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AIRCRAFT HYDRAULIC DRIVE ENERGY LOSSES AND OPERATION DELAY ASSOCIATED WITH THE PIPELINE AND FITTING CONNECTIONS

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Abstract. Theoretical research on hydraulic processes occurring in aircraft hydraulic drives is presented in the studies. Installation of angular fitting connections in aircraft pipeline systems influences hydrodynamic processes and fluid flow characteristics analysed in the research. The provided analysis is based on a validated numerical model utilizing Navier–Stokes equations and the k-epsilon turbulence model. Fluid flow inside the aircraft hydraulic drive pipeline system was investigated with flow rates up to 100 l/min. A mesh independence study was conducted for numerical simulation of the fluid flow. The obtained results include fluid pressure drops, energy losses, and operational delays associated with fluid flow vortex formations at 45° and 90° angular fitting connections. Additionally, compared results from standard methods of calculation for angular fitting connections, including the equivalent length and equivalent length same shape methods.

Keywords: aircraft, hydraulic drive, pipeline, operation delay, energy losses, fitting, CFD, design stage.

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1. Introduction: energy losses and operation delay connected with hydraulic pipeline system

The hydraulic systems in the aircrafts take one of the important role and are critical for a smooth flight and aircraft functioning. The aircraft hydraulics are used on aircraft of all sizes to operate most of their equipment such as landing gears, brakes, flaps, thrust reversers, and flight controls. Thus, the hydraulic system performs the function of moving and actuating the critical and the basic components, according to Leśniewski et al. (2022) and Urbanowicz et al. (2021). In the aircrafts, exist two main hydraulic system types: the basic hydraulic system and power hydraulic system, according to Aeroclass (2021) (Figure 1a). The basic hydraulic drive system of aircraft has two further operation approaches: open and closed coil hydraulic system and consist from basic hydraulic elements: reservoir, pump, distribution valve, actuators etc. In the open coil system, there is no pressure within the system, but only the fluid flows, due to which the actuator in the system remains idle In the closed coil system, the fluid is under pressure all times. In both type of aircraft hydraulic systems for connecting its elements in one operation system a different variety of the specific elements (high-pressure hoses, metal pipelines, fittings etc.), according to Karpenko (2022) and Lubecki et al. (2021), is forming the structure of hydraulic drive. According to Nishimura and Matsunaga (2000), pipelines and fittings are not only used for connection of hydraulic equipment's, their second task is to provide of ensuring the correct direction of flow inside the hydraulic drive. At the same time, in the aircraft, according to Karpenko (2022), Shen and Dongbiao (2022), the 1/3 of mechanical failures are issues in hydraulic systems. Accordingly, maintenance and exploitation operations related to hydraulic systems account for one-third of the entire mechanical problem also connected with a delay of operation or sudden power losses in the system (Reveley et al., 2011).

Aviation hydraulic control are often accompanied by backup systems to ensure the safety of aircraft operations. Ensuring the reliability of these systems is essential for maintaining aircraft safety standards. That why, monitoring the condition of aircraft hydraulic systems is significantly important in both academic and industrial fields (Bertolino et al., 2021; Mehmood et al., 2021; Stosiak, 2012). Evidently, to ensure the safe and reliable operation of aircrafts' hydraulic system, fault diagnoses and prediction of the hydraulic system failures are crucial for researcher (Lu et al., 2017). The main type of faults may occur in aircraft hydraulic systems connected with a reduction in the supply

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pressure, power losses or sensor errors caused by issues in the fluid flow (Zhang et al., 2022).

According to Kudźma and Stosiak (2013) and Yan et al. (2019) researches, even a minor resistance inside fluid flow can brought in final a major impact on the power consummation and operation time of hydraulic drive. For correct control of hydraulic elements, in order to achieve energy-saving in hydraulic drive, for linear control models (Kai et al., 2015) and nonlinear/adaptive control systems (Kong et al., 2019) is critical to achieve circumventing mismatch during control processes by controlling fluid pressure, flow and correct direction of the fluid, according to (Yan et al., 2019). Along with different control methods for the energy reduction and optimization of drive performance the correct flow of the fluid and determination of its characteristics inside hydraulic drives have deemed like one of major research interests.

