

The Spiral Slingatron Mass Launcher

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Abstract. The dynamics and engineering of a spiral slingatron mass accelerator are described together with the status of experiments. The potential utility of this mechanical device for space launch applications is discussed.

INTRODUCTION

A mechanical mass accelerator concept called a slingatron has been proposed (Tidman, 1996, 1998, 2000; Tidman and Greig, 1999) and computer models developed (Tidman, 1998; Bundy et al, 2000; Cooper, Tidman, and Bundy, 2000) for the dynamics of both spiral and circular versions of this machine. Here we discuss the design of a spiral slingatron in which a projectile (or stream of projectiles) could be accelerated to high velocity.

The device consists of a spiral steel tube (Fig.1) along which drive motors are distributed so that the entire tube gyrates around a circle of small radius r with a *constant* gyration frequency f cps. The machine transfers stored inertial energy directly into projectile kinetic energy with no intermediate steps, and work is done on a projectile sliding through the spiral because the accelerator tube is continually pulled inward at the projectile location against the centrifugal force of the projectile. The accelerating force experienced by the projectile is an example of a coriolis force and is proportional to the projectile mass. As the projectile swings out around the spiral into turns of increasing radius R , it also maintains phase stability with the small-radius gyration of the entire tube. This phase locking enables it to move out around the spiral turns with the same frequency f so that its increasing velocity V is approximately equal to $2\pi Rf$.

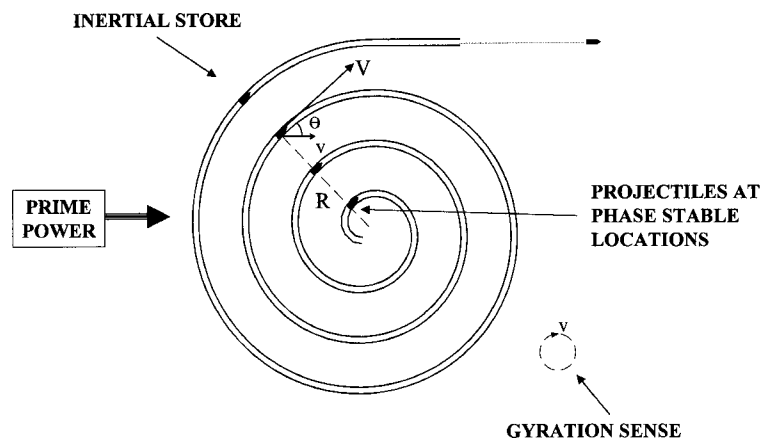


FIGURE 1. A Spiral Tube mounted on Distributed Drive Motors (not shown) that propel it around a Small Gyration Circle of radius r and frequency f cps with the sense shown. Projectiles released with the correct phase at the entrance accelerate through with a Stable Phase relative to the Gyration and Increasing Speed $V = 2\pi Rf$.

The dynamics is similar (but not identical) to whirling a mass around at the end of a string as in a conventional sling, but with the string growing in length so that the whirling frequency, f cps, is constant. However, there is no string to break in the slingatron and the guide tube can contain the projectile up to huge speeds since the mechanical impulse per unit length, $mV/R = 2\pi mf$ (delivered by the projectile centrifugal force sweeping along the tube) is constant along the spiral. The tube wall thickness is thus also constant along the spiral. The device can be viewed as a *mass-cyclotron* (Tidman, 1998).

Conventional motors distributed along the guide tube could be used to swing the spiral around its gyration circle and continuously supply inertial energy globally to the spiral for extraction by an ongoing stream of projectiles passing through the spiral. The launcher could be operated as a rapid-fire device with a maximum shot frequency equal to the gyration frequency f , and for a given design its system mass is proportional to mV^2 .

No gun injector is needed. A projectile anchored in the spiral entrance will accelerate through the spiral provided it is released when the tube is moving forward at the projectile location so that the projectile initial speed is the same as the gyration speed $v = 2\pi rf$. In this case it is also necessary for the first turn of the spiral to have a radius of curvature that is no more than a few times the gyration radius, and an interior diameter slightly larger than the projectile diameter so that the projectile can negotiate the first turn. Thus a mechanical feed of projectiles into the entrance could maintain the supply of projectiles for a required launch frequency.

Note also that the absence of hot propellant gas in the guide tube allows a higher velocity, projectile mass, and fire rate, than conventional guns without overheating the guide tube. Although the spiral guide tube is long, it could be constructed from segments with taper-mouthed connections that approximate an Archimedes spiral, or for example a spiral consisting of a series of semi-circles of increasing radius with constant gaps between turns.

The two basic issues involved in construction of a slingatron are the sliding friction coefficient of the projectile (with its attendant mass loss), and implementation of the mechanical system needed to propel the gyration. In the following sections we discuss an approximate formula for the acceleration, the sliding friction coefficient at high velocity, the projectile behavior in a curved tube, and summarize some simple approximate relationships. The mechanics and the role of air drag are also discussed, along with an experiment on sliding friction and potential space applications.

