Sharp edges miss the point

Introduction

In rocketry, we all know that lethally-sharp forward edges are best at supersonic airspeeds, right?

Wrong!

Missile design literature is ‘economical’ with the truth when it clashes with mil-head doctrine; recently-declassified papers (which we’d all read anyway) show that they deliberately hid the reality.

We need to separate the sharpness requirements of the aerodynamic design of our rocket vehicles into design for best Lift, design for lowest Drag, and at higher supersonic airspeeds, the design for survivable aerodynamic heating. Safety of personnel is also an important issue should we decide to juggle with razor-sharp bits of rocketry!

These differing requirements may not ‘point’ the same way: sharpness at supersonic airspeeds may be good or bad depending on what you’re designing for.

This paper focusses on swept fins and tangent ogive nosecones, but the trends are applicable to any similar shapes.

See our paper ‘Rocketry aerodynamics’ for more aerodynamic definitions, including discussion of static stability.

Items in **bold** appear in the glossary at the end of this paper.

Economical with the truth

It’s well known that at subsonic airspeeds, rounded nose-tips and fin leading edges create considerably less Drag than sharp ones. Furthermore, rounded fin leading edges create considerably more subsonic Lift.

At transonic and supersonic airspeeds however, much of the missile design literature attests to the efficacy of lethally sharp front edges.

But old literature is not always correct, especially since missileers classify those aspects of scientific truth that they hope give them the advantage over the enemy du-jour.

For example, the genuine merits of basalt fibre over glass fibre were hidden for a century just in case this might be militarily advantageous (it wasn’t, and in any case all ‘sides’ independently discovered it.) What *did* occur were innumerable civilian deaths that could have been prevented had basalt fibre-wound firefighting pressure-vessels been developed a century earlier, not to mention innumerable deaths from Asbestos inhalation.

How sharp is sharp?

First, we have to define ‘sharp’.

As far as the aerodynamics is concerned, a sharp edge could be defined as one that has an edge radius less than one percent of the length of the nosecone or wing/fin chord. At this level of sharpness, the effect of the aerodynamics in the region of the rounded edge are swamped by the aerodynamics of the rest of the body so can be considered negligible.

A *physically* sharp edge would be sharp to the atomic level, but this is neither required nor attainable (please don’t try).

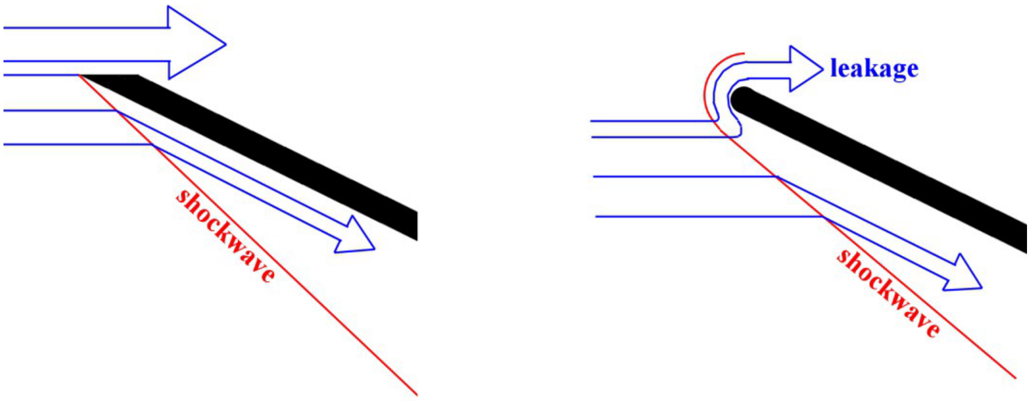
Supersonic Lift

Nose

In rocketry, the Lift of the nosecone is de-stabilising - in terms of static stability - so there’s nothing to gain by increasing the Lift of the nose. A blunter nose-tip probably causes less Lift, so is preferable for that reason, and for reasons we’ll discuss below.

