The $\epsilon-$axle and its Application to a Floating Windmill

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***Abstract*—We describe and analyze a magnetic bearing built using a permanent magnet assembly. The magnetic bearing comprises a conical female magnet assembly and a rotationally symmetric identically polarized male piece. The opposition of the two parts produces a force between them which tends to hold them apart and aligned along an axis of symmetry. We describe the bearing and its use in generating an $\epsilon-$axle, or an axle having a friction of some $\epsilon > 0$. Finally, we integrate this $\epsilon-$axle into a windmill design in which a single point of contact exists on the main axle.**

Keyword-floating windmill; magnetic levitation; ϵ-axle

I. INTRODUCTION

The most important reason that machinery breaks down is the continual rubbing or rolling contact of the various parts that make up the machine. Most machines contain parts that are coupled together using a variety of mechanisms which allow parts to move over one another. There are thousands of varieties of mechanisms for allowing the coupled motion of parts, each of which is designed to limit movement, vibration, friction, or other many motion-related properties. Despite the myriad of inventions designed to assist in the motion of one part over another, all fall short of providing one important service - removing all friction between moving parts in a way that does not require the expenditure power.

The value of such a mechanism cannot be overstated. There are a number of pressure and liquid-based systems which support machinery, making sure that parts do not come into contact [2], [8], [15], [17]. An example of this system is the rolling sphere fountain, in which a marble ball rolls on a flow of water with a negligible amount of friction. The main limitation with this system is that it requires a constant flow of water and energy. As a result, such systems do not find their way into most complex machinery.

Magnetic bearing systems which are powered magnetic systems that hold axles in place with magnetic fields, also allow machinery to run without contact [6], [9], [13], [14], [16]. However, such systems are power intensive, and do not easily find their way into the majority of machinery, particularly those machines involved in the generation of power. This mechanism may be used in certain machines where the vast expenditure of power is permissible but the placement of frictionless axles is necessary.

This paper discusses a new unpowered technology which may be used to reduce friction. The technology allows two parts of a system to be held apart and aligned by an array of permanent magnets. This arrangement essentially creates frictionless joints which then can be used other systems that have coupled moving parts. When applied to a vertical axle wind turbine (VAWT), this magnetic technology enables the axle to have only one point of contact (the point where the axle touches another part of the machine) on one end and the magnetic ball and socket on the other.

The remainder of the paper discusses the magnetic ball and socket along with its various functions. Section 2 reviews the current windmills with their advantages and disadvantages to determine which is best suited to the magnetic ball and socket. Section 3 introduces the basic magnetic ball and socket technology. Section 4 describes the process of integrating the aforementioned magnetic ball and socket to the windmill. Section 5 offers some discussion and concluding remarks.

II. REVIEW OF STANDARD WINDMILL DESIGN

There are many different windmills that are in use today. These windmills range from ones with horizontal axis blades on modern wind turbines to ones with vertical axes. Although the horizontal axle wind turbine (HAWT) is more common, we will be focusing mainly on the vertical axes windmills or vertical axis wind turbines (VAWT), which are divided into three classes: Savonius Wind Turbine (SWT), Darrieus Wind Turbine (DWT), and the giromill [3], [5], [7]. The Savonius Windmill is usually characterized by the S shaped rotor viewed from the top. The Darrieus Windmill is designed in such a way that the air foils are symmetrical and have zero rigging angles; that is, the angle that the aerofoils are set relative to the structure on which they are mounted. The giromill is a version of the DWT.

A. Savonius Wind Turbine

Savonius windmills are characterized by the shape of their blades. The initial design of the Savonius windmill derives from cutting a circular cylinder along the central plane and moving the semicircles along the cutting plane [10]. This design, however, has evolved and been manipulated into various forms. The windmill is a drag-type device; the angle of attack is relatively high and the rotor uses the drag to run itself, despite the fact that the drag reduces its efficiency.