APPROXIMATE RELATIONSHIPS FOR THE DYNAMICS

The approximate equations listed here are useful for guideline purposes as a supplement to the computer models based on more exact equations. An approximate equation of motion for the projectile acceleration in a spiral sling can be obtained, Fig.1, by equating the rate of energy gain for the projectile, $d/dt(0.5mV^2)$, to the power used to pull against the projectile centrifugal force $(mV^2/R)v\sin\theta$, minus the power dissipated by the projectile sliding friction, $\mu mV^3/R$. Note, all three of these powers neglect terms in v^2 , μv , etc. Assuming the projectile mass is also constant, the result is

$$dV/dt = (V^2/R)(vV^{-1}\sin\theta - \mu), \quad (1)$$

where R is the guide tube radius of curvature at the projectile location, V the projectile speed in the spiral tube, v the constant gyration speed (assumed $\ll V$), and θ is the phase angle between the vectors \mathbf{v} and \mathbf{V} . It is also assumed that projectile drag due to residual gas in the guide tube is negligible, so that μ is simply the sliding friction coefficient. We also limit our discussion to spirals for which the gap between neighboring turns is a constant.

When the exact equations for the dynamics are solved numerically, one finds that for much of the range $0 < \theta < \pi/2$, the projectile is stably trapped in a traveling potential well and advances around the spiral turns with an angular frequency V/R approximately equal to $v/r = 2\pi f$, i.e., acceleration occurs. Provided the friction term μ remains smaller than $v\sin\theta/V$ (because μ is decreasing with increasing V), the angle θ undergoes only small oscillations about (and a small cumulative displacement in) its stable value to accommodate changes in the relative magnitudes of the coriolis and friction terms. Phase locking occurs, Fig. 1, because if a perturbation causes the projectile to

move too fast its relative phase θ decreases and the gyration velocity component perpendicular to the tube at the projectile location decreases (as does the rate at which work is done against its centrifugal force) and the projectile falls back, and conversely if it moves too slowly its relative phase θ increases so the projectile experiences a larger accelerating force and catches up. Computer models and analysis show that friction damps oscillations about the stable relative phase as the projectile advances through the spiral.

As long as this situation prevails, and acceleration continues, it suffices to assume $V/R = v/r = 2\pi f$ for the guideline estimates in this section, so that (1) can approximately be written

$$dV/dt = 2\pi f(v\sin\theta - \mu V) \quad (2)$$

We see that the key to achieving a very high projectile velocity V is to mechanically implement a high gyration speed v , and for the projectile to have a small coefficient of sliding friction that is also a decreasing function of V (as we find experimentally). It is also important for the projectile to evaporate only a small fraction of its mass to supply the gas film on which it slides to high velocity.

Projectile Mass Loss

Inclusion of projectile evaporation in the above simple model would add an additional term $-0.5V(dm/dt)/m$ on the right side of equation 1, which in turn would require an additional equation. For an estimate of the effect of mass loss we use the same model as in Sec. IVB of (Tidman, 1998), namely assume that most of the dissipated friction power $\mu mV^3/R$ ends up as energy (mostly internal) of the bearing gas evaporated from the projectile. Also assume that the gas sound speed in the bearing equals V , so that its internal energy per unit mass is $(V^2/\gamma(\gamma - 1))$, where γ is the ratio of specific heats for ideal gases and equals $1 + P/W$ for more general cases, with P the gas pressure, W its internal energy, and P/W the Gruneisen ratio. For these particular assumptions it follows that dm/dt equals the ratio (friction power)/(gas internal energy per unit mass) and (1) becomes

$$dV/dt = (V^2/R)(vV^{-1}\sin\theta - \mu + 0.5\mu\gamma(\gamma - 1))$$

We see that for these assumptions the projectile mass loss is predicted to contribute a term that subtracts about 10% from the sliding friction term in (1). This contribution will be neglected in the approximate formulas used in this paper, but will be measured and discussed in more detail in pending experiments.

Projectile Sliding Friction

We have obtained experimental data for the sliding friction coefficient of projectiles for velocities ranging up to about 2 km/sec. The experiment is described in a later section, and here we only discuss the results as they pertain to the dynamics of the slingatron.

Experimental data that approximates the friction coefficient μ is shown in Fig. 2 as a function of projectile velocity, alongside plots of the term $v\sin\theta/V$ which is proportional to the accelerating force term in Eq.1. We see that for gyration speeds $v > 100$ m/sec, there is a comfortable margin between the accelerating force and the friction drag for lexan projectiles so that acceleration can occur in the gyrating spiral.

Experiments are in progress to extend this friction data (and obtain projectile mass loss data) up to ~ 7 km/sec using a two-stage light gas gun. It should be noted that the above friction coefficient is for small lexan projectiles of mass 0.70 grams, and μ might be smaller for large projectiles since the gas film on which larger projectiles slide is expected to be thicker due to the longer residence time of the evaporated gas in the bearing.

