What is Centrifugal Force?

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Modern physics has mounted an assault on the age-old concept of centrifugal force. As a practicing engineer, this causes an unsettling feeling. This article defends the notion that centrifugal force should be retained, along with centripetal force. They are both constructs of the human mind. With these abstractions, we gain a deeper understanding of the physical universe, and the role of motion into material properties. Applied physics (engineering) and theoretical physics can be complementary.

"What is centrifugal force?" sounds like a trivial question, because all engineers are exposed to centrifugal force in undergraduate courses. It is one of those fundamental concepts in the mechanical engineers vocabulary. In addition, mass balancers apply a weight to make wheels turn smoothly, and for them, the concept of centrifugal force is intuitive. We have a formula and definition of centrifugal force and that should be the end of the story. However, when reviewing my son's physics textbook,[1] I discovered that modern physics teaches that centrifugal force is not real and should be disposed of. This piqued my interest. Later, I heard a well-respected physics professor state that centrifugal force should be removed from our vocabulary. This attack on our applied principles requires some examination.

The question we seek to answer: "Is centrifugal force real or apparent?" Physicists claim that centrifugal force is not real, but an apparent force. The real force in circular motion is the force associated with the centripetal acceleration directed inward toward the center that keeps the article on a circular path (Figure 1). However, engineering texts and application notes from balance machine companies repeatedly use the concept of the outward, or centrifugal, force. That outward force exerts a tug on an unrestrained article that would cause it to fly off if released. There is this tug of war between centripetal and centrifugal force; between physicists and engineers. How can one be real and the other apparent? Does not Newton's third law of equal and opposite reactions apply? These questions will be answered, but first let's define apparent and real.

"Apparent" is defined as:[2]

- Clear or manifest to understanding
- Appearing as actual to eye or mind
- Manifest to senses or mind as real on the basis of evidence that may or may not be factually valid

"Real" is defined as:

- Not artificial, fraudulent, illusory, or apparent
- Existing as a physical entity
- Having objective independent existence
- Capable of being detected

So apparent and real could be considered mutually exclusive, but they also seem to have some overlap, adding to the confusion just by the unfortunate use of these words.

Sorting this out, centrifugal force could be a sensual perception, but may not be real. So if humans were removed, could centrifugal force have an effect on the remaining creatures? The obvious answer is yes, but I am not qualified to judge that. In contemplating centrifugal force, then, we will tread into metaphysical considerations, returning to the roots of science.

Engineering

Some engineering texts ignore centrifugal force and do not mention it. Others define it as a body force; that is, it acts on a mass that is in circular motion. When the circular motion is uniform with constant angular speed at a fixed radius, then the magnitude of this force is defined by the equation:

$$F_c = mr\omega^2 \tag{1}$$

where:

F_c = centrifugal force
m = mass

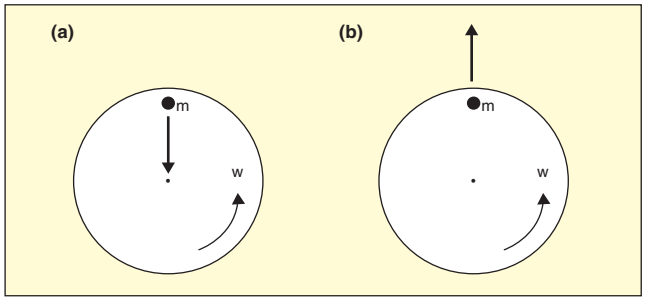

Figure 1. Diagrams of: (a) centripital force; and (b) centrifugal force.

r = radius
ω = circular frequency of rotation

This is nothing less than Newton's second law ($F = ma$) applied to rotation. The term $r\omega^2$ is defined as the radial acceleration, and the term mr is the unbalance. This equation is a relationship. It does not tell us what centrifugal force really is, but only how it relates to other known quantities. It does provide some insight, though. It is a force associated with motion, specifically, rotating motion. If there is no rotating motion, so that the circular frequency term is zero, then there is no force. The same argument could be used for either the centripetal or the centrifugal force. They both disappear when the circular motion ceases. Neither would exist without the other.

