NOVEL CONCEPTS FOR NOISE REDUCTION IN AIRCRAFT HYDRAULIC SYSTEMS

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Abstract

The problem of high noise levels generated by hydraulic systems is well known. In commercial aircraft hydraulic systems are located close to passengers. Therefore, hydraulic noise emission can affect the passengers comfort due to continued disruptive noise. Passive pulsation dampers installed downstream the pump are state of the art in aircraft hydraulic systems. Nevertheless, new functional requirements such as variable pump speed demand novel pulsation damper concepts which are presented in this paper.

Various tests have been performed on both, aircraft and hydraulic test rig in order to analyze the mechanisms of hydraulic noise generation and transmission. The pressure and flow pulsations generated by the pump have also been measured. Based on that, pulsation damper concepts have been developed. The focus is on active or adaptive dampers, which are capable to adapt to changed operation conditions.

A dedicated fluid-borne noise test rig was set up which enables the measurement of fluid-borne noise characteristics of aircraft hydraulic components. The results can be used to rate different pumps by their noise characteristic or determine the transmission loss of damper devices. Furthermore, simulation models can be derived which enable the prediction of pressure pulsations in hydraulic circuits.

1. INTRODUCTION

Besides the efforts towards the more electric aircraft, the hydraulic power distribution system of commercial aircraft is still essential for the actuation of primary and secondary flight control surfaces, landing gears, steering system and brakes.

Generally, one important disadvantage of hydraulic systems is that they often have a high noise emission. In commercial aircraft, hydraulic systems are located close to passengers. Therefore, hydraulic noise can affect the passengers comfort. The main source of noise, mostly the pump, excites pressure pulsations into the circuit, which in turn lead to structural vibrations. While the audible noise is mainly an unpleasing effect, structural vibrations are related to fatigue and reliability and should be minimized during the design process.

2. AIRCRAFT HYDRAULIC SYSTEMS

Commercial aircraft feature multiple hydraulic circuits to meet the safety requirements. The hydraulic consumers are distributed to the different circuits in order to achieve the required reliability of the actuation systems. Also redundant actuators are used to drive the flight control surfaces. Each hydraulic circuit is pressurized by one or more hydraulic pumps which are either driven by the engine gearbox or an electric motor. The schematic diagram of a typical aircraft hydraulic circuit is illustrated in FIGURE 1. An axial piston pump with variable swash plate and hydro-mechanical pressure control is used to maintain a constant static pressure in the circuit. The pump discharge port is connected to the circuit by flexible hose for mechanical isolation. Often a pulsation damper is installed in the high pressure line in order to attenuate the pressure pulsations excited by the pump. The high pressure manifold features a filter element, valves and pressure sensors and distributes the hydraulic power to the consumer located in different sections of the aircraft.

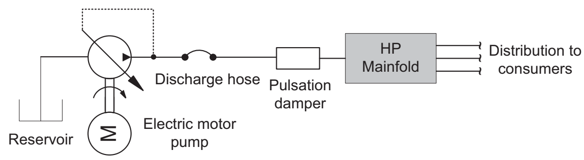

FIGURE 1. Schematic diagram of aircraft hydraulic system

The restricted installation conditions in an aircraft require complex pipe routing and pipe mounting on lightweight structures. Unfortunately, installation of hydraulic equipment near the cabin and the passengers is unavoidable. This makes the aircraft hydraulic system especially prone to continuous noise emission.

For the development of future aircraft there are strong ambitions to reduce maintenance costs and extend maintenance intervals of any aircraft systems and hence the hydraulic system. This may require new concepts of the hydraulic power distribution systems in order to meet changed functional requirements. This includes new system architectures, the utilization of electric motor pumps with variable speed and changed system installation.

Passive pulsation dampers are state of the art in current aircraft hydraulic systems. As long as the operation condition of the hydraulic system is not changed significantly, passive pulsation dampers are very effective in pulsation attenuation. Nevertheless, the considerations above make novel concepts for noise reduction and hence pulsation attenuation necessary.

Regarding hydraulic noise emission there are two main aspects to be considered. First, audible noise generated by the hydraulic system affects the passenger comfort which is generally unwanted by the airlines. The noise impact into the cabin may increase further due to installation of pump with higher power, pump installation near the cabin and new operation modes. Hence, there is a great demand on reduction of airborne noise emission of the hydraulic system.

