Effects of inclined cylinder ports on gaseous cavitation of high-speed electro-hydrostatic actuator pumps: a numerical study

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**ABSTRACT**

Raising the rotational speed of electro-hydrostatic actuator (EHA) pumps is a useful way to improve their power density. However, gaseous cavitation tends to occur in the displacement chambers at high speed, reducing the effective delivery flow rate of EHA pumps. It is a common approach to reduce the gaseous cavitation by increasing the inlet pressure. However, this conventional approach requires additional devices to boost the inlet line, which decreases the EHA pump’s power density. The contribution of this study is to reduce the gaseous cavitation by introducing inclined cylinder block ports for EHA pumps, which only modifies the cylinder ports and needs no additional devices. A computational fluid dynamics (CFD) model was developed to investigate the effects of the inclined direction of cylinder ports on the gaseous cavitation. The simulation results showed that the inward-inclined design of cylinder ports could effectively decrease the gaseous cavitation using centrifugal effects of rotating fluid. Compared with a standard cylinder block, the cylinder block with inward-inclined ports could increase the effective delivery flow rate by 4% at an inlet pressure of 1 MPa and a rotational speed of 20,000 r/min.

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1. Introduction

As a newly developed self-contained power device, the electro-hydrostatic actuator (EHA) has been successfully applied in the field of aerospace, such as primary flight control, landing gears, thrust vector control, and engine actuation systems (Alle, Hiremath, Makaram, Subramaniam, & Talukdar, 2016; Maré & Fu, 2017). In recent years, EHAs also seek potential applications in other fields, such as robotics, wind turbines, and transportation vehicles (Karanović, Jocanović, & Jovanović, 2014). The EHA combines the advantages of electric and hydraulic technologies and is generally characterized as smaller size and higher power density compared to electric actuators and traditional hydraulic actuators (Alle et al., 2016). A typical EHA system mainly consists of a servo motor, hydraulic pump, bypass valve, and a hydraulic actuator (Habibi & Goldenberg, 2000), as shown in Figure 1. The servo motor directly drives the bi-directional pump that is also called EHA pump (Zhang, Chao, & Xu, 2018), providing the actuator with pressurized fluid. The rotation direction and delivery flow rate of the EHA pump control the direction and velocity of the actuator, respectively.

As one kind of positive displacement pumps, axial piston pumps are often chosen to be EHA pumps. Figure 2 shows the schematic cross-section of an axial piston pump, where the cylinder block accommodates an odd number of pistons at equal angular intervals. Each slipper is connected to a piston through a socket-and-ball joint. A reasonable gap height between the slippers and swash plate is kept by a retaining mechanism (not shown in Figure 2). The shaft and cylinder block are coupled by the spline, and they are supported by two bearings at both shaft ends. A compressed spring is nested in the cylinder block to push it towards the valve plate. As the cylinder block rotates along with the shaft the slippers slide against the angled swash plate, forcing multiple pistons to advance into or withdraw from the cylinder block. The varied displacement chambers fulfill the task of discharge and suction of hydraulic fluid through two valve-plate openings, and the mechanical energy is converted to hydraulic energy.

Power density is of importance to EHA pumps, and raising rotational speed is a common way to improve it because a small pump displacement can benefit from high rotational speed for a certain delivery flow rate. However, high-speed rotation leads to gaseous cavitation in the displacement chambers when the fluid pressure drops below the gas saturation pressure (Schleihis et al.,...
Three main factors contribute to the pressure drop of hydraulic fluid. First, the pressure loss is caused as the hydraulic fluid enters the cylinder block and then accelerates to the piston velocity (Manring, Mehta, Nelson, Graf, & Kuehn, 2014; Totten & Bishop, 1999). Second, the reverse flow creates a pressure undershoot in the displacement chamber as the suction stroke begins, which can make the transient pressure below the saturation pressure (Harris, Edge, & Tilley, 1994). Finally, the centrifugal effect due to the cylinder block rotation causes an inhomogeneous pressure in the radial direction in the displacement chambers (Kunkis & Weber, 2016). Consequently, the localized displacement chamber pressure becomes rather low near the rotation center.

The dissolved gas will release from the hydraulic fluid and becomes free bubbles once the gaseous cavitation happens, which adversely affects the performance of the whole EHA system in the following two ways. First, it decreases the effective delivery flow rate of the EHA pump (Kunkis & Weber, 2016; Vacca, Klop, & Ivantysynova, 2010), reducing the position accuracy of the actuator. Second, the released gas decreases the effective bulk modulus of hydraulic fluid (Gholizadeh, Burton, & Schoenau, 2012), leading to a slow response speed of the whole EHA system.

