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On the Measurement of the Characteristic Rotation Decay Time for a Baseball

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Abstract. We calculated an exponential characteristic rotation time decay, or spindown time, for a baseball to be $\tau = 7\mathrm{s} \pm 2\mathrm{s}$ from a continuous sequence of a baseball initially rotating at approximately 800 rpm. We recorded this sequence using a high speed digital video camera recording at 420 fps during the apparent weightless regime which results from an aircraft flying proscribed parabolic trajectories. Thus, while the rotating baseball was essentially weightless and stationary with respect to the cabin of the aircraft, we definitively established that the rotation decay is significant over durations as short as 1.2 seconds on a baseball with a low translation velocity of less than 0.5 m/s.

Keywords: baseball, spin of a ball, decay, rotation, physics, microgravity, parabolic trajectory

1. Introduction

For almost as long as baseball has been played, scientists and engineers have been interested in understanding and describing the game on the field. What are the details of what happens when a bat strikes a ball and as the ball flies through the air? For many years in the "early" history of baseball physics, a great debate raged about whether a baseball really curves or it just an optical illusion. That issue has been well settled and we have a rather good and detailed experimental understanding of the Magnus force on a spinning baseball, forcing the ball to curve in accordance to Newton's laws of motion. Nevertheless, the interaction of a baseball, an elaborate composite of cork, rubber, different wools and string, covered in two pieces of cowhide laced together by a pattern of raised stitching, all interacting with either a solid bat or a moving air-stream, has been described as more difficult than rocket science [Adair, 2005].

In the analysis and discussion in the science and engineering literature, it is well established that the flight of the ball through the airstream is determined by Newton's 2nd law from the combined force of gravity, drag, lift, with the drag and lift affected by any atmospheric conditions [Bahill, Baldwin, and Ramberg, 2009], including wind velocity. The equations for how to include all these forces are also well enough established so that we know that both the lift force and the drag force depend on the rotation rate of a baseball. However, to the best of our knowledge and for the proper implementation of rotation rate into these canonical equations, there exists no experimental data describing how that rotation rate changes with time.

The currently accepted expression for the magnitude of the lift force is,

$$F_L = \frac{1}{2} C_L \rho A v^2, \tag{1}$$

where ρ is the air density, A is the cross-sectional area of the ball, v is the speed of the ball, and C_L is the lift parameter, or fudge-factor, which should more properly be referred to as a lift function as it is not constant for a typical ball in flight but depends on the non-dimensional ratio of the angular to linear velocity of the rotating ball, otherwise known as the Spin Parameter (SP), where,

$$SP = \frac{R\omega}{v}. \tag{2}$$

Here R is the radius of the ball and ω is the angular velocity. Alaways and Hubbard [2001] have

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provided the most complete discussion justifying equation (1), including historical precedents and summaries of much earlier work, including their own determination of $C_L\left(SP\right)$. In the most recent experimental work to date, Nathan (2008) has also measured the $C_L\left(SP\right)$, and found it to be in rough agreement with earlier work, but slightly smaller at larger *SP*.

Adair [2002] has presented

$$C_L = 2C_D S\left(1+\frac{v}{2C_D}\frac{dC_D}{dv}\right), \tag{3}$$

with the drag coefficient (or function) C_D from the standard drag force equation,

$$F_D = \frac{1}{2}C_D \rho A v^2 \tag{4}$$

as a first principle derivation of the lift coefficient. The evidence from other sports which use spherical balls indicate that the drag function is best parameterized by the Reynolds number (Re), the lumped parameter ,

$$\mathrm{Re} = \frac{2\rho R v}{\mu}, \tag{5}$$

that displays how ρ, R, v, and the dynamic viscosity μ scale with each other to effect drag.

In the end though, all representations of the effect of lift depend on the rotation rate, and thus all implementations of lift models currently lack detailed experimental knowledge of how the rotation rate decays with time.