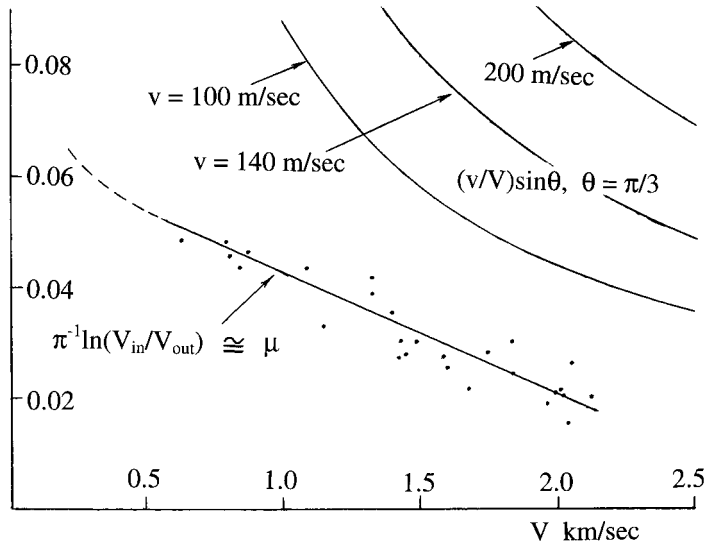


FIGURE 2. Data approximating the dimensionless Sliding Friction Coefficient μ of 0.7 gram Lexan Projectiles fired through a Semi-Circular Arc of Steel Tube, compared with the dimensionless quantity $v\sin\theta/V$ which is proportional to the Accelerating Force Term in Eq.1 for three values of the Gyration Speed v .

An earlier version of the accelerator, namely a circular slingatron (analogous to a synchrotron), was investigated in which a magnetically levitated sled was suggested (Tidman, 1996., Tidman et al, 1995) as a means to reduce the sled friction at high velocity. However, the spiral system discussed here, in which the projectile slides in a steel tube on its self-generated gas film, has many engineering advantages such as easier projectile insertion and exit, constant gyration speed operation, a larger accelerating force at low speeds where the friction is larger, and a rapid-fire capability. The spiral slingatron (cyclotron) has a larger system mass than the circular slingatron (synchrotron), and although the spiral has a high energy efficiency when operated as a repetitive fire device, its efficiency would be low for single shot operation in which the gyration kinetic energy is not recovered.

Curvature of the Guide Tube and Projectile Geometry

The guide tube has a radius of curvature R that goes from R_{in} for the inner turn to R_{out} for the outermost turn. If the projectile consisted of a perfectly rigid cylinder of length l_p , it would be supported in the tube on its two ends with its mid-section above the tube surface a height δh given approximately by

$$\delta h/l_p = l_p/8R, \quad (3)$$

as in Fig.3. However, the projectile is not rigid and experiences a centrifugal force pushing it against the outer bore of the guide tube. In most cases (except for a couple of inner turns) δh is sufficiently small, and the centrifugal force sufficiently large, that the projectile elasticity provides the small amount of flexure (well below its elastic limit) needed to push it into tight contact with the tube curved surface along the projectile length. As the projectile travels around the spiral this flexure decreases as R increases, and can be reduced to zero at exit by straightening out a segment of tube just before the exit, as shown in Fig. 1.

We noted earlier that projectiles can be fed mechanically into the inner turn where they acquire the gyration speed v from the tube motion. Provided they are released when the tube is moving forward parallel to its own axis ($\theta = 0$) the projectiles can accelerate on through the spiral. However, in this case the inner turn must have a small radius of curvature equal to a few r . The projectile will then be required to slide at low speed around the first turn on skid material on its two ends, until it acquires enough speed and tube radius to flex into contact with the track along its length.

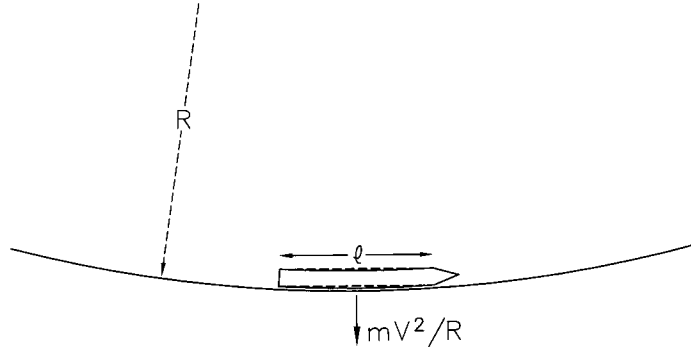


FIGURE 3. Small-Amplitude Projectile Flexure (below its Elastic Limit) brings it into Tight Contact with the Curved Guide Tube. A Plastic Coating, or a Sled or Sabot, could also be used and Discarded at Exit.

Various projectile designs could be considered such as coating the projectile with a plastic layer that would evaporate and supply its gas bearing (in which case it might be desirable to slowly spin the projectile for symmetric wear). Alternatively one could consider using an evaporating sled or sabot to carry the projectile, and discard the sled at exit.

