Railgun Bore Geometry, Round or Square?

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Summary — **There are two fairly evenly divided schools of thought on whether "square" or "round" is the better geometry to employ for railgun bores. The question is examined from the point of view of research launchers as well as of fieldable launchers. Many criteria are examined and the conclusion is reached that "square" is better for research launchers. The same conclusion is reached for fieldable launchers but the case is not quite as strong.**

Index Terms — **bore geometry, electromagnetic launcher, propulsion, railgun.**

I. Introduction

There is no obvious answer to the general question, should rail launchers be designed with round bores or with "rectilinear" bores (e.g., square). The choice will depend on what is required of the launcher such as, is it a research device or a device that must be fieldable, should it be maintainable or is it a throw-away item. The simplistic view, that a rail launcher is just another type of gun and so should also have a round bore like any other gun, is not helpful. The electromagnetic driving mechanism is so different from the use of propellant-generated gas that unorthodox arrangements should also be examined.

In what follows, the basic geometries, round and square, are examined. Other geometries are also possible, rectangular, hexagonal, the four-rail pair launcher, and the open top (one-sided) launcher. These are not discussed further here. The geometries we consider are shown in Fig. 1.

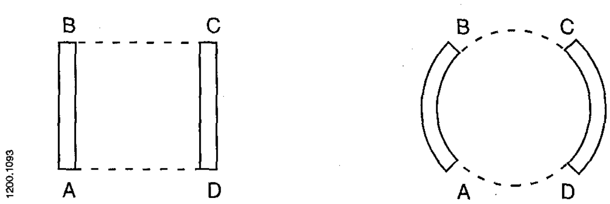

Fig. 1. The geometries are similar in that the inside rail corners A, B, C, D form squares in both cases. Both are shown having area of one square unit. Rails shown are 0.1 unit thick.

A. The Propelling Force

Obviously, the main difference between railguns and ordinary guns is their propulsion mechanism. A discussion of the specifics is helpful.

The analogue of propellant gas pressure in an ordinary gun is magnetic pressure but the concept must be used with caution. Clearly there is no "pressure" on the nonconducting spacers that are required to maintain rail spacing. The electromagnetic force experienced by the armature which drives the launch package is the Lorentz or "J cross B" force. This acts only on current-carrying elements of the launcher. This leads to the well known lumped parameter force law, $F = L' I^2/2$, where L' is, as usual, the inductance gradient of the launcher.

Because the numerical value of L' is small ($\sim 0.5*10^{-6}$ μH/m), to get useful velocities, current must be high. A major challenge in designing railguns is the handling of the necessarily high currents, particularly at the armature rail interfaces. Any means that are available to reduce current must be examined. High on this list is the value of L'. This should be made as large as is reasonable. We discuss this first.

B. The L' Issue

The simple breech-fed launcher

It turns out that for "reasonable" rail launcher geometries, the L' values are quite similar. Because magnetic field lines must close, adequate space between the tops and bottoms of the rails must be provided for the magnetic flux to leave the bore, flow around behind the rails, and return to the bore. In Fig. 2, (a), (b), and (c) have reasonable geometries, while (d) does not.

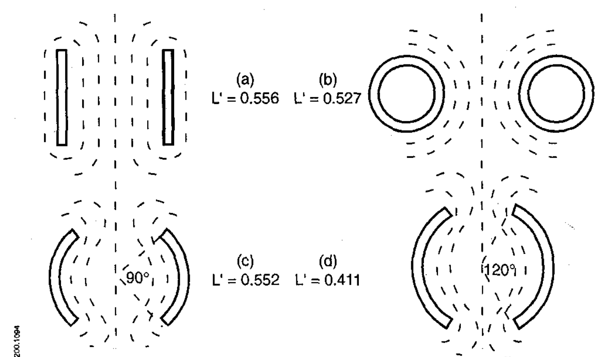

Fig. 2. L' values (μH/m) for four railgun geometries shown. Field lines are indicated.

In computing the values of L', rail thicknesses have been taken as 1/10th of the bore size. Note that L' is geometry dependent only. It is not size dependent. In case (b), the distance between the rails has been taken as equal to rail diameters. (It is thought that Hansler in his rail launcher work in Germany during WWII experimented successfully with round rails [1].) References used to obtain the L' values are (a) [2], [3]; (b) [4]; (c) and (d) [5].

