Hydrodynamic Lubrication

Experiment with 'Floating' Drops

Jaywant H Arakeri and K R Sreenivas

This article gives the principle of hydrodynamic lubrication and also presents the new phenomenon of levitating drops over liquid film flow, which is explained using hydrodynamic lubrication theory.

Introduction

Friction plays a large and essential role in everyday life although we usually never think about it. For example, friction provides the support when we walk; without it we would not be able to move forward and indeed it would be impossible to stand up without additional support. When we grip an object and stop it from falling we again use friction.

In many engineering systems, however, when two surfaces slide against one another friction is a nuisance. In this case friction has two undesirable effects: (1) it increases wear and (2) work that is not useful, needs to be done to overcome it. Thus, reducing friction will not only increase the life of a component but also increase the efficiency of the system.

Friction between surfaces may be reduced by lowering the coefficient of friction; or it may be reduced by introducing a new substance – a lubricant – between the surfaces. The lubricant can be solid (e.g. graphite) or fluid (oil, water, air). The lubricant should also be able to support a load, if any, acting normal to the surface.

Hydrodynamic lubrication is one method used extensively to support load and reduce friction. In this article we describe a

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simple but fascinating experiment, which may easily be done in a school or college laboratory (or even at home), that demonstrates hydrodynamic lubrication.

Principle

To understand the principle of hydrodynamic lubrication consider a block sliding on a horizontal table (*Figure 1a*). The force required to move it with constant velocity is equal to the frictional force $= \mu W$; μ is the coefficient of sliding friction and W is the weight of the block. For many common surfaces μ is about 0.3. Thus we would require 0.3 kg force to slide a block weighing 1 kg.

If we now put a liquid film of thickness h between the block and the table surface (*Figure 1b*) the force required to move the block with constant velocity u is $P = \eta u A / h$; η is the coefficient of viscosity of the liquid and A is the bottom surface area of the block. Note that now the friction force depends on the velocity of the block. As an example let the block slide over a 0.1 mm water film with a velocity of 20 cm/s (about walking speed). Then $P = 0.03$ kgf, a tenth of the earlier friction force. But this reduction in friction is useless as the liquid film as shown in *Figure 1b* cannot support the weight of the block. The liquid will flow out of the sides under the weight.

What we need is not only that the friction be reduced but also that the weight be supported. Both are achieved if the block tilts slightly forward as it moves (*Figure 1c*).

In many engineering systems, when two surfaces slide against one another friction is a nuisance.

It may seem counter-intuitive that the block should tilt forward instead of back to support the load. The support of the weight, i.e., the *bearing action*, is explained as follows. The block, as it moves forward, drags the liquid into the gap. This liquid has to move into a gap which is narrowing and the pressure that builds up in the gap supports the load. Note the two important ingredients for bearing action: one is motion which drags the
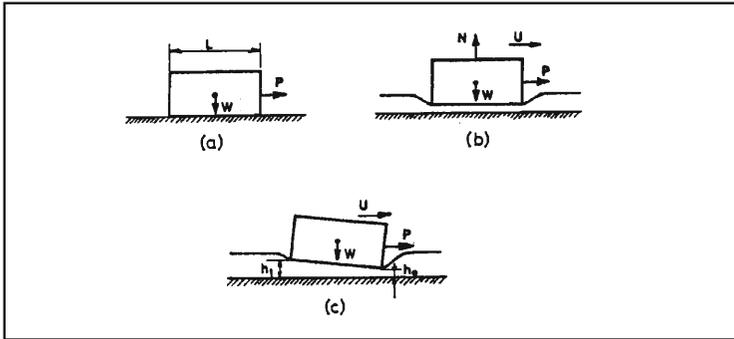
Figure 1   A rectangular block of length L, surface area A and weight W sliding to the right with velocity U under different conditions. Force P is required to slide the block. (a) Block sliding on a solid surface, P = friction force = μW. A normal reaction exerted by the table surface supports the weight. (b) Block sliding with the bottom surface parallel to the table surface on a liquid film. P = $\eta(UA/h)$ where η is the viscosity of the liquid. To support the weight, an external force N = W is required. (c) Block sliding on the liquid film but tilted forward (i.e., $h_0 < h_1$). P is same as in Figure 1b but now a 'bearing' pressure develops in the film which supports the weight. Bearing pressure arises as the liquid is dragged to the right into a narrowing gap.

liquid and the other is dragging of the liquid into a narrowing gap or a constriction. If either ingredient is absent the load cannot be supported.