In engineering practice, it is effective to avoid the gaseous cavitation of common axial piston pumps at high speed by increasing their inlet pressure (Kunkis & Weber, 2016; Manring et al., 2014; Yin, Nie, Xiao, & Hou, 2016). For instance, an external charge pump or a pressurized reservoir is used to boost the inlet line, but these additional devices bring about parasitic losses and decrease the pump’s power density.

This paper aims to reduce the gaseous cavitation in high-speed EHA pumps by introducing inclined cylinder ports instead of standard ones for the cylinder block. The small modification of the cylinder ports gives the advantage to this new design compared to conventional method of boosting the inlet line, since it can improve the suction performance of EHA pumps without an additional power source. A CFD model for the EHA pump was developed to explore which inclined direction of cylinder ports could reduce the gaseous cavitation. The gas volume fraction and effective delivery flow rate of the EHA pump were compared between standard and inclined cylinder ports under different operating conditions. Based on the comparison results, the advantageous inclined direction of cylinder ports was finally determined for the high-speed EHA pump.

2. Comparison of different cylinder ports for the EHA pump

Figure 3 shows the configurations of three different cylinder ports for an EHA pump. The standard cylinder port (Figure 3(a)) runs parallel to the cylinder bore while the other two types of cylinder ports (Figure 3(b,c)) are inclined relative to the cylinder bore. On the one hand, too small inclined angle $\gamma$ of the cylinder port almost makes no difference to the suction performance of the pump. On the other hand, the inclined angle is limited by the cylinder configuration and strength. In this work, the inclined angle of the cylinder port is designed to be 11°. For the standard cylinder port, the hydraulic fluid travels straight into the cylinder block from the valve-plate opening. The centrifugal force $F_c$ has almost no impact on the entering flow because its direction is perpendicular to the flow direction. For the outward-inclined cylinder port the hydraulic fluid moves towards the inside wall of the cylinder bore where the gaseous cavitation probably take place at high speed (Kunkis & Weber, 2016). However, this outward-inclined design tends to reduce the entering fluid since the flow and the component of the centrifugal force $F_1$ are in opposite directions. In
contrast, the inward-inclined design makes the entering fluid and the component force $F_1$ have the same direction, which forces more hydraulic fluid to flow into the cylinder bore. However, in the third design, the hydraulic fluid rushes towards the outside wall of the cylinder bore, which may fail to fill the cavitation region near the inside wall of the cylinder bore.

As shown in Figure 4, it seems that the outward-inclined design is advantageous to reduce gaseous cavitation near the inside wall of cylinder bores by changing the flow direction (Kunkis & Weber, 2016); while the inward-inclined design offers a promising approach for reducing the total gaseous cavitation in the displacement chambers by improving the suction performance of EHA pumps. Therefore, further investigation is needed to determine which inclined direction is helpful to reduce the gaseous cavitation and to improve the effective delivery flow rate of the high-speed EHA pump.

In recent decades, rapid improvements in the computational power have made computational fluid dynamics a useful tool for real-life case studies (Akbarian et al., 2018; Ardabili et al., 2018; Mou, He, Zhao, & Chau, 2017). Due to the complex structure of the pump, it is difficult to observe the flow field inside the pump experimentally. Therefore, the effects of the inclined direction of cylinder ports on the gaseous cavitation will be investigated numerically in the following section.

3. Simulation model

The numerical analysis was conducted using a commercial CFD software called PumpLinx® which is developed by Simerics Inc. This CFD code can accurately include the physical model for cavitation. Based on the work of Ding, Visser, Jiang, and Furmanczyk (2011), the cavitation model used in the code is described through the following equation:

$$\frac{\partial}{\partial t} \int_{V(t)} \rho f_v dV + \int_S \rho [(v - v_s) \cdot n] f_v dS$$

$$= \int_S \left( D_v + \frac{\mu_t}{\sigma_f} \right) (\nabla f_v \cdot n) dS + \int_V (R_e - R_c) dV$$

where $V$ is the control volume and $S$ is its surface area, $n$ is the surface normal of $S$ and is pointed outwards, $\rho$ denotes the fluid density, $f_v$ denotes the vapor mass fraction, $v$ denotes the fluid velocity, $v_s$ denotes the velocity of surface motion, $D_v$ stands for the vapor diffusivity, $\mu_t$ stands for the turbulent viscosity, and $\sigma_f$ stands for the turbulent Schmidt number.