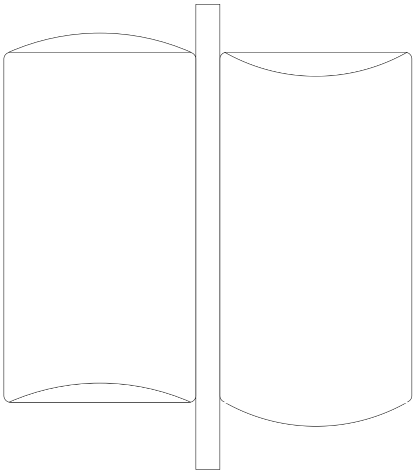

Figure 2.1: A side view of the Savonius wind turbine.

The Savonius wind turbine:

- is relatively easy to maintain because the moving parts are built close to the ground and also because it is less expensive than the HAWT;
- has the blades that are vertical and therefore are able to catch the wind at any horizontal angle, stultifying the yaw mechanism (the mechanism that allows the windmill to turn to the wind) ;
- usually has a lower tip-speed ratio and is therefore less likely to break at high wind speeds.

Savonius wind turbines generally are built on a vertical axis utilizing a bearing system consisting of at least two bearing assemblies at the bottom and top of the turbine. The inactivation of either one of these bearings, either from mechanical failure or for some other reason, requires that the central axis be disassembled and the bearing assembly replaced. The cost of such a replacement can be in the tens of thousands of dollars.

B. Darrieus Wind Turbine

The Darrieus rotor is a lift device, characterized by curved blades with an air-foil cross section [12]. The rotor on this device is shaped in such a way that the windmill runs with a pressure difference between the two sides of the blade. The Darrieus wind turbine generally has the same structure as the Savonius wind turbine (SWT) in terms of the ball bearing placement and the generator location.

This wind turbine can attain high speeds by reducing drag due to its rotor shape (it essentially chops the air as it spins and has very little air resistance), which increases the possibility of it wearing down. The ball bearings have a high possibility of wear due to metal fatigue, the gear box can fail due to wear, and high tip-speed ratio (TSR) can render the windmill itself unstable. These rotors have a relatively low starting torque and have high power output every given rotor weight. These windmills have a rather high efficiency of about 35% [1], but their reliability is low as the TSR tends to be very high: the higher the TSR, the lower the reliability.

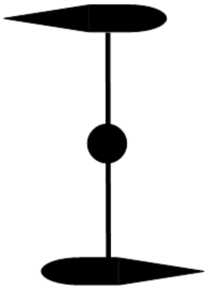

Figure 2.2: A Darrieus wind turbine viwed from the top down. The axle in the center is oriented perpendicular to the ground.

These windmills have various advantages:

1) The blades on the DWT are able to attain very high speeds because of their shape.
2) The windmill can spin in one direction regardless of the direction of the wind.
3) High TSR makes it a suitable mechanism for generating power.
4) These windmills have a high airfoil pitch angle (angle of attack), improving the aerodynamics while decreasing drag.

The Darrieus windmill also has its disadvantages:

1) It has a low reliability because of the high TSR and the high torque ripple (the amount of torque measured by subtracting the minimum torque during one revolution from the maximum torque from the same motor revolution) it produces.
2) The windmill is unstable due to its speed.
3) Some windmills usually need starters because some Darrieus windmills are not self starting.

These windmills each usually have two ball bearings and a generator. Again, the ball bearings and the gears in the generator are the numerous points of failure that cause many problems. The high speeds that the Darrieus windmills attain only quicken the wear and metal fatigue on the machinery [11].

The giromill is another type of DWT that, instead of curved blades from top to bottom, has straight blades perpendicular to the ground. The windmill is oriented in such a way that it looks like the letter “H” when at a standstill. The operating mechanism is about the same as the DWT but the giromill tends to be more stable as the “egg-beater” style blades create more torque ripple than the straight blades.