The second aspect refers to the design process of hydraulic systems. Primary functional requirements are considered for the development of the system as loads and dynamics of the actuators, pressure levels, safety functions etc.. The integration of the hydraulic distribution system into the aircraft structure is further a challenging task. Even though the circuit design includes pulsation dampers in order to reduce pulsations, noise related issues often appear for the first time when the first hydraulic circuit is set up for testing.

Fluid-born and structure-borne noise can significantly affect the performance of the hydraulic circuit. It can lead to leakage, loosening of pipe clamps or even component fatigue and failure. These conditions need to be diminished at the development stage and shouldn't appear in normal operation. Nevertheless, a certain level fluid-borne and structure-borne noise cannot be avoided. From that point of view noise reduction is of major importance in order to develop reliable hydraulic systems.

Generally, it is possible to perform theoretical fluid-borne noise analysis of a hydraulic circuit but this is usually not part of the design process since it is rather complex and requires dedicated measurements and software. Besides that, up to now it is nearly impossible to predict the structure-borne and airborne noise emission of a hydraulic system [1].

In conclusion there is a great demand on noise reduction of all three types. Noise reduction approaches can be applied at different stages in the noise generation and transmission path. Nevertheless, not all are accessible by the system integrator. The reduction of fluid-borne noise is especially important since it excites structure-borne and airborne noise and propagates through the system. Therefore, the reduction of fluid-borne noise is an important target for the development of low noise hydraulic systems for future aircraft applications.

3. NOISE IN HYDAULIC SYSTEMS

There are three types of noise present in all hydraulic systems which have an inter-relation between each other. The audible noise, which can be defined as any kind of unwanted sound [2], is referred to as airborne noise (ABN). Mechanical vibrations are called structure-borne noise (SBN) and the term for fluid pulsations is fluid-borne noise (FBN). Noise energy can be transformed between the different noise types [3]. FIGURE 2 illustrates the generation and transmission of hydraulic noise.

Obviously, airborne noise can be unpleasing or even harmful and therefore should be minimized. Fluid-borne and structure-borne noise may degrade the performance of hydraulic systems. They can cause leakage or valve oscillation and finally end in component fatigue and failure [1]. Therefore, critical levels of fluid-borne or structure-borne noise should be avoided during operation.

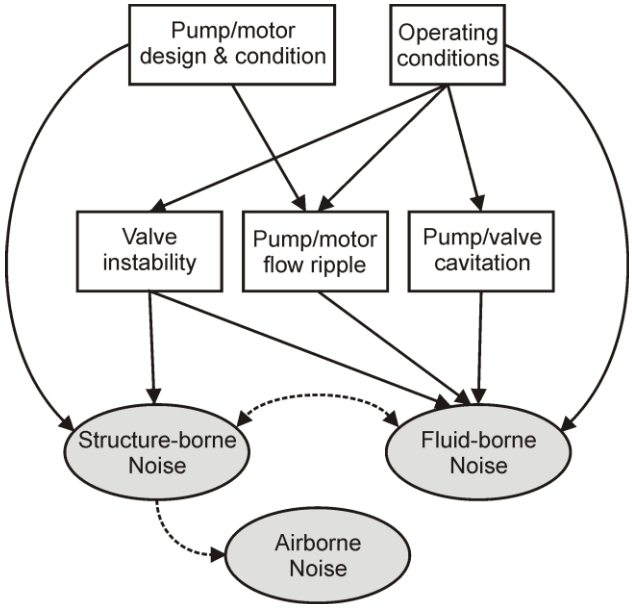

FIGURE 2. Generation and transmission of noise (acc. to [1])

3.1. Airborne Noise

The term airborne noise describes pressure fluctuations of the air associated with oscillations of the air particles. For hydraulic applications only the audible frequency range of about 20 Hz to 20 000 Hz is relevant. Lower frequencies are referred to as infrasound and higher frequencies as ultrasound [4]. ABN can be generated in different ways:

- In hydraulic systems ABN usually arises from vibrations of components (SBN) which are transmitted in the machine structure. They propagate to the surfaces and finally excite the surrounding air.
- ABN can also be directly excited, e.g. through the movement of machine parts as cooling fans for example.