Let us look at the various parameters that affect the load carrying capacity

$$W \simeq C\frac{\eta UAL}{h_0^2}$$

(C = 0.07 for L/B = 1 and h_1/h_0 = 2. Here L is the length of the block and B is the width. The form of the equation remains unchanged with changes in the values of the two ratios; only the constant C changes). The frictional force,

$$F \simeq \eta\frac{UA}{h_0}$$

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is about the same as when the gap is parallel. Interestingly the coefficient of friction $= F/W = h_0 / (CL)$ is independent of the value of viscosity.

Note for a given area (A) and length (L) the load that can be supported increases linearly with speed and viscosity and inversely as the square of the gap. Therefore generally, hydrodynamic lubrication is associated with surfaces having relative motion, small gaps and high viscosity oils. Under special circumstances however, like light loads or high speeds, air bearings have been used.

[1] *Reynolds number* is a measure of the ratio of inertia to viscous forces and is, perhaps, the most important dimensionless number in the study of *fluid mechanics*.

There are two conditions under which hydrodynamic lubrication and the associated bearing action occur. One is that the Reynolds number[1] be small, i.e., when $\rho U h_0 / \eta \leq 1$. Here, ρ is the density of the fluid in the gap. A low Reynolds number implies that viscous forces are important and are in fact responsible for the dragging in of the fluid and the resulting pressure build up. The second condition is that the angle of the narrowing passage (angle of tilt in *Figure 1c*) be small.

Hydrodynamic lubrication finds a number of engineering applications, the most common being the *journal bearing* (see *Box*). When we slip wearing rubber-soled slippers on a wet bathroom floor, it is a manifestation of hydrodynamic lubrication!

'Floating' drops

Now we describe the fascinating but simple experiment which illustrates hydrodynamic (really aerodynamic) lubrication. Take a glass tube of internal diameter 1/4" ($\approx$ 6 mm) connected to one end of a flexible (say rubber) pipe. The other end of the flexible pipe is dipped in a container (bucket) of water. Let the water flow out of the glass tube by siphon action. Use a valve to adjust the flow rate.

Journal Bearing

The most common example of hydrodynamic bearing is the journal bearing (*Figure 2*). It is a circular shaft (journal) rotating inside a circular bush with a thin film of oil separating the two. The gap between the shaft and the bush is generally about 0.001 to 0.002 times the shaft diameter. Usually a load W (eg. weight of the impeller in a pump) has to be supported. When the shaft is rotating, position of the shaft with respect to the bush is shown in *Figure 2b*. Rotation of the shaft drags in the oil into a narrowing gap (marked A in the *Figure*). According to our discussion earlier, bearing pressure develops and this in turn supports the load. The oil film ensures low wear and low friction. In practice, the design must ensure a minimum film thickness to prevent breakage of the film and the subsequent contact between the shaft and the bush surfaces. When the load is high or the shaft speed is low this minimum film thickness cannot be maintained. In these cases roller element bearings (eg. ball bearings) or hydrostatic bearings are used. Interestingly even in ball bearings, we have hydrodynamic lubrication at the ball surface.
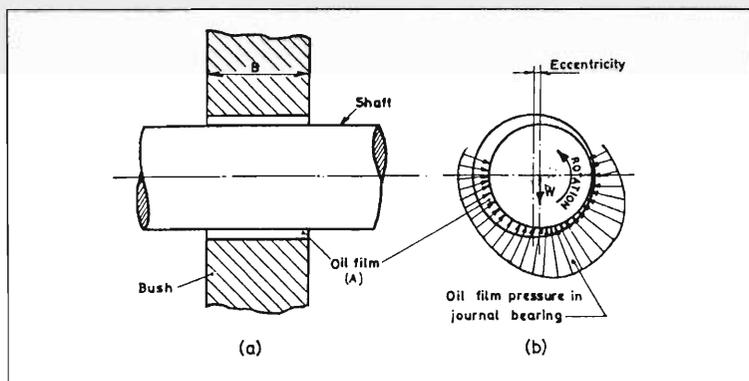

Figure 2 Journal bearing (a) front view indicating shaft, bush and the oil-film. (b) cross-section in the side view indicating the pressure developed in the oil-film and the relative positions of shaft and bush when the shaft is rotating.