C. Conventional Wind Turbines

The conventional windmills are forms of the HAWT and have rotors that only run when the wind is blown on them [4]. Consequently the whole windmill must be turned to meet the wind for it to function: modern yaw devices typically use sensors to turn the windmill to the wind. These windmills have lift based rotors that, like the DWT, run as a result of a difference in pressure on both sides of the blades. These types of windmills are generally used to generate power. These windmills have their advantages:

1) The blades are to the side of the windmill’s center of gravity, making it stable.
2) The towers can be tall due to its stability.
3) Most of these windmills are self-starting
4) They have an efficient power output.

These conventional wind turbines also have their disadvantages:

1) These windmills have difficulty operating near ground.
2) They have trouble functioning in turbulent winds because the yaw device and blade bearing require smooth wind flows.
3) Their massiveness makes them both cumbersome and costly to maintain (transportation and installation make up more than 20% of the equipment cost.

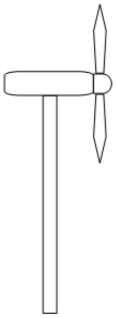

Figure 2.3: A conventional wind turbine.

These windmills have many points of failure such that the malfunction of any one point can render the machine useless. Conventional wind turbines have an axle that is connected to the blades on one end and to the gearbox of the generator on the other. The ball bearing holding the axle is one point of failure and the gearboxes are another. The yaw device is comprised of a gearbox run by a motor, making it another point of failure.

D. Common Problems

The main weakness of the wind turbines discussed is the maintenance necessary and the wear caused by certain points of failures (i.e. ball bearing assemblies, gear boxes, etc.). In current wind turbines, replacing these points of failures can become very expensive and render the turbine inefficient. For example, the ball bearing assembly replacement in a wind turbine can cost up to $10,000[18] because of the need of cranes and crews. This paper will introduce a new technology and discuss a way to remedy these points of failures and hopefully drastically reduce the cost of repairs when they are necessary.

III. THE BALL AND SOCKET

The static magnetic ball and socket is comprised of a distinct male and a female part. When these parts are combined, they exert magnetic forces on each other which simulate the mechanics of a conventional ball and socket design. The female support in this design is a cone with a cavity located within the interior of the circular base. Lining the cavity of the female support are magnets slotted into a number of grooves that are evenly distributed in a circle on the interior wall of the conical cavity. These are set at a uniform angle to the axis of symmetry about the cone’s axis of symmetry, parallel with the interior wall. Rotational symmetry is achieved from the even placement of these magnets, which allows the device to rotate continuously without change to either the field of objects or the resulting vector fields. In addition, the magnetic poles are aligned and consequently produce a stable, even force that is used to create the rotationally invariant ”socket” magnetic field which the female support simulates.

A magnet or a set of magnets can be used to create the male support, which is placed on the base of the structure and within the female cavity. These magnets are comprised of the same material as the magnets located within the female support. Regardless of the number of magnets used, the male support must have a singular pole facing outwards, with repulsive forces of equal size formed in a spherical radius around the male support. These repulsive forces define the ”ball” magnetic field used in this device.

The static magnetic ball and socket is formed by centering the female support directly above the male support and parallel to the base of the device. The magnetic forces mentioned previously in both the male and female supports align and repel each other, thus producing the levitation required in this particular design. The design is illustrated in Figure 3.1.

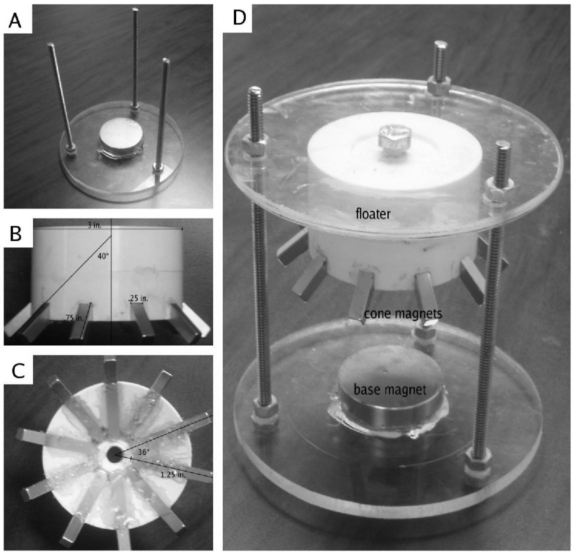

Figure 3.1: These are two example magnetic ball and socket assemblies. The conical region contains a magnet assembly which provides a rotationally invariant pseudo conical magnetic cavity. The base magnet creates a toroidal magnetic “ball” which fits “into” the magnetic socket.