If not restrained, then this rotation would cause the mass to fly off on a tangent to an observer viewing from an external inertial frame of reference. To an observer on the wheel, and rotating with it, the outward motion would appear to be directed outward along a radius. The restraining force is centripetal force, which is defined by the angular acceleration:

$$Centripetal\ Force\ = mv^2 / r \tag{2}$$

where v^2/r is the radial acceleration (same as $r\omega^2$)

With these two mathematical definitions, the magnitude of centrifugal force and centripetal force are exactly equal, only differing in sign. Centrifugal force = $mr\omega^2 = -mv^2/r$. Centripetal is the force that constantly pulls inward on the body, keeping it at a constant radius in circular motion. The dimensional units of both centrifugal and centripetal force, $kg{\cdot}m/s^2$, computes correctly to a force by Newton's second law: $F = ma$.

Work, by physicists' definition, is a force multiplied by the displacement; work = $F \times d$. This ignores internal material strain, but this will be taken up again later. The displacement in uniform circular motion is an infinitesimal movement toward the central axis. Since centripetal force is also in the same direction, the energy can be considered positive as doing work on the rotating mass. Centrifugal force, on the other hand, is opposite the direction of the infinitesimal displacement, so the energy is negative, and the rotating mass does work on the connection, or on the wheel. The centrifugal force can be considered as the equal and opposite resistance offered by the body to the connection at the wheel.

If centripetal force was the only active one, then the rotating body should have all mass elements in compression, and it should never fly apart. This clearly is not what happens. Tensile stresses cause cracking and eventual disintegration at higher speed, so tensile (or outward) forces are clearly at play.

A rotating wheel is a noninertial reference frame and Newton's first and second laws do not apply. However, the third law of equal action and reaction makes sense if we consider the rotating wheel as a stationary frame of reference. This is valid in some engineering constructs (specifically, space-vector modulation in three-phase AC motors) to visualize the forces and to simplify the mathematics. If I take as my reference the rotating frame, then there is a balance of centripetal and centrifugal forces.

From *Principles of Dynamics*, 2nd Edition, by Donald T. Greenwood, page 24; ". . . if a particle is whirled in a circular path by means of a string attached to a fixed point, then the inertia force is a so-called centrifugal force which is equal to the tensile force in the string. On the other hand, the external force on the particle is the centripetal force of the string acting radially inward toward the fixed point at the center of the circular path. By the law of action and reaction, the centripetal force is equal in magnitude to the centrifugal force but is opposite in direction."

Balancing

Consider a wheel mounted on a shaft with bearings, and supported on a bathroom scale (see Figure 2). When at rest, the scale registers the total weight, which is mg, and depends on the local gravitational field. When rotating, without the unbalance mass, the total weight remains the same. Now add the unbalance mass, *m*, and the scale will increase to account for the added weight. When rotated, the scale will register a sinusoidally varying force, in addition to the static weight. The average force will still be the total static weight of the objects on board, including the unbalance.

On top of this average will be a varying force whose zero-to-peak value will be caused by the rotating unbalance. The zero-to-peak value will not be the unbalance mass, but rather the centrifugal force as defined by the mass, radius, and speed squared. This is a real force that can be measured. It can even be measured in a zero-gravity field. The force due to the unbalance, which is directed outward when considering the phase relationship, is clearly a centrifugal force.

Balancers routinely apply correction weights to remove the oscillating force that the unbalance created. The centripetal force acting on the correction weight serves to keep it in position on the wheel, while the centrifugal force does the nullifying. All this is good engineering knowledge, but it does not answer the question of *real* or *apparent*. To consider this further, we must dive into physics, and then a little philosophy.

