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FOCUS ON ANALOGIES, ANECDOTES AND PARADOXES FOR ENHANCING EFFECTIVENESS OF TEACHING - SOME EXAMPLES IN FLUID MECHANICS

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Introduction

He who can, does; he who cannot, teaches. This mischievous statement is attributed to George Bernard Shaw who must have meant it in the lighter vein. Anybody can teach, some say; this uncharitable view is often expressed by people who look down upon the teaching profession. Good teachers are born, not made, say some, who think that teaching skill is an inborn gift. These views reflect two extreme positions. Up to the level of secondary education, a person seeking a teaching job is required to possess a teacher training certificate or a Degree of Bachelor of Education. However, in higher education, a degree in teacher training is not required. To be a good teacher, a person requires not only sound knowledge in his field of specialization and communication skills but also a good grasp of psychology of learning. A teacher who may be good in his subject but cannot arouse interest in the students while delivering the lecture, cannot motivate them to learn; coverage of the subject in depth continuously for an hour or more, without sprinkling a little humour here and there or making a slight digression now and then for introducing analogies or anecdotes can be monotonous for the student who may feel that it is dry and insipid. A lecture can be made highly stimulating by making it interactive, asking questions and encouraging the students to raise questions. Deliberately making an incorrect statement in the course of a lecture can be used as a technique to test whether the students are attentive or not. Sharp reaction from the students pointing out the mistake and coming up with correction is to be welcomed as desirable feed back. Such a technique will be found to be extremely useful in driving home fundamentals of the subject. There are innumerable instances of great scientists committing blunders before they came up with a new theory or derived a new formula. Generation of new knowledge by proceeding from the known to the unknown either theoretically or experimentally, is no easy process. Many faltering steps are to be expected on the way to progress. Fear of committing mistakes in applying known principles to problem dealing with unknown situations is a hindrance to acquisition or generation of new knowledge. A conscientious teacher who pays attention to the psychology of learning will always try to dispel such fear. Giving examples of mistakes committed by great scientists in the process of making significant contributions, will instil confidence among the students to try out bold and innovative solutions to complicated problems. Concepts implanted in the minds of learners with the help of analogies, anecdotes and paradoxes will be remembered for long. Analogies make it easy to understand difficult concepts but they should not be carried too far since precision is sacrificed to some extent while doing so.

A few topics in fluid mechanics are chosen here to illustrate how effectiveness of teaching can be enhanced through the use of analogies and anecdotes for creating motivation among the learners. What is turbulence? Is it a friend or foe to mankind? What causes attraction between ships on parallel course, leading to collision some times? Why does radial outward flow between parallel circular discs cause attraction between them? Why is a dimpled surface provided for a golf ball? What is a streamlined body? What is the lesson learnt by Engineers from the collapse of Tacoma Narrows Bridge? Why do tall chimneys sway in the wind? These and a few other topics in fluid mechanics will be covered in this paper as illustrative examples.

The author of the article is inspired by the most beautiful and lucid way in which Sir Graham Sutton explains some of the basic concepts in aerodynamics with the help of analogies in his book "The Science of Flight" [1]. The author has taken the liberty of quoting him extensively (with slight alteration in few places) and wherever quotation marks are found without reference to the source, it may be construed by the reader that the reproduction is from the same source[1].

PART - I

Basic Concepts of Viscosity, Compressibility & Turbulence

A fluid is a substance which deforms continuously under the action of a shear stress, however small this stress may be. Liquids and gases come under the category of fluids. An ideal fluid is one which is frictionless and incompressible. The frictionless fluid has zero viscosity and cannot sustain any shear stress at any point. Hence any force acting on any elemental surface of a fluid is normal to that surface. The ideal fluid concept greatly simplifies the mathematical treatment of fluid motion, although no such fluid actually exists. All real fluids posses the physical property of viscosity. Liquids such as castor oil or honey are referred to as 'thick' and liquid such as water as 'thin'. Lubricating oils are classified as 'heavy' or 'light' oils. The property expressed by these adjectives has nothing to do with the density of these liquids which exhibit to a greater or less extent, resistance to change of shape. A highly viscous liquid cannot be poured rapidly or cannot be stirred easily. Gases such as air also possess viscosity (but at a much lower level) which cannot be detected easily. "The viscosity of a fluid is a consequence of its molecular structure. A given volume of a fluid consists of an enormous number of tiny molecules darting at very high speed continuously, colliding with each other and with the boundaries. The energy of the incessant motion which is quite random, manifests itself as temperature. The property of viscosity can be traced to the irregular unceasing motion of the molecules in a fluid. The same agitation also causes diffusion of heat (or conduction of heat as we call it) in a fluid and also diffusion of matter. Because of the small size of the molecules and the extremely small distances they travel before hitting the other molecules, the molecular conductivity or heat or diffusion of matter in gases is a very slow process".