Let the jet of water impinge on a horizontal surface (eg. glass plate) kept about 8 cm below the end of the glass tube. We get a thin film of water which flows radially outward. At some distance we observe that the film height abruptly increases. This is known as a *hydraulic jump*. (Hydraulic jumps are commonly observed in flowing streams, rivers, etc. Hydraulic jumps are analogous to
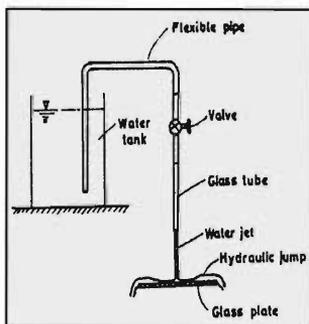
Figure 3 Schematic diagram of the set-up.

Figure 4 Photograph showing release of a liquid drop above the film and just ahead of the hydraulic jump. The syringe is slowly withdrawn once the desired drop size is reached.
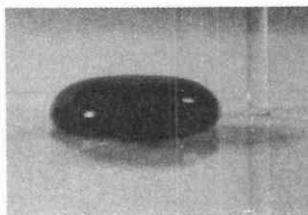

Figure 5 Photograph indicating the water jet and a levitating water drop. Dye in the drop gives the dark colour.

shock waves in air formed, for example, when an airplane flies at supersonic speeds.) The radius at which the jump occurs increases with flow rate. For the present experiment keep the flow rate ($\approx$ 7 cc/s) such that the radius of the jump is about 2 cm. It must be ensured that the water jet is steady. The water jet coming out of a tap will not do as the flow is usually 'disturbed' and unsteady. *Figure 3* shows a schematic of the set-up.

Once the jet flow is set up, take water in a syringe. Place the tip of the syringe needle close to the surface of the film and just ahead of the hydraulic jump. Slowly release a small drop of water by pushing the piston (*Figure 4*). Take the needle out of the drop. You will see that the drop will not mix with the flowing water film but 'float' (*Figure 5*). There cannot be contact between the drop and the film because then the two would just mix. Actually there is a very thin ($\approx$10 μm) air layer below the drop; the drop is not really floating but levitating on this air layer. Some skill needs to be developed to conduct the described experiment.

It can be shown that the drop is supported by bearing action. The flowing film drags in air into a narrowing gap below the drop (*Figure 6*). The resulting pressure build-up supports the drop. The hydraulic jump is essential to keep the drop stationary; it prevents the drop from flowing with the stream.
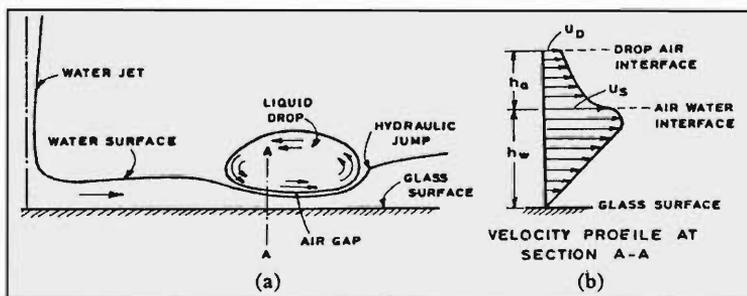

Figure 6 (a) Schematic showing the water jet, flowing water film, air gap and induced motion in drop. (b) Velocity profile in the air layer and the water film. Induced velocity in the drop, U_D, is small for viscous drops. Film thickness $h_w \approx 0.1$ mm and air-gap thickness, h_a is estimated to be ≈ 10 μm.

The drop-liquid need not be of water. Drops of oil, soap water, glycerol, etc. levitate; but drops of liquid like alcohol, having high evaporation rates and which are miscible in water do not levitate.

Depending on the drop size and drop liquid properties (viscosity and surface tension) a fascinating variety of shapes are obtained (*Figure 7*).

