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Finless Rockets Using Engine-Driven Gas-Dynamic Stabilization

By M. Dean Black

Introduction

Finless rocket design has long been a subject of debate among rocketeers wishing to build and fly true scale models of space launch vehicles and large military rockets which do not normally possess prominent fins typical of tail-heavy model rockets. The methods of building and flying such finless or small-finned rockets already exist but are not familiar to most model rocket builders. The purpose of this paper is to bring these methods to the attention of more rocket builders and to explain the differences between techniques which actually work and those which seem reasonable but will not provide the necessary stability.

The methods that will be explained involve passive stabilization of rockets (not requiring active guidance systems based on gyroscopic sensors and activation of aerodynamic or thrust vectoring controls). These passive stabilization systems allow scale models to be built and flown with or without fins and if desired even without the use of launch rails. Stabilizing tail cones such as those employed on blow-gun darts and on some rockets will not be considered as "finless" designs since flared tail-cones contribute to the dimensions and appearance of the rocket as do fins. The principal subjects of this paper are 1) rockets stabilized by motor-driven finless re-direction of air and 2) rockets stabilized by motor driven angular momentum depletion about the yaw and pitch axes.

Finless Redirection of Air Flow—Air Inlet at or Near the Exhaust

Finless redirection of air uses the engine exhaust and the tail end of the body tube to deflect ambient air flow without the use of fins. The finless redirection of ambient airflow can be achieved as easily as recessing the rocket motor a short distance into the base of the body tube of the rocket (Figure 1). Nose weight is required for this. Turbulent mixing of exhaust flow with air inside the body tube results in an expanding cone of mixed gases (yellow) that leaves the body tube along the longitudinal axis of the rocket. At the same time more ambient air is being drawn into the base of

the rocket (light blue) to replace that air which is being ejected with the exhaust.

The air entering the base of the rocket originally had a velocity and a radius of action (V_{wind} and R_{wind}) relative to the center of gravity (CG) of the rocket, defining how much angular momentum the captured ambient air brings to the rocket. Since the captured air leaves the rocket along its longitudinal axis ($R=0$), the angular momentum *leaving* with the captured air is reduced to near zero. The net captured angular momentum turns the rocket into alignment with the relative wind. That is to say, it aligns the rocket into the relative wind and thus "stabilizes" it. This is also what fins do: receive the ambient air at the angle of attack, θ , from which it approaches and then redirects the air to the rear more in-line with the rocket's longitudinal axis. The recessed rocket motor thus works like fins, but unfortunately at the expense of a considerable decrease in thrust.

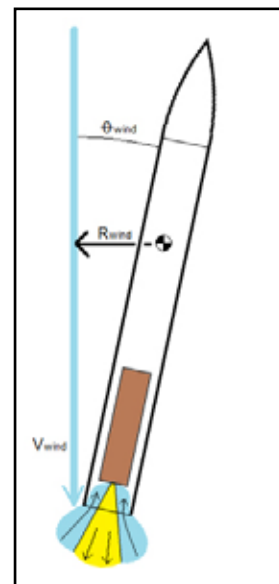


Figure 1: Recessing the motor will cause mixing of air with the exhaust.

The suction required to draw in the ambient air (light blue in Figure 1) increases as the motor is recessed at greater depths within the body tube. If the motor is recessed too deeply, the suction becomes great enough that the drop in pressure expands the cone of outgoing gas (yellow) until it cuts off the intake flow altogether. This cut-off of intake flow results in an abrupt loss of thrust usually termed Krushnic Effect by modelers. It is possible to push the nozzle of the motor a little more than half the body diameter into the base of the body tube without triggering the cut-off of intake flow and the associated loss of thrust.

There is an easy way to prevent the intake and ex-

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Engine-Driven Gas-Dynamic Stabilization

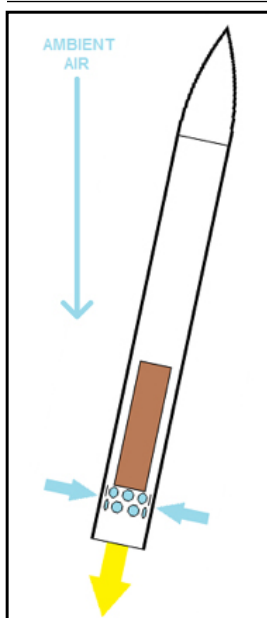


Figure 2: Engine exhaust combined with redirected air flow.

haust flows from having to compete with each other for flow area: keep these flows physically separated.