3.2. Structure-borne Noise

The principle sources for structure borne noise in hydraulic systems are alternating loads, unsteady forces or torques in terms of value, direction or point of application, which act on the machine structure. These loads are either generated due to the equipments functionality or are being transmitted through attached components [4], [5]. Frequently, these vibrations result from fluid pulsations in the fluid system (FBN).

3.3. Fluid-borne Noise

Fluid-borne noise is defined as the unsteady component of pressure and flow in the fluid of hydraulic circuits. There are different principle sources for these pulsations (or ripples) in a hydraulic circuit but the main one is usually the pump (or motor, respectively). Besides that, valves can also be important noise generators. All kinds of positive displacement pumps create an unsteady flow which is superimposed on the mean flow rate. For constant pump speed the flow ripple is periodic in nature. The interaction of the flow ripples with the fluid in the attached circuit creates pressure fluctuations which depend on the circuit design. The pressure fluctuations propagate through the fluid at local acoustic velocity. Wherever there is a change in pipe cross-sectional area, a pipe-junction or component, a partial reflection occurs, leading to a wave travelling back and being partially reflected somewhere else in the system. These multiple travelling waves arising from reflections result in a complex standing wave in the fluid in the pipework. More precisely, the pressure ripple waveform at one location in the circuit can be quite different to the waveform at another location and is highly dependent on the systems operation condition. The pressure ripples create fluctuating forces on the pipes which lead to vibration (SBN) of the pipework, attached components and the supporting structure. This can again result in the radiation of ABN [6]. Fluid pulsations in hydraulic systems can be categorized as follows [7]:

1) Periodic signals: pump pulsations or valve whistling
2) Stochastic signals: e.g. cavitation noise
3) Transient signals: e.g. water hammer effect

Dealing with pulsations of pumps, periodic signals are of particular importance. The discontinuous functionality of hydrostatic displacement devices leads to an inherent flow pulsation. Even especially optimized pumps show this behavior. The frequency spectrum of these pulsations is dominated by few narrow-banded portions. The human ear is very sensitive to this tonal character of the frequency spectrum, which is therefore especially displeasing [7].

3.4. Transmission of Noise

There are different transmission paths of SBN and FBN between the components in a hydraulic circuit. Therefore the noise emission of a single component is not the crucial factor. The behavior of the surrounding system must rather be considered. In many cases noise attenuation can only be achieved by the consideration and optimization of the entire hydraulic system [4].

Pumps usually generate as much as 1000 times more energy in the form of SBN or FBN than they do in the form of ABN. All these noise types act on the hydraulic structure and machine elements and frequently end up emitting more ABN than that generated by the pump itself. Because of this interaction it is important to control all three types of noise. Since control methods are different for each type of noise, it must be distinguished between the types even though they come from the same source [3].

3.5. Noise Reduction

As illustrated in FIGURE 2 noise reduction measures can be applied at different stages. In addition to the pump the prime mover can also be a significant generator of structure and airborne noise. Electric motors that drive pumps often have fan cooling systems that produce airborne noise. Structure-borne noise can be transmitted through the mounts, drive shafts and pipes and finally ending up generating airborne noise. Several techniques can be applied in order to reduce the transmission of structure-borne and airborne noise [1]:

- Acoustic enclosures and cladding,
- isolation mounts,
- flexible hoses,
- damping materials,
- pipe clamps.

In order to reduce the fluid-borne noise levels in hydraulic systems a number of different approaches can be followed. Four main categories can be separated [1]:

- Reduction of pump or motor source flow ripple,
- tuning of the circuit in order to avoid resonance conditions,
- the use of attenuation devices including pulsation dampers,
- the use of flexible hose to isolate hydraulic components from the circuit.

4. SYSTEM ANALYSIS

For the development of low noise aircraft hydraulic systems the noise transmission paths of the different noise types from the pump into the cabin have to be identified. Various tests have been performed on both, aircraft and hydraulic test rig in order to analyze the mechanisms of hydraulic noise generation and transmission. The pressure and flow pulsation generated by the pump have also been measured.