Fins

The Lift of wings/fins increases markedly as the edge is sharpened because the shockwave caused by the leading edge ‘attaches’ to the edge rather than standing ahead of it. In contrast, the rounded shock that stands some distance ahead of a *rounded* edge allows spillage of underwing compressed air - which is the basis of most of the Lift of a supersonic wing/fin - round the gap between edge and shock. ¼ of the Lift can be lost by this spillage, particularly if the leading edge is swept back.



Sharp and blunt edge flow at angle of attack

See our paper ‘Supersonics and Waveriding’ for more discussion of wings with sharp edges at supersonic airspeeds.

For typically-sized rocketry fins, the area of the fins is relatively small compared to the length of the vehicle. Sharpening the leading edge to improve fin Lift therefore only gives a slight improvement in static stability; it would be easier just to increase the fin area slightly. This minor increase in fin size needn’t increase fin Drag as we’ll see below.

Supersonic nosecone Drag – Wave Drag

As local areas of the flow around the rocket vehicle go supersonic, shockwaves will be formed. Shockwaves are a vocal manifestation of the flow’s upset at having to change direction, and is a dissipative process (a tantrum!). Energy is wasted creating the sudden, thin, discontinuity in pressure and density that constitutes a shock. Wave Drag (lumped-in as a form of pressure Drag) is an accounting for this loss of flow energy.

Traditional supersonic theory says that the higher the nosecone **fineness ratio**, the weaker the physical strength of the shockwave, and hence the lower the Wave Drag. This is because slender noses *generally* produce shocks which are highly swept-back: the greater the sweep, the weaker the shock.

The swept conic shocks emanating from a sharp nosecone tip are hence referred to as ‘weak shocks’ as opposed to the physically more energy-dissipative ‘strong shocks’ standing essentially unswept just ahead of blunt noses.

It’s worth pointing-out that the terms ‘weak’ and ‘strong’ are actually our labels for the two equally physically possible roots of the classic quadratic equation relating nosecone surface slope to the resulting shockwave angle. This causes confusion: highly-swept ’weak’ shocks are much more likely to occur over gentle slopes, and ‘strong’ shocks at blunt edges, but not always!

One of the two supersonic engine intakes of the SR71 aircraft would occasionally 'unstart' with potentially catastrophic Thrust asymmetry consequences unless the pilot was literally on his toes for the entire mission – this level of concentration was exhausting for him. In contrast, the Concorde's intakes were designed acknowledging that the aforementioned quadratic equation occasionally rolls a bad dice: they never 'unstarted' during the Concorde's entire operational history.

Whilst Wave Drag is certainly one of the major supersonic Drag components, it isn't the only one. Just as in subsonic flow, least overall Drag generally occurs when the various Drag components are balanced – are essentially equal. Excessively slender nosecones can lengthen the overall length of the rocket vehicle, causing excessive vehicle surface area and hence excess viscous Drag.

Stupidly slender noses also have structural/mass issues; limiting our noses to a length-to-base diameter ratio of five is a good design rule-of-thumb.

To recap, basic supersonic aerodynamic theory says that sharp edges cause the least wave Drag at supersonic airspeeds. But these oft-repeated theories are long in the tooth (1940's) – devised without the inclusion of viscosity or even 'boundary layer' theory. The classic rocketry nosecones were devised by the same authors at the same period in history.

The blunt truth

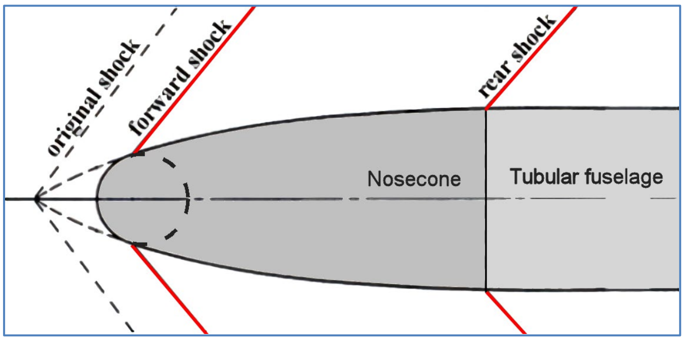
Whilst it's certainly still true that one of the primary Drags at transonic and supersonic airspeeds is Wave Drag, it's a lesser-known fact - because the data was restricted - that minor blunting of the edge causes less Wave Drag at transonic and low supersonic Mach numbers.