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It is interesting to note that the two cases, (a) and (b) have the same value of L', 0.56 [3]. Note that the penalty of reducing the throat areas between the tops and bottoms in case (d) is to reduce L' by 27%. If the horns are brought closer together, L' falls further. It is also interesting to note that L' is the same for cases (a) and (c). It is clear that the value of L' is set largely by the relative size of the area that the field must leave.

Concerning the necessity for magnetic flux to be able to return freely around behind the rails, the author did an experiment in Australia to test this. The inductance gradient of a rail pair 6-m long with geometry similar to (a) above was measured using a bridge and found to be 0.56 μH/m. It was then encased outside the bore with Ferrite which has a high magnetic permeability. Inductance gradient was again measured and found to be 0.90 μH/m, an interesting if not surprising result, showing that reducing the magnetic circuit's reluctance increased L'. Hindering flux flow as in case (d) above results in the reduced L' shown. If a rail launcher is regarded as a two-dimensional electromagnet, then by placing iron (laminated as in a transformer) in the magnetic circuit, the iron can be designed to provide an augmenting field of as much as several tesla, the saturation field strength for iron.

It can be seen that the L' for the three reasonable geometries above are similar. Because of this insensitivity of L' to bore shape (for reasonable geometries), it is evident that the choice of which is best, round bore or square bore, depends on factors other than L'.

The augmented launcher

One possible strategy for increasing L' is to increase the field in the gun's bore by using field augmenting turns. From examination of Fig. 3 it can be seen that, for a given current, the use of one augmenting turn increases the propelling force by a factor of three.

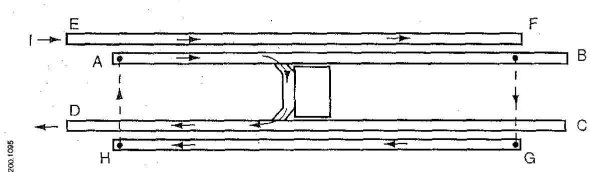

Fig. 3. Schematic of a rail launcher with one augmenting turn in series with the main rails.

The reasoning is as follows. The field at the armature is created by current in the main rails, AB and CD, and also by the current in the augmenting rails, EF and GH. The field produced at the armature by the augmenting rails is twice that produced by the main rails because it "sees" current in the augmenting rails both behind it and in front of it. So if the rails on each side are thin and close together, the field produced at the armature will be three times higher than in the unaugmented case.

C. Forces in Gun Barrels and Rail Launchers

At the risk of stating the obvious, the difference as far as internal forces are concerned between ordinary gun barrels and rail launchers is the following. Ordinary gun barrels must withstand the pressure of the propellant gasses. Locally, this produces forces in all directions as indicated in Fig. 3(a). The barrel is not much more than a simple pressure vessel and the logical way to restrain these forces is to use a round structure like a barrel. (Early gun barrels were just that, fabricated using staves and hoops.)

The forces in a rail launcher are quite different. There are electromagnetic repulsion forces between the rails as indicated in Fig. 3(b). The restraint required for each rail acts in one direction only. Further, the restraining members must be magnetically transparent; they must allow the magnetic field between the rails to exit freely. This means that solid metal cannot be used. The restraint must be electrically nonconducting in the down-launcher direction so that induced currents do not prevent exit of the field.

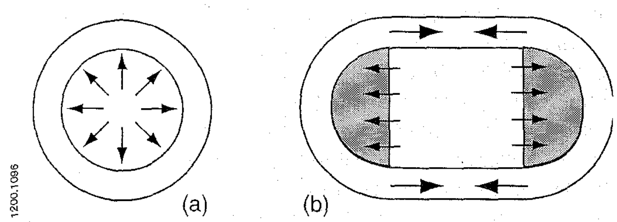

Fig. 4. Forces in a gun barrel (a), and in a rail launcher (b). The launcher rails, of arbitrary shape, are shown shaded.

D. Armature Types

In order to generate the propelling force in a rail launcher, it is clear that current must be carried from one rail to the other in an "armature." There are three basic types of armature.

The metallic contact armature

For military applications, solid nonarcing armatures are the armature of choice, provided that they can remain nonarcing up to the velocities required (3.5 km/s for the anti-tank application) and do not cause unacceptable rail damage. The metallic contact armature is one which makes smooth metal-on-metal electrical sliding contact. Until recently, rail "gouging" [6] has been a problem.