Holes punched in the body tube near the base of the motor (see Figure 2) allow ambient air to enter the body tube from the sides without passing thru the base of the body tube in counter-flow to the exiting expanding cone of mixed exhaust gases and entrained air. A major collapse of thrust is no longer likely and thrust losses can be kept small with adequate flow areas for the ambient air entering from the sides.

This technique of using entrained air to provide “pseudo-fin” behavior is an alternative to the use of clear plastic fins to stabilize scale models of finless rockets.

These pseudo-fin rockets still require nose weight and a launch rail to get up to an adequate air speed before the fins, or “pseudo-fins” in this case, will stabilize the rocket. The use of pseudo-fin redirection of air is a means of stabilizing finless or small-finned scale models while staying within current NAR rules requiring the use of a launch rail.

When the exhaust jet from a rocket engine enters the atmosphere, the two mix in a turbulent cone that grows larger in diameter at about $\frac{1}{4}$ times the length of the mixing cone. If an engine firing in a body tube mixes in a turbulent mixing cone of this angle, the length of body tube needed to mix to the full internal diameter of that body tube is about

4D, four times the diameter of the body tube.

Mixing length of Body Tube $\approx 4D$

The holes letting air into the sides of the rocket should provide enough flow area to match the cross-sectional area of the turbulent mixing cone where the cone leaves the body tube. For example, if the end of the body tube is 2D downstream of the rocket nozzle, then the diameter of the mixing cone will be approximately half the diameter of the body tube ($D/2$) where the flow leaves the body tube. The cross-sectional area of the mixing cone where the flow leaves the body tube will be approximately $\pi(D/2)^2 \div 4 = 0.20 \times D^2$. The total area of the holes admitting ambient air thru the sides of the rocket should then equal at least 0.20 times the square of the diameter of the body tube. For different distances of the end of the body tube downstream of the engine, the total area of the holes required will also be different.

Experience with pseudo-fin rockets will provide a useful introduction to the general subject of gas-dynamic stabilization of rockets which will familiarize model builders with techniques that are also applicable to a more capable stabilization system called induction tube stabilization. Induction tube stabilization is not dependent on the rocket's air speed and allows the launch of rockets without launch rails.

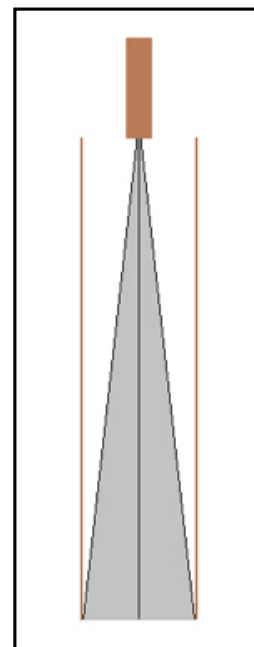


Figure 3: A body tube used for mixing with the exhaust cone needs to be about 4 times the diameter of the tube.

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Engine-Driven Gas-Dynamic Stabilization

Induction Tube Stabilization—Air Inlet at or Near the Center of Gravity

Induction tube stabilization of rockets has been in limited use for at least 50 years. The author's first flight of an induction rocket, a scale model Minuteman, was in 1964. Induction tube stabilization differs from pseudo-fin stabilization in that it is not dependent on the speed of the rocket into the wind to provide stability. Induction tube stabilization is enabled by engine thrust, not air speed, and it stabilizes the rocket by freezing its pitch and yaw angles rather than by aligning the rocket into the wind. The outward difference in appearance between rockets with pseudo-fin action and induction stabilized rockets is the placement and size of the air intake.

Induction tube stabilization is what is called a limited degree of freedom system in that the rocket's pitch and yaw angles are fixed during powered flight. This is similar to what a launch rail does during the initial few feet of a conventional model rocket's rise. It keeps the rocket from pitching over or yawing off to the side. In the case of an induction stabilized rocket, the vertical alignment is preserved much longer—until thrust termination of the engine. This is what makes rail-less launches practical. A short rail is still required to brace the rocket against winds while it is sitting on the launch pad. A long, flexible rail, however, is inappropriate since bending of the rail during launch could cause binding between the lug and the rail when the gas-dynamic system resists tilting of the rocket.

