More Efficient Fluid Power Systems Using Variable Displacement Hydraulic Motors

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Abstract

The approach and landing phase is dimensioning for today's aircraft fluid power systems. In this flight phase, large hydraulic consumers (flaps/slats, landing gear) have to be operated while the available hydraulic power reaches it's minimum due to the reduced engine speed.

During most of the flight the installed resources exceed the hydraulic power requirements by far; resulting in a low overall-efficiency.

This paper presents an approach to increase the efficiency of today's fluid power system by using variable displacement hydraulic motors (VDMHs). Two applications will be introduced: the VDMH driven slat/flap power control unit (PCU) and the bi-directional hydraulic-electrical power conversion unit (HEPCU).

The variable displacement PCU reduces the design loads for the fluid power system during take-off and landing. Compared to conventional PCUs used today, a flow reduction of about 50% is expected using the VDHM technique.

The HEPCU transfers hydraulic into electrical power and vice versa depending on the current load and flight situation ("hydraulic-electrical power management"). The main benefit from this approach is down sizing the primary power sources (engine driven pumps and generators), a significant increase in reliability and a higher efficiency for both, the hydraulic and the electrical power generation system.

Symbols

A	Surface area
C	Capacity
E	Bulk modulus
J	Inertia
K	Gain
M	Torque
P	Power
Q	Flow
V	Displacement, Volume
W	Work, Energy
d	Viscous friction number
i	Current
p	Pressure
x	Actuator stroke
ω	Revolving shaft speed
η	Efficiency

Indices

CDHM	Constant displacement hydraulic motor
F	Friction
LE	Leakage
L	Load
M	Hydraulic motor
P	Piston
R	Return
S	Supply
SV	Servovalve
VDHM	Variable displacement hydraulic motor
fl	Fluid
hm	hydro-mechanical
hyd	hydraulic
in	Input
mech	mechanical
out	Output
t	total
vol	volumetric

Abbreviations

AC	Alternating current
CDHM	Constant displacement hydraulic motor
CSMG	Constant speed motor generator
DG	Differential gear
EDP	Engine driven pump
EHSV	Electrohydraulic servovalve
HEPCU	Bi-directional hydraulic-electrical power conversion unit
IDG	Integrated drive generator
IGBT	Insulated gate bipolar transistor
PCU	Power control unit
POB	Pressure-off brake
SOV	Solenoid valve
T/O	Take off
TUHH	Technical University Hamburg-Harburg
VDHM	Variable displacement hydraulic motor
VSCF	Variable speed – constant frequency

Introduction

Since the late 1930s hydraulic systems are used in all kind of aircraft. The importance of these systems has grown significantly since then and the hydraulic power demands have consequently increased greatly.

Modern commercial aircraft are equipped with three or four independent hydraulic systems. Hydraulic power is needed for a large variety of functions including primary and secondary flight controls, brake systems, door actuation, landing gear systems and nose wheel steering.

In flight, engine driven pumps (EDPs) supply the pressure system. For ground and emergency operation additional electric motor driven pumps are provided. The universally used pump type is the variable displacement pump designed to guarantee a constant system pressure.

FIGURE 1 shows a typical load profile for an aircraft hydraulic system. Dimensioning is the approach phase when large consumers (slats/flaps, landing gear) have to be operated while the available hydraulic power provided by the EDPs reaches it's minimum due to reduced engine speed.

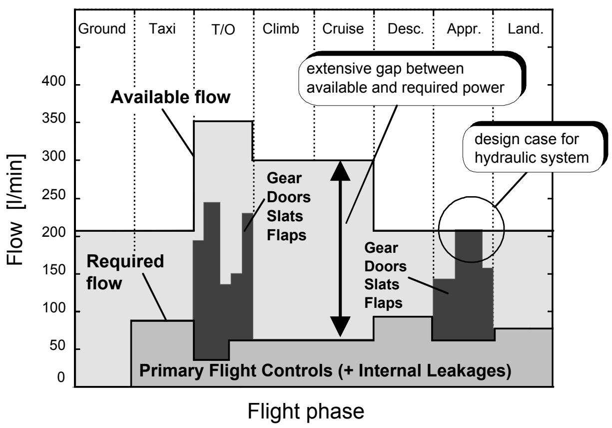

FIGURE 1 - Typical hydraulic load profile for a commercial aircraft

During cruise phase hydraulic power is only needed for operating the primary flight controls and for covering internal leakage. This purpose requires only a rather small amount of hydraulic power. Concerning a long range flight the installed power resources exceed the power demands by far for more than 90% of the mission time.