There are numerous benefits that arise from the use of magnetic forces in the creation of the static magnetic ball and socket, the main benefit involving the suspension of the female support above the male support. Because this design prevents contact between the two supports, the suspension eliminates friction. The absence of any discernible friction prevents the loss of energy released as heat while also mitigating the requirement for cooling elements that would otherwise be required for the heat generated through this friction. The two repulsive forces also create a stable position, which allows for the horizontal stabilization of the device with respect to the ground without loss of rotational symmetry.

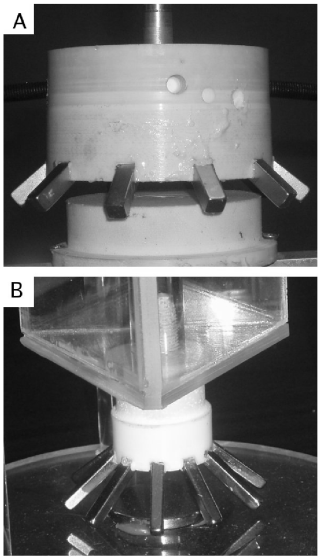

Figure 3.2: This figure illustrates two instantiations of the “ball and socket” assembly. In each one, bar magnets oriented at 50° from vertical are arranged in a conical array at 36° intervals. The juxtaposition of this cone with the “ball” configuration produces a restorative force that is both vertical and horizontal.

Figure 3.2 illustrates two slightly different conical regions in which ten bar magnets oriented at 50° from vertical are evenly placed around the conical region. Diagram A has bar magnets with dimensions of 0.25”$\times 0.25$”$\times 2$” oriented around a cylindrical base magent of diameter 2” and width 0.5”. Diagram B has slightly smaller dimensions, with each magnet on the female support $1/8$” $\times$ $1/8$” $\times$ 1” oriented around a male supporting magnet of diameter 1” and width $1/8$”.The magnetic field of each bar magnet is oriented perpendicularly to one pair of sides. The resulting conical arrangement has a rotational symmetry with respect to $36n^\circ$ where n is an integer.

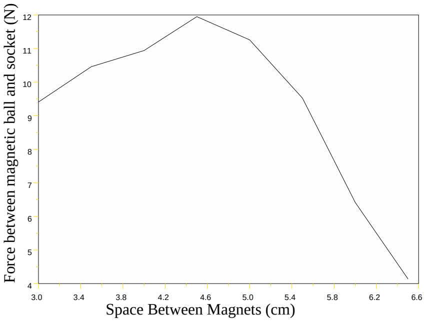

Figure 3.3: This illustrates the force between the magnetic ball and socket pieces as a function of distance between them. The force increases as the distance increases until it reaches a maximum and decreases.

Figure 3.3 illustrates the force between the two as a function of the distance between them. Notably, the force increases as the two parts approach one another. However, the repulsive forve rapidly disappears if the two pieces come too close to one another due to an attracting node in the center of the cone. It is likely that this node would not exist in a true conical magnetic field. Use of this technology would thereby require an application that did not produce transient forces greater than the maximum, thereby causing the two parts to collapse into one another.

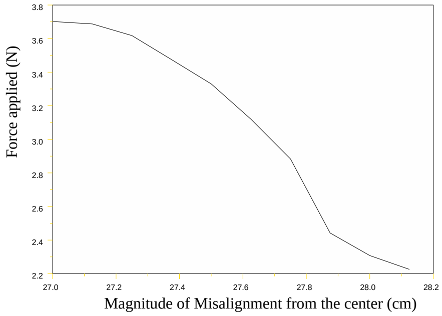

Figure 3.4: This figure illustrates the transverse force as a function of the angular deflection of the socket. All angles are in radians and all forces are in Newtons.

