Notes on Configuration Aerodynamics

OK Time to start off about Drag Bookkeeping!

Drag is separated into types:

Parasite drag, and induced drag.Parasite drag comprises of Friction/Form drag, which is from skin dfrction, pressure drag (sometimes called "form drag" and additional profile drag due to lift (drag from 2-D airfoils at Lift)

There's theren Interference Drag, which is drag due to intersection geometry.

There is the drag itself, then the drag due to lift there as well.

The last is wave drag, which is drag due to generation of shock waves. Drag due to volume and drag due to lift.

Induced drag is drag due to lift generated by vorticity.

Anyway, as humans we like to reduce problems down to their simplest parts.

There's a little bit of arbitrariness to it.

A model for calculating PARASITE DRAG is to partition the drag into.....flat plate skin friction, "wetted area," and form factor.

D_0 = q_inf* sum (Cfi * Swet * FFi

Q_inf is dynamic pressure, Cfi is the equivalent flat plate skin friction coefficient, based on the reynold's number, and FFi is form factor, which captures the effect of thickness and other parameters on "form drag." (Pressure drag due to the boundary layer.)

Swet = effectively just the surface area of the aircraft.

But....we like to normalize things. So instead of D0, let's do Cd0

Cd0 = D0/q_inf*Sref

Where Sref is the wing refearea by tradition

OK LET'S BREAK IT DOWN

Cf – the Flat Plate Skin Friction Coefficient

Cf – the shear stress, tau, along the surface of the body. Tau is a result of the boundary layer.

Along the body of the aircraft, fluid accelerates to the freestream velocity in the boundary layer.

If mu is the coefficient of viscosity, tau = mu * dV/dy

Cf is the integral of tau over the whole airfoil. (x.

Cf : LAMINAR VS. TURBULENT

(turbulent is sometimes called "fuller"

Dv/dy at y=0 for a laminar boundary layer is less than dv/dy for y=0 at a turbulent boundary layer.

So, tau for laminar is lesss than tau for turbulent.

However, laminar boundary laters are more likely to separate, which causes a HUGE drag increase!

If the laminat flow remains attached, then, generally speaking, Cf,lam is less than Cf, turb.

Gere are some semi-emperical Cf for laminar vs. turbulent flow:

Cf = 1.328 / sqrt(Rec) for laminar

Cf = 0.074/(rec)^1/5 for turbulent

Rec is Reynold's number based on averaged chord r characteristic length.

Rec = rho_inf*v_inf*c / mu_inf. This is the "global "reynold's number

Generally speaking, as Reynold's number increases, Cf decreases.

The decreasing slope for laminar is steeper in theory and for empirical data. Howwver,e the turbulent slope starts with a much higher Re.

Acounting for transition in estimating Cf….

It’s really hard to estimate it! So sometimes you just guess.

Flat Plate skin friction corefficient

Knowing/guessing transition location

1. Compute Cf, turb over whole airfoil.

   By using Rec

2. Compute Cf ober the laminar portion using Rextr
3. 3. Computer Cf, lam over laminar portion by using Rextr
4. 4. Determine the total Cf as….
5. Cf = (xtr/c)*Cf,lam,xtr + (Cfturbulent,c – (xtr/x)Cf,turb,xt)

A NEW DAY

OK time to talk about Form Factorr.

Things are actually not flat plates in reality@

Silly definition of form factor:

The ratio of the drag coefficient iver one surface with the skin friction coefficient of a flat plate.

FF = Cdf, surface / Cf,flat plate

Form factor is some multiplier to account for “thickness effects.”

EMPIRICAL FORM FACTOR METHODS

FF = 1 + 2(t/c) + 60(t/c)^4

FF is, in general, a function of ALL geometric features as well as Mach number and Reynold's number.

FF = f(t/c, AT, TR, lamda, M)

Generally commercial airlines have a t/c = 0.16.

Fighter jets have thinner airfoils.

FF can be a factor of total wing design and use different functions and inputs./

How do you choose from all these different form factor equations??? Omg.

The interesting thing about empiricism is that if you're building the airplane and testing in a wind tunnl, wind tunnel tests are superior to CFD.

Be mindful of which windtunnel data you're using through!

We'll just use the Horner model for Form factor

.

So what about Non-wing stuff?

How about the Fesulage?

