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Optimal Conceptual Design of Aircraft Fuel Transfer Systems

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This paper describes early considerations that have to be made when designing an aircraft fuel system. Emphasis is placed on illustrating the impact of top-level aircraft requirements on low-level practicalities such as fuel system design. Choosing between concepts is one of the most critical parts of any design process. Different concepts have different advantages, and the concept that is the best choice is often dependent on the top-level requirements. This paper shows how optimization has been used successfully at Saab Aerospace as a tool that supports concept selection. The example studied is the design of a fuel transfer system for a ventral drop tank and the optimization results in different conceptual designs depending on the top-level requirements.

I. Introduction

IN the past, before the 1980s, new aircraft models were developed just a couple of years apart. Such short development cycles were common for both civil transports and military combat aircraft. In those days, there was no lack of experienced engineers in the prestudy phase of a new aircraft project. As the time between aircraft development projects gets longer, experienced personnel in the field of basic aircraft systems are difficult to find in the initial stages of a new design. Although well-educated engineers are available, lack of experience of aircraft supply systems is becoming an increasing problem. Furthermore, basic aircraft system design is a field that has been neglected both in literature and the educational system.

Making the right design decisions in the conceptual phase is vital to the success of any large design project. Conceptual analysis is considered by many to be the most important step in the design of a new product. Pahl and Beitz [1] state that "*In the subsequent embodiment and detail design phases it is extremely difficult or impossible to correct fundamental shortcomings of the solution principle. A lasting and successful solution is more likely to spring from the choice of the most appropriate principles than from concentration on technical detail*." Rectifying an error late in the design phase or during production can be 100 times more expensive than in the planning phase, and retrofitting a modification in an operational aircraft is extremely expensive. Methods that support engineers in making the right decisions during the early stages of a design project are therefore immensely valuable. Furthermore, it is important "*to extend the view of aircraft system design beyond the preliminary aircraft design level*" as stated by Scholtz [2]. The importance of aircraft system design is also motivated by the fact that in medium-range civil transport, systems account for about a third of the aircraft empty mass as well as a third of the development and production costs. The ratio is even higher for military aircraft.

Optimization is commonly used to support and speed up aircraft design. Traditionally, optimization has been widely used in disciplines such as structural engineering and aerodynamics, and recently also in the growing field of multidisciplinary design optimization [3–5]. The methods used range from analytical techniques to heuristic and stochastic search methods such as genetic algorithms, simulated annealing, and a great many more [6,7]. Approximation techniques such as response surface methods [8] and Kriging [9] are also frequently used. In this paper, the focus is on using optimization based on dynamic simulation models to support conceptual design of aircraft fuel systems, using a nongradient based optimization method, namely the Complex method [10].

This paper is organized as follows. Section gives a general description of aircraft fuel systems accompanied by a detailed description of different fuel transfer methods and the requirements stipulated for the systems. In Sec. III, a design example of a drop tank is presented including the modeling approach, the optimization algorithm used, and the problem formulation. The results of the optimization are presented in Sec. IV, and lastly Sec. V concludes the paper.

II. Aircraft Fuel Systems

Most aircraft fuel systems consist of several tanks due to structural, slosh, center of gravity (CG) management, or safety reasons. The tank configuration of the Saab fighter Gripen is shown in Fig. 1.

The general fuel system layout consists of one or more boost pumps that feed fuel to the engine from a collector tank (or engine feed tank), usually a fuselage tank placed close to the center of gravity. The collector tank is replenished by a fuel transfer system, pumping fuel from the source tanks. Source tanks may be other fuselage, wing, or drop tanks. The system may be pressurized to avoid engine feed cavitation at high altitude and to aid or provide means for the fuel transfer.

The fuel system complexity varies from the small home-built aircraft with low system complexity to the modern fighter, where the fuel system might be critical for CG reasons and therefore very extensive with triple redundancy. If pressure refueling is required, a refueling system of some complexity must be added as well. The fuel may also sometimes serve as a heat sink, which adds a subsystem for cooling. Some of the fuel subsystems that may be identified in a modern aircraft are: engine feed system, fuel transfer system, vent and pressurization system, refueling system, measurement and management system, cooling system, and explosion protection system.

Fuel transfer is defined here as moving the fuel from one tank to another. The target tank is usually the engine feed tank, that is, the tank from where the engine is fed. According to Gartenberg [11], there are two different approaches to fuel transfer. One is to provide a main tank from which all engines are fed and which is continuously replenished by the other tanks in the aircraft. The other is to provide separate fuel tank groups for each engine in multi-engine aircraft.