Summary of Approximate Formulas

Note that the gyration frequency f cps, gyration radius r , and gyration speed v , are constant. However the projectile speed V increases as it advances out along the spiral. Provided the projectile can adjust its slowly changing phase angle θ , Fig.1, to a value inside the stable quadrant $0 < \theta < \pi/2$ to accommodate the velocity dependence of the friction coefficient, it will remain stably phase-locked with the guide tube gyration so that $V/R = v/r$ and acceleration continues. For a spiral designed with constant gaps ΔR between neighboring turns, the velocity gain per turn ΔV is also approximately constant as follows from (2). The following list of approximate formulas is then useful:

$$\begin{aligned}
 \text{Velocity Gain/Turn} &= \Delta V = 2\pi(v\sin\theta - \mu V) = \text{const.}, \\
 \text{Radial Gain/Turn} &= \Delta R = 2\pi(r\sin\theta - \mu R) = \text{const.}, \\
 \text{Gyration Speed} &= v = 2\pi r f = \text{const.}, \\
 \text{Projectile Speed} &= V = 2\pi R f, \\
 \text{Projectile Acceleration } dV/dt &= f\Delta V = \text{const.}, \\
 \Delta V/\Delta R &= V/R = v/r = \text{const.}, \\
 \text{Number of turns} &= n = (V_{\text{out}} - V_{\text{in}})/\Delta V = (R_{\text{out}} - R_{\text{in}})/\Delta R, \\
 \text{Length of Guide Tube} &= L_{\text{tube}} = \pi(R_{\text{out}} + R_{\text{in}})n, \\
 \text{Number of Swing Arm Modules} &= N = L_{\text{tube}}/L_{\text{seg}}, \\
 \text{Energy gain of projectile per module traversed} &= 2\pi m L_{\text{seg}} f^2 \Delta R,
 \end{aligned} \tag{4}$$

where the tube segment length between clamp centers is L_{seg} , and subscripts are used to denote values at the entrance (in) and exit (out) of the spiral. Since the projectile will be pushed forward by the breech block in the spiral entrance prior to its release, its initial speed V_{in} will approximately equal the gyration speed v . There will be a period of adjustment in the first turn in which the above formulas are not accurate until the projectile locks into its stable position.

The spiral can be operated with high efficiency in a multi-shot mode, but would have a low efficiency for launch of

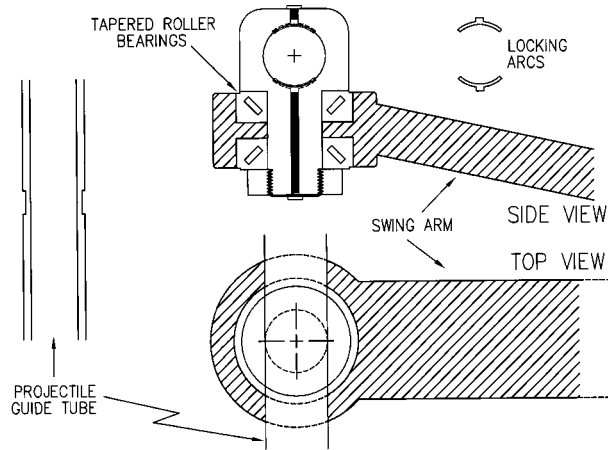


FIGURE 4. Structure of a Clamp with its Tapered Roller Bearings at the end of a Swing Arm. These Clamps are distributed along the Guide Tube to Propel its Gyration.

a single projectile unless a large fraction of the inertial energy stored in the spiral is recovered.

MECHANICAL DESIGN

In order to swing the entire spiral around its gyration circle of radius r , the guide tube is attached to “swing arms” via “clamps” that turn on tapered roller bearings as shown in Fig. 4. The swing arms are oblique to the gyration plane of the spiral tube, so that they can be spaced fairly closely along the tube without mutual collision occurring. Close packing of the clamps also avoids resonance between the gyration frequency f and transverse elastic vibrations of the tube segments. For example in Fig. 5 they are shown spaced so that the tube segment length between the centers of adjacent clamps is $L_{seg} = r$.

Design Strength and Maximum Gyration Speed

The swing arms in Figs 4 and 5 experience tensile stress that remains parallel to the arm as it swings around the gyration circle. For this we choose to conservatively design the arm using a “design strength” of $S = 50,000$ psi (assuming 4140N steel) which is approximately its fatigue endurance limit for cycled stress (even though this stress

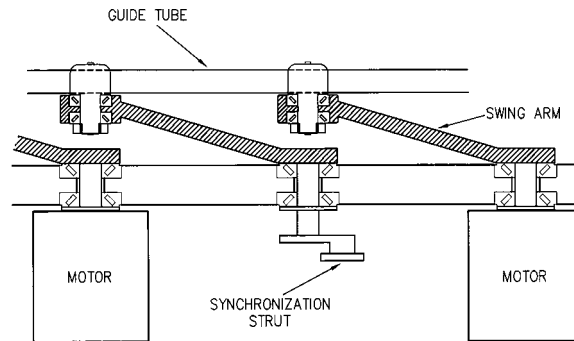


FIGURE 5. Distributed Swing Arms are Oblique to the Spiral Plane to allow them to be Closely Packed along the Guide Tube.