Although the most critical need for reliable rotation decay data is for its use in C_L, Adair [2002] has argued based on some wind tunnel experiments that for moderate rotation rates, C_D may depend on the rotation rate by a factor of

$$1+\left(\frac{R\omega}{v}\right)^2. \tag{6}$$

Given the large difference in the behavior of C_D with Re as reported by various researchers [Meyer and Bohn, 2008; Tobin, 2008; and Sawicki, Hubbard, and Stronge,

2003], we do not claim that the rotation decay rate is vital in describing drag, but we speculate that not including the effects of rotation decay is a contributing element of wide differences reported in the literature on the drag function C_D.

2. Background on Rotation Decay

As previously stated, to the best of our knowledge there is no experimental data on rotation decay for baseballs, though both Smits and Smith [1994] and Tavares, Shannon and Melvin [1999] have measured and modeled rotation decay (referred to as spin down effects) for golf balls. Smits and Smith (1994) used wind tunnel methods and Tavares, Shannon and Melvin [1999] used a radar gun approach described as ‘novel” by Nathan [2008].

Adair [2002], using the lift force, equation (1), and his expression for C_L, equation (3), has modeled and calculated a spin-down time τ of 5 s so that the rotation rate of the ball will decrease its rotation rate by $1/\tau = 1/5$ for each second of flight. (This is certainly a significant decrease in the rotation rate of a long fly ball, though our own simulations indicate the most pronounced effect of including a rotation decay time occurs on low, long line drives.) On the other hand, Sawicki, Hubbard, and Stronge [2005] believe Adair’s numerical estimate to result in a value of τ that is “unreasonably low” and that the “actual characteristic time is long enough that spindown can be effectively ignored.” Brief interviews with major league professional players and coaches provided no help. Of three individuals questioned about catching long flyballs, one said they seem to be spinning the same as off a bat, one claimed they seem to spin slower, and one claimed that they seem to spin faster [Ballou, 2006]. Thus we are confident that all involved, player and scientist, will admit that the issue is best explored by experiment.

In embarking on this line of research, we are developing three experimental modes: (1) imparting a known rotation to a baseball, releasing a baseball from a height, and recording it rotation at the bottom; (2) projecting a baseball upwards from a JUGs pitching machine and recording its rotation rate at launch and return; and lastly (3) suspending a baseball with a known rotation rate in an air- stream while continuously recording it rotation rate. All these methods have their advantages and disadvantages, and at present none of these set-ups have been fully developed to the point of producing publication quality results, though as always, work is ongoing.

For all of these modes, we still need to record and when possible control several other variables that could modify the rotation decay time. These are velocity and acceleration vectors, seam orientation, and ball and lace surface conditions. Thus we leaped onto a recent opportunity to perform measurements of a baseball's rotation decay time on an aircraft flying parabolic trajectories, which, in an apparent weightless environment allowed us to make the measurements under both essentially zero velocity and zero acceleration conditions. This paper is a report on those measurements.

3. Experiment Plans and Experiences

As has been well know since the time of Galileo and his Dialogues Concerning Two New Sciences, an object in free fall experiences no body forces as the entire body responds to the gravitational force by accelerating at g. This effect has been worried over and exploited as a useful laboratory environment by those at NASA and other space agencies for well over fifty years. In fact, it is now a standard end of the chapter problem in introductory physics textbooks.

Our plan was to impart an initial rotation speed to a baseball, and continuously record its angular position as a function of time while the ball, at essentially zero acceleration and very low velocity, stayed in one place with respect to the accelerating laboratory reference frame. Typically during these types of parabolic trajectories the cabin experiences approximately 20 - 25 seconds of 1/100 g of which the middle 10 - 15 seconds approaches 1/1000 g. These apparent acceleration levels are for the cabin itself, and of course any object that is anchored to it. A freely "floating" or freely tethered object can experience an even lower acceleration field. Thus, we anticipated we would be able to record, if properly released, upwards of 15 - 20 seconds of a rotating baseball, softball and golf ball. In addition, we had planned to conduct with the eight scheduled free-fall trajectories an experimental protocol comprised of a major league specification and a NCAA regulation baseball, 2-seam and 4-seam orientation of a rotating major league baseball, and repeated measurements on a major league 4-seam rotating baseball. But as the poet Robert Burns has written, "The best laid schemes of Mice and Men/oft go awry,".

