Flow Along A Grooved Cylinder

Kern E. Kenyon

4632 North lane, Del Mar,
CA, 92014, USA
Email: kernken@aol.com

Abstract

Two buoyant wooden cylinders, 30.5 cm long and 5 cm in diameter, moving through still water were compared to see which one experienced the lesser friction: one with completely smooth rounded front and side surfaces and the other with a smooth rounded front but with a series of concentric grooves cut into the otherwise smooth side surface. Holes were drilled into the flat bottoms to insert weights for adjusting buoyancy. The hole in the smooth cylinder was deeper so that without weights attached, the cylinders weighed the same in air. Equal weights were added to each cylinder and made flush with the flat bottoms, and the extra volume of the deeper hole was filled with water. Several runs were made releasing the cylinders simultaneously in the vertical position from the bottom of a swimming pool 152.4 cm deep. Every time the top of the grooved cylinder reached the air surface before the top of the smooth cylinder did, and by an average distance of one cylinder length. Clearly the grooved cylinder experienced significantly less friction. It will be interesting in the future to vary the parameters (groove number, size and shape) and find out how the friction changes. Also a mathematical theory is needed for increased understanding and prediction of new results.

Key Words: grooves reduce friction

1. Introduction

Consider laminar flow parallel to the long axis of a solid cylinder that has a rounded front and a flat bottom. Two different configurations are to be compared: in one the cylinder has a perfectly smooth side surface, and in the other cylinder concentric grooves are cut into the otherwise smooth side. Central to the comparison is the question: which cylinder experiences the greater friction force from the fluid as it flows by the solid? Most engineers and scientists would agree that there should be less friction associated with a smooth surface. If this conjecture is correct, it will turn out that most people are wrong, as demonstrated below.

How are the grooves to be made? Very few guidelines exist, so the method of trial and error has plenty of room in which to operate. If a single groove in a cylinder's side leads to a measurable decrease in friction, then it is clear that two or more grooves would further reduce the friction. What are not known a priori, besides the optimum number of grooves, are their size, shape and orientation to the flow which produce the minimum friction under most circumstances.

In a previous attempt to understand better this fluid/solid interaction [1] a similar comparison was carried out with two wooden and buoyant croquet balls, one with the grooves left in place as it originally came from the manufacturer and the other with the grooves filled with water proof wood putty and then sanded to obtain a smooth spherical surface. Twenty consecutive trials in four feet of water in a swimming pool showed that the grooved ball rose to the surface significantly faster than the smooth one did every time when simultaneously released from the bottom of the pool.

Having a race between grooved and smooth croquet balls in water was suggested by reading the history and physics of golf balls with dimples traveling through air [2]. If spin is eliminated from the problem, a golf ball with dimples has been observed to travel farther than one with no dimples. In fact, the more dimples the ball has, the greater the travel distance is likely to be.

2. Groove Physics

Qualitatively the decrease in friction that occurs when a fluid flows past a solid body with small-scale grooves in its surface can be readily explained [4], although there is no mathematical theory available that predicts quantitative results. For example, irrotational theory, usefully employed in so many fluid flow situations over a long period of time, does not appear to be a convenient tool to apply in the present context.

Laminar flow along a wall with a single groove in it has been observed to basically jump the groove [3], implying that the no-slip boundary condition, operating on the surfaces outside the groove, does not exist at the groove opening. Consequently, velocity gradients in the fluid normal to the streamlines are much diminished across the opening to the groove causing friction to be smaller there.

Another aspect of the physics of flow in the region of the groove starts with Bernoulli's equation: the pressure is least where the speed is greatest along streamlines in steady flow, and any modification of this law due to friction is taken to be negligible [4]. Since there is virtually no flow in the groove, the pressure is relatively high there. Across the groove's opening the speed is high, so the pressure is relatively low there. Thus an upward pressure force keeps the flow at the opening out of the groove.

3. Cylinder Trials

A grooved buoyant ball ascending in water faster than a smooth ball, though startling at first, would seem to be a fact capable of standing alone. [Apparently golf ball dimples have stood alone for more than 100 years.] However, in the minds of some the flow of fluid around a grooved sphere is a little complicated to visualize, perhaps because the flow continually encounters grooves whose diameter is first increasing and then decreasing again. Therefore, a comparison was planned between grooved and smooth cylinders where this complication does not enter.

Also behind the croquet ball results lies a technical glitch that might be considered undesirablealthough not totally damaging: there is slightly more wood in the smooth ball, assuming both balls weighed exactly the same initially, because wood putty was added to smooth out the grooves. This gives the smooth ball a tiny advantage in the race since its buoyancy is a little bit larger.