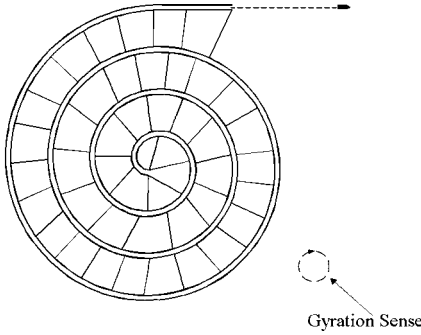


FIGURE 6. Synchronization Struts between Turns of the Spiral. They are located at the bottom of the Drive Shafts and execute a Circular Motion of radius smaller than the Gyration Radius r of the Spiral.

is not cycled). This allows some added strength for the traveling impulse delivered by the projectile sweeping around the spiral as discussed later. Better materials could be used but we choose 4140 simply for an example.

However, the clamps and guide tube experience stresses that are both cycled and in the shear direction, so that more complicated geometrical factors are involved in their stress distributions. For these components we choose a conservative “design strength” limit of $S = 30,000$ psi for 4140N steel.

The maximum shear stress at the ends of a tube segment of length L_{seg} and density ρ propelled around a circle of radius r with a frequency f cps is $2\pi^2 f^2 \rho r L_{seg}$, so that the maximum speed with which the tube segment can swing around is (Tidman and Greig, 1999),

$$v(\max) = (2Sr/\rho L_{seg})^{0.5} = (2S/\rho)^{0.5} = 227 \text{ meters/sec}, \quad (5)$$

where we used $S = 30,000$ psi and assumed $r = L_{seg}$ and neglect the clamp dimensions. We see from Fig.2 that this gyration speed would generate an accelerating force that comfortably overcomes frictional drag of the projectile.

Synchronization of the Gyrating Motion

First note that we can expect the guide tube stiffness to approximately synchronize each module with a substantial number of its nearest neighbors. For global synchronization across the entire spiral we choose to also use struts between neighboring turns throughout the spiral, Figs.5, 6.

However, the gaps ΔR between turns of the spiral (assuming we want to use the minimum number of turns) is typically $\sim 4.5r$, so that the struts are longer than the tube segments. The maximum stress equation $S = 2\pi^2 f^2 \rho r L_{seg}$ that led to (5) also applies to these struts. Thus although they are longer than the tube segment lengths, they can be propelled around a circle with the same frequency f provided they execute a smaller radius than r , i.e., they swing around with a reduced speed. They are thus located at the opposite end (bottom) of the drive shafts as shown in Fig. 5. They are also shown fabricated as flat beams with their large-area surface parallel to the spiral plane to avoid resonance between the gyration frequency f and elastic modes of the struts.

Clamps and Tube Segments

Tapered roller bearings in the clamps and support frame allow the entire spiral to roll around its gyration circle while keeping its orientation the same, i.e., it gyrates but does not spin, Figs 4,5. This motion can be propelled to high speed by motors mounted on the frame. We have chosen not to employ counterweights to balance the radial

centrifugal forces as was done in an earlier design (Tidman and Greig, 1999). This is because it is advantageous to clamp the tube at closely spaced locations, and counterweights would restrict the close packing arrangement of oblique arms needed for a high gyration speed, while only balancing the radial (but not the axial) load on the thrust bearings. There will be some binding of the motion due to clamping of the tube at multiple locations, but some slack or compressibility could be allowed in the clamps, and as the spiral gains speed the centrifugal forces rapidly become dominant as the tube pulls outward on the swing arms.

Finally, note that the tube can be fabricated from a number of segments of tubing that are clamped in place using split locking rings as shown in Fig. 4. Two sets of locking rings and channels would be used in a clamp in which a connection between two tube segments occurs.

Role of Air Drag

Air drag plays a role in two parts of the system. First, the gyrating components consisting of the swing-arms, guide tube, clamps, etc, experience aerodynamic drag as they swing around the gyration circle at speed v . Second, the projectile will snow-plow air in the guide tube and this can become an important source of projectile drag at velocities above 1 or 2 km/sec (depending also on the projectile mass and geometry).

First consider a rapid-fire system. For this case the power inputs required to drive the system typically have relative magnitudes (Power to Maintain Projectile KE Stream) $>$ (Aerodynamic Swing-Drage Power) $>$ (Roller Bearing Friction Power of Drive Modules). This assumes a drag coefficient $C_D \sim 1$ for the arms, clamps, and guide tube, and also assumes that the fire rate is $> 0.1f$. Although one could reduce the swing drag by streamlining the design of the gyrating components to reduce C_D , this might not be worth doing for the case of a rapid-fire system since the prime power input required is dominated by the kinetic energy power of the projectile stream.

One must also consider the air mass snow-plowed by the first projectile that travels through the long spiral in a rapid fire case. This snow plowed mass could be reduced by displacing the air by blowing He or H₂ through the tube prior to firing the first projectile in the stream. Subsequent projectiles would then snow plow out the relatively short column of air that re-enters the tube exit between follow-on shots, i.e., the rapid-fire stream is expected to become self-pumping in that it sweeps air out of the spiral and maintains a low-pressure environment in the tube during a burst.

We next turn to single shot cases and/or cases of spirals designed for very high projectile velocity. For initial experiments at relatively low velocity it would be simpler to use higher powered drive motors to overcome air drag. However at high speeds it becomes more desirable to eliminate air drag from the gyrating system, and necessary to remove air from the guide tube. A relatively simple “tunnel” enclosure along the spiral system would allow one to then operate the entire system in a reduced-pressure environment, thus reducing the power required from the drive motors and allowing the projectile to accelerate to very high velocity.