Our single flight opportunity was chartered through a company that runs these flights for customers who want to experience apparent weightlessness, often referred to as microgravity, as a joy ride and not for laboratory scientists needing the apparent weightless environment. Thus, despite that our particular flight was all laboratory scientists, all the participants were commercial ticketed passengers, and thus we needed to adhere to commercial aviation regulations, including standard boarding checks of passengers and their carry-on baggage by the TSA (Transportation Security Administration). In addition, all the passengers had to work within the rules of the chartered carrier. This humorously resulted in a situation where at first the flight crew wanted to not allow any of the sports balls on-board with us. They did in the end relent from imposing this showstopper. But, not so humorously concerning our ability to run the planned and desired procedures, we ran into several other problems with the charter company's provisions that did result in our plans going awry.

First, as specified well in advance and to our full knowledge, we were not allowed to have the balls unconstrained in the cabin during free-fall trajectories. To meet this specification, we built and took on-board a 60 cm on a side cube PVC frame covered with sports netting, and with slots to gain access to the interior. We anticipated that this unnecessary but not unreasonable requirement would make our measurements a tad more difficult to conduct, but would not preclude them.

However after boarding and without any prior notion, we were then required to anchor the PVC frame to the cabin floor. This one silly restriction caused severe difficulties. We were now unable to hold and move the frame in concert with the rotating baseball inside to both then maximize the time that the ball would be freely spinning and to best video record the ball. This also forced us to do all of our work flat and close against and within 60 cm of the cabin floor as opposed to open and at eye level. Lastly, the promised and needed straps to anchor our feet to the floor of the cabin so that we could performed our work and not go free-floating into the cabin were too few to constrain us during these intervals.

To gain some sense of the difficulty imposed by the absence such straps, take as heavy a book as you can support and hold it out in front of you. Then have someone else remove the book at their discretion (to see the effect you cannot do it to yourself just as you cannot tickle yourself). Under these circumstances, the arm formerly holding the book will uncontrollably move upwards. Now imagine this effect, much magnified, happening to all your major muscle groups once the cabin goes into the free fall trajectory, all while you try to manage to stay close to the floor and releasing a spinning ball from a hand-held drill mechanism without imparting any significant initial velocity to the ball and preserving the orientation of the ball. Thus, and contrary to the promised laboratory conditions and set-up, we found ourselves both with a significantly more difficult basic task and a considerably worse facility (both ability and laboratory-wise) to conduct our measurements and there were significant performance issues.

Doing the best we could under these difficult conditions, we imparted a spin on the baseball using the modified drill and funnel mechanism (Figure 3). Once the plane achieved free fall we released the ball from the mechanism and recorded the resulting motion using a Casio (EX-FS10) High Speed Camera operating at 420 frames per second (fps) which used a frame size resulted in about 45 to 65 pixels across the spinning baseball. Because the released ball had a small initial velocity with respect to the frame, and because we were not able to move the frame to prevent it from interfering with the ball, the ball did indeed come into contact with the sides of the frame terminating the particular measurement ridiculously short of the anticipated 15 – 20 seconds. Under these conditions, we also found it was very difficult to release the ball with the desired orientation, so we quickly abandoned any pretense or intention to do anything but try to get sufficient data on a major league two-seam rotating baseball.

4. Data Reduction and Analysis

In the end the best we could muster was one experimental run of sufficient unimpeded and uninterrupted rotation (1.2s), in a pure two-seam orientation, and with sufficient angular position measurements (15 measurements of angle) to produce precise enough data for publication. This was one of eight anticipated measurements and based on only one-tenth of the expected experimental duration. Nevertheless, no matter how annoyed we were with the inadequate facilities or disappointed in only obtaining one short legitimate experiment, this one measurement still represents more continuous rotation decay data on a baseball then had existed before.

We analyzed this data in perhaps the simplest of manners. We looked for one complete revolution of the special marking, and then counted the electronic frames until we observed approximately one completed rotation. We then made a small angular correction for any over or under rotation to get the angular position as a function of time. We repeated this process again and again for as long as the spinning ball remained undisturbed to produce a series of angular positions as a function of clock readings (Fig. 5). We then calculated the average angular velocity for each subsequent duration using the mid-point of that duration as the clock reading of that particular rotation rate. In the run of longest duration, at 420 fps, this produced 15 independent positions and 14 independent rotation rates.