Figure 3.4 illustrates the transverse force between the two parts as a function of horizontal displacement. This tends to increase as the two parts approach one another. Applications would therefore be quite stable as the forces involved increase and push the two sides of the ball and socket apart as they are moved closer to one another. This means that vibrations and transient forces would not be in danger of overpowering the device and causing a catastrophic failure.

The ball and socket provides soft stabilization both along the axes of the two magnetic fields and perpendicular to it. As a result, it has a wide variety of potential in the stabilization of both stationary and moving pieces. Because of the scalability of magnetic assemblies, we expect that the design described above could be scaled up linearly with a concomittant linear increase in each of the forces involved. In the next section, we shall investigate how to use this to build an $\epsilon-$axle which can reduce the frictional forces of the axle to some small $\epsilon > 0$.

IV. $\epsilon-$AXLE

As we’ve seen in the previous section, the magnetic ball and socket assembly utilizes permanent magnets to provide both vertical and transverse stabilization. This is quite advantageous because it means that the device has many of the characteristics that we’d like it to have in order to use in an axle. We have not as yet been able to provide the type of stabilization required to place this device at both ends of the axle, but using a single magnetic ball and socket assembly, we are able to create an axle with a single point of contact. Such a device has many advantages, which we discuss below.

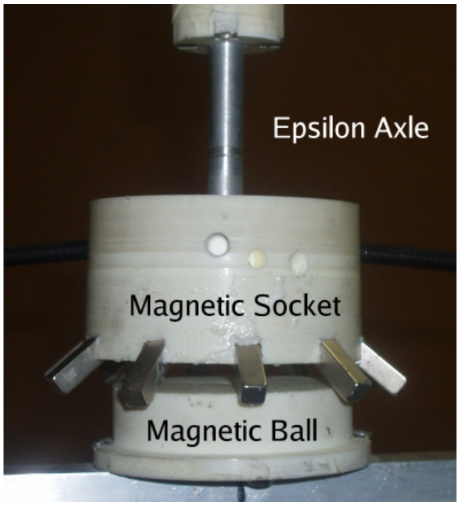

Figure 4.1: This figure illustrates the basic $\epsilon-$axle. At the bottom is a magnetic ball-and-socket assembly. An axle collinear with the axis of symmetry of the cone is connected to the magnetic socket.

The axle is diagrammatically illustrated in Figure 4.1. The axle comprises a rigid cylindrical rod with its central axis aligned with the axis of the cone, attached to the center of the cone at one end, and inserted into a socket at the other end. Such an axle has a single point of contact at one end, at which point it contacts the wall, and a freely floating end. In this configuration, the axle can be used as if the end with the ball-and-socket is fixed with a ball bearing. Because the fixed end with a ball bearing is the only point of contact, this point is the only place where friction can occur. As a result, the axle so described has only this one practical point of failure.

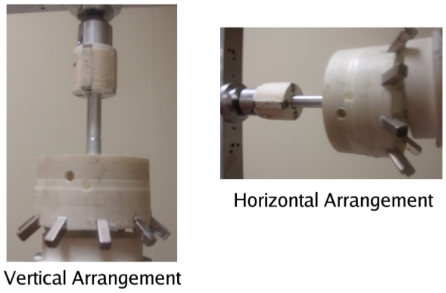

Figure 4.2: This figure illustrates two orientations of the $\epsilon-$axle. On the left, the vertical orientation supports all of the weight, leaving little friction at the contact point. On the right, the horizontal orientation puts pressure on the ball and socket as well as the single contact point.

In practice, the axle may be used at any angle. However, the angle at which the axle is utilized varies between two extremes: completely vertical or completely horizontal. The different orientations are depicted in Figure 4.2. In the horizontal arrangement, the weight of the axle is distributed between the bearing and the ball and socket. In this scenario, the friction on the bearing on one end is not negligible. This becomes a point of failure for the device. Moreover, the magnetic ball and socket acts like a spring, vibrating on occasion when the device is in use. In this configuration, vibrations of the system might be significant enough to allow the detachment of the bearing on the opposite end. This would be a critical failure. Finally, any loading of the axle distributes the weight between the two ends, again causing the type of difficulties just described.