This low overall efficiency can be increased through the consequent use of variable displacement hydraulic motors (VDHMs). Therefore, two approaches concerning the integration of VDHMs in aircraft fluid power system will be presented in this paper.

- Replacing conventional constant displacement motor (CDHM) concepts through VDHM techniques yields in a reduction of consumer demands, especially during the critical flight phases, i.e. take off, approach and landing. One particular application, the use of VDHMs for the slap/flap power control unit (PCU) will be described in detail.
- The concept for a bi-directional hydraulic electrical power conversion unit (HEPCU) will be introduced. HEPCU provides additional hydraulic power "on demand" during the critical flight phases on the one hand and, on the other hand, HEPCU uses the power resources during cruise for generating electrical power.

Both applications are developed at the Section Aircraft Systems Engineering, Technical University Hamburg-Harburg (TUHH). Test rigs (FIG. 6) and comprehensive simulation models were established to examine the two concepts in practical operation.[1]

Variable Displacement Hydraulic Motors (VDHMs)

The principle of displacement controlled hydraulic units enables power control without pressure losses. It is successfully applied in a variety of industrial fields since the early eighties. The use in aircraft's hydraulic systems requires high level reliability and safety under extreme environmental conditions and life time demands.

Although variable displacement hydraulic units are commonly referred to as "motors" they are also able to work as a pump. The term "motor" was established since the first units working with this principle were used as hydraulic motors.

Today's aircraft's hydraulic power controls uses valve controlled constant displacement hydraulic motors (CDHM) at constant pressure supply. The speed control of these motors is realised by varying the hydraulic resistance of the control valve. This kind of velocity control leads to high pressure losses up to 80 %.

The required hydraulic power is provided by variable displacement pumps driven directly by the engine gear box or by AC motors. These pumps are not able to work as a motor due to design limitations.

Design and Function

FIGURE 2 shows the design of a axial piston motor. The motor torque is regulated by the angle of the swash plate changing the motor displacement. It is positioned by a swash plate actuator. The flow to the cylinder is usually controlled by an electro-hydraulic servovalve (EHSV).

The design described allows a very flexible application of VDHMs. Depending on the swash plate angle and the load torque at the output shaft, the unit works either as a pump or as a motor. This kind of hydraulic motor allows to control torque, power, speed and position at the output shaft. Moreover, it is possible to realise pressure and flow control of the hydraulic power supply.(3)

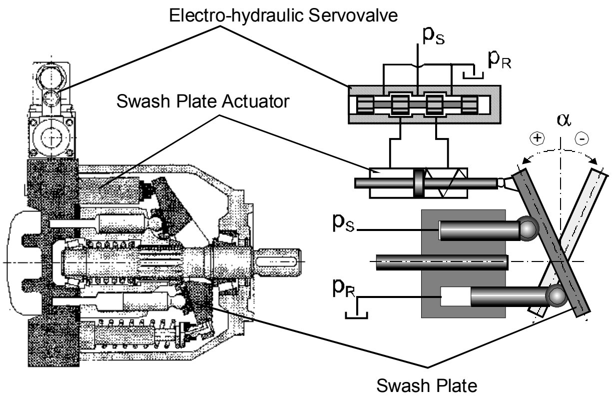

FIGURE 2 - Design of a axial piston motor (Mannesmann-Rexroth, type A10VSO)

Model of the Hydraulic Motor

This section presents a linear mathematical model of the hydraulic unit that captures its main dynamics. FIGURE 3 shows a scheme of a VDHM at constant pressure supply.

When working as a hydraulic motor in a speed control loop, the controlled outputs are the swash plate actuator stroke x_P and the revolving speed at the output shaft ω. The actuating input signal of the EHSV is the current i_{SV}.