Flow of fluids can be classified as laminar or turbulent. Laminar flow is smooth and regular and fluid particles move in laminae without any visible disturbance. Turbulent flow is characterized by irregular motion of fluid particles with lumps of fluid migrating from one region to another, giving rise to a process of mixing. In laminar flow viscosity plays a dominant role by damping any disturbance introduced into the flow motion of a fluid in which whirling lumps of fluid or eddies of different sizes and different orientations are ever present, resulting in intense mixing. Although we do not have any exact definition for turbulence, this state of flow can be easily recognized. Nearly all natural motion of fluids is turbulent. "Both laminar and turbulent motion can be seen in the smoke coming from a cigarette held steadily in hand. At the lighted end, the smoke rises steadily in a thin line showing laminar motion, but higher up, the stream of hot air looses direction and exhibits all the characteristics of turbulence". The same thing can be observed in the smoke coming out of a tall chimney. "Turbulence provides a kind of magnified viscosity, conductivity and diffusivity in which wandering masses of fluid carry heat and foreign matter from one part of the fluid to another. The effect of turbulence can be understood by looking upon it as a continuous mixing process in which the eddies behave like molecules. With the help of this analogy, the meteorologist have made considerable stride in the study of the atmospheric turbulence. It has been found that in the atmospheric processes the coefficient of enhanced viscosity, enhanced conductivity and enhanced diffusivity caused by turbulence (which may be referred to as *coefficients of eddy viscosity, eddy* conductivity and eddy diffusivity), are several thousand times larger than the corresponding molecular coefficient. In this way, the air near the ground is provided with very efficient and automatic mixing. If this were not so, it would have been impossible for all forms of life on this earth to survive. The air at breathing level, would be intolerably hot or very cold and extremely humid or very dry. But for turbulence in the atmosphere, smoke would cling to the ground probably for days which will be a climate of extreme unlike what we know now. Atmospheric processes which are of crucial importance to mankind such as evaporation from seas and lakes, spread of heat from ground to the upper regions of the air and clearing of local pollution, all controlled by rapid diffusion due to turbulence". The innumerable mixing processes on which we depend in day to day life in the domestic arena as well as in industrial sector are all examples of beneficial effects of turbulence to mankind. The frictional resistance offered to the motion of fluids through conduits and the drag force exerted by the fluids on bodies such as ships or airplanes moving through fluids are relatively high if the flow is turbulent. This is to be expected as a necessary evil.

Fluid motion, in which density of fluid particles does not undergo any changes, is referred to as incompressible flow. The assumption of incompressibility of a fluid is equivalent to the postulate that the velocity of sound in the fluid is infinity. We are justified in speaking of gases such as air as incompressible in fluid motion occurring at slow speeds because the molecules are not squeezed together to cause any noticeable change in density. As the speed of a body moving in air increases, the disturbances become more intense and the whole character of the phenomenon changes. As a simple analogy, let us take the case of a person driving a car along a country road who encounters a flock of sheep. "The flock of sheep has its own peculiar speed of adjustment to such a situation and nothing can change its speed. If the car slows down to the walking speed the flock will make way for it without a great deal of crushing. But any attempt to drive either the car or the sheep at high speed will end in trouble, because the flock cannot adjust its pattern of flow past the car sufficiently rapidly to get out of the way. When a body moves through the atmosphere at slow speeds, the air in its vicinity is likewise able to take up the resulting changes of pressure without much crushing together of the molecules or in other words, without noticeably increasing the local density. If the body is moving at a velocity comparable with that of sound, density changes in its vicinity are much more pronounced". The compressibility of air in high-speed flow cannot be ignored; this will again be dealt with later when we discuss about air resistance.

Reynolds' experiments

In 1883, Osborne Reynold, Professor of Engineering in University of Manchester carried out a series of simple experiments to study the motion of water to a long straight glass tube attached to a reservoir. From the results of his experiments, he established existence of two types of flow, laminar and turbulent. He published his results in the Philosophical Transactions of the Royal Society, London under the title 'An experimental investigation of circumstances which determined whether the motion of water shall be direct or sinuous and the law of resistance of parallel channels'. In the experimental set up, the glass tube was carefully insulated from external vibration and the reservoir was also protected from any outside disturbance. A dye was introduced into the flow through a subsidiary thin tube to observe the fluid motion. The flow was started with slow speeds which were increased in small steps. "At low speeds the dye makes a thin line parallel to the walls of the tube and the motion is orderly like that of a well disciplined army regiment. As the flow speed is increased gradually in small steps ensuring that there is no change in the appearance of the filament of dye, suddenly a dramatic change is found to occur. The coloured line no longer keeps it straight path and is violently agitated and the dye quickly spreads over the whole tube. At the far end, it is not possible any longer to distinguish the original filament. At a certain critical speed, the motion changes to one of extreme disorder. The fluid particles still move in general towards the tube outlet as before, but with all sorts of secondary motion causing them to cross and re-cross the main direction. The orderly manner has given place to the wild rush of the mob". The orderly type of flow is referred to as laminar flow and the flow characterized by the agitated motion is called the turbulent flow. Reynolds found that a non-dimensional parameter given by the product of the velocity of flow and the diameter of the tube divided by the kinematic viscosity of the fluid, has to exceed a critical value of 2,200 for the flow to become turbulent. The flow is invariably laminar if this number is below 2,200. It has been found experimentally that the flow can be laminar at Reynolds' numbers exceeding 2,200 provided there are no vibrations or disturbances and the inlet conditions are smooth. Laminar flow has been obtained at Reynolds' Numbers as high as 40,000. But the slightest disturbance can change it abruptly to turbulent flow. Reynolds' Number is of great significance particularly in aerodynamics and that is why these experimental results, though they appear to be very simple, are to be dealt with at length to make the students appreciate its importance.

Turbulent flow may be looked upon as motion of a fluid with eddies of different sizes and different orientations moving with it. However, the analogy of eddies as microscopic counter paths of molecules in laminar flow, should not be carried too far. "Molecules in a gas are permanent bodies and the branch of the mathematical physics known as kinetic theory of gases arose because it was found possible to deduce the physical properties of gases by treating molecules as elastic balls". Eddies are not permanent; they are born and also disappear in the flow. They cannot be treated as if they are lumps of matter with definite mechanical properties. "For this reason the mechanical theory of turbulence is more difficult and less developed than the corresponding molecular theory".