4.1. Noise Transmission Paths

Several tests have been carried out on an aircraft in order to analyze the transmission paths of noise, generated by the hydraulic pump, into the aircraft cabin. Four different transmission paths have been investigated, see FIGURE 3.

- Transmission of airborne noise emitted by the pump through the structure,
- Transmission of structure-borne noise through the flexible pump mounting,
- Transmission of fluid-borne noise through the pump discharge line (high pressure, HP) and suction line (low pressure, LP), respectively.

In order to investigate the single transmission path all other paths have been decoupled. For the fluid-borne noise isolation a long flexible hose and a large volume pulsation damper have been utilized. The structure-borne noise transmission has been isolated by detachment of the pump from the mounting and external support.

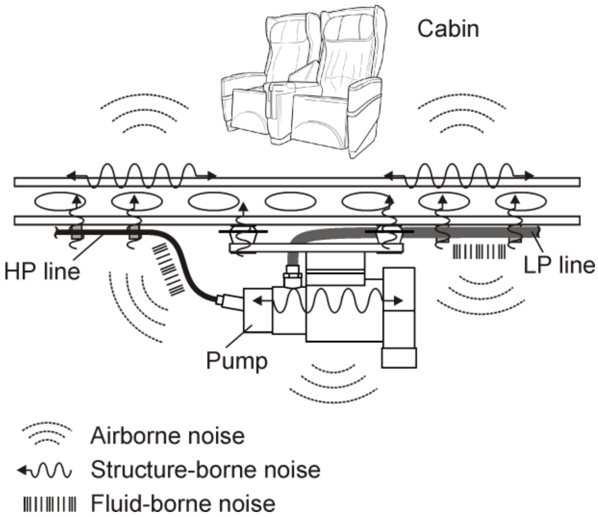

FIGURE 3. Noise transmission paths in an aircraft

For each modification the sound pressure level has been measured inside the aircraft cabin. The comparisons of the results show that the main transmission path is the fluid-borne noise in the pump discharge line. The utilization of a pulsation damper results in significant reduction of cabin noise. Fluid-borne noise in the suction line only has minor effect on the cabin noise. The structure-borne noise transmission is sufficiently reduced by the flexible pump mounting.

These tests prove the effectivity of pulsation dampers which are state of the art in aircraft systems. Nevertheless, these passive dampers have unchangeable characteristics and only achieve best attenuation at their specific design operating point.

4.2. Measurement of Pump Ripple

In order to develop efficient attenuators to reduce the fluid-borne and hence hydraulic noise, it is necessary to analyze the pump ripple characteristics. Therefore measurements have been carried out on a hydraulic test rig. FIGURE 4 illustrates the measured pressure ripple at the discharge port of a piston pump.

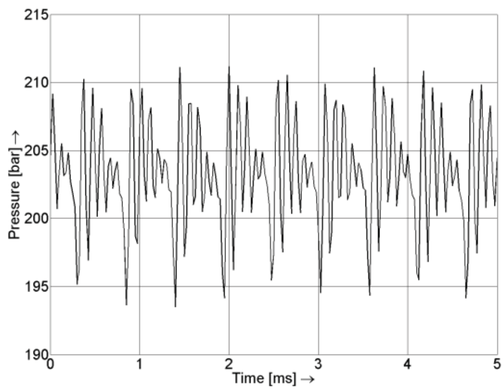

FIGURE 4. Pressure at the pump discharge port

For the characterization of the pulsation waveform, harmonic analysis has been performed using Fast Fourier Transformation (8k FFT, Flat top window, 75% overlap). FIGURE 5 shows the amplitude spectrum (RMS) of FIGURE 4. The fundamental frequency is given by

$$f_f = \frac{z \cdot n}{60} \quad (1)$$

where z is the number of pistons and n the pump speed [rev/min]. In addition, a number of strong higher harmonics occur which is typical for piston pumps.