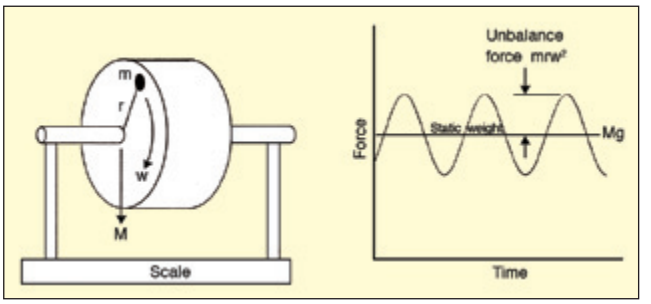

Figure 2. Rotating wheel (left) with unbalanced mass (m) supported on a bathroom scale; and graph force of time (right).

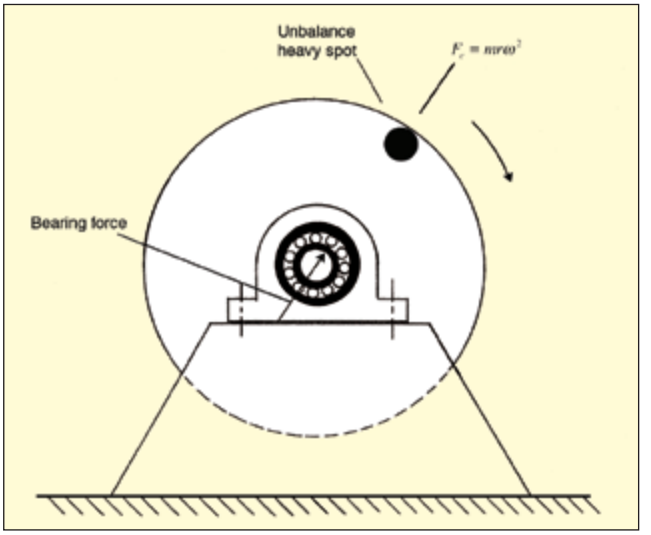

Figure 2. Bearing force and subsequent wear caused by unbalance.

Dynamic Effect of Rotation

There is no need to convince a pilot being tested in a centrifuge that centrifugal force is real, or a child that loses grip on the rail of a merry-go-round, but is it possible to be deceived? We know that unbalance causes serious damage at the bearings and fatigue cracking on the stationary parts (see Figure 3). Is this damage caused solely by the centripetal force? If the correction was not applied, then there would be no centripetal force from a nonexistent correction weight. What is the force that caused the previous damage before the correction weight was added? I must conclude that it was some manifestation of the centripetal force on the previous uneven distribution of mass about the rotating axis.

But the centripetal force is, and was always, there working on every small element of mass and directed inward. Further, the centripetal forces must have been unbalanced so that there was more on one side than the other. These inward-directed forces should generate compressive stresses in the material. More uneven weight distribution (that is, more unbalance) will create larger compressive stresses. Following this logic further, some huge amount of unbalance should create such an abundantly large inward centripetal force that the rotor will collapse into a black hole. This conclusion is ridiculous, so the logic is faulty somewhere along the way. My suspicion is that the magnitude of the force calculation is correct, only that the direction is corrupted.

Pumps and fans impart energy to fluids. The fluids are not constrained by a centripetal force inward. Fluid packets are captured between rotating vanes and flung outward, resulting in a velocity pressure. Since power is a force multiplied by velocity, (Power = Force × Velocity), there is obviously a force involved in putting energy into a fluid, and this force must be outward to create a positive pressure.

A rotating frame under uniform circular motion is a noninertial frame, and some principles of physics do not apply the same as in an inertial frame. Specifically, Newton's second law, $F = ma$, must be expanded in a rotating frame to consider translational motion, rotating acceleration, Coriolis acceleration, and gyroscopic precession. The bottom line is that with no rotation, there is neither centripetal nor centrifugal force. These forces are created by rotation, which are by definition, non-inertial. So they are dynamic effects and are man made. So centrifugal force is not a natural force, but a man-made one. But just as a man-made lake is still a lake, centrifugal force is still a force.