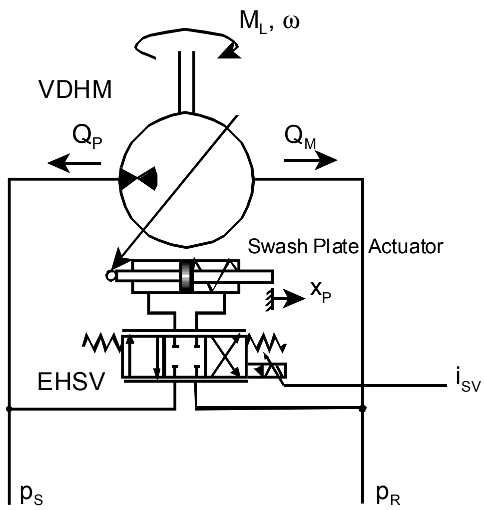

FIGURE 3 – Scheme of a VDHM

Compared to CDHMs, attended by control valve induced power losses, the hydraulic input power of a VDHM $P_{hyd,in}$ at constant differential pressure supply

$$P_{hyd,in} = \left(p_S - p_R\right) \cdot Q_M \qquad (1)$$

is only reduced by the hydro-mechanical efficiency η_{hm} and volumetric efficiency η_{vol}. The mechanical power $P_{mech,out}$ at the output shaft is calculated by

$$P_{mech,out} = M_L \cdot \omega = P_{hyd,in}\eta_{hm}\eta_{vol} = P_{hyd,in}\eta_t \,. \qquad (2)$$

The power balance (2) describes the power loss of a VDHM. Usually, the volumetric and hydro-mechanical efficiency is very high. Generally, VDHMs are used to work with an overall efficiency of 90 % at the operation point.

For controller design purposes a mathematical model of the hydraulic motor is needed. The mechanical system of the VDHM is described by the equation of momentum

$$J\dot{\omega} = M_M - M_F - M_L \,. \qquad (3)$$

Neglecting the stiction moment, the friction term M_F is reduced to the viscous part

$$M_F = d_M \omega \,. \qquad (4)$$

The motor torque M_M is calculated by

$$M_M = V_M \frac{\left(p_S - p_R\right)}{2\pi}, \qquad (5)$$

with a linear dependence between the displacement V_M and the actuator stroke x_P

$$M_M = \frac{V_{M,max}}{x_{P,max}} \frac{\left(p_S - p_R\right)}{2\pi} x_P = K_{Mx} x_P \,. \qquad (6)$$

Equations (3) to (6) lead to a first order differential equation

$$J\dot{\omega} + d_M \omega = K_{Mx} x_P - M_L \,, \qquad (7)$$

a linear, time-invariant ordinary differential equation with the actuating input x_P. The transient behaviour of the revolving speed ω depends on the difference between motor torque M_M (x_P) and load torque M_L.

Simplified the swash plate actuator is represented by an integral behaviour

$$\dot{x}_P = \frac{Q_{SV}}{A_P} \qquad (8)$$

and the flow of the EHSV stands for a proportional term

$$Q_{SV} = K_{SV} i_{SV} \; . \tag{9}$$

When working as a hydraulic pump the controlled output is the supply pressure p_S. The derivative of the pressure is calculated by

$$\dot{p}_S = \frac{1}{C_{hyd}} \left(Q_P - Q_L - Q_{LE} \right) , \tag{10}$$

with the hydraulic capacity C_{hyd} which is a function of the system volume V_{hyd} and the hydraulic fluid's bulk modulus E

$$C_{hyd} = \frac{V_{hyd}}{E} \; . \tag{11}$$

The load flow Q_L stands for the consumed system flow and the leakage flow Q_{LE} is represented by

$$Q_{LE} = K_{LE} \, p_S \; . \tag{12}$$

The pump flow Q_P for a constant speed is given by

$$Q = \frac{V_{M,max}}{x_{P,max}} \cdot 2\pi \cdot \varpi \cdot x_P = K_{Qx} x_P \tag{13}$$

in which the actuating input x_P can be derived from equations (8) and (9). The speed ω depends on the driving unit (engine, AC motor), respectively. Equations (10) to (12) lead to a first order differential equation