The hybrid armature

The hybrid armature is one in which the current is carried most of the way from rail to rail in a metallic conductor, but in which current is transferred from rails to armature in plasma "brushes." This is described as an arcing contact. When smooth metal-on-metal contact changes to arcing contact, "transition" is said to have occurred.

Hybrid armatures have not been found to produce gouging at high velocities. To obtain very high velocities, it may be desirable to force an armature to transition before the gouging threshold velocity is reached. It is not known at present if this is an area that requires special attention.

The plasma armature

The plasma armature is one in which current is conducted from rail to rail entirely by plasma. The propulsion force on the launch package is transferred from the armature by plasma pressure on its rear face. Historically, much work has been done with plasma armatures, but they are of little interest for military applications because of their high resistance. Voltage drop across them is hundreds of volts rather than the 10 or 20 volts dropped across metallic contact armatures. The energy deposited in them resistively causes rail damage and reduced propulsive efficiency.

E. Research Rail Launchers

The selection of round or square bores depends in part on the particular application being considered. In the case of research rail launchers, the answer is clear. They should have square bores for the following reasons.

Rails as a diagnostic tool

The rails themselves are an important diagnostic. Their appearance after one shot enables much to be learned about the processes that occurred. It is therefore desirable to use them once only.

A further point in favor of flat surfaces is that they are easier to examine after a shot than curved ones. When examining gouges for example, it is simpler to define a reference surface when it is flat. For optical microscopy of the rail face, lighting is more easily controlled on flat surfaces.

Experimental costs

Because rails are used only once, the cost of a rail pair is an issue. It is desirable to use stock material for the rails without having to either machine it before use or to order special shapes. Rail faces are usually sanded and cleaned before a shot and this is more easily done with flat surfaces. Time taken to install rails for a shot and removing them after a shot is also a factor. The simpler the design, the simpler and less time consuming it is to work on.

Uniformity of field

Finally, one strong point in favor of square bores for research rail launchers is that because the magnetic field between the rails is quite uniform, it is simpler to design armatures and to understand armature function during a shot. There are fewer uncertainties in the armature region in square bores than in round bores. This is particularly important trying to understand what physical processes are involved. The uncertainties introduced by field nonuniformity are much reduced when analyzing the results of experiments.

F. The Fieldable Rail Launcher

In the real world, as distinct from the laboratory world of pure and applied research, many factors must be considered before making the choice, round or square. Many of the arguments brought forward by the proponents of each option have been have been incomplete, or the issue has been pre-judged. In what follows, we attempt to put the pros and cons in perspective for the two geometries.

Current per unit rail height

The more severely an object is treated, the shorter its life becomes. Current per unit rail height is a good measure of how severely the interface between armature and launcher rail is treated [7]. In the case of the simple breech-fed large caliber high velocity launcher, current densities can be as large as 50 kA/mm of rail height. This is a very high value and it is possible that acceptable rail life cannot be obtained with current densities of this magnitude. It is quite likely that current densities of around one half of this are as high as can be tolerated. Using a single turn of augmentation with its three-fold increase in L' allows current to be reduced to 58% for a given force. This is a reasonable gain but it does have a price which must be paid. Complexity is increased as is launcher mass.

Heat rejection

A general problem with rail launchers is that the heat that is generated resistively in the rails must be removed in some way. Minimizing the distance from the rails to the outside world allows more heat to be removed by simple conduction. Reduced current can allow reduced current density in the rails and reduce resistive heating. There is no obvious connection between bore geometry and heat rejection.

Bore sealing

The issue of ease of bore sealing is sometimes given as a reason to choose round bores. But when solid armatures are used, sealing is unimportant. With solid armatures, the top and bottom of the bore can be left open as can the breech. It is possible that some kind of local sealing may be required for hybrid armatures but general bore sealing is not required and, in fact, may be detrimental. Plasma armatures might require general sealing but their use has been ruled out. (Note however, plasma armatures were successfully sealed in the Melbourne square bore railgun using "tulip" seals [8].) Bore sealing is a nonissue for fieldable rail launchers.

Launch package rotation in bore

It has been observed occasionally that round launch packages in round bore rail launchers have rotated sufficiently far to move the armature contacts partly off the rails [9]. If this were ever to become a general problem, then some steps would have to be taken to prevent rotation from occurring. Such rotation cannot occur in a square bore rail launcher.