According to European Standard (2015) and International Standard Organisation (2016), pipeline assemblies must be clearly, permanently marked and correct type of fittings should be used. By different manufacturing's recommendations (Parker Hannifin Ltd., 2019) and safety guides (Eaton, 2020) its strongly recommended to avoid distorting assembly and installation of pipelines. In Eaton safety guide (Eaton, 2020) is pointed that – improper installation of the hydraulic pipeline can result in death, bodily injury, or property damage caused by spraying fluids or flying projectiles. Proper pipe installation is essential for satisfactory performance, reduce energy losses, increase operation time and increasing service life of hydraulic drive. One's of the main recommendation include that a straight fitting connection cannot be used for connecting an equipment's installed in the different level or a plane. In this case is recommended to use 45° or 90° fittings connections, to avoid permitting adequate flexing and allow for length changes due to expansion or contraction, some of recommendations is showed in Figure 1b (draw by author according to a safety guides information).

According to Chuang and Ferng (2018), even the changes of fluid flow by bending of pipeline or using T-shape adapters etc. can lead for a greater fluid pressure (energy) loss. At the same time, for a fitting connection doesn't exist normally theoretical studies, the approximate characteristics for describing fittings was established by experiments in the 1980s by Crane Co (1982) what is to old and required a revisions. The one main aspect which is leading to mistakes is the misuse, during design and calculation, the coefficients characterizing the flow characteristics. With taken in account mentionable above and that the fitting have a complex diameter changes in connection, by Karpenko and Bogdevičius (2020), the are requirements to study an pressure losses and characteristics (coefficients) of hydraulic drive angular fittings.

According to Valdes et al. (2014), to describe and evaluate an quantifying efficiency of fitting connections, mostly used parameters with is include: pressure drop, resistance and flow coefficients. The classic method used for describing an effective using of hydraulic elements is New Crane method, also know like K method, (Crane Co, 1976), based on establishing of ratio of the indexed resistance constants and pressure drops by the losses denoted in the Weisbach-Darcy formula used for each type of the local/minor resistance. The more accurate method for investigating a parameter of hydraulic elements is ranking the two-K method (Hooper, 1981) where the K method is complemented by laminar and turbulent flow equations. However, this complementation is not give an significant change, since, the determination coefficients can be altered to by like fluid flow function.

Moraesa et al. (2017) estimate that a pressure drop on fitting elements can be accepted for system modelling, according to the method of equivalent length. The equivalent length method is based on the technic when the investigation of losses at fitting connections can by accepted like calculation losses by adding the equivalent length of fittings to hose (with the same hose inner