$$C_{hyd} \dot{p}_S + K_{LE} \, p_S = K_{Qx} x_P - Q_L \; . \tag{14}$$

Controller Design

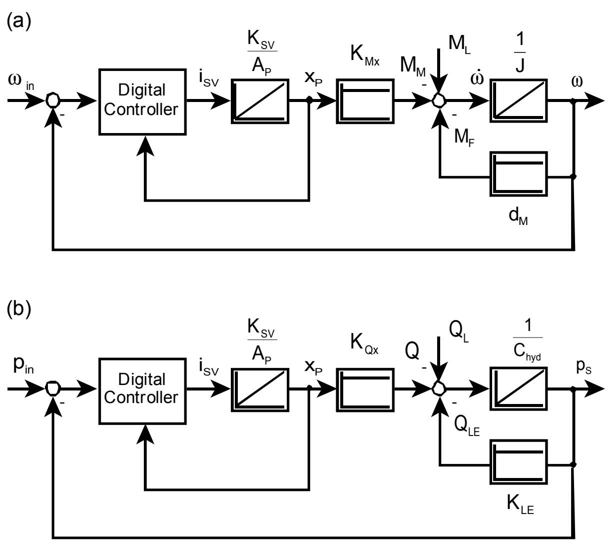

FIGURE 4 - Simple block diagram of a speed control loop (a) and a pressure control loop (b)

The use of VDHMs in aircraft environment requires robust and discrete-time controllers. The reduced linear plant of the open loop, presented by equations (7), (8) and (9), completed with the speed control system is shown in FIGURE 4 (a). The pressure control loop based on equation (10) and (11) is shown in FIGURE 4 (b).

The digital controller calculates the actuating signal of the servovalve i_{SV} using motor shaft speed ω or system pressure p_S.

Moreover, the swash plate position x_P can be controlled independently. This might be needed to stabilise the control system because of several kinds of disturbances e.g. leakage of the swash plate actuating cylinder leading to undesired movement of the swash plate. Besides the motor torque can be set adjusting the swash plate actuator e.g. for starting sequences.

Aircraft Applications

Bi-directional hydraulic-electrical power conversion unit (HEPCU)

Modern civil aircraft's hydraulic and electrical power generation systems are largely separated. The transfer options between both systems are limited to ground and emergency operations. The conventional transfer units used today (electrical driven motor pumps, hydraulic driven emergency generators) are working exclusively mono-directional.

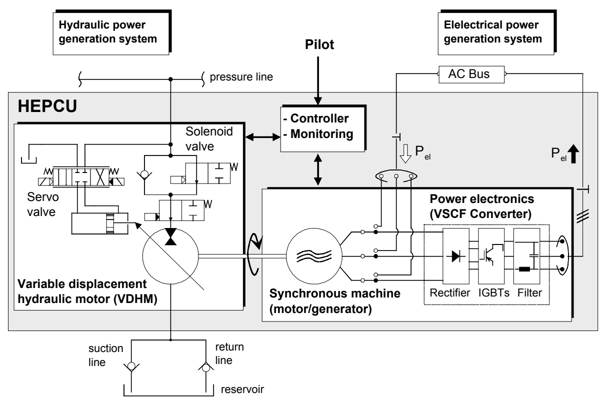

FIGURE 5 - Bi-directional hydraulic-electrical power conversion unit (HEPCU)

A far stronger coupling of the hydraulic and electric power system can be achieved by using a bi-directional hydraulic-electrical power conversion unit (HEPCU). Combining a variable displacement hydraulic motor (VDHM), an electrical synchronous machine and highly integrated power electronics, the HEPCU is able to work either as a pump or as a generator (compare FIGURE 5). With this functionality, HEPCUs can replace today's AC motor pumps and hydraulic driven emergency generators.

When working in pump mode, the electrical motor drives the VDHM converting electrical into hydraulic power. In this mode the hydraulic unit works in a pressure control loop supplying the 3000 psi hydraulic system.