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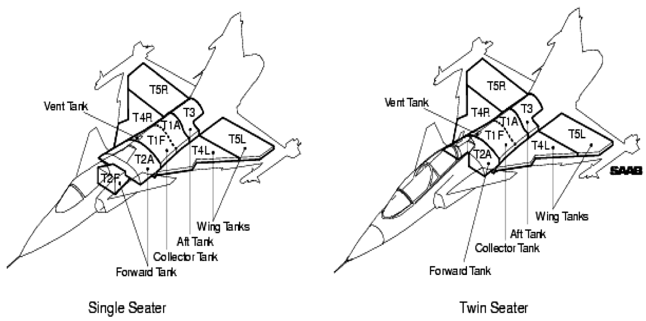

Fig. 1 Fuel tank configuration of Saab Gripen.

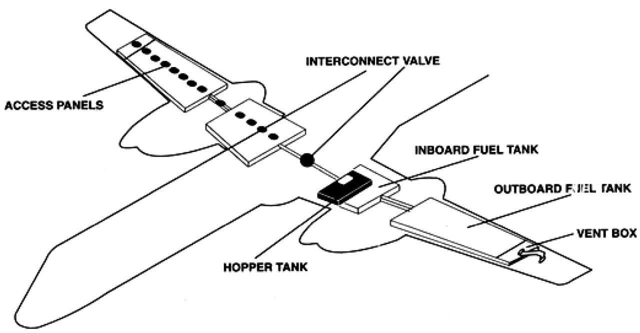

Fig. 2 Dihedral gravity transfer.

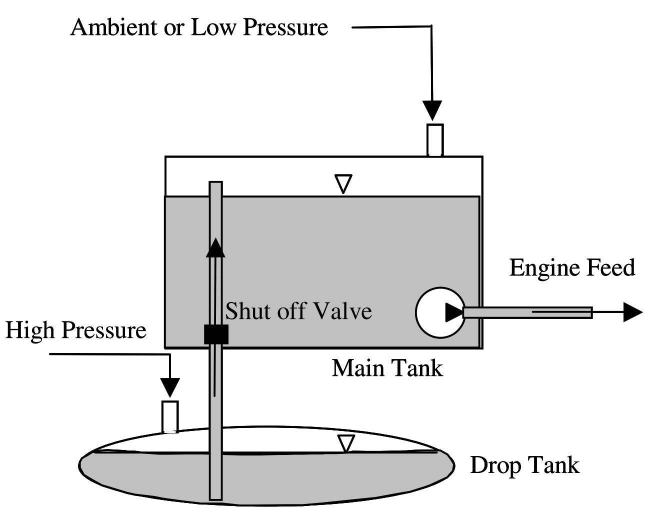

Fig. 3 Siphoning fuel from a drop tank hanging below the aircraft.

Another reason for moving fuel between tanks could be CG management, as stated by Raymer [12]. The example given by Raymer is MD11, where fuel is pumped to the horizontal tail to keep the CG at the aftmost limit while cruising. There are four methods of fuel transfer that differ in principle, according to Gavel [13].

A. Gravity Transfer

The simplest way of transferring fuel is with gravity. This method is used in general aviation and commercial aircraft dependent on tank configuration. The condition, of course, is that the target tank is located as a low point. An example of an aircraft with gravity transfer is Saab 2000, shown in Fig. 2, where the dihedral aids the transfer of the fuel from the outboard to the inboard tank.

B. Siphoning

A more complex transfer method is siphoning. A schematic example of fuel siphoning from a drop tank is shown in Fig. 3. The source tank is pressurized, thus pushing fuel to the target tank.

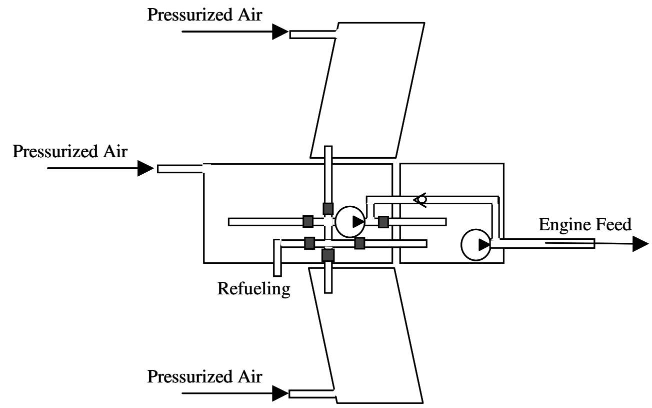

Fig. 4 Inline pump transfer system.

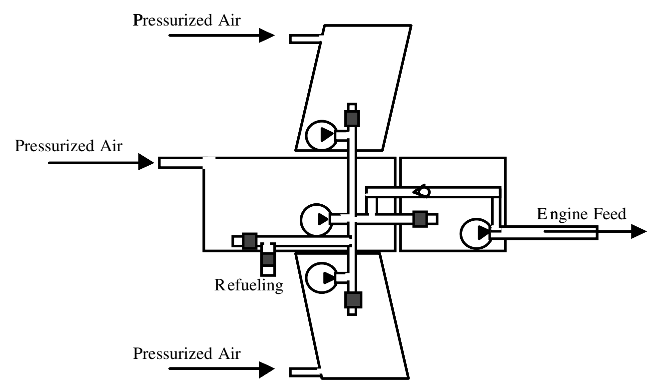

Fig. 5 Distributed pump transfer.