Whilst the Wave Drag immediately at the blunter tip does cause more Drag, experiments show that an expansion then occurs immediately behind it, a pressure reduction. This locally-reduced pressure is acting on the forward-facing slope of the nosecone – it therefore has a component in the opposite direction to the Drag (and is therefore a Thrust). So, the overall force in the Drag direction is less than for a sharp tip.

Basically, the classic shock theory is being muddied by viscosity: 'boundary layer' flows are subsonic just downstream of a 'strong' shock, so the downstream flow isn't as disconnected from upstream as classic theory would have us believe. Considering the ever-presence of a tip boundary layer, can a truly sharp edge ever exist in reality?

Nose-to-fuselage junction Drag

It's well-known that a shockwave occurs at the junction between the nosecone and the cylindrical fuselage of a typical rocket vehicle. Imperfect machining around the joint aside, the airflow over the nose is instantly forced to follow a straight edge rather than a curved one, and it manifests its annoyance as another shockwave. (This is one of many reasons to avoid classically-tubular fuselages if you have the capability to make your own.)



For *blunted* nosecones, an additional shock occurs at the junction between the essentially spherical nosetip and the rest of the nosecone behind the tip.

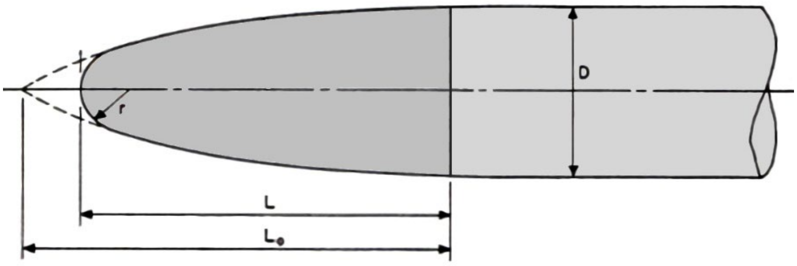
This forward shock 'pulls the teeth' as it were, of the nose-to-fuselage junction shock, resulting in two shocks that are weaker in combination than the original single junction shock. Weaker shocks give less wave Drag.

Nosetip blunting

Blunting of a nosetip (or fin leading edge) can be geometrically defined by the *blunting ratio* ***b***: the ratio of the essentially spherical nosetip diameter ***d*** divided by the diameter of the base of the nosecone ***D***:

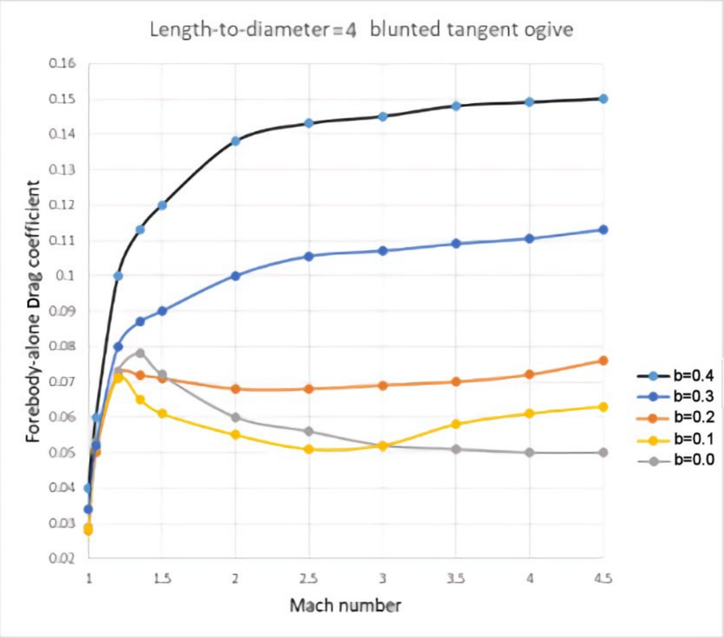
$$\boldsymbol{b = \frac{d}{D}}$$

Note that in the following pages of this paper, the **fineness ratio** (length to diameter ratio) of the nosecone is based on the *blunted* length ***L*** rather than the un-blunted length L_0 (see Ref. 4 for details).