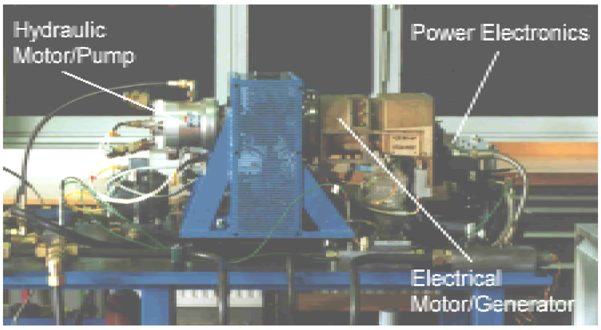

FIGURE 6 - HEPCU test rig at the Section Aircraft Systems Engineering at TUHH

In generator mode, the hydraulic unit works as a speed controlled motor driving the synchronous generator. The generator produces a wild-frequency voltage depending on the motor speed. This voltage is rectified and supplied to a VSCF converter (VSCF = variable speed constant frequency). The converter, build up of highly integrated IGBTs (insulated gate bipolar transistors), produces a constant frequency voltage which fits the strict requirements of today's electrical power generation systems (115 VAC, 400 Hz).

In both modes, the HEPCU is able to work as an emergency or ground power source, similar to today's AC motor pumps or emergency generators. The HEPCU combines both functions in a single unit.

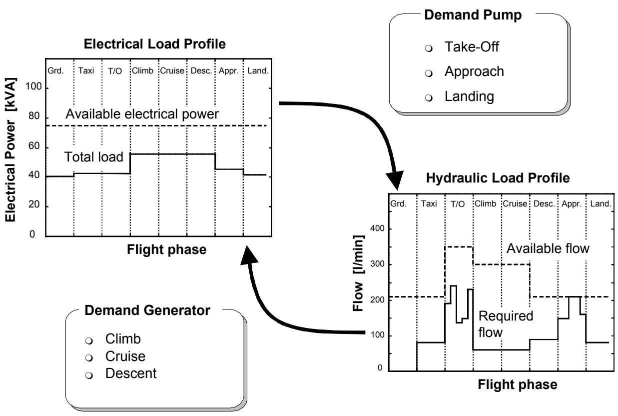

FIGURE 7 - Bi-directional power transfer

In addition, the HEPCU is able to work in parallel to primary power sources (engine driven generators and pumps). This functionality is used for a hydraulic-electrical power management concept:

Typical hydraulic and electrical load profiles show that the maximum loads in both systems do not occur simultaneously (FIG. 7). There is an extensive hydraulic power consumption during take-off, approach and landing when large hydraulic consumers (gear, flaps/slats) are operated. During cruise, only a rather small amount of hydraulic power is needed for the primary flight controls, whereas the electrical power consumption reaches its maximum (operation of galleys and passenger entertainment systems).

With the HEPCU working as a "demand pump" or as a "demand generator", a power transfer between the systems depending on flight phase and load situation becomes possible. During cruise hydraulic power is transferred into electrical power, whereas during take off and landing electrical power is converted into hydraulic power.

This flexible transfer option reduces the design requirements for both systems because the maximum loads can partly be supplied from the other system, respectively. As a result, down-sizing the installed power sources (engine pumps and engine generators) is the main benefit of this approach.

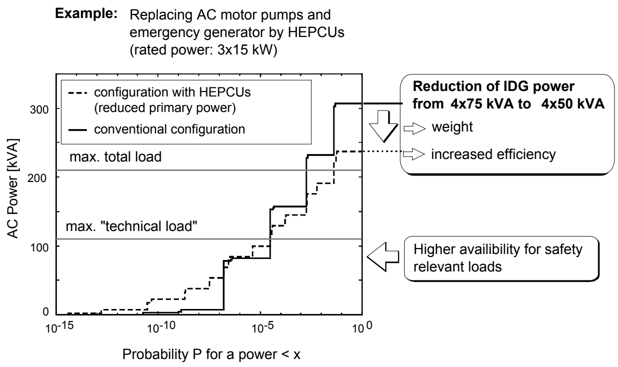

FIGURE 8 - Increased power availability for the AC power generation system

In addition to this weight and cost benefit, the use of HEPCUs increases the flexibility in power distribution between the hydraulic and electrical system. This results in a higher reliability and better power availability for both systems (FIG. 8).