Launcher maintenance

Launcher maintenance has been raised as an issue. Rail life is likely to be shorter than is bore life in a regular gun. The contention is that round bores can be honed while the process of smoothing a damaged square bore would have to be akin to broaching, a less accurate and slower process. In this context, it should be noted that rail launcher barrels are a fabricated entity, not something that is machined from one piece of material like an ordinary gun barrel, so that even the apparently simple honing process is not all that simple. The hone stones must cross and recross the discontinuities between rail and insulator. The fact is that because they are fabricated in the first place, rail launchers could at some appropriate stage in their life be re-fabricated if that were economically reasonable. Honing may also exacerbate bore centerline deviations.

Stability of bore shape

No rail launcher can possibly have the same mechanical stability as regular gun barrels. They require rails separated by insulators contained in some suitable fabricated structure. With repeated firings, it is probable that rail launchers will experience some movement and creep of rail-to-insulator surfaces. Over time, it is likely that the original mating of these faces will change from what it was when the gun was first assembled. This is likely to matter more for a round bore launcher because the rail surfaces and insulator surfaces are initially aligned. In a square bore launcher these surfaces are already "misaligned" by 90 degrees. Any small movement will be immaterial. It is likely that launch packages and armatures should be able to tolerate such distortions in both bore shapes.

Sabot mass

At first sight it would look as if rail launchers designed for some particular duty and having the same bore areas would have the same sabot mass for square bore as for round bore. It could be however that there would be some mass penalty in the square case because of the lack of azimuthal symmetry. Certainly the structural codes required to design square sabots would be more complex than for round sabots. The fact that codes for round bore sabots already exist might weigh the scales a little in favor of round rather than square, but that cannot be allowed as a major driver.

Sabot separation

The issue of sabot separation arises because of the thought that rail launchers may have to have two petals rather than four. This might well be the case for mid-riding armatures but is not the case when base-push armatures are used. Four petals can be used in this case just as they are in powder guns. But in any case, this issue has little bearing on which bore shape is the more appropriate.

Cost and ease of manufacture

The cost of rail launchers that are to be fielded is not such an important issue as it is for experimental launchers in which the rails are used only one time, but it is something worth thinking about. The component parts required to assemble a rail launcher will cost less when they can be used in the "as-supplied" condition. Special processes and extra machining can be costly. The cost factor favors square geometry.

Armature simplicity

As stated above, the magnetic field between the rails in the armature position is quite uniform in a square bore launcher. This makes the armature problem less severe and anything that helps the armature helps the whole system, the armature being the system's most critical component. The distribution of current and strength of magnetic field in the armature region is difficult to compute with certainty even with the best computer codes available. To compound the problem by using anything but the simplest geometry only makes sense if there are other overriding factors involved. This is quite a strong point in favor of the square bore geometry.

Rail complexity

To date, the prevailing view has been that the rails of a rail launcher will have the same cross section and will be made of the same material(s) along their whole length from breech to muzzle. It should be kept in mind that the duty required of the rails vary greatly along the launcher's length. For example, in a breech-fed system the rails near the breech must carry higher currents for longer times than rails near the exit end of the launcher. For this reason it may well be desirable to have a reduced rail cross-sectional area near the muzzle. This would mean that a simple extrusion for a rail could not be used as supplied. Machining would be required. Another issue is that the armature start position probably requires special rail treatment. It is possible a transition trip might be needed somewhere along the launcher. This will require special rail treatment. All of these things are more easily accomplished with flat rails than with round bore rails.

Launch package guidance

The two prime functions of the launcher are the same as for any gun. The first is to provide the propulsive force. The second is to give in-bore guidance to the package to get acceptable repeatability of launch (i.e., the accuracy requirement). It is a general engineering principle that separate requirements should be met using separate equipment, if that is possible. It may be necessary, not just desirable, to use something other than the rails for in-bore guidance. Round bore guns provide some guidance on the insulators, but good guidance may require a more advanced geometry than either round or square.

II. Conclusions

It is the conclusion of the author that square is the best bore shape to use for research launchers.

For the first generation of fieldable rail launchers the position is not so clear. However, it is clear from the considerations examined above that the use of flat rails is preferred to the use of curved rails, i.e., "square" is better than "round." Because there is no compelling reason to use the round bore geometry, it is more practical to use the simpler square bore geometry.

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