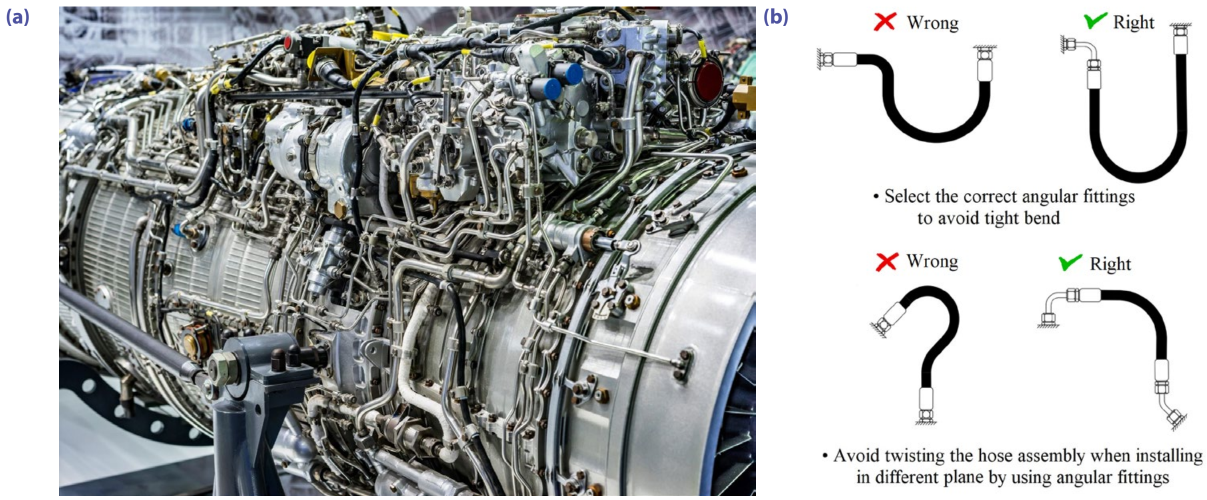


Figure 1. The typical aircraft hydraulic drive system composition: (a) – part of the aircraft pipelines system by Aeroclass (2021); (b) – recommendation according hydraulic pipeline installation

diameter). The main disadvantage of current method is a lack of information by changes in cross-section configuration of fitting connection and possible angular shape of connection for a modelling and main calculation, since a fluid flow vortex in the fitting connection can lead even to the turbulent processes.

In research Li et al. (2019) is pointed that use of Computational Fluid Dynamic (CFD) has advantages by a time and finance costs for research on flow processes in the hydraulic drive system. CFD based on Finite Elements Method (FEM) or Finite Volume Method (FVM) is technology commonly used for simulating the 3-D laminar and turbulent flow with a high degree of accuracy. According to Karpenko and Bogdevičius (2020), by taking into account the time costing, resource spend on the simulation inside hydraulic pipeline, the Standard k-ε model is can be accepted for research on the hydrodynamic processes of fluid flow through angular fitting connections. According to Liu et al. (2020) research the smaller pressure drop occurs in the system, the lower is the power cost of hydraulic units and the fast operation time reaction can be achieved. That why is have a relevant actuality to investigate how an angular fitting connections inside aircraft hydraulic drive influence on it operation parameters

The main problem for a current research is that due to changes in the size of the cross-sectional area of fitting connection and an angular direction of fluid flow inside pipelines, the formation of the flow vortex occurs at fitting connections, which lead that the local losses are significantly higher. A significant problem in this case is to find an effective research methodology that allow analyzing influence on fluid pressure losses and determining the resistance coefficients and time operation delay on real angular fitting connections.

2. Research objects and fluid flow simulation numerical formulation

The structure of any pipeline connections in the hydraulic drive includes two fittings in connection with hydraulic equipment's (pumps, valves, throttles, cylinders etc.), shown in Figure 2a. By research Karpenko and Bogdevičius (2020), for current research the main popular standards BSP (British Standard Pipe cylindrical thread made according to the British National Standard, 2005) was selected. For simulation purposes, the cross-section of angular fitting connections with a fluid flow inside was created 3D models, presented in Figure 2b. In the research, two types of angular fitting connections 45° and 90° by DKR types (swage/angular fitting with a nut) and AGR (swage/ straight fitting with a treat) of connection composition.

The changes in the shape, configuration and size of cross-sectional area of the fluid flow in the fitting connections and pipeline/equipment's is a main issue. In the current research the 08 DASH (1/2″ or 12,7 mm) conditional passage of pipeline is used, since by Karpenko and Bogdevičius (2020) research was disclose that a pipeline of 08 DASH diameter of the conditional passage is one of the most frequently used diameters in the hydraulic drives.

The fluid flow movement inside angular fitting connections was considered in 3-dimentional. The local velocity's for numerical modelling is equal to average velocity and remains to be unsettled. The dynamics of the compressible and Newtonian fluid flow is governed by Navier–Stokes equations and represented by the conservation of momentum, in this case, from mass conservation, the divergence of the velocity field is zero ($\nabla u = 0$). Movement and

(a)

