One of the Mysteries in Fluid Mechanics

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Abstract

This paper is not about known mysteries, such as what is turbulence, or how tornadoes, or twisters, work. It is about a discrepancy between an existing theory and actual measurements of flow induced forces. The flow case where the discrepancy occurs is not presented in fluid mechanics textbooks. Rather, it is presented in fluid power textbooks, when the origin of flow induced forces in hydraulic valves is discussed.

The existing theory explaining the origin of flow forces in hydraulic valves is based on Newton's law of motion: Flow force is a reaction force, and its magnitude equals mass times acceleration. Both parameters can be accurately estimated, so the theory can be easily verified.

In the paper, simultaneous recordings of the static pressure distribution in a valve orifice are presented. The measurements show that the jet has a strong tendency to attach itself to the nearest wall. This effect is known as the Coanda effect, and is omitted by the theory. We know that the static pressure in the jet is lower than in the surrounding fluid. If such a jet were attached to a wall of a container, a force perpendicular to the wall would result. This phenomenon cannot be explained by Newton's mechanics.

Introduction

Let us consider a flow case in which a liquid jet, perpendicular to a wall, impinges upon the wall. We would apply Newton's laws of motion to calculate the reaction force (Fig. 1) resulting on the wall. The reaction force could be simply measured with a load cell. We also could estimate the reaction force experimentally by measuring the static-pressure distribution on the wall. All forces, theoretical and experimental, should be the same. The static pressure P1 on the wall in the area of the jet impingement would be higher than outside this area, say P2 on the opposite side of the wall. What would be the pressure P3? According to Bernoulli's equation we would expect this pressure to be lower than P2. The question arises how pressure P3 contributes to the reaction force.

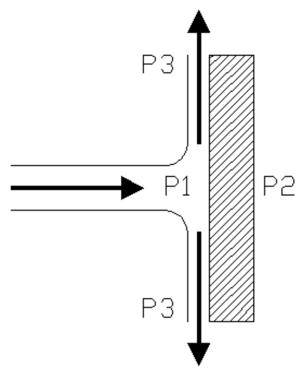

Fig.1. Jet perpendicular to a wall

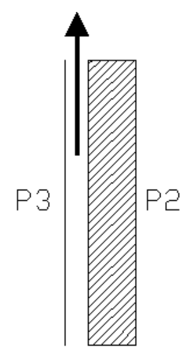

Fig.2. Jet parallel to a wall

We could arrange the jet differently, so it is parallel to the wall, as shown in Fig. 2. Static pressure P3 in the jet can also be expected to be lower than pressure P2. Reaction force would appear on the wall, even though it would be perpendicular to the jet. According to Newton's laws of motion the reaction force on the wall should be equal to zero

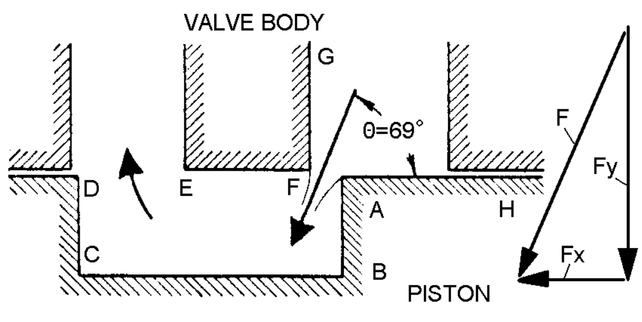

Fig. 3. Flow in a hydraulic valve

A related flow case exists in a hydraulic valve, Fig. 3. The jet enters the control volume ABCDEF with velocity v at the vena contracta. The axial reaction force, which acts on the piston HABCD, tries to close the valve, or to make the valve opening FA smaller. The magnitude of the force creates a problem at high pressures and large flow rates, and requires the application of larger control forces[1,2]. At present, solenoid forces in electrohydraulic valves are usually sufficient to overcome the flow-induced forces. If necessary, two-, three-, or four-stage flow control valves can be used.

However, the theory presented in fluid power textbooks, see Fig. 3, does not seem to agree with actual flow phenomena. By assuming that the jet angle θ is 69 degrees, it disregards the Coanda effect[6]. The Coanda effect causes the jet to attach to the nearest wall, and is known from many applications, such as in fluidics. Without the Coanda effect, an airplane could not fly: The stream of air would not attach to the upper part of the airfoil, and thus the lift force would not exist. There is abundance of information about the Coanda effect, which is available on Internet[3,4,5]. In a hydraulic valve, the Coanda effect also should cause the jet to attach to the wall AB, or EF.

The axial reaction force Fx would exist on the piston, even if the jet angle θ were equal to 90 degrees. The static pressure acting on wall AB would be lower, again according to Bernoulli's equation, than on wall CD. There is a discrepancy between the concept of control volume (ABCDEF), which employs Newton's laws of motion, and actual fluid behavior, as represented by Bernoulli's equation, or the Coanda effect.

According to the momentum theory, the radial component Fy of the reaction force, see Fig. 3, should be more than twice the axial component Fx. Since the reaction forces result from the static-pressure distributions on walls inside the control volume ABCDEF, we would expect that the static-pressure on wall EF would be more than two times lower than on wall AB.