The vertical configuration finds all the weight of the $\epsilon-$axle squarely resting on the magnetic ball and socket. As a result, the actual contact friction of the axle can be fractionally vanishing. This means that the bearing will typically be used to keep the axle from tipping and to keep it in place vertically. However, the actual wear on the device can be infinitesimal. The weight is actually resting on the magnetic ball and socket. As a result, the system will experience vertical vibrations. The system will be protected from vibrations by the vertical limit of the bearing at the opposite end of the axle.

One of the important consequences of the vertical design of the $\epsilon-$axle is that the axle's frictional wear at the bearing end decreases as the load increases. This is a result of a counterbalance against gravity provided by the ball and socket. This means that several devices that are traditionally limited because of difficulties caused by friction can be designed and built so that such limitations are erased. For use in windmills, this means that the large rotor holding the blades may be balanced against gravity using the $\epsilon-$axle, mitigating the need for expensive bearings that ultimately fail and require expensive maintenance. Other devices, such as the Crookes radiometer, might be designed on a larger scale because the parts of the devices that cause prohibitive friction would no longer cause the same problem. In the next section, we examine the application of this device to windmill systems.

V. INTEGRATION OF WINDMILL

The $\epsilon-$axle is a simple application of the magnetic ball and socket that creates many different opportunities for the generation of windmill systems that require relatively little maintenance. In this section, we examine the design of windmills based on this design.

As mentioned previously, the use of a vertical axle is preferred over a horizontal axle. This means that the windmill type that will benefit in design more from the $\epsilon-$axle is the VAWT. This windmill requires very few changes to its basic design - the bottom bearing assembly can be replaced with a static magnetic assembly while the top bearing may be replaced by a single bearing assembly consisting essentially of a cup and bearing.

Savonius wind turbines utilizing the $\epsilon-$axle need only have the magnetic ball and socket assembly and the top bearing assembly rather than the multiple bearing assemblies that are typically used. This limits the repair cost of the Savonius type windmill. Moreover, removing a complete bearing assembly and changing it to a single bearing in a cup reduces the overall cost. The magnetic ball and socket may be expected to compare in cost to the bearing assembly typically used. The Darrieus type windmill is similarly improved in its cost. However, as the Darrius type windmill suffers from low reliability due to high TSR, the $\epsilon-$axle can mitigate this design flaw, as it is unlikely to suffer from high speeds. As a result, the $\epsilon-$axle may be expected to improve the reliability and therefore value of the Darrius type windmill. We illustrate a simple giromill in Figure 5.1.

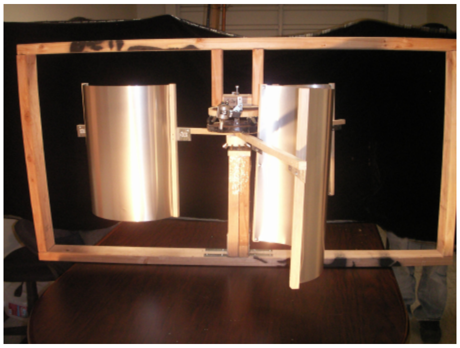

Figure 5.1: This figure illustrates the use of the $\epsilon-$axle in building a simple giromill. The axle supports the complete weight of the giromill allowing for very small frictional losses.

One important design requirement of the $\epsilon-$axle derives from the use of a "flexible" bearing assembly. The ball and socket assembly, as we have seen earlier, is not rigid; it is possible to push it from the side and move the axle. This is a problem from a design sense because if transverse forces push with enough force against the ball and socket assembly, the two sides of the assembly may grind against each other, potentially destroying it. The situation is depicted in Figure 5.2.