The vapor generation $R_e$ and the vapor condensation rate $R_c$ are given by

$$R_e = \frac{\sqrt{k}}{\sigma} \rho \rho_v \left[ \frac{2 (p - p_v)}{\rho_l} \right]^{1/2} \left( 1 - f_v - f_g \right)$$
\[ R_c = C_e \frac{\sigma}{\rho_l};\rho_v \left[ \frac{2 (p - p_v)}{\rho_l} \right]^{1/2} \]  

(3)

where \( C_e \) and \( C_c \) denote the coefficients of cavitation evaporation and condensation, respectively.

The relationship between the mass fraction \( f_v \) of vapor and the density \( \rho_m \) of the fluid mixture is described as (Ding et al., 2011)

\[ \frac{1}{\rho_m} = f_v + f_g \rho_g \rho_l / \rho_v + 1 - f_v - f_g \]  

(4)

where \( f_g \) is the gas mass fraction, \( \rho_v \) is the vapor density, \( \rho_g \) is the gas density, and \( \rho_l \) is the liquid density.

In addition, the CFD code can also account for the fluid compressibility. This is critical to accurately model the gaseous cavitation because the fluid compressibility affects the reverse flow that is an important contributing factor to the gaseous cavitation.

The fluid domain was extracted from the original CAD data of an EHA pump prototype and then imported into PumpLinx®. The grid solution needed to consider the relative motion of fluid domains because there were moving/rotating parts and stationary parts in the EHA pump. For this reason, the entire fluid domain was divided into several volumes, and the stationary part (valve plate), the moving parts (pistons) and the rotating part (cylinder block) were separately meshed. The volume mesh totally contained 119,168 cells, 423,862 faces, and 176,967 nodes. Figure 5 shows a view of the entire computational domain and mesh.

The PumpLinx® offered two types of meshers: general mesher and rotor template mesher. The general mesher used a body-fitted binary tree method to create a mesh for the stationary valve-plate openings and relief grooves, while the rotor template mesher created a structured hex mesh for the moving pistons and rotating cylinder block. The specialized template mesher allowed for relative motions between the neighboring fluid volumes by connecting them to each other through implicit interfaces. To avoid time-consuming computation and improve numerical stability, the computational domain did not include lubricating interfaces such as cylinder block/valve plate interface, piston/cylinder block interface and slipper/swash plate interface. Therefore, the external leakage flow was not considered in this CFD model.

The main characteristics of the investigated EHA pump prototype are summarized in Table 1, and the fluid properties involved in the CFD model are listed in Table 2.

4. Results and discussion

All the simulation results presented in this section were obtained under steady-state conditions after ten revolutions of the cylinder block. Figure 6 gives the sample results for gas volume fraction in a displacement chamber, which is an indicator of the instantaneous degree of gaseous cavitation. The higher the gas volume fraction is, the more serious the gaseous cavitation is. Note that both the inlet and outlet pressures are absolute pressure. The good repeatability of simulation results in the last three revolutions (Figure 6(a)) suggests that the steady-state of the EHA pump has been achieved. To better understand the gaseous cavitation occurred in the EHA pump, it is necessary to take a closer look at the varied gas volume fraction in the displacement chamber. Taking the first one of the last three revolutions for example, as shown in Figure 6(b), it is observed that the gaseous cavitation mostly takes place during the suction phase. This is to be expected because the displacement chamber pressure is far lower during the suction phase than during the discharge phase. The occurrence of gaseous cavitation is mainly attributed to the reverse flow, insufficient supply, and centrifugal effect of the rotating fluid.
The region A–B on Figure 6(b) shows a rapid rise in the gas volume fraction due to the reverse flow and insufficient supply. The reverse flow at the start of the suction phase creates a significant pressure undershoot, contributing to the rather low transient pressure in the displacement chamber (Harris et al., 1994). What is worse, the piston experiences acceleration during the initial part of the suction phase but the cylinder port has not yet been fully communicated with the valve-plate opening (Kunkis & Weber, 2016). As a result, the displacement chamber is undersupplied and the entering fluid fails to follow closely the accelerating piston, which leads to a low transient displacement chamber pressure due to the increased void volume. Therefore, the combination of reverse flow and insufficient supply is the main reason for the rapidly increased gas volume fraction during the initial part of the suction phase.