Siphoning obviously does not suffer from problems with cavitation (as pump systems very often do). One drawback, however, is that the tank becomes a pressure vessel which for reasons of stress is a determining factor for the structure weight. There is also the safety aspect to be considered when using a compressible fluid such as air or nitrogen at high pressure.

C. Inline Transfer Pump

In an inline system, a central pump sucks fuel from the transfer tanks. The pump creates the pressure that compensates for high load factors without the structural impact as in the siphon method. The main advantage with a centralized pump is that the same pump may be used for more than one transfer tank, which gives low weight and is advantageous in small aircraft where space is scarce. Another advantage is that it is possible to group components in an easily accessible area, which facilitates maintenance. The transfer pump can also serve as backup to the engine feed. The Achilles' heel of the inline pump system is cavitation, boiling and dissipation of dissolved air due to pressure loss in suction lines.

A schematic of a system with an inline transfer pump is shown in Fig. 4. Note redundancies such as engine backup and the possibility to siphon the fuel (if the main tank is depressurized) in case of transfer pump failure. Note also that it is possible to group the components.

When designing an inline pump transfer system, there is a great risk that transfer capacity will not meet requirements due to a high vapor/liquid (V/L) ratio in the pump suction line. In addition, a high V/L ratio also causes cavitation that may cause damage to the pump itself. Therefore, cavitation needs to be considered during conceptual design of any aircraft fuel system.

D. Distributed Pumps

To minimize problems with vaporization and dissolved air, the pump can be placed in the bottom of the transfer tank. An example of a system with distributed pumps is shown in the schematic in Fig. 5.

Distributed pumps are less sensitive to high altitudes than inline

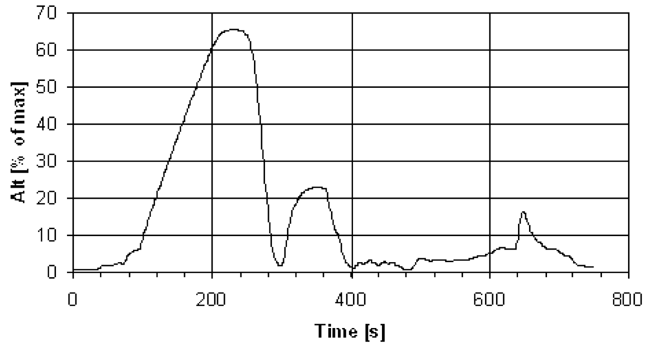

Fig. 6 Altitude as a function of time.

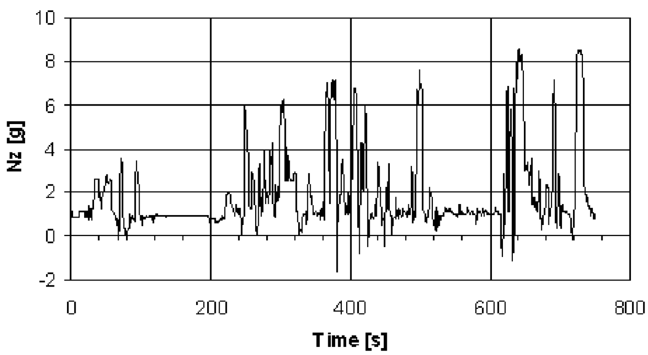

Fig. 7 Load factor as a function of time.

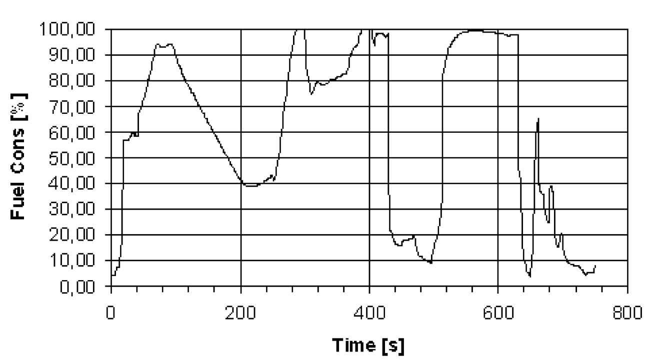

Fig. 8 Fuel consumption as a function of time.

pumps. In fact, the load factor actually increases the absolute pressure on the pump suction side due to fuel head. At high altitudes, however, some form of pressurization aid is still needed. The system may achieve a high transfer capacity, but it has the disadvantage of being heavy and maintenance is more complex due to the restricted access to the system components. There can also be a space problem in small high-density aircraft.

E. System Requirements

The complexity of the transfer system depends on the performance requirements set by the mission profile. An aircraft's mission profile is one of the most important factors when choosing the type of transfer system. If an unsuitable transfer system is chosen, the fuel system may become a limiting factor for flight operations, for instance with regard to tactical performance in the case of a fighter aircraft.