In addition, the grooved ball carries water along with it within the grooves when ascending producing in effect a small decrease in its buoyancy while moving, whereas nothing analogous to that happens to the smooth ball. However, in spite of the two slender advantages the smoothed ball has, it was the grooved ball which traveled faster.

Hard wood (mesquite) was machined to make the cylinders, which were 30.5 cm (1 ft.) long and 5 cm (2 in.) in diameter. To reduce the buoyancy somewhat metal washers were added inside holes drilled into the flat bottoms, centered on the long axes. For the smooth cylinder the hole was drilled deeper until the two cylinders weighed the same (to one part in one hundred) in air without any washers attached. Equal numbers (13) of washers were then fixed inside both holes such that when in place, the cylinders again weighed the same in air.

Square cross-sectioned grooves, 4 mm by 4 mm, were cut into the surface on one cylinder oriented so that the mean flow along the side would be normal to them. There were 17 grooves equally spaced at 11 mm apart. The other cylinder had a perfectly smooth surface. A sealant coating was applied to keep water from entering the wood, but with this type of hard wood it is doubtful if any water would enter the wood during the time it takes to do a few trials, even without a coating of sealant.

After being released under water in the vertical position, the cylinders would always remain vertical until reaching the air/water boundary. No wandering movement of the cylinders about the vertical was detected, and terminal velocity was quickly reached. Fluid filled the grooves and traveled with that cylinder as it rose upward. Similarly, water filled the part of the hole in the smooth cylinder that was not occupied by washers, which volume equaled the sum of the volumes of all the grooves. Of course the water trapped in the hole at the bottom of the smooth cylinder traveled upward with that cylinder but it did not at all affect the frictional interaction between flowing water and wood.

Results from several consecutive runs (4 or 5) in a swimming pool 152.4 cm (5 ft.) deep are summarized as follows: the top of the grooved cylinder reached the air surface before the top of the smooth cylinder did every time and by an average distance of one cylinder length!

4. Discussion

Following the encouragement provided by the cylinder trials just described, one might well feel more at liberty to hypothesize about practical applications of reducing friction by means of grooved surfaces on solid bodies moving in fluids other than the established dimpled golf ball and the proposed grooved inside surface of a pipe [4], which still needs to be substantiated.

Why not put vertical grooves on the hull of a ship below the waterline, whereby the practicality would be the saving of fuel costs by the decreased friction between water and the metal or wood sides of the ship?

What man has fairly recently discovered by accident (golf ball dimples) can sometimes be noticed in nature, even existing well before homo-sapiens came along. Most species of fish have scales causing their sides to be not completely smooth. From a photograph of the skin of an Alaskan salmon, slightly magnified, one can see a diamond shaped pattern of grooves embedded in the overlapping scales. The smaller of the two interior angles (about 60 degrees)of the diamond point vertically, and the vertical scale is about 5 mm. Salmon swim great distances annually, so any way they can reduce friction would be a definite advantage to them. For salmon the diamond shaped grooves apparently work better than if the grooves were all parallel and vertical (i.e. normal to the mean flow when swimming horizontally).

Man-made solid bodies that are designed to move through water, whether built out of wood, metal, plastic or whatever material, always have surfaces that are smoother than the sides of fish with scales. For example, great care is taken to polish the outside of a rowing shell before an important crew race is run across a body of water.

Finally, a reader might wonder why the choice was made to put grooves instead of dimples on the surface of one of the cylinders. My best answer at this time is that the streak photograph of flow jumping a square groove in a flat wall [5] was so convincing that I had to try grooves first. Also concentric circular grooves are more consistent with the cylindrical geometry of the problem.

5. Conclusions

A particular experiment illustrates the general phenomenon of how grooves in the surface of a solid body can greatly reduce the force of friction when that body travels at constant speed through a still fluid. Two buoyant wooden cylinders were released at the same time in the vertical position from the bottom of a swimming pool: one had a series of concentric grooves cut into the otherwise smooth side and the other one had a completely smooth side. The top of the grooved cylinder reached the air surface before the top of the smooth cylinder did five times in a row by an average distance of one cylinder length where the water depth was five cylinder lengths, providing strong evidence that the grooved cylinder experienced significantly less friction.

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References

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An experimental study of turbulent flow past four cylinders in square arrangement with a space ratio of (T/D = P/D = 2.88) is performed. The investigation focuses on effects of Reynolds number and the shape of cylinders on the force and pressure coefficients of the cylinders. Two cases are investigated: four smooth cylinders (case1) and four grooved cylinders (case2). The cylinders are equipped with two grooves placed on the external surface at 90Â° and 270Â° degrees. The pressure distributions along the tubes (22 circumferential pressure taping) were determined for a variation of the azimuthal