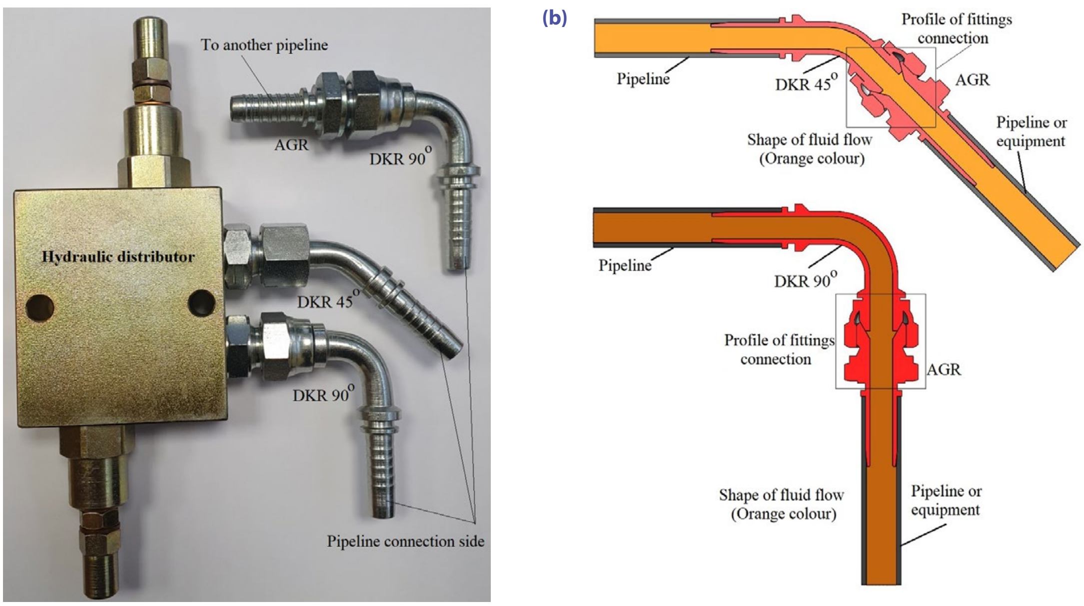


Figure 2. Fittings view under research: a) view of the angular fitting connections in hydraulic system; b) cross-section of angular fitting connections 3D models

continuity equations for the fluid in the pipeline-fitting connection-equipment (Karpenko et al., 2022):

$$\begin{aligned}
&\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}= \\
&-\frac{\partial p}{\partial x}+\frac{1}{\mathrm{Re}}\left[\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{xy}}{\partial y}+\frac{\partial\tau_{xz}}{\partial z}\right]; \\
&\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}= \\
&-\frac{\partial p}{\partial y}+\frac{1}{\mathrm{Re}}\left[\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{yz}}{\partial z}\right]; \\
&\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=, \\
&-\frac{\partial p}{\partial z}+\frac{1}{\mathrm{Re}}\left[\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z}\right],
\end{aligned} \tag{1}$$

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0\,. \tag{2}$$

Numerical computations was carried out by commercial software ANSYS Workbench. Simulation software was configured for a study of the fluid flow in 3-dementional geometry, and the standard k–ε turbulence model was selected to analyses fluid flow, since this type of the modeling was well validated in Karpenko et al. (2022) research. For the standard k–ε turbulence model, the following transport equations for turbulent kinetic energy k and turbulent dissipation ε are implemented:

$$\begin{aligned}
&\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+ \\
&2\mu_t E_{ij}E_{ij}-\rho\varepsilon; \\
&\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+ \\
&C_{1\varepsilon}\frac{\varepsilon}{k}(2\mu_t E_{ij}E_{ij})-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k},
\end{aligned} \tag{3}$$

$$\mu_t=\rho C_\mu k^2/\varepsilon, \tag{4}$$

where $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ – constants of the k-ε turbulence model, taken from Karpenko et al. (2022).

For numerical simulation was used the standard mineral hydraulic oil (Hydraux HLP 46) that conforms to the German National Standard (2017). The properties of hydraulic oil used for numerical simulation can be found in Karpenko et al. (2022). The boundary conditions used for the CFD equations calculation a shows in Figure 3a with example of the applied boundary conditions.