When determining the maximum transfer capacity, the rule is that maximum transfer capacity should always correspond to the maximum engine consumption in the entire envelope and under all operational conditions. "*The rate of fuel transfer into the engine feed tanks shall not limit air vehicle performance*" according to [14]. However, the same reference also states that there is a "*practical limit*." And so, the intended mission profiles permitting, the maximum fuel transfer may be lower than engine consumption at short periods of augmentation, high altitude flight, and a high or negative load factor. The length of such periods should be set in relation to total fuel content and time for replenishment.

The requirement factors at aircraft level that have the most significant impact on the transfer system are the following: engine consumption, load factor, altitude, temperature, and type of fuel. An example of how a mission profile may be presented to the fuel system designer, thermal operation excluded, is shown in Figs. 6–8.

In the development of the Saab Gripen transfer system, no less than 12 profiles were used in the trade study between different concepts. A serious problem during the prestudy phase is that the mission profiles are often very vague.

F. Summary of Transfer Methods

When choosing the transfer system, each tank should be analyzed separately with regard to desired mission profiles, but also to criteria such as cost, weight, power consumption, etc. A summary of the advantages and disadvantages of the three active transfer methods described above is shown in Table 1. Table 2 gives an overview of transfer methods used in different aircraft.

III. Design Problem

The design case used in this paper demonstrates how optimization can support the design of a fuel transfer system from a drop tank. A drop tank is fitted to a combat aircraft to extend its operating range. The aircraft has an existing inline pump system for fuel transfer from the wings and fuselage tanks. It would of course be beneficial if the existing system could also be utilized for the drop tank.

Three concepts are considered in this study: a hook up to the existing inline system, siphoning, and the existing inline system with pressure assistance, see Fig. 9. The unassisted pump (ambient pressure in the source tank) is lightweight and relatively low cost, but will most likely suffer from cavitation as altitude increases. The siphoning proposal is the opposite; high weight, high cost, but also high performance. The combination where the pump is aided by tank pressure in order to minimize cavitation, is somewhere in between as regards weight and performance. The concepts have to be assessed against the mission profile. Is the drop tank intended for ferry flight, ground attack or interception missions?

The top requirements that will influence the system design are

1) Flight altitude: As altitude increases, the formation of gases on the suction side of pumps will lower the fuel flow and may eventually damage the pump.

2) Turn rate: If the load factor n_z (the z component of the load vector) increases the fuel head will increase and the flow will decrease.

Table 1 Transfer methods

+	−
Siphoning	
Low weight	n_z dependent pressure level
Low cost	
Low energy consumption	Structural weight
Simple	
High flow at low n_z	
Compact	
Inline pump	
+	−
Compact	Cavitation at high altitude
Easy access possible	Cavitation at high n_z
Redundant engine feed	High V/L gives flow reduction
	Complex
Distributed pumps	
+	−
Cavitational resistance	High weight
Low V/L	High cost
Redundant engine feed	Complex
	Bulky

Table 2 Examples of transfer methods for different aircraft. Wing tanks are denoted by WT, fuselage tanks FT, and drop tanks DT

Transfer method	A/C model
Gravity transfer from WT	SAAB Trainer SK60 SAAB Commuter a/c 340 and 2000
Siphoning all tanks	BAE Trainer HAWK SAAB 35 Draken Dassault Mirage 2000 Convair F-106
Inline pump all tanks	SAAB Multi Roll Combat a/c 39 Gripen
Inline pump from FT and WT. siphoning from DT	SAAB fighter a/c 37 Viggen
Distributed pumps all tanks	Concord
Distributed pumps from FT and WT. siphoning from DT	MIG 29, F16, F18 Euro Fighter Typhoon

3) Engine fuel consumption: The higher the fuel consumption, the higher the demand on the transfer flow.

4) Thermal operation: The temperature will influence the gas formation; however, this is ignored in the present study. This is a valid assumption if operating in ISA (International Standard Atmosphere) with a kerosene-based fuel such as JP-8. If operating in a hot climate or using a wide cut fuel, the temperature will begin to have a significant impact on system performance.

A. Fuel System Modeling

The system was modeled in Easy5, which is a commercial program intended for system modeling using the power port technique. At first, the use of the existing Easy5 hydraulic components library was considered, but this proved impractical because it is intended only for liquid phase fluids. When modeling a pressurized fuel system in an aircraft, the components must handle both liquid and gas (fuel and air or inert gas). An old, in-house, FORTRAN code developed during the 1970s was reused and converted to fit Easy5. The conversion into Easy5 not only provided a graphical interface, but the modeling itself could then be done by dragging and clicking, which minimized the number of possible errors. The components are able to handle both fuel and air as illustrated in Fig. 10. The library also handles a varying two-dimensional load vector. The fuel and air library is described in Ellström [15,16].

