a general pump, tube and consumer model. The system modeling approach, based on stationary flow and pressure computation was shown. Additionally, the system sizing process and key performance determination were explained.

One main future goal for ArOLab will be an optimization of the system architecture. Therefore, first the sizing process will be treated. Here it is strived for an optimal sizing for pipe networks and pumps. The optimization criteria have already been identified but a suitable algorithm has to be found, implemented and tested for operability. The further integration of ArOLab into a new hydraulic system design toolchain is another main goal. For this objective the first step has already been made by implementing an import function for handling qualities and requirements data in ArOLab. For using the gathered system knowledge in later design phases a system model export is aspired. This should prevent time-consuming and error-prone remodeling of the system architecture for dynamic, thermal or realtime analyses. Additionally, further functions for improving the assistance during the design process are planned. Especially the post-processing of the sized system can be improved. Here the acquired data has to be processed to enable a fast evaluation and documentation and in general a better assistance to the design engineer.

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