The numerical model is based on FVM. The investigation area is 3-dimentional volume closed from the all sides and divided by mix of tetrahedral and pyramid elements. The mesh refined near changes in the cross-sectional area and around restrictive place, as necessary in order to obtain more accurate results. Close to the walls, boundary layers maximally affect velocity gradients in the normal direction to the wall. From 5 to 10 inflation layers (IL) were created with expansion factor of 1.2–1.6 depending on shape of the connections and changes in the diameter for flow (see Figure 3b). The used model was well validated in the research Karpenko (2021) and was used for current research.

The study of mesh independence study was conducted by creation different type of mesh for angular fitting connection for determination a mesh quality affected on the results of CFD numerical simulation and to limit the maximum element size requirement (Figure 4a). The number of elements and primarily obtained results and simulation time using which is summarised the main characteristics of the mesh is shown in Figure 4b (where, EL – equivalent length; EL-SS – equivalent length-same shape).

It is important to note that mesh resolution plays a pivotal role in the final CFD results. At Mesh M3, Mesh M4 and Mesh M5 the pressure drop obtained results give the almost same value. Mesh M3 and Mesh M5 have nearly 4–5% difference by the results of pressure drop, but numerical solution time has a significant difference. By a minor difference between Mesh M5 and Mesh M3 results, but significant different in the time cost, the Mesh M3 was accepted in the research for numerical simulations.

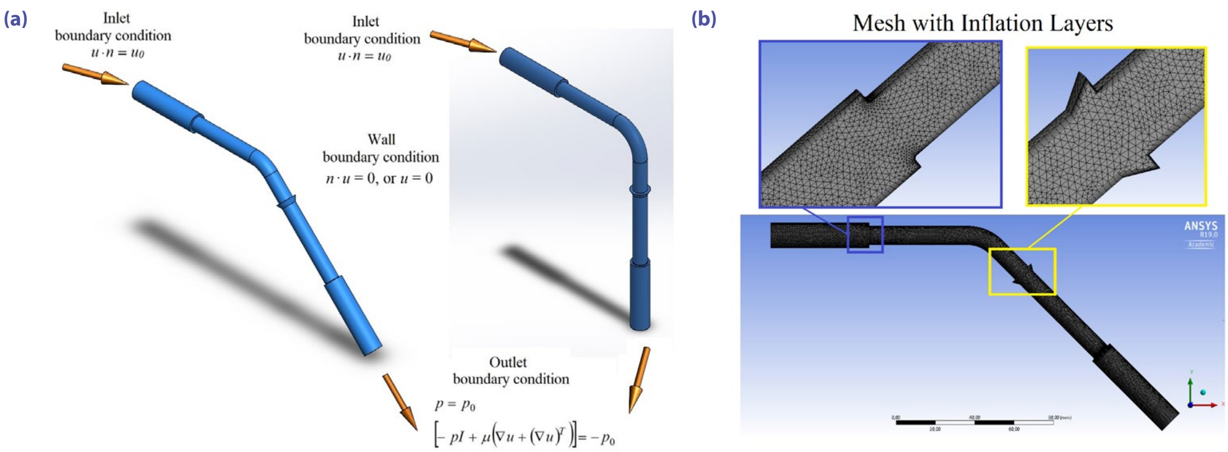
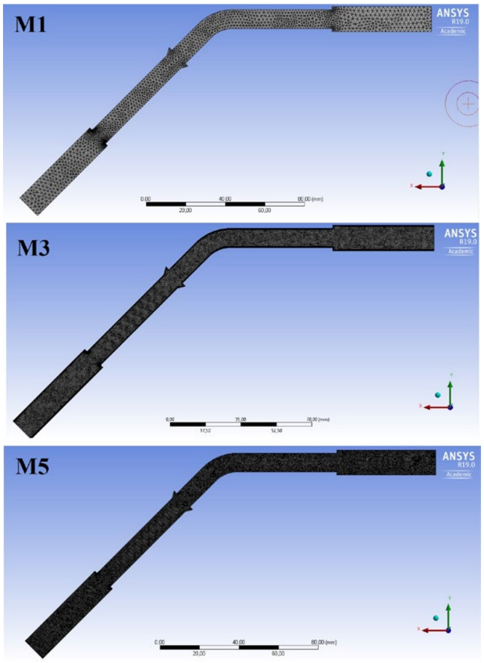