Several EDSU papers on the subject of beneficial blunting are fixated on tangent-ogive nosecones with fineness ratios of two, as these form the basis of military jet nose design. However, we can assume that the trends are applicable to rocketry nosecones of higher fineness ratios.

For a tangent-ogive of fineness ratio two, Ref. 1 says that the optimum blunting ratio to give minimum transonic Wave Drag is about 0.35



This chart is plotted from Ref. 2 for a (blunted) fineness ratio of 4 tangent ogive, for different bluntness ratios ***b*** including ***b=0*** (sharp).

Note that these data are for the Wave Drag (pressure Drag) of the forebody alone, assuming a perfectly aerodynamic afterbody and no (additional!) viscous/boundary layer effects.

Below about Mach 0.7 there are no shockwaves, therefore these curves drop to zero at Mach = 0.7

Ref. 2 also relates the effect of increasing (blunted) nosecone fineness ratio, and increasing Mach number up to 4.5:

As (blunted) fineness ratio is increased from 2 to 4, the optimum blunting ratio in the subsonic and transonic region (up to about Mach = 1.3) drops down to around 0.2, then steadily drops to 0.1 at around Mach 3. Above Mach 3, zero blunting gives lowest Drag.

Ref. 3 shows similar blunting ratio trends for straight-cone nosecones.

As peak **Drag loss** occurs just after Mach 1 for most HPR rocket vehicles (at maximum **Dynamic pressure**, or ‘max q’) then based on these data, I would recommend a blunting ratio of between 0.1 and 0.2 for HPR rocket nosecones. A pragmatic value would then be 0.15, i.e. 15% of the nosecone base radius.

Aerodynamic heating

Since the 1950’s it has been known with chagrin that sharp edges tend to melt-off if launched from ground level to airspeeds exceeding Mach 3.

It’s found both mathematically and experimentally that the heating rate $\frac{dQ}{dt}$ experienced by a nosetip or leading edge depends inversely upon the nose radius r (and hence the bluntness) of the edge:

$$\frac{dQ}{dt} \propto \sqrt{\frac{\rho}{r}}$$ where ρ is air density.

Consequently, most vehicles flying above Mach 5, such as the Space Shuttle, had profoundly rounded noses and wing-edges; seriously blunt.

Many hypersonic vehicles have insulating heat-shields. What little heat that does flow through the heatshield accumulates (integrates) with time, therefore the vehicle has only a finite time it can spend hypersonically before its internal fuselage overheats.

There is another approach however: if the higher heating rate commensurate with a sharp edge can be ‘drained away’ at the same rate, then the edge can remain at a survivable temperature for an indefinite time because the time-integrated heating doesn’t accumulate.

To allow this, the edge has to be made of a conductive material: able to conduct the heat away to cooler regions of the airflow such as the lee of the wings. This also relieves the thermally-induced stresses at the edge.

On a Mach 3 HPR rocket, this would entail having the forward centimetre or so of nosetip and/or fin leading edges manufactured from solid metal such as aluminium or copper.

However, also note the density term in the above heating rate equation. Simply performing the high-speed flight at much higher altitudes ameliorates the heating: blasting off a sea-level launchpad at Mach 3 isn’t worth it – the **Drag loss** alone is utterly horrendous.

Safety issues of razor-sharp edges

High speed impact

If we ignore the potential for injury during handling, it is a fallacy that sharp edges would cause more damage to persons or property due to a high-speed impact even though at first sight they look ‘more lethal’. Googling the shape of commercial bullets reveals just as many sharp ones as blunt ones.