If we believe in the atomic/molecular theory of negative electrons spinning around a positively charged nucleus, then there must be a naturally created force that prevents the electrons from collapsing into the nucleus. The only conceivable answer is an outward force, not an inward one acting alone. This must be a naturally occurring outward force and not a man-made one. I chose to call it centrifugal force, but since it is not man-made, perhaps another word is more appropriate to separate natural from man-made rotating outward forces.

It is easy to see how a ball rotating on a string will place the string in tension. The force on the ball is inward toward the center. Now cut the string while in rotation and the inward force disappears, as does the outward force on the hand. The outward apparent force in the rotating frame is what we call centrifugal force. In fact, when the string is cut, the ball just continues on a tangent straight-line motion by virtue of the energy imparted to it during rotation. It is then in equilibrium in an inertial frame in uniform straight-line motion.

So the observation of no outward motion before the string is cut we imagine to be in equilibrium in a rotating frame. After the string is cut, the ball is in equilibrium in an inertial frame and just moves off on a tangent straight-line motion as if no forces are acting on it at all. Now what do we make of all this? The ball no longer has the centripetal and centrifugal forces acting on it, but if the ball hits someone, then they would certainly say that the ball possessed some energy. This linear energy we know was imparted to the ball by the loss of balance between the centripetal and centrifugal forces.

Both forces, centripetal and centrifugal, are imaginary, or both real. They appear and disappear together. They both exist in a

rotating frame, and are of no consequence in an inertial frame; that is., they lack any positive characteristics. They are balanced in an imaginary sense. Which one does the damage depends on your favorite flavor of tea. More practically, centripetal force constrains the object to remain on a circular path, while its alter ego, centrifugal force, causes the tension in the string. Cause and effect are both real, even though they were created by the circular motion and disappeared when the circular motion ceased.

Physics

Physics teaches that there are four natural forces in the universe:

- Gravitational
- Electrostatic
- Strong nuclear
- Weak nuclear

Magnetism can be explained, at least theoretically, with electrostatic principles. Thermal expansion, which can create extremely large forces that engineers cannot stop but only accommodate, can likewise be explained in terms of the natural nuclear forces. How about centripetal and centrifugal forces? How can they be explained in terms of the known natural forces? In other words, what is the source of centrifugal force? I will not attempt to explain this, only acknowledge the conundrum. Let's consider more mundane points of view.

Newton's second law provides an operational definition of force. It is something that causes motion. The motion is, in fact, an acceleration scaled by the mass, $a = F/m$. (For those of us in the dynamic world of vibration, we know that the motion measured is also a function of frequency, but for the present discussion, let's assume that Newton's second law is valid at low frequencies.)

In astronomical terms, the centripetal force holding heavenly bodies in circular motion is gravity. Centripetal force is the operative one that keeps heavenly bodies in orbit, and we usually attribute this to gravity. This is evident. This is also a pseudo-inertial frame, and a centrifugal force appears to be absent. Remove gravity (an impossible experiment), the centripetal force disappears, and the apparent centrifugal force, which was invisible before, suddenly causes a change in motion. This is all intuitive, based on knowledge, experience, and logic. How would a nonhuman explain this change? We do not perceive gravity because we are born into it, just as a fish does not perceive water. A fish will perceive, and react to, the absence of water. Likewise, a human will acknowledge the absence of gravity and be comfortable in its presence.

There really are no ideal inertial frames in our part of the universe, but theoretically speaking, we can imagine inertial frames somewhere, where there is no such thing as a centrifugal force. In this perfect inertial frame, there is absolute rest. Nothing moves, or everything moves together in the same direction at the same speed, and the place is dead or in a state of perfect balance, as in a heavenly sense. In that case, one can also acknowledge the presence of another greater force in the universe that can create, destroy, and alter the known physical properties of mass, space, and time. Our imaginations can take us to any place that we choose to wander.

Centrifugal force only exists in noninertial frames as a geometric construct to make the body appear to be in equilibrium. I remember a physics exercise where we (the students) were asked to calculate the different weights of a person at the equator and at the poles. The composer of this problem perceived that the centrifugal force at the equator, due to Earth's rotation and directed outward, would counteract the gravity force and the person would weigh less at the equator than at the poles. I have difficulty imagining how centripetal force could produce this effect.