Figure 3. Views of numerical simulation model for angular fitting connections (1/2): a) boundary conditions of the fluid flow for ANSYS fluent simulation; b) mesh example of the numerical model

(a)



(b)

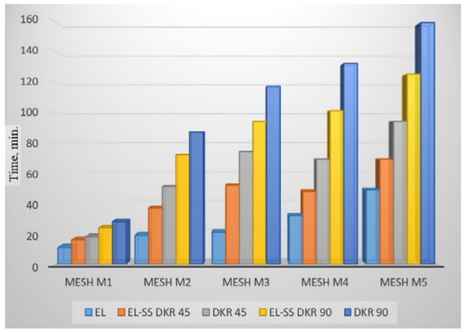
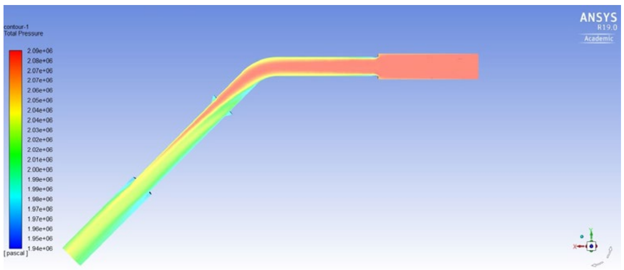


Figure 4. Views of numerical simulation model for angular fitting connections (2/2): a) mesh resolution of the grid independence study; b) summarised results from grid independence study

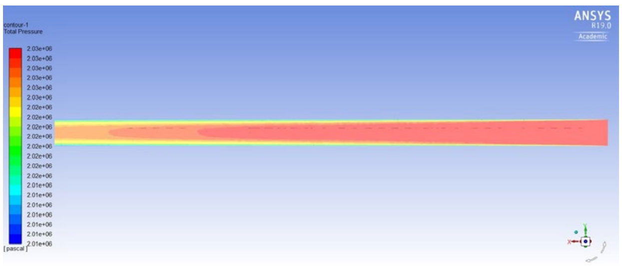
3. Results from the numerical simulation and discussion

By numerical simulation was obtained the pressure drops on the different angular fitting connections in the flow rate range up to 100 l/min. The total pressure profile of fluid flow on angular fitting connections, EL and EL-SS methods in Figure 5 is displayed. The fluid flow vectors on the angular fitting connections are provided in Figure 6, like additional results, since the fluid flow vortex problem processes one of the main parameter influenced on the hydraulic drive operation delay. All provided results on the Figures 5 and 6 were taken from the ANSYS Fluent with corresponded to the inlet flow rate 50 l/min and fluid pressure at outlet 2MPa (middle point of simulated flow rate range).

(c)

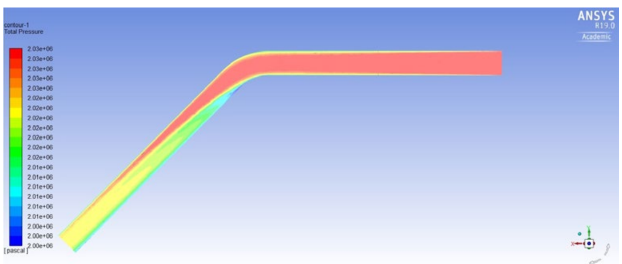


(a)



(d)

(b)



(e)

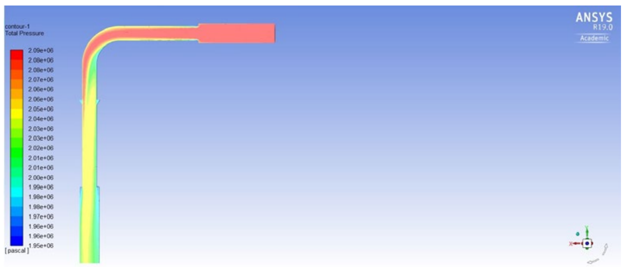


Figure 5. The view of the total fluid flow pressure across angular fitting connections: a) EL method; b) EL-SS method for DKR 45° connection; c) DKR 45° connection; d) EL-SS method for DKR 90° connection; e) DKR 90° connection