If the rocket vehicle goes off course during ascent, or if the parachute fails, a robust blunt edge will cause ‘blunt trauma’; just as big a hole as a sharp edge.

In practice this means that a plastic nosecone with a hollow tip filled with lead shot will cause just as much damage as a sharp metal nose-tip of similar mass.

Having said that, a fully metal nosecone on a model rocket represents a point mass of high density far and above that needed for static stability. This should be avoided for safety, as it’s effectively a small cannon-ball.

Low speed impact

Low speed impacts are a different story: a sharp edge descending swiftly under a small parachute will cause a puncture, whereas a rounded edge will not. For this reason, many model aircraft organisations recommend rounded edges (minimum nosetip radii).

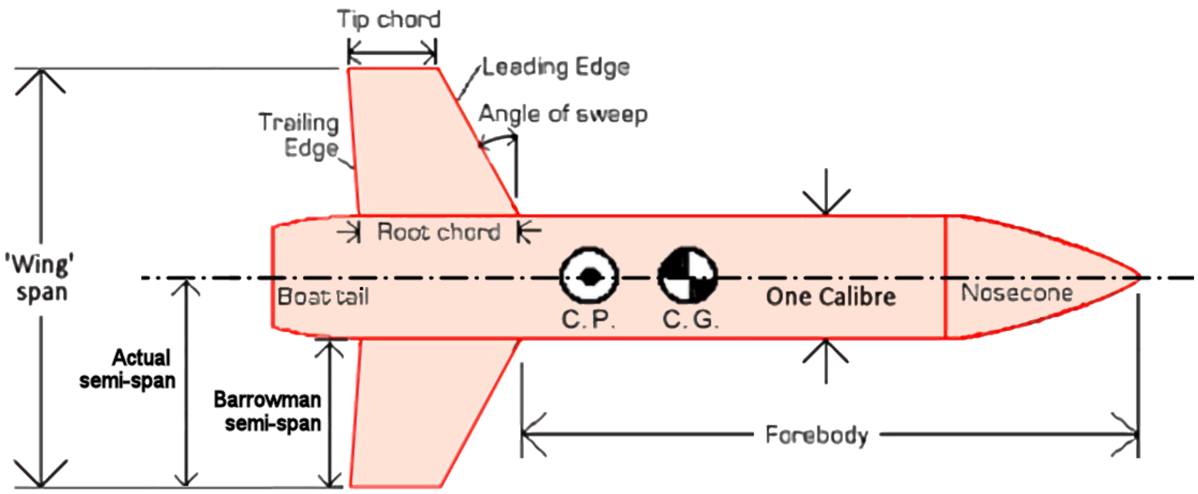
Ground handling

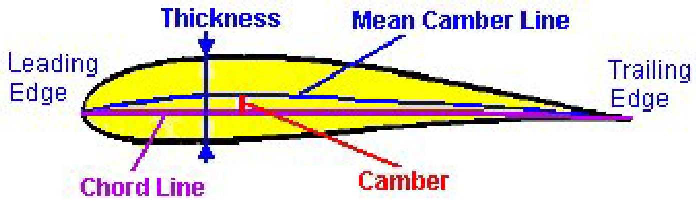
Fully metal fins on model rockets would be made of very thin sheet metal due to the small scale involved, which would result in very sharp edges which are a handling hazard.

Sharp edges at any scale represent the potential for handling injury during manufacture, ground handling, and ground recovery. Precautions must be taken to protect personnel, such as protective covers.

Glossary

Geometric definitions:





Angle of attack α: This is usually referred to as ‘alpha’, and corresponds to the angle between the incoming airflow direction (usually the Freestream direction) and some vehicle or fin datum such as the wing chord line.