Projectile Traveling Impulse to Tube

As the projectile advances around the spiral turns it exerts a centrifugal force mV^2/R that sweeps across a unit length of tube in a time $1/V$, i.e., it delivers a traveling impulse per unit length $mV/R = 2\pi fm$ that remains *constant* along its path. For the case that the tube segment length between clamps is $L_{seg} = r$, the transit time across a segment is $(r/2\pi fR) \ll f^{-1} = \text{gyration period}$, and this transit time is usually much less than the time taken for the tube segment displacement (treated as a beam) to deflect to its maximum displacement.

Provided the projectile remains in a phase stable location within the quadrant $0 < \theta < \pi/2$, the tube segment plus the arms attached via clamps to its ends can all recoil in response to the above impulse, so that an estimate for the free recoil speed of these components is $\sim vm/(m_{seg} + m_{arm} + m_{clamp}) \ll v$. Although this seems small, it should be

evaluated in detail using computer models for the elastic response of the system. In the interim we have chosen conservative “design stress limits” to allow for the above traveling impulse. We have also experimentally fired 0.7 gm projectiles (without tube rupture) at 1.7 km/sec through a semi-circular guide tubes with an 8 in. radius of curvature and wall thickness 0.1 in. to test projectile containment limits.

Scaling of a Design

Suppose a slingatron has been designed and operates to accelerate projectiles of mass m to velocity V . To achieve a higher velocity for the same projectile one could add spiral turns to the system using identical guide tube, drive modules, and swing arms, etc. Provided the sliding friction coefficient of the projectile continues to decrease at least as fast as $1/V$, the projectile velocity would continue to increase as $V = 2\pi fR$ and the system mass would increase as R^2 . Thus the system mass for constant projectile mass and a constant design choice is proportional to V^2 .

Next consider what happens if one built a geometrically similar system with the same values for the swing velocity v and projectile velocity V , i.e., a system with all its spatial dimensions simply multiplied by α . The projectile mass and the mass of all other components would then increase as α^3 . However, the swing radius and the spiral radius would both increase as α , so that all the centrifugal accelerations would decrease as α^{-1} , and the centrifugal forces would increase as α^2 . Since the strengths of the swing arms and all other components are proportional to the cross-sectional areas of these components, i.e., to α^2 , it follows that the scaled geometrically similar system would be mechanically viable as was the original design. We see that the system mass for a given slingatron design is approximately proportional to mV^2 .

SLIDING FRICTION AND MASS LOSS EXPERIMENTS

Figure 7 shows the layout of an experiment carried out to obtain data for the projectile velocity loss due to sliding friction up to about 2 km/sec. This experiment is currently undergoing an upgrade in which a two-stage light gas gun is installed to provide data to ~ 7 km/sec.

For the velocity range up to ~ 2 km/sec, small lexan projectiles of mass 0.7 gm were fired from a powder gun of bore diameter 0.27 in. into a long evacuated guide tube. After traveling 340 calibers the projectile passes through a section of guide tube with long slots through which the propellant gas vents into an evacuated blast tank. Then, after a total travel of 466 calibers it passes through a triplet of optical red lasers spaced with gaps of 12 in., then around a semi-circular section of the steel guide tube of ring radius 17 in., through a second triplet of lasers, and on into the impact tank at the end of the system.

The laser triplets located at the input and output ends of the semi-circle of guide tube provided an accurate measurement of the projectile velocity V_{in} going into the curve, and V_{out} leaving the curve. As the projectile passes through the semi-circle it is pushed against the outer wall of the tube which results in a frictional force $-\mu mV^2/R$. In Fig. 2 we plot data for the quantity $\pi^{-1}\ln(V_{in}/V_{out})$, which equals the friction coefficient in the limit of zero projectile mass loss, and assign the value of this quantity to the average velocity $0.5(V_{in} + V_{out})$. This is a reasonable approximation for our purpose since the velocity loss $V_{in} - V_{out}$ is small compared with V_{in} . The equality $\mu = \pi^{-1}\ln(V_{in}/V_{out})$ in the limit $dm/dt = 0$ follows by setting $v = 0$ in (1) and replacing the time derivative d/dt by the projectile path derivative Vd/dx . A pressure probe was also used to verify that an insignificant propellant gas pressure remained behind the projectile as it entered the curved section of tube.