Power Control Unit (PCU)

Today's high lift systems of civil transport aircraft are driven by power control units (PCU) using valve controlled fixed displacement hydraulic motors. FIGURE 9 shows a typical trailing edge (flaps) of a conventional high lift transmission system with PCU. Because of reliability reasons the PCU is driven by two independent hydraulic actuating circuits. The speed of both hydraulic motors is summed by a differential gear (DG). In the case of a single hydraulic system failure the high lift system can be operated with half speed. The position of the whole transmission system is set by throwing pressure-off brakes (POB). Using VDHM driven PCUs enables smooth start-up and positioning sequences. Moreover it allows steady position control of the high lift system.[(1),(2)]

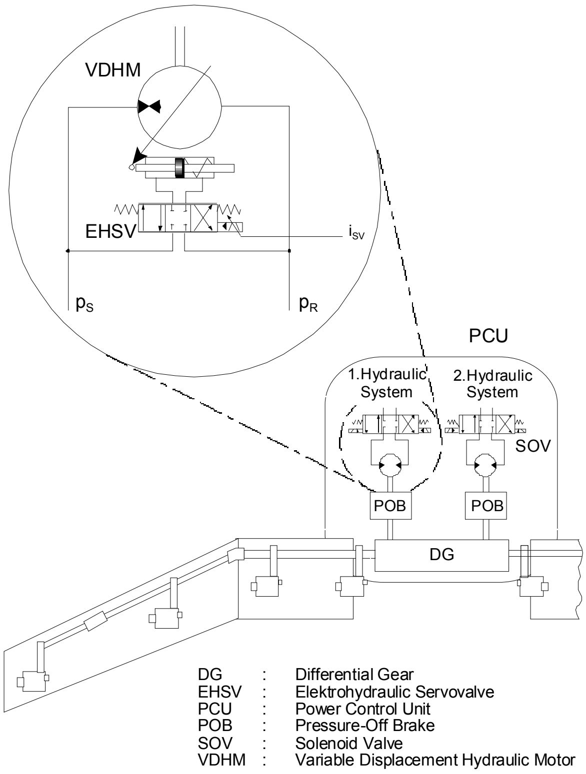

FIGURE 9 - Conventional high lift transmission (flap-) system with VDHM driven PCU

The power requirements of future large civil transport aircraft open an attractive field for the application of VDHMs. Especially the PCU-operation during landing approach is one decisive design case of hydraulic power supply (compare FIGURE 1). FIGURE 10 demonstrates the theoretical, simulated power transients of the speed controlled conventional CDHM and the VDHM concept for a given load profile at PCU output of a full flap extension operation. The power loss between the mechanical output power and the curve of the VDHM hydraulic input power is explained by the losses due to total efficiency η_t of the unit whereas the difference between CDHM and VDHM can be found in valve induced pressure losses.

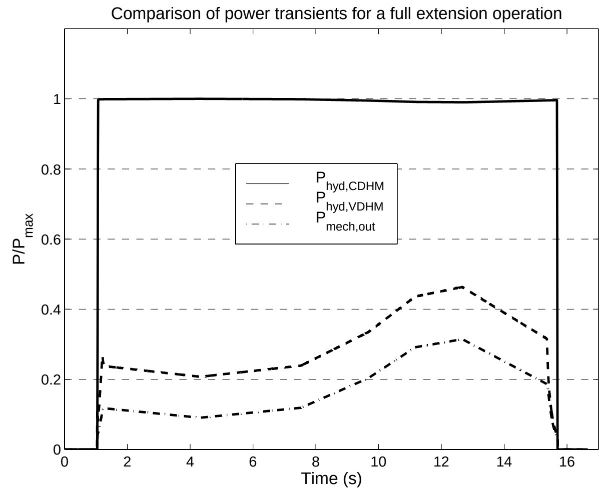

FIGURE 10 - Comparison of power transients between CDHM and VDHM

The comparison of power peaks and hydraulic work shows the VDHM concept's advantage. The power peak at maximum load demand is reduced to 47% (FIG. 11). The overall hydraulic work needed is decreased to 32%.