The gas volume fraction starts to generally drop (region B–C) as the reverse flow is finished and the cylinder port is connected fully to the valve-plate opening. The oscillation of gas volume fraction during this phase results from the combining effects of the inherent pressure ripple, constant centrifugal effect, and varying piston velocity. These factors are dependent on the operating conditions and together influence the transient displacement chamber pressure and gaseous cavitation.

When the piston arrives at the discharge side (region C–D), the cylinder port begins to be connected to another valve-plate opening. The displacement chamber pressure increases from the suction pressure to the discharge pressure, and the gaseous cavitation reduces rapidly. Eventually, the displacement chamber pressure rises to the discharge pressure and the gaseous cavitation is almost disappeared for the remainder of the discharge phase (region D–E).

The severity of the gaseous cavitation depends upon the operating conditions, especially the inlet pressure and the rotational speed. Figure 7 shows the influence of inlet pressure on the gaseous cavitation for the standard cylinder port. In the first place, it can be seen that increasing the inlet pressure can dramatically reduce the peak value of the gas volume fraction. This is partially because the inlet pressure becomes more sufficient to be consumed by the pressure losses during the suction phase, and partially because the lower differential pressure between the suction and discharge ports reduces the reverse flow. In the second place, it is found that the gas volume fraction starts to decline earlier with the increasing inlet pressure, i.e. \( \theta_{0.1} > \theta_{0.5} > \theta_{1.0} > \theta_{1.5} \). This can be explained by the fact that the hydraulic fluid is able to follow the accelerating piston more closely and the reverse flow is finished in a shorter time for a higher inlet pressure. When the inlet pressure is too low (for example, 0.1 MPa), the gas volume fraction with a high peak value starts to decline too late so that it remains at a high level during the whole suction phase. Consequently, the basic task of suction and discharge of the working fluid cannot be completed, leading to a breakdown of the delivery flow rate. Similarly, too high rotational speed can also lead to severe gaseous cavitation for a certain inlet pressure, as shown in Figure 8.

Therefore, it is necessary to avoid excessive gas volume fraction for high-speed EHA pumps with low inlet pressures. As previously stated, the inclined cylinder ports are expected to reduce the gaseous cavitation of EHA pumps. Figure 9 shows a comparison of gas volume fraction in an individual displacement chamber between standard and inclined cylinder ports. It is clear that compared with the standard cylinder port, the inward-inclined cylinder port reduces the gaseous cavitation while the outward-inclined cylinder port increases the gaseous cavitation.
Figure 7. Gas volume fraction in a displacement chamber at different inlet pressures for the standard cylinder port (Outlet pressure: 28 MPa; rotational speed: 10,000 r/min).

Figure 8. Gas volume fraction in a displacement chamber for the standard cylinder port at different rotational speeds (Inlet pressure: 1.0 MPa; outlet pressure: 28 MPa).

Figure 9. Comparison of gas volume fraction in a displacement chamber for three different cylinder ports (Inlet pressure: 0.1 MPa; outlet pressure: 28 MPa; rotational speed: 10,000 r/min).

Figure 10 compares the three-dimensional region of gaseous cavitation between standard and inclined cylinder ports. It is observed that compared with the standard cylinder ports, the region of gaseous cavitation in displacement chambers becomes larger for outward-inclined cylinder ports but smaller for inward-inclined cylinder ports. The total fraction of gas volume in the displacement chambers for standard, outward-inclined, and inward-inclined cylinder ports are 15.2%, 15.9%, and 14.1%, respectively.

Figure 11 gives a deeper look into the distribution of gas volume fraction on a special plane that passes through both the centerlines of the cylinder block and cylinder bore. It can be seen that the gas volume fraction is radially inhomogeneous, where the gas volume fraction is much higher near the inside wall of the cylinder bore than near the outside wall. This is because the centrifugal effect pushes the heavy hydraulic fluid towards the outside wall but leaves the light entrained air near the inside wall when the mixture of liquid and air in the cylinder block rotates at high speed. For the standard cylinder port, the gas volume fraction of a displacement chamber in Figure 11 is 35.3%, and for outward-inclined and inward-inclined cylinder ports, the gas volume fractions are 35.2% and 31.9%, respectively.

The outward-inclined design of cylinder ports does not reduce the gaseous cavitation near the inside wall of cylinder bores as expected. Instead, the gaseous cavitation of outward-inclined design occurs in larger areas compared with the standard design. This is mainly because the velocity of the entering fluid is too low to overcome the strong centrifugal force at the cylinder port for high-speed EHA pumps. In contrast, the inward-inclined design decreases the gaseous cavitation near the inside wall of cylinder bores. This suggests that for an EHA pump with inward-inclined cylinder ports, its suction performance can be improved with the help of the centrifugal effect at the cylinder port.