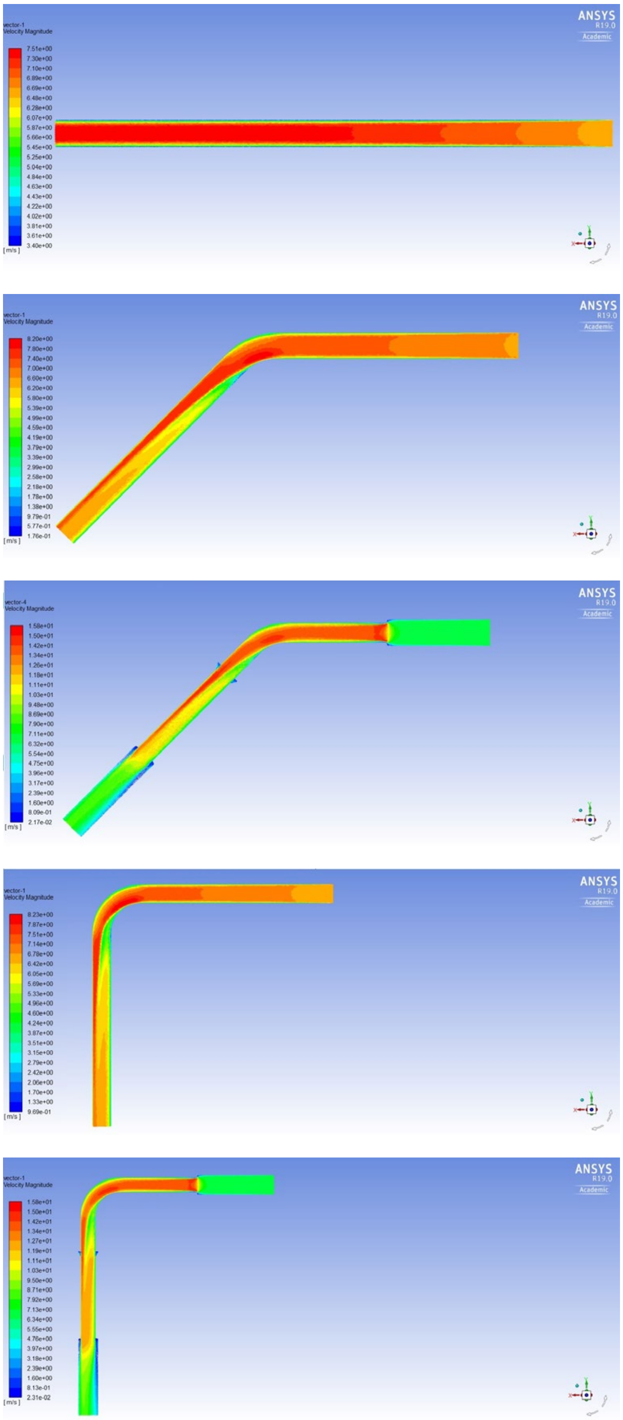


Figure 6. The view of fluid flow vectors across angular fitting connections: a) EL method; b) EL-SS method for DKR 45° connection; c) DKR 45° connection; d) EL-SS method for DKR 90° connection; e) DKR 90° connection

The energy losses (power) at angular connections were calculated from the obtained fluid pressure losses (see Figure 7) and operation delay, according to flow coefficient (The flow coefficient is a relative measure of its efficiency at an allowed fluid flow. Flow coefficient describes the relationship between pressure drop across the fitting connection orifice and the corresponding flow rate), and displayed the delay of operation in hydraulic drive connected with a fluid flow, the time-efficient operation chart is shown in Figure 8.