We can explain the different shapes by considering a balance of forces. First consider the balance of forces on one-half of the drop:

• We find that motion is induced in the drop: it 'spins' about the horizontal axis as shown in *Figure 6*. We call the force associated with this motion *inertia force*. Higher the viscosity

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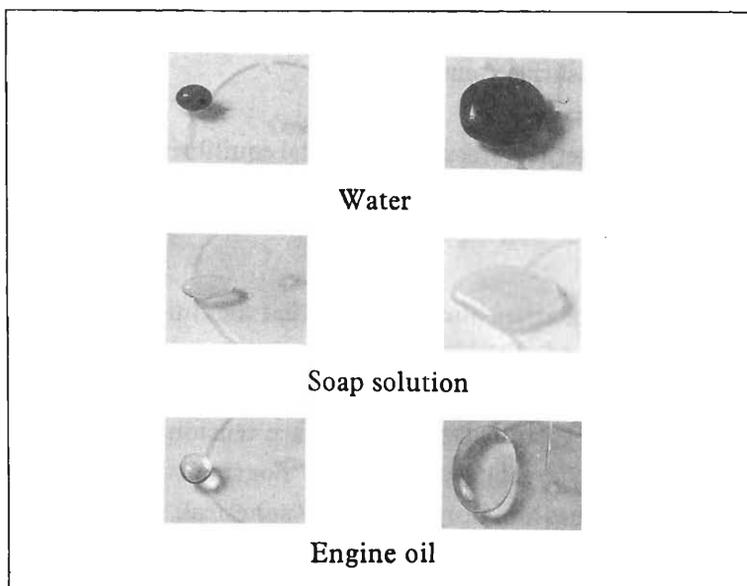
Water

Soap solution

Engine oil

Figure 7 Photograph showing the effects of drop size and drop liquid properties on the drop shape. Volumes of the drops in the left hand column are about 0.1 ml and of those in the right hand column are about 1 ml. The 1 ml drops are 'flatter' compared to the 0.1 ml drops. Very little motion is induced within the engine oil drops because engine oil is very viscous. Shortening of the 1 ml engine oil drop is due to external forces. Soap-solution has lower surface tension than water. Thus soap-solution drops are elongated in comparison with water drops.
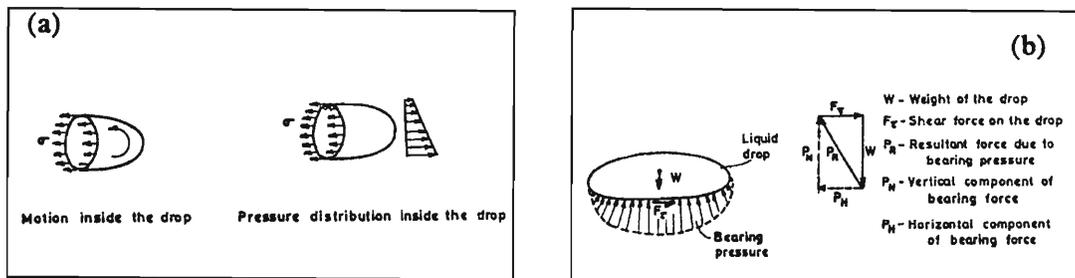
Figures 8a and 8b . (8a) Internal force balance. Surface tension force (σ) balances forces due to inertia and hydrostatic pressure. (8b) External force balance, weight (W) of the drop is balanced by the vertical component (P_N) of the resultant force (P_R) developed due to bearing action. The horizontal component of bearing force P_H balances the shear force (F_τ) exerted by the flowing air.

of the drop liquid, lower is the induced motion and thus lower is the inertia force.

• Due to gravity the pressure inside the drop increases linearly. We call the force due to this pressure *gravity force*.

• Force due to surface tension.

We have two external forces for horizontal equilibrium of the full drop (*Figure 8b*): shear force exerted by the air and horizontal component of the bearing force.

The inertia force arises due to the fact that the fluid has to turn around 180° and is balanced by the surface tension force. A higher inertia force elongates the drop in the flow direction. The gravity force is again balanced by surface tension and tends to flatten the drop: larger drops are flatter. For small drops, surface tension dominates and drops are nearly spherical. The external forces balance each other and tend to shorten the drop in the flow direction.

An interesting and relevant question is whether solid (e.g. plastic) spheres will levitate in the same manner as liquid drops. The answer is no. A deformable surface is necessary so that there is sufficient area over which the bearing pressure can act.

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