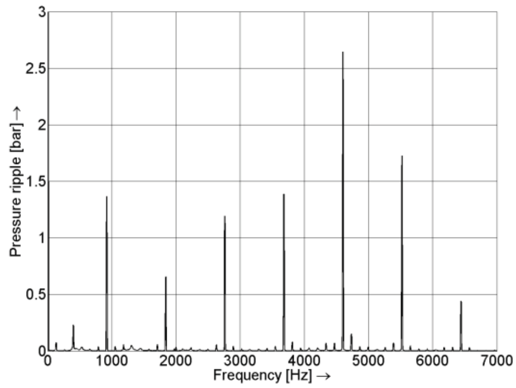

FIGURE 5. Amplitude spectrum of pressure ripple

Since the excited pressure pulsation is dependent on the circuit characteristics it is not an adequate measure to quantify the pump ripple. A test method for the determination of source flow ripple, source impedance and pressure ripple generated by hydraulic pumps is given in [13] which will be implemented in the ongoing project. As a first attempt the flow pulsation generated by the pump has been determined in order to set requirements for damper devices. Unfortunately the flow pulsation can not be measured directly since high dynamic flow transducers are not available. A pair of pressure transducers in a reference pipe can be use in the same way as a sound intensity probe in the field of acoustics. The details of the measurement are described in [8]. The schematic of the transducer setup in a reference pipe is illustrated in FIGURE 6.

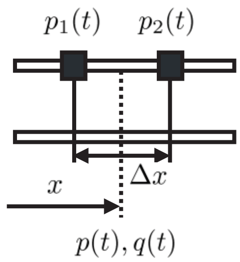

FIGURE 6. Pressure transducer setup

The flow variation at the position x in the pipe can be determined by the recurring equation [8], [9]

$$\begin{aligned} q_x(t) \;&=\; e^{-R_f \Delta t} q_x(t-\Delta t) + \frac{A\Delta t}{2\rho\Delta x} e^{-R_f \Delta t/2} \\ &\quad [p_1(t-\Delta t) - p_2(t-\Delta t) + p_1(t) - p_2(t)] \end{aligned} \quad (2)$$

in which A is the cross-sectional area of the reference pipe, x the distance between the two pressure sensors, t the sampling period, ρ the density of the fluid. R_f is the resistance factor given by

(3) $$R_f = \frac{8\nu}{r_0^2}$$

where v is the kinematic viscosity of the fluid and r_0 the inner radius of the reference pipe. The time history of the pressure variation $px(t)$ at the position x in the pipe is assumed to approximately be the average value of the two pressure signals [8]

(4) $$p_x(t) = \frac{p_1(t) + p_2(t)}{2}$$

After determination of the harmonic components P_x [1] and Q_x [2] of the pressure pulsation and flow pulsation, their progressive wave and regressive wave components, P_{xp}, Q_{xp} and P_{xr}, Q_{xr} can be obtained [9]

(5) $$P_{xp} = \frac{1}{2}(P_x + Z_0 Q_x),$$

(6) $$Q_{xp} = \frac{1}{2Z_0}(P_x + Z_0 Q_x),$$

(7) $$P_{xr} = \frac{1}{2}(P_x - Z_0 Q_x),$$

(8) $$Q_{xr} = \frac{1}{2Z_0}(P_x - Z_0 Q_x).$$

In these equations Z_0 denotes the characteristic impedance of the reference pipe given by

(9) $$Z_0 = \frac{\rho \cdot c_0}{A}.$$

c_0 is the speed of sound in the reference pipe and is assumed to be c_0 = 1337 m/s in this example.

Several tests have been carried out under various operation conditions. As result of the performed tests the spectra and the progressive wave component of the flow ripple in the calibrated pipe have been determined. An example is given in FIGURE 7. This represents the pulsation emitted by the pump and is the basis for defining requirements for pulsation damper concepts. It should be noted that the results do not express the inherent pump source flow ripple. It would have been preferable to measure the pump characteristic at the discharge port directly under specific conditions on a dedicated test rig. A detailed description of an appropriate measurement method is given in the International Standard ISO 10767-1 [13]. Nevertheless, the obtained results are sufficient for a first estimation of the required flow pulsation as a requirement for an active pulsation attenuator.