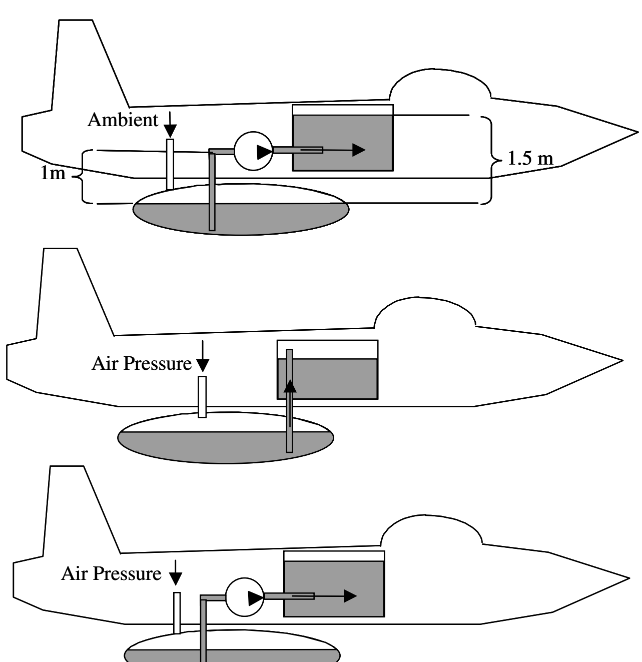

Fig. 9 Three concepts of fuel transfer systems. From the top, unassisted pump, siphoning, pressure-aided pump.

1. Modeling of Pump Cavitation

At pressure levels that are high relative to the vapor pressure level, the gaseous products consist mainly of air that has previously been absorbed by the fuel. At pressure levels approaching the vapor pressure, the gaseous products are primarily volatile components of the fuel. A method for V/L ratio determination is described in Gartenberg [11]. However, determination of the V/L ratio is difficult and computationally heavy and therefore not practical in the conceptual phase when there may be a great many concept proposals and the system information is subject to a high degree of uncertainty. An effort has therefore been made to develop an approximate method more suitable for conceptual design.

A test with an inline transfer pump was performed to investigate flow reduction as a function of tank pressure. The test setup is outlined in Fig. 11 and the results of the test are shown in Fig. 12. The pump was run with constant power while the pressure inside the tank was lowered. Pump pressures on both sides are plotted against fuel flow.

The test was performed with JP8, which is a kerosene-based fuel with a low true vapor pressure. This implies that it is dissolved air rather than boiling that causes the flow reduction. From the diagram, the following assumptions were made: If the suction side pressure is greater than 70 kPa (obtained by extrapolation of the curves until the

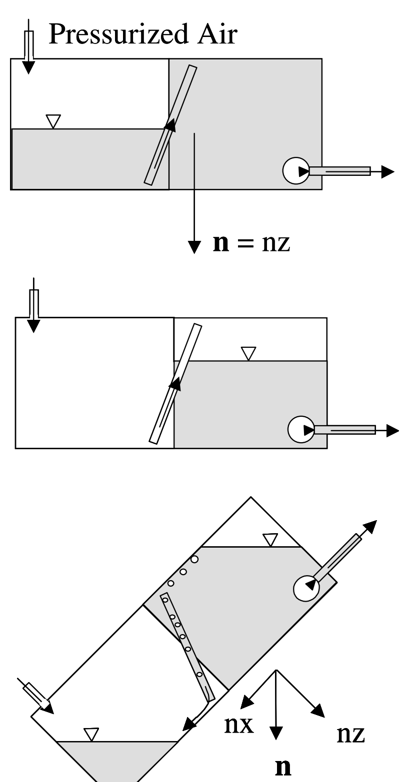

Fig. 10 Illustration of components that can handle not only the fuel and air combination but also a 2-D load vector.

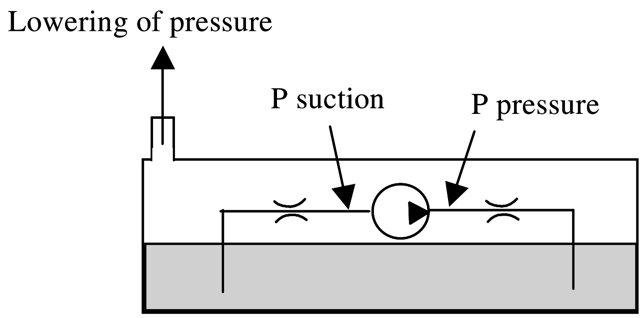

Fig. 11 Test rig for flow reduction test.