To explain how eddies are formed and turbulence arises, we can only give a qualitative answer. We would like to know mathematically under what circumstances steady laminar motion of a fluid breaks down into turbulence. "Essentially this is a question of stability and there is a well developed mathematical technique for attacking such problems. An expression representing a small disturbance is introduced into the equations which are then examined to determine the conditions under which the disturbance subsides indicating that the flow is stable or will grow indefinitely in which case the system is unstable and the system will ultimately break down into turbulence. The complexity of the situation is such that the solution has evaded the ablest of mathematicians for the last one century".

The Bernoulli Theorem

In mechanics of fluids, no other name appears so prominently as that of Danial Bernoulli (1700-1782) who enunciated the energy principle named after him in his book 'Hydrodynamica' published in 1738. Danial Bernoulli came from a family of mathematicians and his father, Johann Bernoulli (1677-1748) was Professor of mathematics at the university in Basil, Switzerland. Newton and Leibniz were contemporaries of Johann. When controversy arose between these two regarding priority in the invention of calculus, Johann supported Leibniz who was his close associate. The period of about one century from the time of Galileo to that of Bernoullis was marked by advances in physical science which surpassed what all was accomplished for over 1000 years before. Danial Bernoulli, his colleague Leonhard Euler (1707-1783) and D'Alembert (1717-1783) were the pupils of Johann. Danial Bernoulli experimented and wrote on various phases of fluid motion, coined the word hydrodynamic formulated the energy principle, devised the manometric technique and proposed the principle of jet propulsion. From his experiments on fluid motion, he could sense the constancy of the sum of velocity head and piezometric head (sum of pressure head and datum head) at different sections as the area of cross section of flow changed and arrived at his principle. Euler was the first to explain the role of pressure in fluid motion. He formulated the basic equations of motion ignoring viscosity and derived the Bernoulli equation from them. Euler introduced the concept of cavitation and the principle of centrifugal machinery. Euler first conceived of pressure as a function of space and incorporated pressure gradient in his equations of motion. For steady, irrotational flow in a gravitational field, Euler showed in 1755 that Bernoulli equation could be derived from his equations of motion. It should be impressed upon the students that the Bernoulli equation as derived from Euler's equations of motion shows that the Bernoulli sum (sum of velocity head and piezometric head) remains constant for a given streamline and can vary from one streamline to another, if the flow is rotational. Fluid motion in a forced vortex and a free vortex can be taken as illustrative examples. Water contained in a cylindrical vessel (open at the top) rotating about vertical axis with constant angular speed assumes the shape of a paraboloid at the free surface. This is a case of a forced vortex in which the streamlines are concentric circles. The tangential velocity at any point on a given streamline is directly proportional to its radial distance from the axis of rotation. Mathematically it can be shown that the flow is rotational and the Bernoulli sum, though constant for given streamline, varies from one streamline to another. In other words, the Bernoulli theorem cannot be applied to any two points or any two streamlines. On the other hand, if we take the case of a free vortex in which the tangential velocity at any point on a streamline is inversely proportional to its radial distance from the axis, the flow can be shown to be irrotational and the Bernoulli sum will remain the same for all the streamlines. It was pointed out by one of the students of the author that he came across a worked example in one of the text books, showing as if the total energy (Bernoulli sum) remains constant for any two points in the flow. The student considered two different points on the free surface and observed that both the velocity head and the datum head were larger at the point lying at a greater radial distance and he could not understand why Bernoulli equation was found to be invalid in this particular case. Special emphasis on the blunder committed in the text book (while pointing out that the irrotationality condition is not satisfied here), will ensure that the students would not commit such mistakes on fundamentals.

There are several phenomena (involving flow of fluids) which appear to be paradoxical at first sight but can be explained with the help of Bernoulli's theorem. Let us take an interesting case of collision between ships on parallel course [2]. "In the autumn of 1912, the Ocean liner Olympic, one of the world's biggest ships at the time, was streaming ahead out on the high seas when another much smaller ship, the Cruiser Hawk rapidly approached it on a parallel course. The Hawk sharply veered off its course as if obeying some invisible force, turned towards the big liner and rammed into it. The impact was so great that it made a big gash in the Olympic's hull. The case of mutual attraction between ships on parallel course is not new. If the ships are small the attraction is not much. In the case of two ships on a parallel course we have a channel of water between them. In an ordinary channel the walls remain stationary and the water moves where as in this case the water remains stationary and the walls move. However this does not make any difference with regard to action of forces. In the narrower portion of the moving channel the water exerts a smaller pressure on the walls than elsewhere. The sides of the ships facing each other are subjected to lower pressure than the two outer sides. The pressure of the water on the outer sides causes the ships to move towards each other, the smaller boat moving much faster". If we stand in the open space between two tall buildings, we experience motion of air with high speed and what happens between ships on parallel course is a situation some what similar.

As another example, let us take the case of radial outward flow between parallel circular discs. Make a hole at the centre of a circular cardboard disc and fasten it to a short tube perpendicular to its surface, adjusting the tube to fit tightly into the hole. If we now take another light circular disc and keep it close to the card board disc and blow air through the short tube, it will be found that the lighter disc does not fly off. The harder we blow air, the more will be the tendency of the lighter disc to stick to the card board disc. The students could be asked to use the continuity equation and the Bernoulli equation to show that the pressure between the discs is below atmospheric, causing this seemingly paradoxical phenomenon. As a slight variation of the same, a ping-pong ball may be kept inside the conical portion of a funnel and air may be blown through the stem of the funnel. If the conical portion is kept pointing towards the ground, the ball will be found to defy gravity. Once again, the same analysis as in the case of radial outward flow between the parallel discs will be found valid to be in this case also. As yet another variation, observe what happens when a ping-pong ball is kept on a jet of air issuing vertically upwards, the ball will keep dancing on the jet but will not fall down.