Quantifying the stabilizing effect of engine-driven gas-dynamic systems is straightforward because of the simplicity of the hardware and the directness of the application of fundamental principles of gas dynamics and angular momentum management. There are no mysteries associated with these systems. They are well understood and very



Figure 4: Major elements of a basic induction tube rocket are a forward body tube, an aft body tube, and a forward engine mount, all seen here. The open intake is between the fore and aft body tubes. No launch lug, fins or nose weight are needed.

robust in fulfilling the requirements to perform their function.

For induction rockets the intake is larger and it is placed at or near the center of gravity rather than near the base of the rocket. An intake at the center of gravity has near-zero radius of action for any momentum in the ambient air entering the intake. Nose weight is not required due to the forward placement of the engine.

The purpose of the large induction tube (lower body tube) is to maximize gas flow out the bottom of the rocket. It is this flow which extracts angular momentum from the rocket's rotations about the yaw and pitch axes at a rate equal to (the mass flow rate \times the tangential velocity of the exhaust, ωR_{exh} , \times the radius of rotation of the exhaust, R_{exh} , about the rocket's CG). Omega, ω , is the rocket's angular velocity about its pitch or yaw axes. The mass flowrate in the induction tube follows from Newton's 2nd Law of Mo-

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Figure 5: This photo shows a basic induction stabilized rocket assembled and painted, with a rail-less launch pad.

tion:

$$\begin{aligned} \text{Thrust} &= \text{Rate of change of Momentum} \\ &= \text{Mass flow rate} \times \text{Discharge velocity} \\ &= \rho A V \times V = \rho A V^2 \end{aligned}$$

Solving for the velocity in the induction tube gives:

$$V = \sqrt{(\text{Thrust} / (\rho A))}$$

where "ρ" is the density of the gas in the tube and A is the cross-sectional area of the induction tube. Since the flow in the induction tube is predominantly air, the density ρ

will be close to the air density. The mass flow in the induction tube will then be approximately:

$$\text{Mass flow rate} \approx \rho_{\text{air}} A V \approx \rho_{\text{air}} A \sqrt{(\text{Thrust} / (\rho_{\text{air}} A))} = \sqrt{(\rho_{\text{air}} A \times \text{Thrust})}$$

For the black induction tube rocket pictured in Figure 5, with a 2.09" diameter induction tube and a C6 engine, this mass flowrate is about 15 times the mass flow rate of the engine alone, so the mass flow rate of ambient air is about 14 times the mass flow rate of the engine. This high 15:1 increase in mass flow rate provides the means by which angular momentum about the rocket's pitch and yaw axes is depleted.

Multiplying the mass flow rate by the tangential velocity at the base of the rocket, ωR_{exh} , and the radius of action of that tangential velocity about the CG, R_{exh} , gives the rate of angular momentum depletion by the gas discharged out the base of the rocket:

$$\text{Rate of angular momentum depletion} = \omega R_{\text{exh}} 2\sqrt{(\rho_{\text{air}} A \times \text{Thrust})}$$

This Rate of Angular Momentum Depletion (RAM-D) equation is the heart and soul of what induction stabilization is about. The large mass flow rate times the square of the large radius of action of that flow out the base of the rocket make the induction stabilization effect very strong.

The following chart summarizes the critical design features of an induction stabilized rocket of the simplest constant-body-diameter design. Both pseudo-fin and purely induction stabilized finless rockets will cease to face directly into the wind after thrust termination. For this reason a "hybrid" system is sometimes employed with induction stabilization. In the hybrid system, the induction tube provides

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stability during engine thrust, allowing launch without a rail, and small fins provide stability during coast. The small fins take advantage of the far forward center of gravity provided by the forward mounted engine in induction stabilized rockets. (Pseudo-fin rockets will not be steered directly into the wind by small fins due to the rear mounted engine.) If 4 fins are used, the individual fin areas should be about $0.35 D^2$. The small size of the fins is consistent with the forward mounted engine so added nose weight is not required. Most induction rockets are flown without fins.