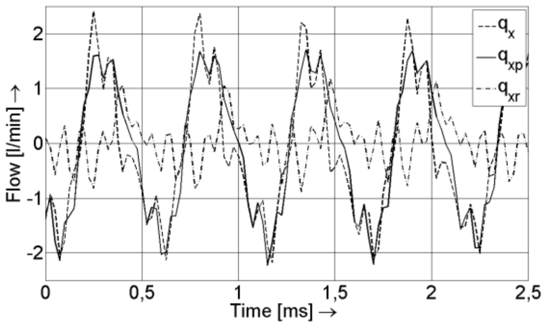

FIGURE 7. Flow ripple in reference pipe

5. NOISE REDUCTION CONCEPS

Different means for noise reduction are already applied to the aircraft hydraulic system. These include the use of flexible hose, flexible pump mounting and pulsation dampers. Nevertheless, upcoming issues relating to hydraulic noise and new functional requirements of the hydraulic system makes the improvement of noise reduction concepts necessary.

The result of the system analysis (ref. to section 4.1) is that the most promising approach to achieve hydraulic noise reduction is the attenuation of fluid-borne noise emitted by the pump. For the given application not every possible approach towards fluid-borne noise reduction can be followed. The following needs to be considered.

- The reduction of pump flow ripple is usually not accessible for the system integrator since the pump type as well as the operation conditions are subjected to restrictions other than ripple characteristic only.
- Tuning of the overall hydraulic system by judicious system design and avoiding resonant conditions is a very promising approach. It is very complex since it requires detailed component models and simulation.
- Pulsation dampers are already applied to the current aircraft hydraulic systems. Since passive dampers have fixed attenuation characteristics, the performance is dependent on the operation conditions, pump speed, temperature and static pressure. Therefore, optimal pulsation attenuation can not be reached in all operation condition.

5.1. System Requirements

The intent is to develop a pulsation damper which is capable to ensure optimal pump pulsation attenuation in any operation condition. Variable pump speed from 50% to 100% of maximum speed shall be considered. The attenuation factor to be achieved by the utilization of the pulsation damper shall exceed the performance of passive damper devices used at present over the given frequency band. Furthermore, the device shall be able to adapt to changing operation conditions as pump speed, static pressure, temperature, delivery flow, fluid type or condition. The device must not affect the overall reliability of the hydraulic system.

[1] Pressure pulsation harmonic at position x in frequency domain
[2] Flow pulsation harmonic at position x in frequency domain

5.2. Pulsation Damper Concepts

The different types of hydraulic pulsation dampers can be categorized as follows [1], [4]:

- *Passive pulsation dampers* show constant characteristics during operation and do not consume secondary energy. Reactive type dampers work on the physical effect of interference, while dissipative types absorb the acoustic energy by using absorbent material or orifices. Most hydraulic dampers are of reactive type or a combination of the two. Generally the attenuation characteristics of passive silencers are not optimal over all operation modes.
- *Adaptive pulsation dampers* work on the same principles as passive ones and feature at least on variable design parameter (diameter, length, volume, etc.). This leads to a damper with adaptive attenuation characteristic, e.g. the resonance frequency.
- *Active pulsation dampers* work on the principle of active noise cancellation. The pressure ripple in a pipe is sensed and an anti-phase pressure signal is generated by the active damper to cancel it out.

5.2.1. Active Pulsation Damper

An active pulsation damper concept offers the most flexibility for the given application. It can adapt to changed operation conditions and could be utilized in different hydraulic circuits as well as pump types.

Active dampers work on the principle of active noise cancellation as illustrated in FIGURE 8. The flow pulsation is cancelled out by generation and superposition of a pulsation with the opposite phase. Therefore only the mean flow remains. This principle is well known in the field of acoustics and multiple applications exist. Several attempts have been made to use active noise cancellation methods to reduce FBN in hydraulic systems [10], [11], [12]. Nevertheless, none of these could succeed economically so far.

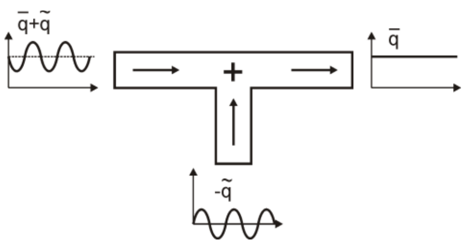

FIGURE 8. Principle of active noise cancellation in hydraulic systems (acc. to [7])

In order to apply active noise cancellation techniques to hydraulic pulsation damping devices two main tasks must be solved [7]:

1) Generation of anti-phase pressure pulsation,
2) control of the generated anti-phase pulsation.