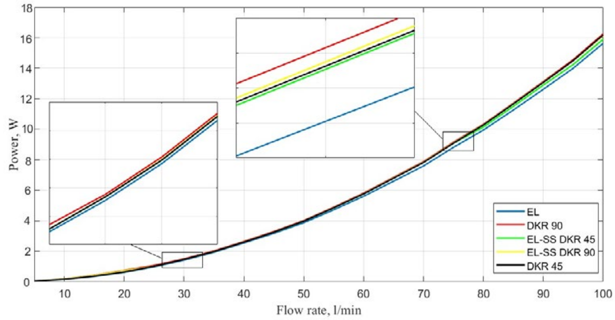


Figure 7. Energy losses at the angular fitting connections

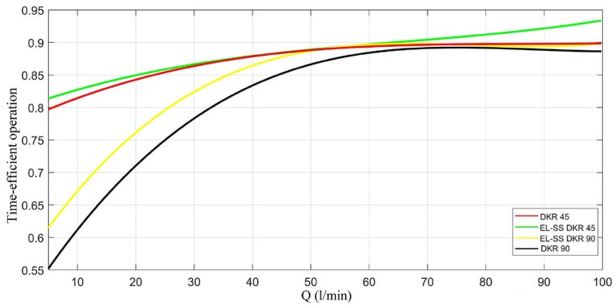


Figure 8. Time-efficient operation at the angular fitting connections (based on flow coefficient)

The differences between change in the cross-sectional areas of real angular fitting connection and classic methods for calculation had a significant impact on flow characteristics. The significant difference in flow characteristics at different flow processes inside angular fitting connections is observed. Research results on investigation of energy (power) losses in real profile of angular connection demonstrated significant power losses compared to simple EL method. Even comparing with EL-SS method difference in power losses between calculation with real profile of angular fitting connection is approximately 15% due to laminar flow and the difference in turbulence flow is grow up to 26%.

The EL method of calculation (strait pipe) had the most optimal flow characteristics that why the operation delay is can be counted like not existed (flow coefficient equal to 1 what mean the 0 of time delay). EL-SS method included that for 45° connection (time operation decrease from 0.924 to 0.827) and for the 90° connection (from 0.851 to 0.652) and performed worse. Flow characteristics of real angular fitting connection profile is for 45° connection (time operation decrease from 0.901 to 0.802) and for the 90° connection (from 0.843 to 0.551) and performed the least effectively. In case of operation delay can be found that using EL-SS method or real fitting connection the delay of operation will increase for ~13% for 45° connection (depend from the flow rate) and ~33% for 90° connection, what is really critical and must be taking in account during projecting aircraft hydraulic systems.

The results from the modelling are showed that the equivalent length and equivalent length same shape methods is not acceptable as accurate technique for calculating pressure, energy losses and operation delay in the angular fitting connections. The conducted research disclosed that each types of angular fittings connection is required additional investigation before installation in the aircraft hydraulic pipelines system.

4. Conclusions

With reference to theoretical research on simulating the hydrodynamic processes of angular fitting connections and straight pipeline, the obtained results showed that due to changes in the size and configuration of the cross-sectional area, flow velocity, the separation of transit flow from the walls of the channel and the formation of vortex occur at fitting connections. In the research the influence of hydrodynamic processes on the fluid flow characteristics by installation angular fitting connections in the pipeline systems was analysed. The provided analysis is based on validated numerical model by using Navier–Stokes equations and k-epsilon turbulence model. The dynamics of fluid flow in the hydraulic system was investigated taking into account the main parameters of flow rate up to 100 l/min. To simulate fluid flow, a mesh independence study was performed. As a result, fluid pressure drops, energy losses and operation delay connected with fluid flow vortex at 45° and 90° angular fitting connections was obtained. Research results on investigation of energy (power) losses in real profile of angular connection demonstrated significant power losses compared to simple EL method. Even comparing with EL-SS method difference in power losses between calculation with real profile of angular fitting connection is approximately 15% due to laminar flow and the difference in turbulence flow is grow up to 26%. In case of operation delay can be found that using EL-SS method or real fitting connection the delay of operation increases for ~13% for 45° connection (depend from the flow rate) and ~33% for 90° connection, what is really critical and must be taking in account during projecting aircraft hydraulic systems. In the research confirmed that utilizing the equivalent length method and equivalent length same shape method is inappropriate for investigating angular fitting connections.

Disclosure statement

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