Although the method itself is introductory physics simple, the results of the method itself are accurate and precise. Prior to the flight we used a strobe-light to measure the rotation rate of a baseball mounted on a drill. We then used the method just described and obtained very close to the same rotation rate. For example, in one typical test of this method, we measured a baseball via the strobe to have an average rotation rate 2770 rpm while with the high speed camera at 1000 fps we measured it to be 2785 rpm (the difference between 1000 fps and 420 fps is not significant here as either frame rate is much faster than the rotation rate itself). Thus, the method itself is not a significant source of uncertainty in these experiments. The measurement of the position is made to within ± one pixel position. We estimate that the most significant error occurs from the difficulty of holding the camera to a fixed position with respect to the rotating baseball.

Despite these uncertainties, in this one reliable run, we see that the rotation rate is clearly and significantly slowing. The slowing trend is noisy, as seen by the rotation rate versus time data (Figs. 6) so that it is not justified to least-squares fit the data to several different equations as a means of comparison or discrimination. But, we note that for this data, the translational velocity although not identically zero, is less than 0.5 m/s, and thus much slower that the velocities used in the models by Adair [2002], or that Smits and Smith (1994) used as illustration. Furthermore those models assume, or derive, a rotation decay rate that depends on the combination of the linear and rotational speeds, such that,

$$\frac{d\omega}{dt} \propto v\omega. \tag{7}$$

This leads to a characteristic decay time dependent on velocity,

$$\tau_v \propto \frac{1}{v}. \tag{8}$$

This of course implies that at $v = 0, \tau_v = \infty.$ Since we do not think it reasonable that under zero velocity conditions that a rotating baseball will continue to spin indefinitely, we speculate that there are really two characteristic decay times, one for $v = 0$, which we will from now on refer to as τ_0, and τ_v as described above in equation (8). Furthermore, we speculate that any measured characteristic rotation decay time, τ, would be the appropriate combination of the two times (of which we assume is the inverse of the sum of the reciprocals of the two decay times as is standard in the combination of multiple scattering times). However, this combination of τ_0 and τ_v as a function of v is the only object of measurement as we cannot measure τ_v directly.

For the sake of any measurement of τ we simply assume that the velocity is constant enough so that equation (8) effectively reduces to,

$$\frac{d\omega}{dt} \propto \omega, \tag{9}$$

which leads to,

$$\omega(t) = \omega_0 e^{-t/\tau}, \tag{10}$$

where ω_0 is the initial rotation rate at $t = 0$. Lastly, since the translational velocity is very small, we assume that our measured extracted characteristic rotation decay time is essentially τ_0 for the $v = 0$ case.

To obtain one estimate of the rotation decay time, we performed a two parameter $(\ln \omega_0$ and $1/\tau)$ linear least squares regression of t to $\ln(\omega)$ from equation (10) for our one uninterrupted rotation rate sequence. This yielded a result of $\tau = 6.8\text{s} \pm 1.5\text{s}$. As we can see, with this noisy data (Figs. 6), a linear fit would be as good (if not better) as an exponential fit as the exponential fit itself looks rather linear. One perhaps should not expect more with a 1.2 second sampling of an approximately 7 s characteristic decay time. Nevertheless, since a linear decay rate would make little physical sense, we did not consider any other form for the variation of rotation rate with time other than an exponential.

The large variation in time of the measured rotation rates, leading to the large uncertainty in the rotation decay time, may be artifact of the numerical derivative used to convert the angular position to rotation rate. We thought that we may do better if we were able to extract a rotation decay time more directly from the angular position data. If we integrate the equation for rotation rate (equation 10 above), we get,

$$\theta = \theta_0 + \omega_0 \tau \left(1 - e^{-t/\tau}\right). \tag{11}$$

From here, we performed a non-linear minimization of the sum-squared error between θ and $\theta_0 + \omega_0 \tau (1 - e^{-t/\tau})$ for each (θ, t) ordered pair. This yielded $\tau = 6.9\text{s} \pm 0.4\text{s}$. Based on a suggestion of Nathan (2010), we expanded the exponential to three terms which transformed the equation for θ (equation 11) to,

$$\theta = \theta_0 + \omega_0 t - \frac{\omega_0}{2\tau} t^2, \tag{12}$$

which can be fit linearly resulting in $\tau = 7.4\text{s} \pm 0.6\text{s}$.