The gaseous cavitation directly affects the pump’s effective delivery flow rate or the filling ratio that is defined as the ratio of the effective delivery flow rate to a theoretical one. In turn, the filling ratio can be regarded as an indicator of the gaseous cavitation occurred in the EHA pump, and a large filling ratio indicates a lower degree of gaseous cavitation.

Figure 12 gives a comparison of filling ratio for the three types of cylinder ports. The EHA pump with inward-inclined cylinder ports has the highest filling rate at low inlet pressure due to the improved suction performance as described previously. Compared with the standard design, the inward-inclined design increases the filling ratio of the pump by 10% when the inlet pressure is 0.1 MPa and the rotational speed 10,000 r/min. However,
the difference in the filling ratio between these three types of cylinder ports becomes negligible at higher inlet pressure. This is because the suction performance is improved and the reverse flow is reduced considerably for all types of cylinder ports as the inlet pressure becomes enough high.

However, once the rotational speed continues to rise and reaches a critical level for a certain inlet pressure, the inward-inclined design offers a competitive advantage of low degree of gaseous cavitation or high filling ratio again, as shown in Figure 13. For instance, at an inlet pressure of 1.0 MPa and a rotational speed of 20,000 r/min, the filling ratio of the EHA pump with inward-inclined cylinder ports is 4% and 9% higher than those with standard and outward-inclined cylinder ports, respectively. In other words, the inward-inclined design of cylinder ports decreases the dependence of the filling ratio of the EHA pump upon the rotational speed, especially at high rotational speed.

Actually, commercial axial piston pumps with a spherical valve plate usually integrate a similar inward-inclined-port cylinder block as well. However, the inward-inclined cylinder port has not yet been identified as an improvement of suction performance due to the centrifugal effect. Instead, it is usually considered as a well-known design to realize a low tangential velocity of the entering fluid and a low sliding velocity between the cylinder block and valve plate (Kosodo, 2012; Manring et al., 2014; Zecchi & Ivantysynova, 2013). In fact, the simulation results in this work show that the inward-inclined cylinder port has great potential for improvement of suction performance and thus reduction of gaseous cavitation regardless of a flat valve plate.
5. Conclusions and future work

In this work, we have presented inclined cylinder ports for high-speed EHA pumps to reduce gaseous cavitation. A CFD model was developed to examine the effects of inclined direction of cylinder ports on the gaseous cavitation. Based on the simulation results presented in this paper, the following conclusions can be drawn:

1. The gaseous cavitation tends to occur in EHA pumps at high rotational speed and low inlet pressure, which leads to a declined filling ratio and even a breakdown of the delivery flow rate. The gaseous cavitation mainly occurs during the suction phase due to the pressure loss, reverse flow, and centrifugal effect.

2. The centrifugal effect of the rotating fluid creates a radially inhomogeneous gaseous cavitation in the displacement chambers during the suction phase. High gas volume fraction appears near the inside wall of cylinder bores. It is difficult to eliminate this type of gaseous cavitation because of the inherent rotating fluid governed by the main pump kinematics.

3. The inward-inclined cylinder ports take advantage of the centrifugal effect of the entering fluid at the cylinder ports to improve the suction performance of EHA pumps. Compared with the standard cylinder ports, the inward-inclined ones reduce the gaseous cavitation by 1.1% and increase the filling ratio of the pump by 10% when the inlet pressure is 0.1 MPa and the rotational speed 10,000 r/min.

4. The outward-inclined cylinder ports fail to reduce the gaseous cavitation in the displacement chambers because the velocity of the entering fluid is not enough to overcome its centrifugal fluid at the cylinder ports.

Gaseous cavitation is a serious threat to the effective delivery flow rate of axial piston pumps at high speed, which has been demonstrated numerically and experimentally in previous studies. We devise this research to present an inward-inclined design of cylinder ports to reduce the gaseous cavitation of high-speed EHA pumps. Although this new design has been verified numerically in the present work, one shortcoming of this research may lie in the absence of experimental verification due to practical constraints. Therefore, future work will focus on fabricating a high-speed EHA pump prototype (maximum rotational speed reaches up to 16,000 r/min) and comparing its actual delivery flow rate between the above three types of cylinder blocks.

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