There are several functional principles of pulsation generation which can be categorized into:

- Displacement principle,
- direct principle,
- active resistance principle.

5.2.1.1. Displacement principle

A displacement body (piston or diaphragm) is connected to the hydraulic circuit. The body displaces fluid by forced movement and therefore generates flow pulsations. High dynamic actuation is required to drive the displacement body. Two different set-ups are possible. The displacement body can rather be compensated or uncompensated to the static pressure level [12].

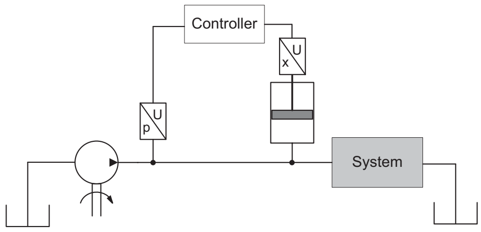

FIGURE 9. Displacement principle (acc.to [12])

5.2.1.2. Direct Principle

The direct principle is based on the generation of an additional flow pulsation (acoustic hydraulic power) which is applied to the fluid in the pressurized line. Three options exist [10]:

- Drain dynamic flow from the hydraulic circuit to a lower pressure system (0),
- supply dynamic flow to the hydraulic circuit from a higher pressure system,
- both, drain and supply dynamic flow to the hydraulic circuit.

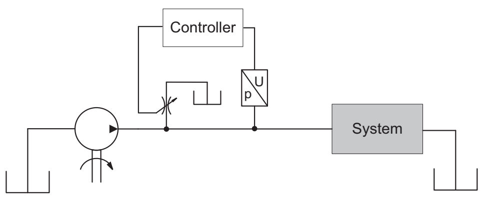

FIGURE 10. Direct principle (acc. to [10])

5.2.1.3. Principle of Active Resistance

The pump delivers flow into the system with a high dynamic hydraulic resistance (0).

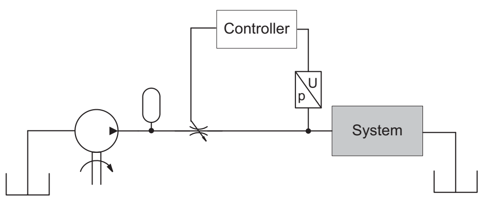

FIGURE 11. Active resistance principle (acc. to [11])

The hydraulic energy of the flow ripple wave crests is stored in the capacity downstream the pump by slightly closing the resistance. During the following wave through the resistance is opened whereupon the stored fluid volume is discharged to the system. In result the required power for cancellation of the flow pulsation is mainly taken form the fluid itself [11]. In general, the resistance can be any kind of proportional of rotary valve. A high dynamic actuator is required to drive the proportional valve or adapt the rotary valve characteristic, respectively.

5.2.2. Adaptive Pulsation Damper

The attenuation characteristic of passive dampers such as side branch, helmholtz or expansion chambers are dependent on their geometrical dimensions. It is essential to satisfy two requirements [7]:

- The functional principle of the passive silencer must be suitable to meet the design requirements in terms of dimensions, weight, attenuation, etc..
- The frequency adaptation must be economic, robust and accurate.

For example, the helmholtz damper illustrated in 0 provides good attenuation in a narrow frequency band. The optimal frequency is given by

$$f_{opt} = \frac{c}{2\pi}\sqrt{\frac{A}{V \cdot l}} \quad (10)$$

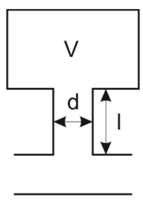

FIGURE 12. Schematic of a helmholtz damper

For a given speed of sound *c* the optimal frequency can be adapted by variation of the length *l*, cross-sectional area *A* and volume *V*. 0 shows the transmission loss of a helmholtz damper with different volume.