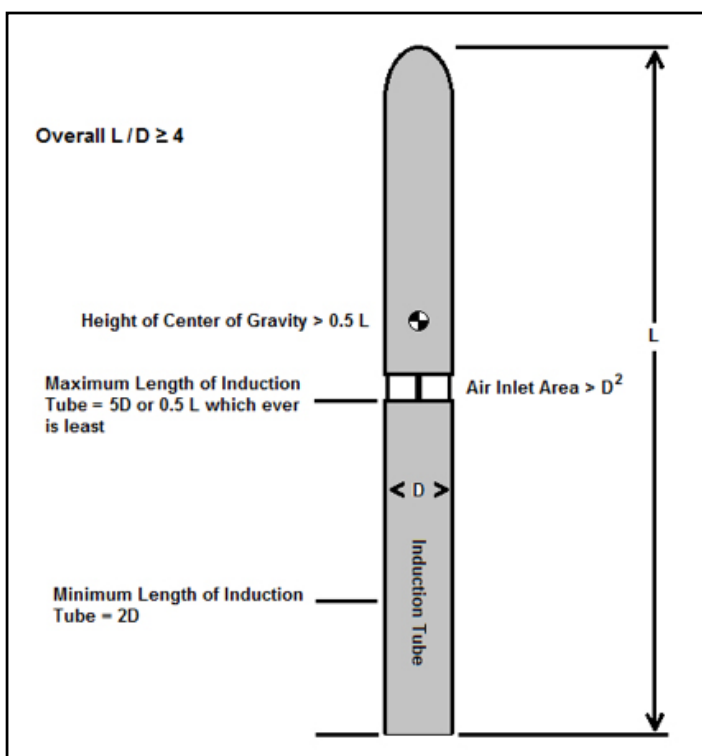


Figure 6: Suggested guidelines for a basic induction stabilized rocket of constant diameter.

The resistance to changes in pitch and yaw angles during the thrust-powered portion of the flight gives induction stabilized rockets different flight characteristics than conventional model rockets. Induction rockets launched at angles other than vertical still tend to maintain near-constant pitch and yaw angles. This feature makes it possible to launch

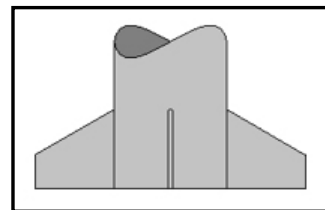


Figure 7: Size of fins relative to body diameter used on constant-diameter induction stabilized rockets to maintain alignment directly into the wind during coast.

inductors at somewhat larger angles off the vertical without the rocket following a gravity curve into the ground. Delay times should be kept small for such lower elevation launches, however, since the unusual "nose up" attitude will not be maintained after engine thrust ceases unless the rocket has a strong spin. Nose-up flight attitudes tend to cause "lofting": extended horizontal range due to the generation of lift and associated altitude gain due to that lift. Once again, *post-thrust* lofting is only pronounced in inductors that remain stable after thrust termina-



Figure 8: William F. Cook's *INDUCTIVE MAYHEM* is a beautiful example of a basic, well built induction stabilized rocket.

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Figure 9: Dean Black's IRBM induction stabilized model includes a few extra parts for static display.

tion by virtue of a strong spin. Spin stabilization is a fairly complex topic that warrants a separate analysis of its own, and will not be addressed in this article.

Beware the Center of Pressure

Unfortunately it is sometimes the case that people's opinions, even if untrue, become canonized as facts. When this happens, the truth can be buried so deep that no amount of contradictory observation will persuade true believers to consider otherwise. Case in point is the long accepted fallacy that the transverse CP of a rocket has any relevance to the in-line CP of a rocket facing almost directly into the wind. I am taking exception to the half century old NAR treatise on *Rocket Stability* that has been accepted as fact but never been proven since the beginning of model rocket time.

More to the point, I am taking exception to the statement that "Experience has shown that if the center of gravity and the center of pressure are determined as outlined above, your rocket will have ample stability if the center of gravity is ahead of the center of pressure by at least one half the diameter (caliber) of your rocket."

A single exception will disprove this statement. That exception is a fin-less rocket of constant diameter, except for the nose cone which can have any shape not exceeding the diameter.

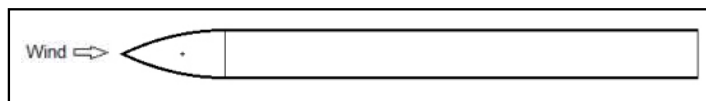


Figure 10: Determining the CP of the constant diameter rocket.