For the velocity range up to ~ 7 km/sec a two-stage light gas gun (LGG) of bore size 0.27 in. has now replaced the powder gun described above. The semi-circular section of tube has also been replaced with a tube section of ring radius 30 in. In addition, after the projectile exits from the laser triplet at the end of the semi-circle of guide tube (and before the catch tank), it will enter a 12 turn ring constructed from a series of tubes connected end-to-end and

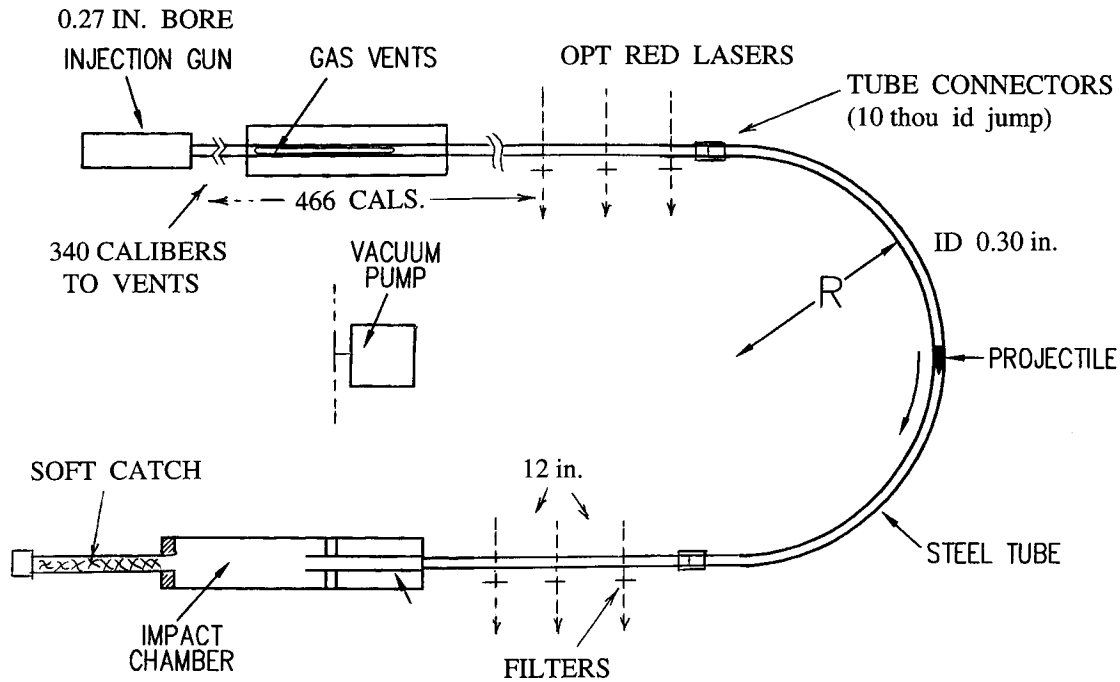


FIGURE 7. Layout of the Sliding Friction Experiment.

bent into the multi-turn ring. This will serve as a “soft catch” in which the projectile slides to rest. It will allow one to

measure the projectile mass before being fired from the gun and also after it has come to rest, thus providing information on the mass lost by the projectile in dissipating its entire kinetic energy in sliding friction. This in turn will provide data for the rate at which mass is being lost by the projectile for a given velocity.

POTENTIAL SPACE-RELATED APPLICATIONS

Several ambitious space-related applications are among those that motivate the development of mass acceleration technology. Various kinds of launcher have been suggested for various purposes, including EM launchers such as Railguns and Coilguns, Light Gas Guns including with side injectors, Electrothermal Guns, Ram Cannons, Combustion Light Gas Guns, and more recently Slingatrons.

For example a large ground-based mass launcher capable of accelerating a rocket projectile in the tons range to about 9 km/sec has been suggested by many authors as part of a system for transport of g-tolerant fuel and supplies to depots in earth orbit at a fraction of the current cost of rocket launch. The projectile would be launched obliquely through the atmosphere and requires a rocket kick at apogee for orbit insertion, as well as thrusters for docking with the depot and later de-orbit for recovery. Figure 8 illustrates a slingatron for launch of 1 ton projectiles at 9 km/sec as recently studied at the U.S. Army Research Laboratory under a NASA-funded program (Bundy et al, 2000; Cooper and Tidman, 2000). Direct vertical launch into the interplanetary medium would also become possible if velocities of ~ 12 km/sec were achievable for large mass projectiles.

In a quite different range, an accelerator capable of accelerating 50 gram projectiles to above 25 km/sec would be a valuable research tool, and could motivate the re-examination of impact fusion using magnetized fuel targets, which for useful power production would require a repetitive fire system



FIGURE 8. Illustration of a Spiral Slingatron in which a 1 ton Projectile is accelerated around a 12-turn Spiral of Outer Radius 160 meters to a Speed of 9 km/sec.

Although the slingatron is still in the design and computer modeling phase, we note that it would have several advantages if it works as predicted. First, it is a simple mechanical device that does not involve a flow of high temperature high-pressure gas in the guide tube. The result is that it appears capable of launching large mass projectiles and high fire rates without overheating the guide tube. Second, the accelerating coriolis force does not decouple from the projectile at high speeds, provided the sliding friction coefficient continues to decrease with increasing velocity. This force is also experienced along the length of an elongated projectile. Third, the slingatron would be powered by standard motor technology (electrical or internal combustion) that continuously provides energy globally to the spiral which then directly couples its stored inertial energy into projectiles passing through the spiral, i.e., no intermediate pulsed power conditioning steps are involved in the power train. Finally, the device appears capable of accelerating a continuing stream of projectiles through the spiral in a rapid-fire mode with the maximum rate being the gyration frequency.