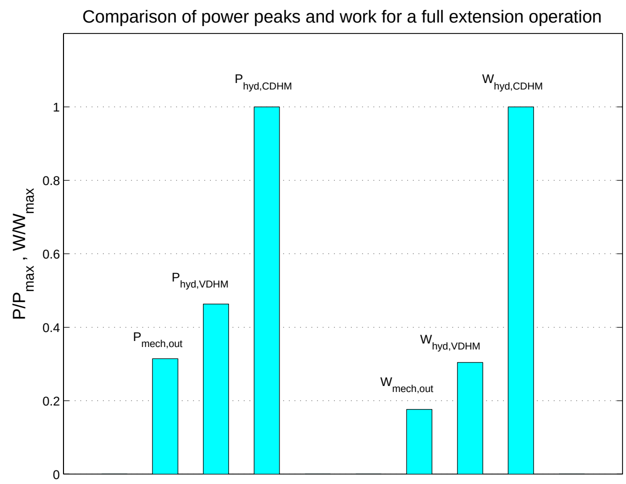

FIGURE 11 - Comparison of power peaks and hydraulic work between CDHM and VDHM

Fluid power system architecture using VDHM techniques

Combining the two approaches, VDHM driven slat/flap PCU and HEPCU, in an alternative fluid power system architecture may lead to a significant change of the typical hydraulic load profile on the consumer and on the power generation side (FIG. 12).

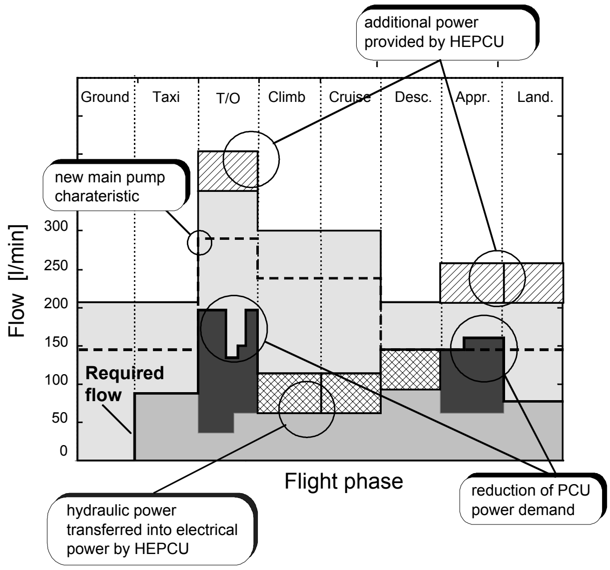

FIGURE 12 - Hydraulic load profile of an aircraft hydraulic system using VDHM techniques

On the consumer side the hydraulic power demands for operating the slat/flap systems during take off and landing decreases by approximately 50% compared to an conventional configuration. This yields in a direct reduction of the hydraulic design load.

With the HEPCU transferring hydraulic into electrical power during cruise, the gap between power demands and power resources decreases. The efficiency of the hydraulic power generation system increases.

On the power generation side the HEPCU provides additional power "on demand" during take off, approach and landing. It depends on the respective hydraulic and electrical system architecture and consumer profiles how much power can be transferred between the two systems. For a typical long range aircraft configuration approximately 20% of the rated hydraulic and electrical power is available for a bi-directional transfer.

By reducing the design load and by providing additional boost power down sizing of the primary power sources (engine driven pumps) becomes possible. For a typical long range aircraft the rated power of the engine driven pumps can be reduced by 30...40%. Besides, the hydraulic installations (pipes, filters, valves, etc.) can be downsized as well. Both results in weight and cost reduction.

Apart from the advantages for the fluid power system the application of VDHMs may also influence other aircraft systems:

The VDHM driven slat/flap PCU is the basis for a variable camber wing. This concept allows to choose an optimum lift coefficient depending on the current flight phase.

The HEPCU influences the electrical power generation system similar to the hydraulic system. The engine driven generators can be downsized because the design loads during cruise are covered from the hydraulic system (electrical power on demand). Besides, the reliability of the electrical system is increased due to more flexible power distribution options.

Summing all effects the application of VDHMs can save up to 20% weight in the hydraulic and electrical power generation systems of a typical long range aircraft.

Conclusion

The consequent use of variable displacement motors (VDHM) on the consumer and on the power generation side can help to increase the efficiency of aircraft's hydraulic systems. Even the efficiency of other systems (namely the electrical power generation system) can be influenced in a positive way.

Especially, the application of VDHMs in future large aircraft is a very interesting issue. Compared to existing configurations the hydraulic power requirements in these aircraft will increase enormously.

With conventional hydraulic system architectures serious design problems are expected for these future large aircraft. These problem can be avoided by using energy saving VDHM-based applications, i.e. the hydrauli-electrical power conversion unit (HEPCU) and the VDHM driven power control unit.

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