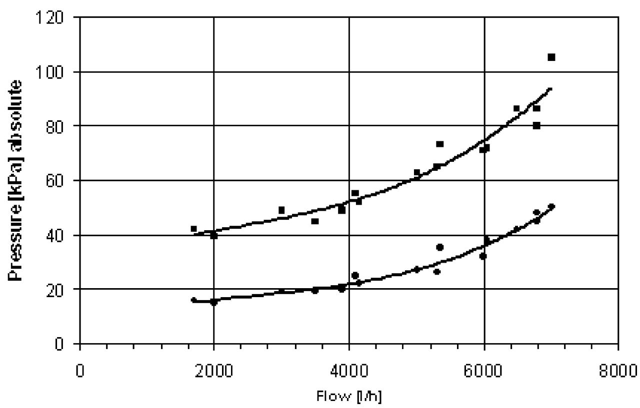

Fig. 12 Flow reduction versus pressure.

pressure side reaches atmospheric pressure) the flow is unaffected, and if the suction side pressure is 17 kPa or below the flow is interrupted. The slope between these two points is assumed to be square. With those assumptions, a pump output reduction factor R is defined according to Eq. (1).

$$R = \left(\frac{p_{\text{suction}} - 17}{70 - 17}\right)^2, \qquad 0 \le R \le 1 \tag{1}$$

The pump output is then reduced by the R factor, so that if R equals 1 there is no significant gas formation and the pump output is unaffected. If the R factor equals zero the fuel flow is zero due to extensive gas formation.

B. Optimization Method

There are basically two families of optimization methods used in engineering, namely gradient and nongradient methods. The gradient methods are widely used and are suitable for problems where the gradient of the object function can be calculated explicitly at each point. This is the case in many structure optimization applications. The nongradient methods, on the other hand, do not rely explicitly on gradient information at each point. These methods are therefore of more general use, because gradient information is not generally available, especially if parts of the object function are evaluated using a simulation model of a nonlinear system. A modified version of the original complex method [10] has been found to be one of the simplest and most easy to use methods, and has been used for simulation based system optimization of for example hydraulic systems, see Krus et al. [17,18].

The complex method starts by randomly generating k feasible points in the solution space. The geometrical figure with k vertices/points in R^n is called a complex. The number of points in the complex has to be greater than the number of optimization variables. Box recommended that the complex consist of twice as many points as optimization variables. The value of the objective function is calculated for each point and the basic idea of the algorithm is to replace the worst point by a new and better point. The new point is calculated as the reflection of the worst point through the centroid of the remaining points in the complex. The reflection distance is varied so that the complex expands to search in new regions and contracts if the new point repeats as the worst. In the next iteration a new point has become the worst, which in turn is reflected through the centroid of the new complex. This procedure is continued until the whole complex has converged to the optimum. A visualization of this procedure is shown in Fig. 13 below. For a more detailed description, see Krus et al. [19].

The complex algorithm has been coded in FORTRAN and implemented in Easy5. The optimization loop starts by randomly generating a set of initial values for the optimization variables. The system is then simulated and performance characteristics such as fuel flow, degree of cavitation, and system weight are calculated. The performance of the system, together with the weight, are then used as inputs to the optimization algorithm in order to calculate the objective function. The optimization algorithm then returns a new set of design variables to the system model, which is again simulated. This is looped until an interruption criterion is satisfied and the system is considered to be optimal. This model architecture is shown in Fig. 14.

C. Objective Function Formulation

The aim of this study is to minimize the weight of the system and simultaneously avoid excessive cavitation and ensure sufficient fuel flow. The design parameters in this study are the pressurization level and the pump size, that is, the maximum power of the pump. The flight data used as input are altitude, turn rate in a specified operation point, or rather ambient pressure and load factor, and type of fuel. The optimization problem could thus be stated as to finding the pressurization level x_1 and the pump size x_2, which minimize the system weight subject to constraints on pump cavitation and transfer flow rate. Here the constraints are handled using penalty functions, and thus the optimization problem could be stated according to Eq. (2).

$$\min F(\mathbf{x}) = m(\mathbf{x}) + P(\mathbf{x}) \qquad \text{s.t.} \qquad x_i^l \le x_i \le x_i^u, \qquad i = 1, 2 \tag{2}$$

where the mass is calculated as

$$m(x) = 2.10^{-3} \cdot x_1 \cdot V_{\tan K} + 8.2 \cdot 10^{-3} \cdot x_2 \tag{3}$$

The mass that we want to minimize is not the total system mass, but rather the additional mass that is dependent on the design variables. The additional mass equals the sum of the pressure

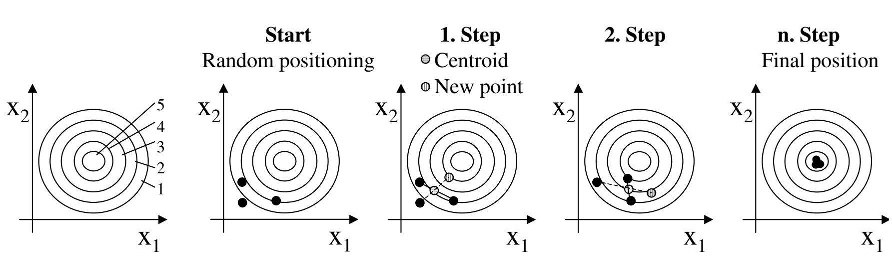

Fig. 13 Illustration of the complex optimization method.