Clearly the extraction of the decay time directly from the angular position data yields a lower numerical estimate of uncertainty. However, this should be expected as we are using both three adjustable parameter and not two, and we are minimizing the sum-squared errors on θ instead of ω.

There are good reasons for one to prefer any one of these three choices for determining the decay rate from the one set of angular position versus time data. Under these circumstances we do not feel that a detailed averaging is legitimate. Rather, we take the first presented result as it best captures what we feel is the appropriate uncertainty. So from all of these results we conclude that the best available estimate of the characteristic rotation decay time from this set of measurements is $\tau = 7.0\text{s} \pm 1.5\text{s}$, though we would have no objection if others preferred to consider this as $\tau = 7\text{s} \pm 2\text{s}$. This, combined with the simple exponential form appears to be the *best* description of how the rotation rate of a baseball varies with time in just the same way that an only child is also considered a parent's *best* or favorite. Unlike many parents however, we wish had been blessed with a whole lot more to be proud about.

5. Conclusion

To be sure, our measurement and analysis begs two important questions. First, could his procedure result in different value of the spin decay based on the parameters not well controlled in these measurements? Briggs [1959] long ago noted that the center of rotation is not necessarily at the geometrical center. Could the lack of control of this asymmetry lead to a different decay rate? Or, could there be sensitivity to the details of surface conditions such as the seam orientation, or the conditions of the seams, or the roughness and irregularities of the surface of the ball?

Second, as these experiments were carried out at essentially zero velocity and zero body force, how can they be applied to a baseball in flight under a constant body forces and changing velocity vectors? Certainly if our speculation about the combination of two decay times, one for $v = 0$ and one for $v \neq 0$, then any decay rate measured at a velocity will be less that our $v = 0$ measured decay rate no matter what the $v \neq 0$ decay rate is.

Both questions deserve more detailed experimental investigations. However, until they have been conducted, from here on I intend to describe a baseball's rotation as decaying exponentially with a time constant of $\tau = 7\text{s} \pm 2\text{s}$ in any discussion of the physics of baseball where rotation rate is germane.