Drag (equation): Aerodynamic Drag (Archaic – ‘air resistance’), is the retarding force experienced by bodies travelling through a fluid (gas or liquid). The equation used to calculate Drag is the product of Drag coefficient C_D, **Dynamic pressure** q, and some reference area S:

$D = q\,S\,C_D = \frac{1}{2}\rho\,V^2 S\,C_D$ (where ρ is atmospheric density.)

Drag loss: The loss of mission energy due to time-integrated Drag. At typical near-sea-level launch altitudes, most model and HPR rocket vehicles lose roughly 8/9ths of their theoretical apogee to Drag.

$\Delta V_{drag\ loss} = \int \frac{D}{m}\,dt$ where m is the current vehicle mass.

Dynamic pressure (*q*) : All aerodynamic forces scale directly with the kinetic energy term: $\frac{1}{2}\rho V^2$ where ρ is volume-specific mass i.e. air density, and *V* is flow velocity. This kinetic energy term is called Dynamic Pressure (q), to distinguish it from its Potential energy counterpart of static pressure *(P).*

Fineness ratio: The length ***L*** of the nosecone divided by the diameter of its base ***D***.

Forebody: The nosecone and forward fuselage.

Freestream (flowfield): □The undisturbed airflow at a large ('infinite') upstream distance ahead of the vehicle, i.e. not local. For example, freestream Mach number is Mach number for the whole vehicle as we'd usually understand it, and not the local Mach number around the nosecone or fins.

HPR: 'High-powered rocket': A model/amateur rocketry designation denoting a rocket powered by 'H' to 'O' class engines.

Hypersonic: Higher supersonic airspeeds where chemical effects caused by the air molecules breaking down as they traverse shockwaves begin to manifest themselves. The exact boundary of hypersonics depends on the criteria being studied, but is generally assumed to mean airspeeds above Mach 5.

Lift (equation): Lift is the force generated by aircraft at right-angles to their flightpath. The equation used to calculate Lift is simply the *Lift coefficient* C_L times **Dynamic pressure** times some reference area *S*:

$L = q\,S\,C_D = \frac{1}{2}\rho\,V^2 S\,C_L$ (where ρ is atmospheric density.) For aircraft, this reference area *S* is the total wing area.

Mach number: The vehicle's airspeed *V* compared to the speed of sound a: $M = \frac{V}{a}$

Model rocket: A rocket vehicle utilising motors of G-class and below.

Shockwave: A thin region where flowfield properties (temperature/pressure/density) suddenly jump in value.

Subsonic: Vehicle airspeed is below Mach 1 (see Mach number).

Supersonic: Vehicle airspeed is above Mach 1 (see Mach number).

Tangent ogive nosecone: A nose cone formed by revolving a circular arc about the central vehicle axis. The arc is tangent to the cylindrical fuselage at the nosecone base. The majority of HPR nosecones are tangent ogives as they give adequate low Drag performance and are easy to design.

Transonic: Above a freestream Mach number of about 0.7, certain parts of the local flow around the nose and fins will hit a local Mach of above 1.0 i.e. supersonic. Similarly, up to a freestream Mach number of about 1.4, certain parts of the local flow around the nose and boat-tail are still subsonic. The transonic zone is this freestream Mach number region where there is a mix of subsonic and supersonic flow. This mixture makes predicting the aerodynamics of the zone difficult and inexact.

Viscous (Drag): Drag caused by the viscosity of the air.

References:

1. ESDU paper 89033, “Pressure Drag and Lift contributions for blunted forebodies of fineness ratio 2.0 in transonic flow”.

2. ESDU paper 80021, “Pressure Drag of blunt forebodies at zero incidence for Mach numbers up to 4”

3. ESDU paper 68021, “Fore Drag of spherically blunted cones in supersonic flow”

4. ESDU paper 77028, “Geometrical characteristics of typical bodies”

5. “The design of the aeroplane”, Darrol Stinton, Blackwell science, 1995.

6. “Hypersonic and high temperature gas dynamics”, John D. Anderson Jnr, McGraw Hill, 1989.

7. “Aerodynamics for engineering students – third edition”, Houghton and Carruthers, Arnold publishing, 1988