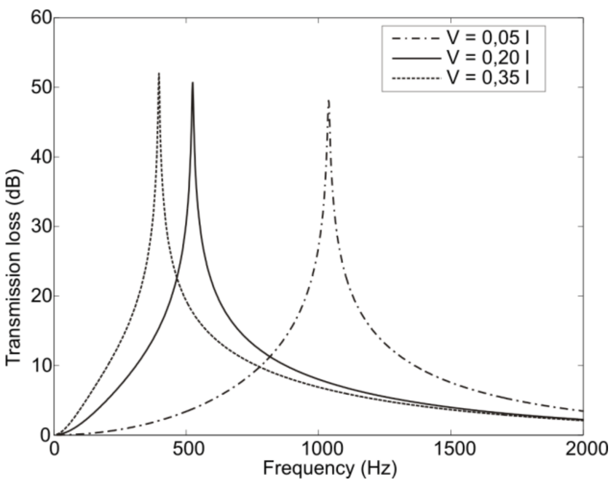

FIGURE 13. Transmission loss of helmholtz damper

5.2.3. Feasible Pulsation Damper Concepts

The evaluation of the different pulsation damper principles with respect to the aircraft requirements result in three feasible concepts, which will further be analyzed. Two are based on an active pulsation damper and one an adaptive damper concept.

The main challenge in the development of an active pulsation damper is the efficient generation of anti-pulsation. For any kind of high dynamic actuation the use of a piezo-actuator is favorable due to its high dynamic, high forces and small size. The first concept is a piezo driven membrane pump. The membrane pump shall be attached in a T junction of the hydraulic line and generate anti-pulsation using the compensated displacement principle.

The second approach is to design a high dynamic resistance which is capable to generate an anti-phase signal to the flow pulsation which is emitted by the pump. Both, the direct and active resistant principle can be followed.

The third concept is to develop a passive adaptive pulsation damper which natural frequency is adapted to the operation condition, in particular to the pump speed. The design process for an adaptive pulsation damper will be carried out to meet the requirements for aircraft application.

5.2.4. Simulation and Experimental Validation

In order to set up a circuit design with low pressure ripple characteristics, other than by trial and error, methods for prediction of the system characteristics are required. The mathematical equations describing the pressure ripple in a circuit become very complex for all but the simplest circuits. Today, different software packages are available to predict the pressure ripple characteristics of hydraulic circuits. By means of simulation the designer can determine what circuit dimensions will cause resonance, and take steps to avoid these conditions [1].

For the simulation of fluid-borne noise in hydraulic circuits, components are commonly represented by impedances. The impedance of a component is the ratio of a pressure ripple harmonic to the flow ripple harmonic at that frequency and is represented as an amplitude and phase spectrum. The fluid-borne noise characteristic of the pump can be represented by its "source flow ripple" and "source impedance" [1].

The determination of pump source flow ripple and component impedances require a dedicated test rig which will be set up at the Institute of Aircraft Systems Engineering. The test rig configuration will be follow the ISO 10767-1 standard [13]. It allows the measurement of fluid-borne noise characteristics of hydraulic components. There are two objectives for the measurements.

1) Rate fluid-borne noise characteristics of components
    - source flow ripple, source impedance and pressure ripple levels generated by pumps,
    - pulsation damper performance (transmission loss),
2) Derive component models from measurement data (transfer matrix, impedance matrix) for simulation of fluid-borne noise characteristics of hydraulic circuits.

Different ratings for the flow ripple or pressure ripple from a pump can be derived from the test data which enables the comparison of the fluid-borne noise characteristics of different pumps.

The test rig will further enable to demonstrate the effectivity of the developed pulsation damper concepts on a reference system. The test set-up is modular and modifiable in order to expand the test capabilities to e.g. measurement of flexible hose properties or fluid structure interaction. Examples for such tests are given in [14], [15].

6. CONCLUSIONS

The complex topic of hydraulic noise generation and transmission in hydraulic systems in general and in aircraft hydraulic systems in particular has been presented in this paper. The aircraft specific boundary conditions and requirements for the hydraulic system have been discussed. The system analysis has shown that the major noise source is the pump. It generates pressure pulsations which are transmitted in the high pressure line and excites the structure. Different noise reduction concepts have been introduced and their feasibility for aircraft application analyzed. Active pulsation dampers are a very promising approach since they can adapt to changed operation conditions. The principle concepts of active pulsation dampers have been presented. Two feasible concepts, a piezo driven membrane pump and a dynamic resistance are being selected for further analysis. Besides that an adaptive passive pulsation damper has been identified as an alternative concept. A dedicated fluid-borne noise test rig is under development which enables to analyze hydraulic components and generate validated simulation models.

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