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Figures

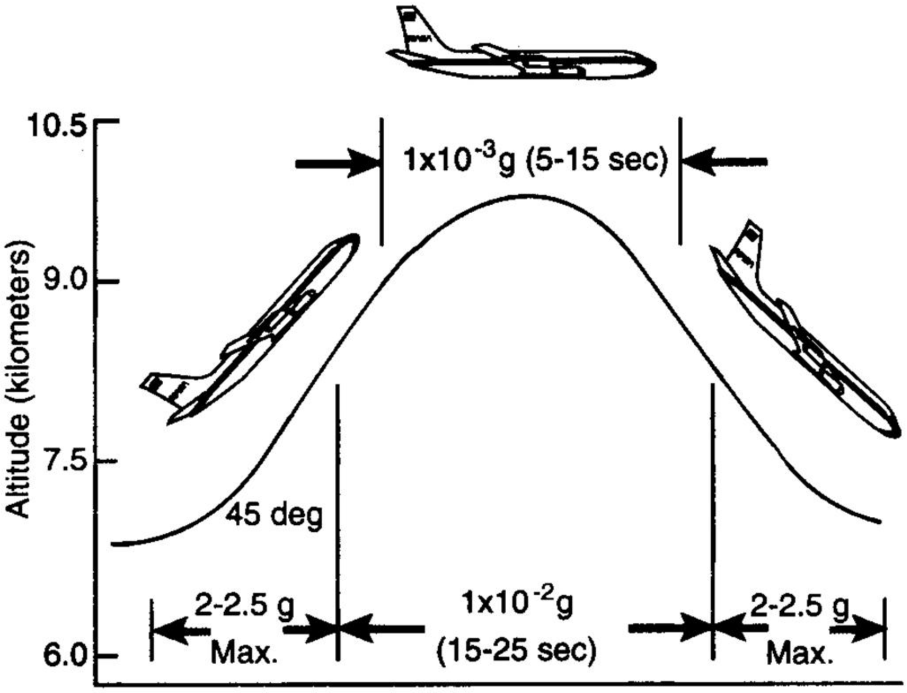

Figure 1

Figure 2

Figure 3