According to the procedure "outlined above" the transverse CP is the center of the area of paper cut-out of the rocket. The **incorrect assumption** is that the lifting CP is near this transverse CP. According to aerodynamic lift theory for small angles of attack, lift (i.e. force perpendicular to the surface) due to wind from the left (shown in Figure 10) is only generated where the width is expanding, so *the small angle center of lift is limited to the nose*. THE NOSE IS WHERE THE CP IS LOCATED FOR SMALL ANGLES OF ATTACK, θ . This small angle lift is directly proportional to θ . Transverse pressure on a rocket is proportional to the dynamic pressure of the air times θ^2 (so called "body lift" as opposed to "wing lift"), so for small angles of attack there

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is virtually NO TRANSVERSE PRESSURE due to near-nose-on wind from the left. Therefore for off-axis deflection of a finless rocket of constant body diameter, the CP MUST BE ASSUMED TO BE AT THE NOSE, NOT NEAR THE



Figure 11: This 1/54th scale model of a Polaris A-1 flies without fins or launch rail. The tiny model is 1" in diameter and about 7.5" long. It is capable of taking off from either a flat pad or a scale submarine launch tube. The air inlets are hidden in the black paint pattern.

CENTER OF THE BODY. That is why a finless rocket of constant body diameter regardless of added nose weight does NOT have its CG ahead of its CP! This only becomes true when the presence of fins, or pseudo-fins as previously described, move the CP much further aft. The NAR *Rocket Stability* paper should be considered inaccurate in its reasoning to justify the assumption that the center of lift that determines destabilizing nose torques should be believed to be near the transverse CP. This will usually lead to an overestimation of a rocket's stability based on a false determination of the critical-lift CP. (In a similar vein, it is common knowledge among pilots that small angle lift on a flat, straight wing is centered near the $\frac{1}{4}$ chord, not at the center of the wing.)

Another pitfall that should be avoided is low Reynolds Number experimental results. More specifically, a rocket that lines up into a gentle breeze (low Reynolds Number due to low speed) will not necessarily behave the same at high flight speeds (i.e. high Reynolds Numbers). Reynolds Number is a relative measure of inertial versus viscous forces based on speed. At low Reynolds Numbers, viscous forces dominate: everything behaves as if it is in a thick stream of slow moving honey. At high Reynolds Numbers things are more dynamic and un-damped. Inertial forces dominate. A rocket that is passive and lined up directly into a slow breeze may refuse to line up directly into the wind at much high speeds. This behavior is exhibited not only by finless rockets but also by arrows. An arrow with a heavy metal tip, if launched without tail feathers will not line up directly into the wind, no matter how heavy the tip. The arrow will move forward with the tip ahead of the shaft but not in line. The tip is cocked off far to the side with the shaft crossing the relative wind at a significant angle. Finless rockets do the same and for the same reason. Hanging a rocket by a string in a gentle breeze is not the same as a wind tunnel

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Figure 12: Induction stabilized model rockets put out a large volume of gas, even with small motors, as seen in this single frame lifted from a video.

test at realistic speed. Once again, too much credence given to the wrong "results" can lead to wrong conclusions.

Accurate determinations of CPs are not a trivial undertaking as is finding the CG. Over-simplification leads to false or unrealistic theories that are best regarded with skepticism. This includes much of model rocket stability theory as presently practiced. Expanding

the scope of model rocket activities will encourage renewed activity in this area.

Conclusion

The Rate of Angular Momentum Depletion equation (RAM-D equation) is a significant advance in the understanding of the gas-dynamic self-stabilization of inductive rockets. This article has introduced the subject of induction tube stabilization and related topics to model rocket enthusiasts in hopes of influencing the future of the hobby of model rocketry by encouraging the adoption of new regulations that embrace the use of inductively stabilized rockets along with traditional fin stabilized rockets in model rocket competitions. By expanding the scope of model rocketry it is believed that the hobby will become more challenging and rewarding to those who participate. The particular

strength of induction stabilized rockets is the ability to fly scale models without fins or launch rails. The physics of inductive stabilization provides a unique educational opportunity to introduce future aerospace engineers to concepts of angular momentum and gyro-dynamics that they would normally not encounter at such a level until later in their careers. Model rocketry is both fun and challenging, and can be even more so in the future.

About the Author:

M. Dean Black is a retired Rocketdyne employee who pioneered induction stabilization for model rockets going back to 1964.



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