Let us turn our attention to another simple experiment. If air is blown between two suspended rubber balls separated by a small distance, will the balls swing away from each other or towards each other? Students who are sharp enough to see the similarity between this situation and in the case of ships on parallel course, will come up with the right answer, saying that the balls will swing towards each other. The stream of air between the balls will posses higher velocity and hence lower pressure, compared with elsewhere, causing the balls to swing towards each other. If the balls touch each other in this process, the flow of air will force them to be separated and to move away from each other and this swinging of the balls will continue.

When Not to Use Bernoulli Theorem

Just as Reynolds' Number serves as a criterion to determine whether a flow is laminar or turbulent, another non-dimensional number known as the Froude Number which is given by the ratio of the velocity of flow to the square root of product of gravitational acceleration and the depth of flow, serves as the criterion to determine whether a flow is supercritical or sub-critical in an open channel. When the Froude Number exceeds unity, the flow is said to be supercritical and when it is less than unity the flow is classified as sub-critical. Hydraulic jump is an interesting phenomenon which occurs when supercritical flow changes to the sub-critical state in open channel. Notable examples of the occurrence of hydraulic jump are sudden increase in depth of flow at the foot of a spillway or downstream of a sluice gate. In these situations, knowing the depth of flow of water moving with high velocity before the abrupt jump in the water levels occurs, it is possible to derive the depth of flow after the jump analytically. For the purpose of deriving relationship between the depths of flow before and after the jump, either the momentum or the energy equation will have to be used in addition to the continuity equation. To stimulate thinking among the students, the teacher can ask them which one they would like to choose between the momentum and the energy equation. Purely, some of the students will plead for the use of Bernoulli equation while others might favour the momentum equation. In fact, the French hydraulician, Belanger Jean (1789-1874), who was the first one to deal with the problem analytically (in 1828) assumed that the total energy remains constant for sections taken before the jump and after the jump as well. In comparing this result with the observations of M. Bidone (1820), Belanger explained the discrepancies (up to 14%) as resulting from accidental errors, but in the lectures delivered by him some time later and in the notes published by him (1845-46), he altered his method and gave a new solution using momentum equation in place of the energy equation. The solution thus obtained was in much closer agreement with the experimental result and this has been accepted since then universally. In the class room, discussion can be initiated as to why the energy equation cannot be used to find the relationship between the depths before and after the jump the students can be guided to arrive at the conclusion that the occurrence of the jump is accompanied by the formation of eddies which extract energy from the main stream and cause loss of energy. Narration of anecdotes of this nature during a course of lecture, will prove to be extremely useful in consolidating the basic principles in the minds of the students.

A somewhat similar situation arises in respect of a sudden expansion in a pipeline. Knowing the velocity of flow before the expansion, the velocity after the expansion can be found using the continuity equation. However, for finding the pressure at a section after the expansion from knowledge of the pressure at a section before the expansion, one gets the doubt whether the momentum or the energy equation should be made use off. If the students recognize the fact that eddies will be formed at the corners immediately after the abrupt expansion, they will conclude that some loss of energy is to be expected and hence the energy equation cannot be used. Using the momentum equation, the pressure at a section down-stream of the expansion can be determined. Once this is done, it is easy enough to derive a formula for the loss of energy at a sudden expansion, using Bernoulli theorem.

Determination of discharge using flow measurement devices such as venturimeters and orificemeters depend upon the use of Bernoulli theorem. It is well known that the most common method used for the determination of discharge through an open channel is to introduce a weir across the channel and to measure the head over the crest of the weir. In the case of flow over a sharp crested weir, it can be shown that the discharge is directly proportional to the length of the weir and to $H^{3/2}$ (where H is the head over the crest), by using dimensional analysis. In text books on hydraulics, for the purpose of deriving a formula for discharge through a rectangular notch or over the crest of a weir, it used to be the practice to consider an elemental strip of depth ÄH and to assume that the velocity of flow through the strip to be . By integrating the expression for discharge through such an elemental strip between the limits 0 to H, one used to arrive at the total discharge. Here, it is necessary to point out the absurdity of the assumptions involved in such a derivation. The actual depth of flow over the crest is considerably less compared with H and this depth is never measured. The actual measurement is taken upstream of the weir where the water surface is not curvilinear and the velocity of water at the free surface has certainly a non-zero value. Taking these facts into consideration, none of the standard text books on fluid mechanics give such a derivation now-a-days. Unfortunately, we still come across questions in the examinations of some of the Universities, asking the students to derive the equation for discharge through rectangular notch, presumably using Bernoulli theorem. Cautioning the students against the adoption of invalid and absurd assumptions will prove to be helpful to them in developing an inquisitive approach and a thirst for a deeper insight.

If the flow direction is reversed in a venturimeter, can it still be used as a flow-measuring device? Students would have observed in the laboratory that the inlet portion of the meter is short and the exit portion is longer. The pressure tapings (for connection to the manometer) are taken at the inlet and the throat sections. Between these two sections, there is no loss of energy. If the exit portion of the venturimeter is also short as is the inlet portion, separation of the flow takes place causing formation of eddies and loss of energy. That is exactly why the exit portion of the meter is made much longer providing gradual expansion of the flow. If the flow is reversed, we will be measuring the pressure difference between the two ends of the short portion in which eddy formation will cause loss of energy. Use of the normal discharge formula would then be invalid and would lead to an erroneous result. Accelerated flow tends to be irrotational and there is negligible loss of energy. In decelerated flow, there will be adverse pressure gradient as a result of which flow separation from the boundaries will take place, accompanied by eddy formation and loss of energy. This fundamental concept should be driven home with appropriate emphasis.