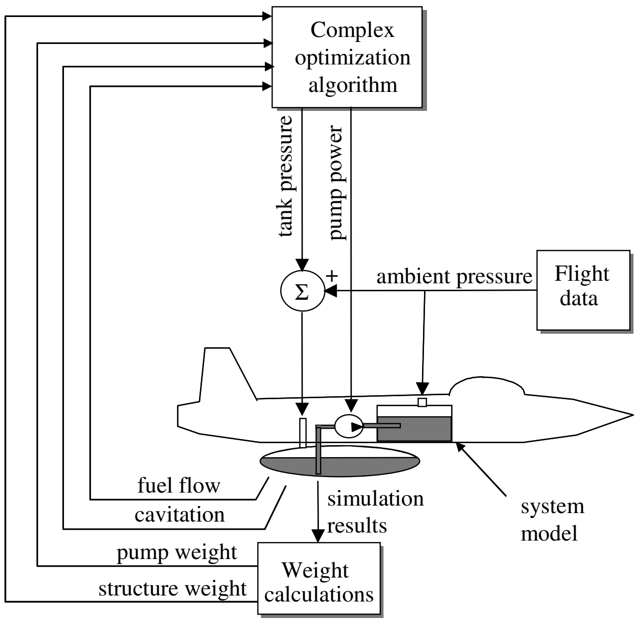

Fig. 14 Schematic of the system model.

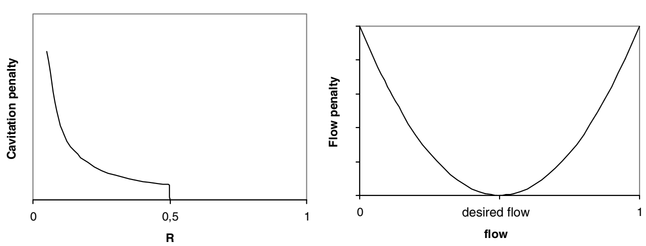

Fig. 15 Schematic diagrams of the penalty functions.

dependent structure weight and the pump weight. Thus, the pipes, couplings, shut off valves, etc., are considered to have the same weight for all concepts and are therefore not included in the objective function. Equation (3) could then be interpreted as stating the pressure dependent structure weight is 0.2 kg per kPa and m^3, which is a valid approximation up to 200 kPa, and the weight of the pump is 8.2 kg per kW, which is a fair assumption up to 1 kW.

The penalty function $P(\mathbf{x})$ is calculated as

$$P(\mathbf{x}) = w_1 p_1(\mathbf{x}) + w_2 p_2(\mathbf{x}), \quad \text{where } p_1(\mathbf{x}) = \begin{cases} 0 & \text{if } R \geq 0.5 \\ \frac{1}{R} & \text{if } R < 0.5 \end{cases}$$

$$p_2(\mathbf{x}) = (\text{actual flow-desired flow})^2 \tag{4}$$

$p_1(\mathbf{x})$ is the cavitation constraint that penalizes designs with excessive cavitation. $p_2(\mathbf{x})$ is the fuel flow constraint that ensures that the desired fuel flow is achieved. The coefficients w_1 and w_2 are needed in order to ensure that the magnitudes of the penalty functions are in accordance with the original objective function. The shape of the constraints functions are shown in Fig. 15. Note that diagrams show $p_1[R(\mathbf{x})]$ and $p_2[\text{flow}(\mathbf{x})]$, where $R(\mathbf{x})$ and $\text{flow}(\mathbf{x})$ are calculated based on the simulation results. $R(\mathbf{x})$ refers to the cavitation reduction factor defined in Eq. (1), where $R = 0$ means full cavitation and $R = 1$ means no cavitation.

As regards the cavitation constraint, it is difficult to say that precisely this or that R value is not allowed. Cavitation to some degree is to be considered as a normal state in fuel pumps at high altitude. Nevertheless it is a fact that cavitation may eventually harm the pump if the vapor/liquid ratio becomes too high. For transfer pumps, a rule of thumb used at Saab is that the cavitation reduction factor should be larger than 0.5. As both the cavitation and the flow constraints could be seen as soft constraints, that is, small constraint violations might be allowed, treating them with penalty functions and weighting factors corresponds well with engineering practice.