Modern physics teaches that centrifugal force is apparent, and should be deleted from our vocabulary. So, by $F_c = mr\omega^2$, a real mass (m) and a real linear dimension (r) undergoing a real rotational speed (ω) computes to an imaginary force. Somewhere here we should also have to insert the square root of –1. The centripetal force, using the same parameters, computes to a real force. How so? Granted, the mass in circular motion is not in equilibrium. It is constantly changing direction, so it is accelerating. Not being in equilibrium, the mass does not need to have equal and opposite balanced forces. According to physics, centripetal force is the real force, and centrifugal is not real.

$F_c = mr\omega^2$ embodies the concepts of force, mass, space, and time – all deep physical and metaphysical quantities. Specifically, forces act on mass. Without mass, there can be no force. Without space, there can be no mass, and without time, there can be no cause and effect. All of these quantities are inventions of the human mind, and therefore, imaginary. Centripetal force, $F = mv^2/r$, necessarily, must also be imaginary, since we cannot sense any of these quantities either. What we detect are motion (from sight), pressure (from feeling), sound (from hearing), smell, and taste. Anything else we derive from these sensations are, therefore, by definition, imaginary. If centrifugal force is considered imaginary, then so must mass, space, time, and gravity necessarily be imaginary. In fact, uniform straight-line motion is indistinguishable from gravity and undetectable. In terms of special relativity, "only relative motion matters."

All is well in the natural world. What has run amuck is physics education. To place things in their proper perspective, centrifugal force is the real one that is created when a mass begins a circular motion. It is a necessary by-product. Centripetal force is the internal material strain that is generated at the same time to keep all the pieces together on a circular path. The two are in balance in whatever frame of reference one chooses to imagine. In celestial motion, the task of centripetal force is done by gravity; the two bodies constrained together feeling the internal strain.

Real or Apparent

Physics also teaches that whatever we can sense is real. This is grounded in the philosophy of Francis Bacon, John Locke, John Stuart Mill, and Thomas Reid. We must trust our senses, because if we cannot trust them, then our perception of reality becomes fuzzier. How do we get to know anything? It is through the senses as input to the mind. The mind, then, builds on the accumulated experiences and contrives associations, which we define as mathematical formulas. What we call knowledge, then, is a combination of sensation, memory, and imagery. We can know things beyond our senses with the faculties of mind and reason.

This centrifugal, or even centripetal, force is a synthetic proposition, or commonly called a theory. It is only true in the context of human understanding. Whether it is true in reality we can leave to the domain of the philosophers. I may also wish to inquire of them if these forces are real or apparent to all animals, insects, fish, birds, and all other creatures with senses.

On a more practical note, if we place our trust in the above-named philosophers and the beliefs of modern physicists who place their trust in the senses, then centrifugal force must be the real one. It is what is sensed as pressure on the hand when swinging the ball on a string. It is the outward force that we feel. The ball experiences the inward pull on the other end of the string. The ball "feels" the centripetal force, not us. It is like a dog pulling on a leash. The dog feels like the owner is doing the pulling. So whatever you wish to call it, centripetal or centrifugal, depends on which end of the leash you are on.

Some philosophers (Socrates and Plato) teach that true knowledge cannot be acquired via the senses. True knowledge is perfect and pure and should not be corrupted by imprecise measurements or subjective observations.

I, for one, will retain centrifugal force as a useful concept in times of peace and war. In the Bible, young David felled the Philistine giant with a rock and a string. He added energy to the rock with the aid of centripetal force. By releasing the centripetal force, the rock departed from circular motion and flew off on a straight-line trajectory as calculated by David to intersect the head of the giant. David needed no knowledge of modern physics or math to accomplish his deed. He cared not whether the operative force was centripetal or centrifugal. David may have slain Goliath with an apparent force, but the giant still ended up dead.

References

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