PART - II

When Common-Sense Approach can be Unreliable

A tricky question deliberately designed to trip the students regarding change in water level in an open channel due to a small obstruction in flow now be examined. Will the water level rise or fall over a hump introduced over the bed of a canal? The general tendency among the students in responding to such a question, will be to think of picking up one of the two alternatives, the probability of majority of students favouring rise as the answer adopting a common sense approach is very high. Little do they realize that the answer could be either rise or fall depending upon whether the approaching flow is supercritical or sub-critical. In other words, the question is incomplete due to inadequate data and a student who really knows the answer is expected to question back whether the flow is supercritical or sub-critical. A careful look at the specific energy diagram for constant discharge per unit width provides the answer. The specific energy over the hump is reduced while the discharge per unit width and the total energy remains constant. Reference to the relevant specific energy diagram shows a reduction in the specific energy is accompanied by a reduction in the depth of flow if the flow is sub-critical. The depth of flow will increase if the flow is supercritical. Hence, the water level will fall over the hump, if the approaching flow is sub-critical and will rise if the approaching flow is supercritical. A similar question regarding a rise or fall of water level between bridge piers in a river is equally interesting. Here, the specific energy remains constant but the discharge per unit width increases. The diagram showing the depth of flow versus discharge per unit width for constant specific energy, will provide the answer. From this diagram it can be seen that an increase in the discharge per unit width is accompanied by a reduction in the depth of flow if the approaching flow is sub-critical. The depth of flow will increase if the approaching flow is supercritical.

Eiffel - Prandtl Controversy over the Drag Coefficient of Spheres

Studies on the resistance to the motion of bodies fully immersed in a fluid show that the effect of roughening the surface of the body is generally to increase the skin friction and consequently the total resistance. But paradoxically, experimental studies carried out by the famous French engineer Gustave Eiffel and the renowned German scientist Ludwig Prandtl revealed that the drag force experienced by spheres is drastically reduced when the surface is rough than when it is smooth for a certain range of Reynolds Numbers. Actually the values of the drag coefficients obtained by the two Europeans was found to be widely varying and controversy arose as to whose results were reliable. All the early work on experimental aerodynamics was done by moving the test bodies through the air whereas the methods adopted by Prandtl and Eiffel, in 1912, was to make the air flow past the body in a wind tunnel. Eiffel was well known for his structural designs. However, he was also interested in investigating the wind pressure on elementary forms by model tests. In his studies on flow past spheres in the wind tunnel, it was found by Eiffel that the drag coefficient was less than half of what was found by Prandtl at Gottingen, for a certain range of Reynolds Numbers. Finally, the controversy was resolved in 1914 when Prandtl used smoke for his experiments in the wind tunnel and demonstrated through photographs, that a wide wake was formed when the surface of the sphere was smooth and that the wake was much smaller when turbulence was introduced artificially by fixing a wide hoop around the sphere, thus making the surface rough. For the students to get a deeper insight into this paradoxical phenomenon, it is essential to introduce the concept of formation of a wake behind a body and its significance. In the case of bluff bodies like cylinders or spheres the flow pattern and pressure distribution around the upstream half of the body will be identical with the pattern predicted by potential flow theory (which presumes that the fluid is non-viscous). However, in real fluids, accurate measurements of pressure taken over the surface of sphere reveals lack of symmetry. Theoretical and experimental results are in close agreement over the front half of the sphere but at the rear, the theory does not even approximately conform with the reality. The flow pattern and the pressure distribution as observed in experiments are completely different. The expected rise of pressure on the rear side does not take place. The air stream finds it difficult to turn the corner as it reaches the downstream half and leaves the surface of the body and forms a pocket of low pressure with eddies. This region of disturbed flow downstream of a bluff body is referred to as the wake. The motion of air on the rear surface of such a body is influenced by the momentum and the forward pull of the fast moving fluid outside the boundary layer on the one hand and the retarding effect of the boundary together with adverse pressure gradient, on the other hand. If the motion is entirely laminar, the air in the boundary layer can be kept moving towards the rear only by the momentum of the air outside the boundary layer by the diffusing action of viscosity. However, if the boundary layer flow becomes turbulent, the powerful mixing action of the air outside the boundary layer with the air closed to the boundary carries the air further before it separates from the boundary. The overall effect is that the turbulent boundary layer extends much farther along the surface of the sphere before it separates, resulting in the smaller size of the wake and a reduction in the form drag. It is a well known fact that a golf ball with a rough or dimpled surface can be driven farther than one with a smooth surface. This fact had been discovered in the early days of golf by Scottish Caddies who used damaged and discarded balls for their practice.

It will be interesting to know that Eiffel earned reputation as an excellent architect of bridges and viaducts. The well known landmarks of Eiffel Tower in Paris and the Statue of Liberty at entrance to Newyork harbour in U.S.A brought special recognition to Eiffel. In 1885, Eiffel designed the wrought iron skeleton for the Statute of Liberty which was to be given as a gift to U.S.A by the French government. He also supervised personally the erection of this statue. Through design of these structures, Eiffel paved the way and prepared the world for the construction of sky scrapers.