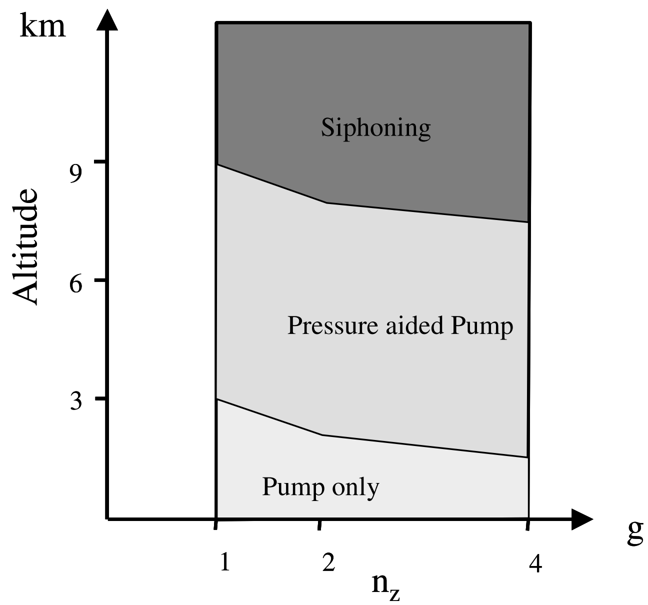

Fig. 16 Preferred concepts as a function of turn rate and altitude.

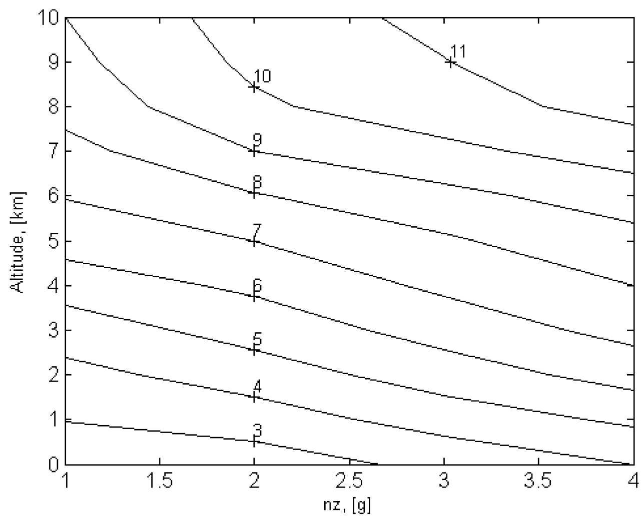

Fig. 17 System weight as a function of turn rate and altitude.

It would have been possible to include additional properties in the objective function. Conceivable properties include number of components, component price, or possibly power consumption. However, at this early stage in the design process, these were omitted.

IV. Results

The optimization problem stated in Eq. (2) is now solved for different mission profiles, that is, different flight altitudes and turn rates in order to investigate how the optimal transfer system changes with changing mission profiles. When interpreting the results, pumps under 100 W and tank pressures under 5 kPa are considered impractical. Thus, designs with very small pumps are considered to be pure siphoning concepts and designs with low pressurization are considered to be pure pump concepts. As expected, the optimal system concept varies with the top-level requirements. For a flow rate of 2.5 kg/s, the optimal concepts as a function of altitude and turn rate are shown in Fig. 16.

It is clear from the figure that as altitude increases the required tank pressure also increases. Eventually, the pressure becomes so high that there is no need for a pump. This occurs at approximately 50 kPa. The impact of the load factor (the slope between the different areas) was not as significant as first anticipated, but can nevertheless not be ruled out as a factor.

Another result of the optimization is to show the weight as a function of the top requirements. As can be seen from Fig. 17, the required system weight increases with increased flight altitude and turn rate. If system weight is critical, this type of diagram could be used in a trade study where system weight is assessed against the top requirements.

V. Conclusions

This paper shows how the use of optimization may facilitate the concept selection process and increase the probability of choosing the best concept depending on the top-level requirements. The use of optimization also increases understanding of how top-level requirements impacts low-level practicalities such as fuel system design.

In aircraft fuel system design, it has often proved difficult to find the switching point where the superior concept is changed. This sometimes makes the designer conservative and leads to the selection of a concept with too high a penalty. There is also a risk for the opposite, and perhaps worse, scenario: that the designer strives to reduce weight and cost and therefore, accidentally, chooses an underachieving concept, and thus induces substantial downstream costs if late redesign or retromodifications should become necessary.

It would not be wise to choose a concept on the basis of the optimization result alone. There are always aspects that are difficult to quantify in an objective function. These could be system simplicity from a robustness perspective or as in this case it might be advantageous to use the same pressure level as in the fuselage and wing tanks. However, the benefit of quantifying the problem when formulating the objective function must not be underestimated. This will enhance understanding of the problem and thus a greater likelihood that the best concept will be chosen. This is valid both for the formulation of the objective function and for the modeling of the system itself. Also, the trade-off diagrams, which are an outcome of the optimization, have a pedagogic value when explaining the problem to high-level decision-makers. This is a vital part of the concept selection process.

Methods like the one presented in this paper are very valuable in concept design, and can speed up the process and provide valuable insight. There is, however, always a risk that when using optimization, an inexperienced engineer may draw the wrong conclusions, perhaps due to an ill formulated objective function. It is, however, the authors' opinion that the process of gaining experience is enhanced and speeded up when using techniques such as the one presented in this paper.

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