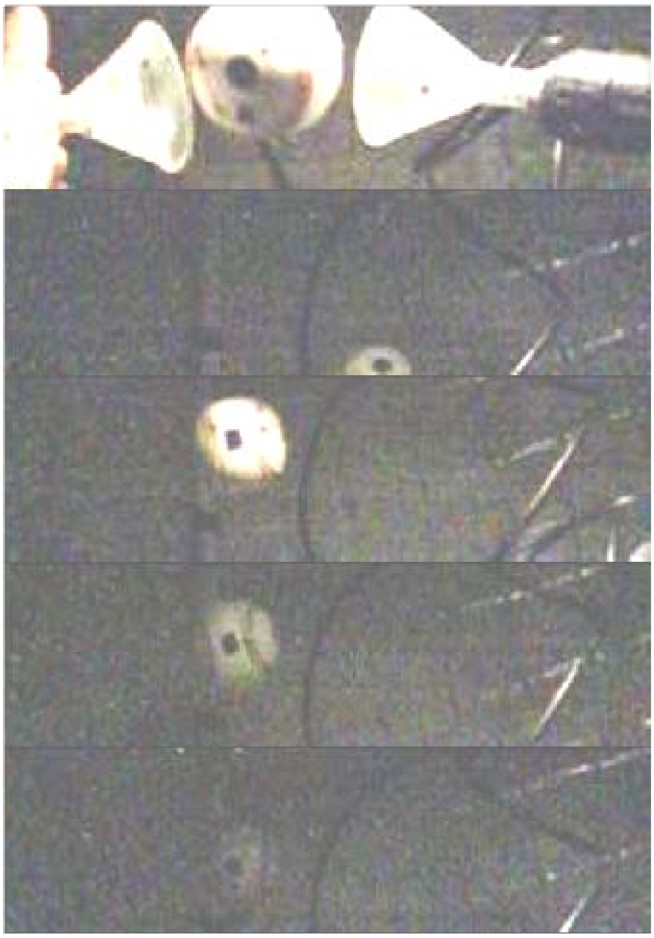

Figure 4

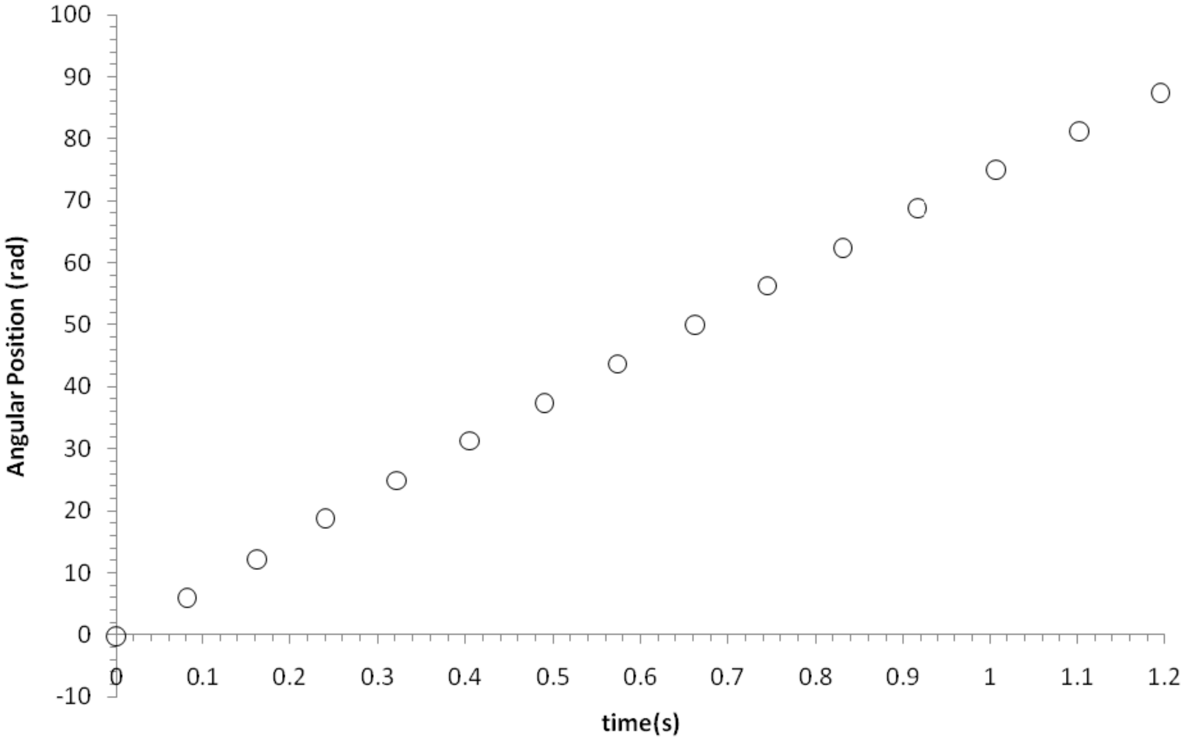

Figure 5

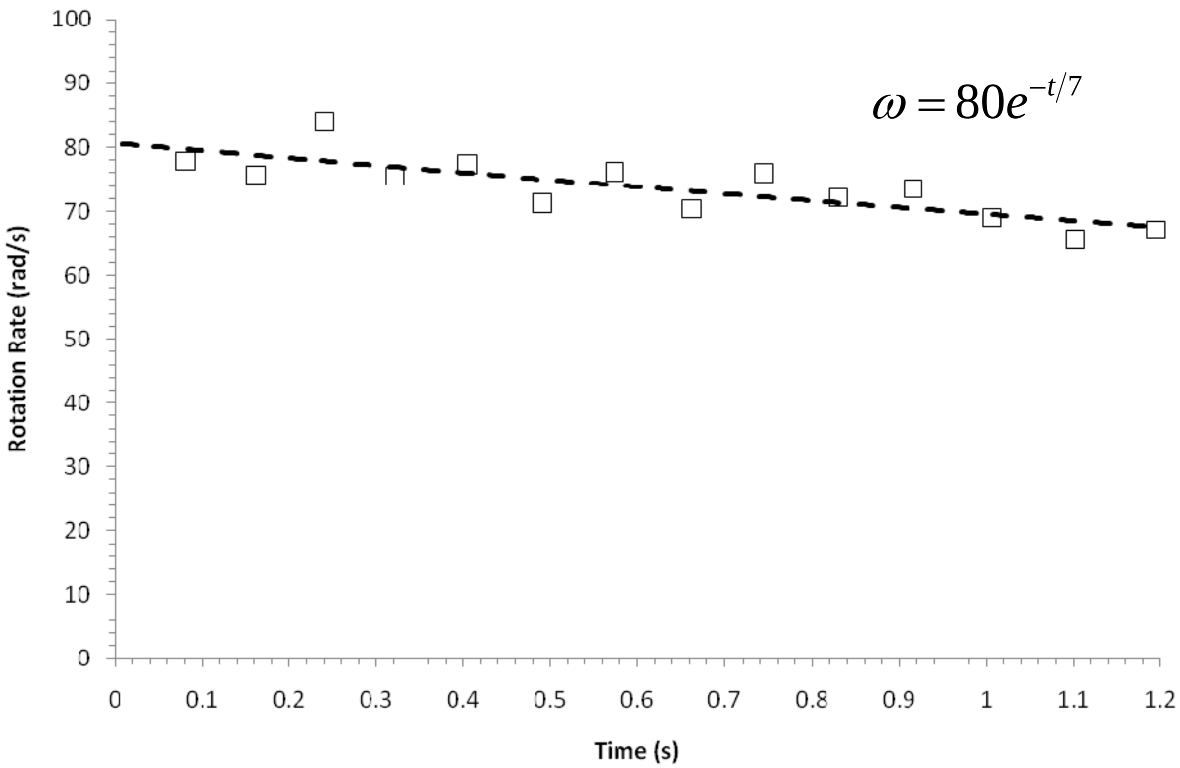

Figure 6