D'Alemberts' Paradox

According to classical hydrodynamics, a body of any shape when at rest and completely immersed in an inviscid and incompressible fluid moving steadily, no experiences force in the direction of undisturbed fluid. This is known as D'Alemberts' paradox. This is contrary to actual experience. A stream of real fluid, liquid or gas, exerts a net force on a submerged obstacle. In 1750, the Berlin Academy sponsored a prize competition on the theory of fluid resistance. D'Alembert was among those who submitted papers for the competition. The Academy decided to withhold the decision until the competitors submitted evidence to support their solution. D'Alembert felt that he would not be able to comply with the additional requirement. However, he presented his theorem in a treatise published in 1752. It was this which contained his famous paradox. D'Alembert could not see any reason to assume that the conditions in the rear were different from those in front of an immersed object and summation of the elementary pressures exerted on each part of the body surface to the paradoxical result of zero longitudinal force on the body. D'Alembert himself doubted the physical significance of this result. The search for the resolution of the paradox occupied many eminent mathematicians for the next two centuries and led to some of the most important developments on the subject. It should be stressed here that it would be wrong to conclude that the study of the ideal fluid is a mere delight of the mathematicians and that it has no practical consequences in aerodynamics. It has been possible to derive, analytically, an elegant expression for the lift force experienced by an immersed object in a direction transverse to the direction of motion, through the use of classical hydrodynamics (Magnus effect), when circulation is introduced.

The Wake Behind a Body

At this point, initiation of discussion on the failure of D'Alembert's theory to predict the drag force experienced by a bluff body like a cylinder fully immersed in a flow, will be appropriate for the introduction of the concept of formation of wake behind the body. Bodies which have sharply truncated tails (such as cylinder or spheres) leave behind them a large disorderly flow pattern referred to as a wake. As the flow enters the rear portion of such bodies, it encounters a situation of adverse pressure gradient due to deceleration. As a consequence, the flow leaves the surface or separates from the boundary causing formation of eddies within which the pressure is much lower than that prevailing on the front part of the body. The unbalanced force due to the difference between the pressures on the front and the rear half of the body thus causes the drag force on the body in the direction of motion. Since this drag depends on the shape of the body, it is termed as form drag as different from drag due to skin friction. It is to be clearly understood that viscosity is not the direct cause for this form drag, although the cause for the formation of eddies is to be traced to the property of viscosity. If trees are uprooted or the roofing sheets of structures are sucked up in a gale, it is not because of the viscous drag but it is the form drag which causes such damage.

While the lift on a stationary cylinder in an air stream is zero, that for a rotating cylinder is not zero. Air is dragged along with the rotating cylinder. This circulation, when combined with the translational flow, causes the velocity on the top side of the cylinder to be higher than that on the bottom side. As a consequence of the Bernoulli equation, the pressure on the bottom side of the cylinder will be higher than that on the top side, giving rise to an upward lift. The lift associated with a rotating cylinder in a translating air stream is called the Magnus effect and it is this effect that causes a slice or hook in golf, a "cut" ball to move off to the side in tennis or ping pong, or a curve ball in baseball[7].

Vibrations due to Vortices Shed in the Wake

In certain weather conditions, electric transmission lines flung between pylons have been observed to oscillate with great amplitude and at very low frequency. In regions where ice can form on these lines during hard winters, the cross section presented to the on coming winds can be of a shape which gives rise to self excitation, leading to galloping of these transmission lines. Some times, tall chimneys are found to sway in moderate winds as a consequence of the periodic shedding of vortices first from one side of the chimney and then the other. "When a vortex leaves, the body is subjected to a reactive force. If the frequency of vortex formation corresponds to the natural frequency of the body (the frequency with which it will vibrate if bumped) large amplitudes of vibration may result". These eddies cause pressure fluctuations and hence the swaying. Once the swaying starts, it is largely self maintaining. It is observed in several cases that the swaying starts when the frequency of vortex shedding coincides with the first natural frequency of the chimney. In other words, forced resonance oscillations cause the swaying to begin with. Once motion starts, it dictates the frequency with which the vortices are shed and thus it becomes self-excited. One of the methods adopted to stop the swaying is to fix guys. The destruction of the mechanism by which the exciting force is produced in another way of tackling the problem. Helical spoilers may be attached to the side of the chimney. This can be in the form of vertical stairs. These have the effect of breaking the pattern of vortices so that no clearly defined excitation acts on the chimney wall. Vortex shedding has been found to be the cause for several interesting vibration problems. The periscope of a submerged submarine, for example, gives a blurred image if it is subjected to oscillations like that of a chimney. Since the fluid flow is unidirectional in this case, a simple solution such as attaching a splitter plate will solve the problem. Galloping of transmission lines due to vortex shedding, can cause high stresses at the supports leading to breakage. In this case, it is not possible to destroy the mechanism causing vortex shedding. Because any projection from the surface of the line will result in corona discharge. Vibration dampers are used to prevent breakage of lines at the point of support. The famous example of self excited oscillation of a structure is that of the Tacoma Narrows Bridge (a suspension bridge in Washington State, U.S.A) that failed in the autumn of 1940 after only a few months of service. The steel structural component responsible for this was not of cylindrical cross-section but was like the letter 'I' placed on its side. After a great deal of research, the bridge was re-built with important modifications which eliminated the mechanism causing excitation by suitable alterations to the surfaces that were presented to the wind. When the bridge was rebuilt, the side plates that had been responsible were eliminated, and the structure stiffened. This changed the natural frequency, and no subsequent difficulty has been encountered. The Tacoma mishap made the structural engineers pay a great deal of attention to wind-excited oscillations in suspension bridges. Structures other than bridges are often subjects for potential Strouhal-Karman difficulties. These include high smokestacks and tall buildings.