Measurements

The magnitude of the jet angle θ (Fig. 3) can be verified by recording the static-pressure distribution on walls AB and EF. Static pressure on walls BC and CD is always equal to the valve outlet pressure. From the static-pressure distribution on walls AB and EF both radial (Fy) and axial (Fx) components of the flow force (F) can be estimated. This is a reliable way to verify the magnitude of the jet angle (θ): $\tan \theta = Fy/Fx$.

Both pressure distributions on walls AB and EF were recorded simultaneously in 24 points along a flow path of 1.2 mm. The piston diameter was 30.280 mm. Both the piston and the valve body had 12 measuring slots each that enabled the recording of the static-pressure distributions on their surfaces. Each of the measuring slots was connected to a precise Bourdon tube pressure gauge with the measuring capacity from vacuum (-100 kPa) to +300 kPa.

The recorded static-pressure distributions are shown in Figure 4. In this Figure, the axes of both coordinate systems also show the actual arrangement of piston and valve body to each other. The static pressure at the origins of both pressure coordinates was chosen to be equal to the valve outlet pressure P2 (atmospheric pressure = zero gauge pressure). This pressure acts on the opposite surfaces (BC and CD in Fig. 3) of the piston. In this way it is easier to estimate how the recorded static-pressure distributions influence the magnitude of the flow forces. The recorded static pressure drawn on the material of the piston, see the hatched area in Figure 4, contributes to the axial flow force acting in a direction to close the valve.

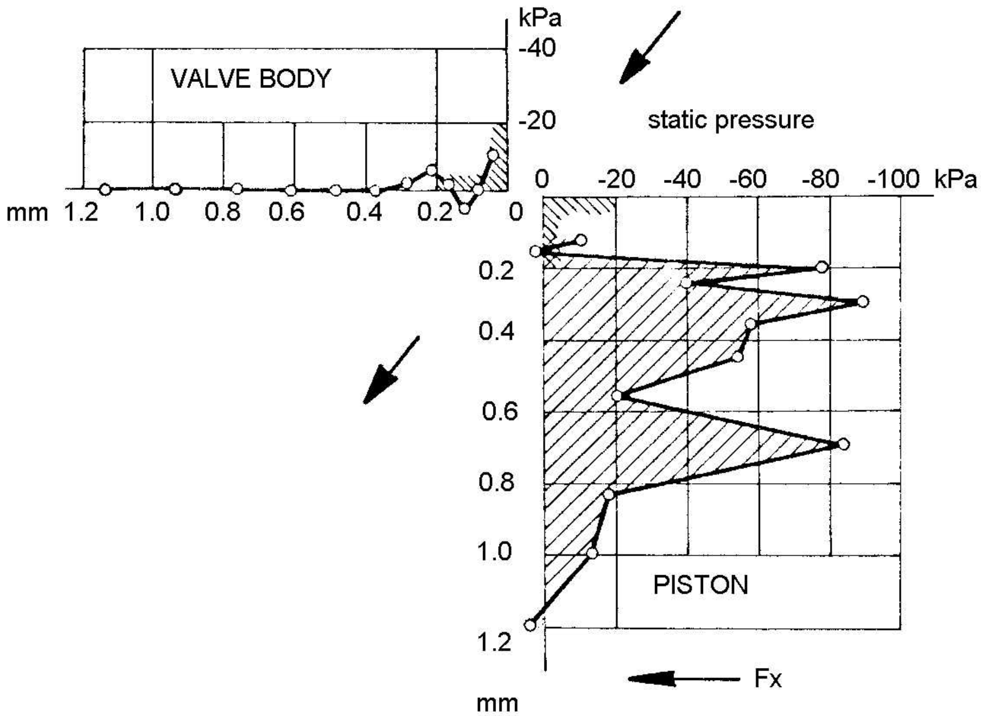

Fig. 4. Static-pressure recordings in a hydraulic valve; valve opening: 0.1 mm, valve flow rate 17.3 L/min, valve inlet pressure: 853 kPa, valve outlet pressure: 0 kPa

The magnitude of the axial flow force on the piston for parameters given in Fig. 4 was 3.1 N based on the static-pressure distribution, and 3.5 N based on the momentum theory, assuming flow coefficient C= 0.8 (contraction) in the vena contracta. The problem is not with the magnitude of the flow force acting on the piston (axial component Fx), but with the radial component Fy acting on the valve body. This force was equal to zero, as can be seen from the static-pressure distribution in Fig. 4. According to the momentum theory the radial component of the flow force should be 2.6 (tan 69 degrees) larger than the axial force. Therefore, a force of 2.6x3.5= 9.1 N should act on the valve body.

From the measurements of the static-pressure distribution in a valve orifice follows, that the jet was attached to the piston (see wall AB in Fig. 3). In such a case, the momentum theory predicts the axial flow force to be zero (cos 90 degrees = 0). But the axial force does exist even with the jet perpendicular to the piston axis, because the static pressure in the attached jet is lower than the valve outlet pressure (outside the jet). The advantage of the static-pressure recordings in a hydraulic valve is that the pressure signals are strong, and that two perpendicular walls exist, on which the pressure can act.

Conclusion

It follows that the momentum theory does not convincingly explain the origin of the flow force in a hydraulic valve. The question arises how to deal with the discrepancy. Does it exist only in a hydraulic valve, or in other flow cases, too? With a better understanding of how the reaction forces are created, it would be easier to make better designs.

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