It has been suggested by Paul Westmeyer that the rapid fire potential of a slingatron might be used to establish a “remote fueling” stream of smart propellant packages for consumption by a vehicle that has an elongated nozzle through its axis. This stream could be fired from a ground based slingatron up into the nozzle in which the packages then explode to generate thrust. In another scenario the stream is pre-deployed and swallowed by the vehicle as it overtakes the propellant packages.

Finally we note that it has long been suggested in the hypervelocity community that a mass accelerator could function as a high specific-impulse thruster. For this application the potential for the slingatron to combine high velocity launch with rapid fire without overheating the launch tube makes it an attractive candidate. Figure 9 shows a combination of 2 counter-gyrating slingatrons in an arrangement that cancels the angular momentum of the 2 projectile streams and also allows re-direction of the unit without precession-inducing torques. Such a thruster would be capable of both high specific impulse (higher than nuclear thermally-heated hydrogen) and high thrust. However it requires a powerful prime power source to utilize its full potential, such as a nuclear reactor.

An interesting prospect is that rocks could supply the accelerated mass ejected by a slingatron thruster. Rocks are widely available on the moon, asteroids, and Mars (which would be re-supply depots in space), and could be reshaped into crude projectiles. Projectiles of any material at very high velocity (e.g. 10 to 20 km/sec) could be converted into gas and dust after acceleration, for example by passing them through a thin tape to shock heat them at the slingatron exit, so that planetary orbits would not be littered with debris.

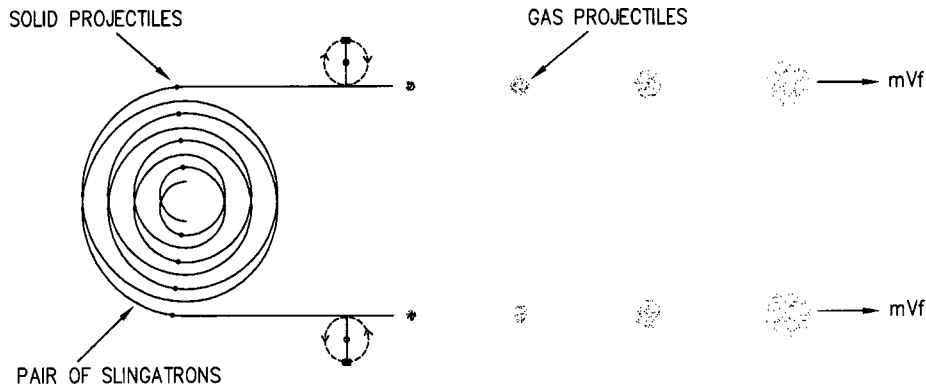


FIGURE 9. Conceptual Propulsion Engine consisting of a Pair of Rapid-Fire Counter-Gyrating Spirals to cancel the Angular Momentum of the Projectile Streams and Precession-Inducing Torques. Projectiles are converted to a Gas at the Spiral Exit to avoid littering with Debris.

SUMMARY

The dynamics and mechanics of the spiral slingatron mass accelerator have been discussed based on approximate equations. The discussion provides some physical guidelines that supplement the computer models based on exact equations. Although the spiral slingatron (which is analogous to a cyclotron) is still in the concept phase, preliminary data for the sliding friction coefficient up to 2 km/sec indicates that the friction coefficient decreases with increasing velocity and the device should work as theorized. This friction data-base will be extended to about 7 km/sec in the near future and an attempt to build a small scale spiral mass accelerator will be made. Finally, we discussed the potential advantages of such an accelerator for a number of space applications.

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REFERENCES

- Bundy, M., Cooper, G. R., Wilkerson, S., and Schmidt, E., "Optimizing a Slingatron-Based Space Launcher Using Matlab," *ARL Tech. Note, 2000, submitted to 10th U.S. Army Gun Dynamics Symposium*, April 23-26, 2001, Austin, Texas.
- Cooper, G. R., Tidman, D. A., and Bundy, M., "Numerical Simulations of the Slingatron," *ARL Tech. Note, 2000, submitted to 10th U. S. Army Gun Dynamics Symposium*, April 23-26, 2001, Austin, Texas.
- Tidman, D. A., "Sling Launch of a Mass Using Superconducting Levitation," *IEEE Transactions on Magnetics*, Vol. 32, No. 1, January, 1996, pp 240-247 (accepted Dec. 28, 1994).
- Tidman, D. A. et al, "Sling Launch of Materials into Space," *Proceedings of 12th SSI/Princeton Conference on Space Manufacturing*, May 4-7, 1995, ed. by B. Faughnan, publ., AIAA, pp 59-70.
- Tidman, D. A., "Slingatron Mass Launchers," *Journal of Propulsion and Power*, Vol.14, No. 4, pp 537-544, July- August, 1998.
- Tidman, D. A. and Greig, J. R., "Slingatron Engineering and Early Experiments," *Proceedings of the 14th SSI/Princeton Conference on Space Manufacturing*, May 6-9, 1999, ed. by B. Faughnan, publ. by Space Studies Institute, Princeton, NJ, pp 306-312.
- Tidman, D. A., "Method and Apparatus for Moving a Mass in a Spiral Track," *US Patent No. 6,014,964*, January 18, 2000.