Streamlined Body

Form drag on a body can be reduced considerably or entirely eliminated by shaping the tail so that the flow follows the contour right up to the point at which the body terminates. An aerofoil or a fish are good examples of streamlined bodies. A streamlined body leaves behind a very small wake. D'Alembert's Paradox is very nearly true because pressure differences are almost entirely eliminated in the case of streamlined bodies. Practically speaking, a streamlined body may be looked upon as one for which the form drag is much less than the drag due to skin friction. Airfoil sections are special streamlined bodies designed to provide lift to an aircraft. Different shapes provide different lift and drag characteristics.

Air Resistance to high-speed Flight

The atmosphere behaves like the hypothetical ideal fluid of classical hydrodynamics, when bodies move through air at low speeds. Up to the eighteenth century, it was thought that the resistance of air to bodies moving through the atmosphere must be very small irrespective of their speed. In 1687, Newton carried out experiments to determine the value of the resistance force by dropping spheres of various weights and diameters from the dome of St. Paul's Cathedral and confirmed the law he deduced theoretically that the resistance is proportional to the square of the diameter and the square of the velocity. Newton's experiments were confined to rather low velocities. It was not until the time of Benjamin Robins (1707-1756) that the real importance of air resistance came to be appreciated. Robins made measurements on the motion of cannon balls by the device known as ballistic pendulum. He summarized that the theory of air resistance as developed by Newton was not valid for high velocities as in the case of cannon shots although it was in close agreement in case of objects moving in slow motion. The air resistance at high velocities was observed to be as high as 3 times that of the value predicted by Newton's theory. It could be seen that the density changes caused by the motion of a body through air may be neglected if the speed does not exceed one-third that of sound. Newton determined the speed of sound in air to be 750 miles an hour and thus motion of bodies moving at speeds below 250 miles per hour in air could be taken as slow motion. It may sound somewhat odd if we speak of gases like air to be incompressible. What is actually meant is that in situations of ordinary slow motion, the molecules of the gas are not squeezed together so much as to cause perceivable change in density. If a body is moving with a velocity comparable with that of sound, the density changes in its vicinity are much more pronounced. Thus it can be seen that the ratio of the speed of the body to that of sound in undisturbed air is an important parameter in the aerodynamics of high-speed flight and this ratio is called the Mach number named in honour of Ernst Mach an Austrian Scientist who made significant contributions in the study of high speed flow. The Mach Number is a non-dimensional number like the Froude Number and speeds with Mach Number exceeding unity are referred to as supersonic speeds and speeds with Mach Number less than unity as subsonic. It is this ratio which largely regulates behaviour of gases at high speeds. Mach number may be looked upon as the ratio of the inertial forces to the elastic forces in the fluid.

The pressure changes which accompany the motion of a body in air at ordinary speeds are exceedingly small and are of the order of one-millionth of the normal pressure of the atmosphere. "A whisper just detectable by a person with good hearing would be made up of changes of pressure as small as a one-billionth of an atmosphere". As the speed of a body approaches the speed of sound, there is an instantaneous rise in pressure and the sudden wave thus caused is called a shock wave. The crack of a whip is an example of such a shock of low intensity.

"At the lower speeds the greater part of the energy used in overcoming the drag is dissipated in eddies in the wake, and for the reduction of drag at such speeds the shape of the tail is rather more important than that of the head. At high speeds the position is reversed. The greatest loss of energy is located in the pressure shocks around the head of the shell, and for high efficiency the shape of the head is more important than that of the tail. Even small shocks at Mach Number 0.7 cause the drag co-efficient to be doubled and as the shock becomes stronger the increase in resistance of the conventional type of wing can be as much as ten-fold. To maintain steady motion with such a tremendous rise in resistance calls for a very large increase in the power expended by the engine".

"The effect of the formation of shock on drag is two-fold. Firstly, the boundary layer thickens at the root of shock wave may separate from the surface. Secondly, some of the Kinetic energy of the motion is degraded into heat in passing through the shock. The sudden sharp increase in the drag of the wing".

"In general, inertia may be ignored in problems for low Reynolds Number (R) and viscous effects may be ignored when R is high. While this approximation is excellent for problems in the laminar regime, it is only partially permissible for high-speed flows. In the latter case, viscosity may be ignored only in calculations for lift and then only when flow separation is negligible (i.e., for a perfectly streamlined body). The boundary layer concept is needed to explain the appreciable viscous drag on bodies operating at high values of Reynolds Number"[7]. But, even this is not enough to explain drag in some high-speed flows. The additional concepts of flow separation and the role of turbulence in making it possible for energy transport into the boundary layer to postpone separation is needed to complete the picture. It took over a hundred years to develop this body of theory. The first part to appear was that for very low Reynolds Number flows and that for an ideal fluid. This was, subsequently, followed by an introduction of the boundary layer and flow separation concepts.

Developments in Aerodynamics

After the Wright Brothers created history in 1903 in U.S.A in achieving heavier-than-air powered fly, Henri Farman did the same in 1904 in France. Their machines were built of sticks and wires and the speeds they attained were 30 to 40 miles per hour. There were no helpful rules for the builders of the airplanes. In 1904, at Gottingen University in Germany, Ludwig Prandtl wrote about the forces on airplane wing as it moved through the air. The men who were building and flying them has strange ideas about how they flew. Scientists were not sure how an airplane could fly. In England, while Frederic Lanchester was developing the theory of flight, Ludwig Prandtl was doing the same thing at Gottingen. The theory became known as Lanchester-Prandtl theory. By blowing air past small models of wings better shapes were developed. It was learnt that most of the lift came from the top of the wing and less of the lift came from the bottom. So, more attention was given to the curve of the top surface. Theodor Von Karman, a mathematical prodigy and a mechanical engineer from Hungary came to Germany to work with Prandtl at Gottingen. He brought ideas from the University in Budapest to the University in Gottingen. Prandtl and Karman developed wing shapes that would be good for fast and high flying airplanes.