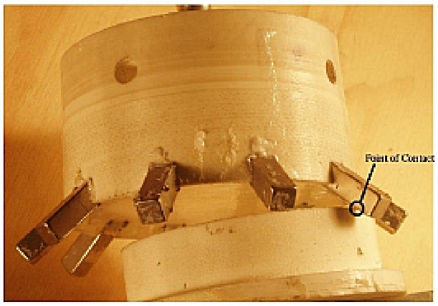

Figure 5.2: Transverse forces pushing against the $\epsilon-$axle could cause the $\epsilon-$axle to grind and destroy the magnetic ball and socket.

In order to mitigate this possibility, one may utilize a long axle which has an attached wing assembly fastened to the top of the magnetic ball and socket. Consider Figure 5.3. In this figure, the length of the $\epsilon-$axle is d_2 and the wings' center of mass is located $d_1$from the top bearing and d_3 from the axle. In this case, any force F acting on the wings and tending to rotate the $\epsilon-$axle around the top bearing will need to overcome a force $F_r \frac{d_2}{d_1}$. What this means is that the longer the axle, the less likely that the force acting on the wings will be able to grind the magnetic ball and socket assembly. It indicates that the axle should be as long as possible in a practical design.

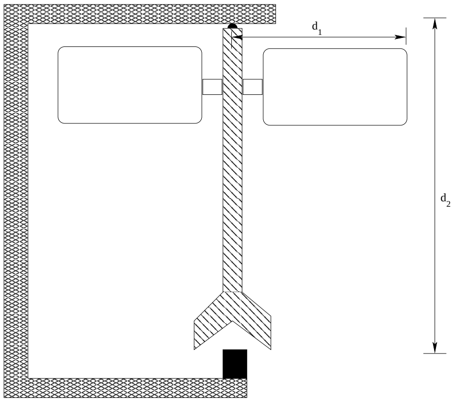

Figure 5.3: The $\epsilon-$axle is stabilized against vertical vibrations of the vanes by opposing tangential forces at the ball and socket. Long axles with large d_2 values compare to d_1 have mechanical stability built in.

VI. DISCUSSION AND CONCLUDING REMARKS

One of the big limitations of most kinds of machinery is that as the machine increases in size and load, the amount of wear and tear on the various components of the machine also increases. This means that pieces of the machine which can be large and expensive can be destroyed by the normal use of the machine, requiring costly repairs to correct the machine. This is particularly true for wind generators whose repair can cost thousands of dollars per repair.

We have introduced a simple unpowered magnetic ball and socket assembly which can be used to mitigate the wear and tear of moving machinery. The device is a simple conical socket piece which "fits" over a magnet which generates a magnetic ball. This assembly stabilizes itself both vertically and tangentially, tending to center the conical piece above the ball piece. When used in an axle, the ball and socket and be used to form what is known as an $\epsilon-$axle. This axle has a single assembly at one end and a solid ball and socket on the other side. It is best used in a vertical orientation, which tends to center its weight on the magnetic ball and socket and thereby limit the wear on the non-magnetic ball and socket. When used in a windmill, the $\epsilon-$axle is valuable because it mitigates wear and allows the windmill to be used without requiring repair often.

The most startling aspect of this device is that the friction actually lessens when the load increases. As we discussed above, this happens when the $\epsilon-$axle is used in a vertical configuration, like it is in a vertical axis windmill. This specific characteristic makes the $\epsilon-$axle ideal for windmills, as it means that the one part of the windmill that is in contact with a stationary frame can have a very minimal amount of friction.

This last aspect of the device opens a variety of possibilities for future mechanical devices. One device might be an adaptation of Crooke's radiometer. This device cannot be used for industrial purposes because the force generated by the solar radiation increases as the square root of the area of the vanes in the device while the friction increases linearly with the area of the vanes. One might envision using this device for such a purpose. Another potential use might be for holding heavy objects which might need to be rotated around a base manually, but held in place once the movement had been completed. This might be accomplished even with very heavy objects. Finally one might explore creating gyroscopes or motors based on these platforms. Utilizing the $\epsilon-$axle might significantly increase the lifetime and reliability of such devices.

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