In 1911, Karman discovered something very important while trying to help a student named Carl Hiemenz who was working with Prandtl. Instead of using flowing air he used water. He studied how water flowed past bodies of different shapes. The purpose was to design better airplanes and boats. While studying flow of water past a cylinder, Carl had some difficulty. He expected the flow of water around the cylinder to be smooth but the flow would not remain smooth. When Carl reported to Prandtl about his difficulty, Prandtl told him that the cylinder was not perfectly round. After ensuring that the cylinder was made perfectly round, the student put it back in the water and started the flow and once again found that the flow was not smooth. While trying to help the student, Karman took a look at the flow pattern and he felt that it was strange as to why the flow was not smooth. When the student went back to Prandtl and told him that in-spite of making the shape of cylinder as perfect as it could be and in spite of making the flow control exact, the flow pattern still remained the same. Prandtl told him not to be discouraged and asserted that there must be a cause and it should be found. At the request of the student, Karman took a look at the flow pattern around the cylinder while the experiment was in progress and pointed out the little circles of water which appeared behind the cylinder. These circles of water turned around and around. Some of these vortices turn to the left and some to the right. Vortices are shed alternately from opposite sides of a body at a definite frequency, at a particular range of Reynolds Number (<2,500). The vortices in one row are staggered with respect to those in the other. Vortex shedding may also occur at high values of Reynolds Number. Such vortices were apparently first observed by Leonardo da Vinci about 1480 in a river behind a bridge pier. Karman did the mathematics of the problem and showed what the distance between the vortices must be and concluded that these vortices represented the drag experienced by cylinder. When Karman showed his calculations to Prandtl, he looked at him with respect and said that it was something commendable. This discovery of Karman proved to be something fundamental in aerodynamics and the stream of vortices came to be known as Karman vortex trail or Karman vortex street. Karman carried out more and more studies on vortices and won recognition as an important man in aerodynamics. Lord Rayleigh, the eminent Physicist, observed that Karman's work explained how wires in the wind can make a sound like that of singing. Vortices also cause this effect on parts of the boat which are under water. High towers sway strangely in the wind. With Karman's theory engineers are enabled to design better boats and towers so that wind or water would have less adverse effect on them.

In the summer of 1912, Karman went to England and met the famous aerodynamicist Frederic W. Lanchester. Important men among others who wrote of theory of flight were M. William Kutta, a German and Nikolai Jhukowsky, a Russian. Karman learnt much from these men. Although Ludwig Prandtl was recognized as the father of airplanes, better airplanes were being built at Aaschen, Germany. And in 1912, Karman was invited to take complete control of the studies in aerodynamics at the Aaschen school. Though reluctantly, Karman left *Gottingen and in a few years, Aaschen* became the centre of the science of aerodynamics.

Lord Kelvin (1824 - 1907), the famous scientist (who coined the word turbulence), believed that powered heavier-than-air flight was not possible. He was proved wrong by the Wright Brothers in 1903 in U.S.A. Jules Verne and H G Wells wrote stories in which space travellers moved faster than sound. But many of the men with whom Von Karman worked believed that supersonic flight was not possible. Von Karman was not held back by these ideas. He thought of faster and faster speeds, although it was predicted that the air would act like a wall and the airplane would be held back as it moved with speeds approaching that of sound. In 1935, Von Karman had written about the first theory of supersonic drag. Three years later, while he was on an assignment at California Institute of Technology, Pasadena, U.S.A, he designed the first practical supersonic wind tunnel. At the same time, he was working with rockets and jets. He was also in contact with Frank Whittle who was developing jet aeroplanes in U.K for the Royal Airforce. By 1946, he was ready with the first theory of supersonic flight. Von Korman suggested that a rocket motor be fitted to the airplane to supply the extra power needed to overcome the increase in drag at supersonic speed. In October 1947, a rocket airplane was flown at speeds faster than that of sound. By 1953 (50 years after the beginning of the powered flight), a plane moving at over 1600 miles per hour (more than twice the speed of sound) was built under his supervision. Von Karman was honoured with the title of 'Father of Supersonic Flight'. "He and Prandtl contributed successively to the analysis of the velocity distribution and resistance for turbulent flow in pipes and along plane surfaces, and the resulting logarithmic expressions now bear their joint names".

Conclusion

Among teachers in higher education, there is a general lack of appreciation of the need for a grasp of psychology of learning. A general feeling that there is no place for spoon feeding and learning should be student-*centred particularly in higher education*, may be largely responsible for this situation. However it is imperative that teachers should pay adequate attention to proper implantation of basic concepts among students. For achieving this objective, ways and means of creating motivation should be continuously explored by the teaching community. Giving analogies and anecdotes in the course of class room lectures can be of great help in creating such motivation among students, while historical references provide opportunity to the learners to know the rich history of the subject and bring key concepts to life. This approach helps the student develop problem-solving skills, gain physical insight into the material, learn how and when to use approximations and make assumptions, and understand when these approximations might break down; all leading to improve pedagogic effectiveness as well as a strong conceptual understanding.

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