For a troughly cylindrical fuselage:

FF = 1 + 60/f^3 + f/400

F = fineness ratio, length to diameter

F = 1/(sqrt(4/pi)*A_max) or f = l/diameter (if circle)

L = length

A_max = max cross sectional area along the fuselage

Basically the air goes around and spreads out over the fuselage.

What is the tradeoff?

Sometimes the Swet is a factor.

The Quest Air Venture is essentially egg-shaped.

Form factors for flow-through Naceelles

FF = 1 + 0.35/f

INTERFERENCE FACTORS

Parts where the aircraft components intersect

Cd0 = sum (Cfi * (Sweti/Sref) * FFi * Qi

Q is the traditional variable used for interference factors

Q is different for each part . If we talk about wing and fuselage, we probably would assign fuselage 1.00 and wing 1.02. Typically we ascribe Q to only one part.

For tails, Qi may be 1.03 to 1.08;

For nacelles, Q might be as high as 1.2.

EXCRESCENCES/"CRUD" DRAG

Parasite drag is driven by the subtle details

-ivets, bugs

-antennae, inlets, flap gpas

-flexibility of the structure

-typically as high as 1.3

VERY hard to estimate.

Cd0 = 1.3 * sum(Cfi * (Swet/Sref) * FFi * Qi

Caution: These parasite drag lectures are valid for….imcompressible subsonic flow

Make sure your airfoil / wind tunnel model is valid!

-Method of STRIPS is a slightly higher fidelity technique (XFOIL)

What if XFOIL STILL isn't good enough?

-CFD – build a good 3D model

-Wind Tunnnel Test – Find an adequate wind tunnel

-Flight test – Build a plane!

WAVE DRAG ESTIMATION METHODS

Wave drag – due to compressibility of air

Low Mach# have no wave drag

A new type of pressure crag happens at high speed. This is embedded in funcamental equations of flow.

It's a change from elliptical PDEs to hyperbolic PDEs.

2 components: according to humans.

-Wave drag due to LIFT

-Wave drag due to thickness

Wave drag due to Lift

-we model as a flat plate at AoA

Wave drag dyue to thickness

-model with a diamond airfoil.

At higher speeds, you get shock waves. On the flat plate model, at a positive AoA, there is an oblique shock on the bottom of the flat plate. And high pressure on the bottom. There is an expansion wave at the top of the flat plate, so there is a lower pressure distribution across the flat plate. This causes a force imbalance in the upward direction, and the component facing away from V-inf is DRAG.

The interesting trend is that if you study supersonic thin airfoil theory, you can make equations like this:

Cl = 4alpha/ (qrtM_inf^2 – 1)

Cdq = 4alpha^2 / sqrt(M^2 – 1)

Almost all drag due to lift is a square problem.

Cdq = Cl^2*sqrt(M^2 – 1) / 4

OK TIEM FOR WAVE DRAG DUE TO THICKNESS

Vertical forces balance out due to symmetry

But there is a differenceof horizontal components of pressure

This induces a force in the direction against V_inf, therefore is drag.

A BG TOPIC in transonic and supersonic flow is – in transonic flight, we talk about boundary later and shock wave interaction.

Sadly, that is outside the scope of this class.

“Wave drag is an inviscid phenomenon for our purposes here.

Empirical Transonic Wave Drag Methods

This is called Lock’s 4th power method

Cdw = 0 if M < Mcr

Cdw = 20*(M – Mcr)^4 if M > or equal to Mcr

Mcr is the minimum M_inf where M = 1 over some portion of the airfoil

This method is DEFINITELY not exact but it’s enough.

We need to know Mcr, which is a characteristic of the airplane.

Semi-empirical method of estimating Mcr and Mdd is the KORN EQUIATIOBN

KORN EQUIATION:

Mdd*cosLAMBDA_0.5 + Cl/(10*cos^2LAMDA_0.5) + t/c / (CosLAMDA_0.5) = KA

MDD = drag divergence Mach# …. Mach# at which drag rapidly increases

KA = airfoil technology factor KA = 0.87 for conventional airfoils, KA = 0.95 for supercrititcal airfoils

t/c = thickness to chord ratio

Cl = airfoil section lift coeff

LAMDA_0.5 = the wing sweep measured from the half-chord line

From this, we can estimate Mcr as

Mcr = MDD = cubert(0.1/80)

TRANSONIC WAVE DRAG estimate via method of strips

OK how do you apply this? B/C not eevery part of the wing is the same.

You can use “method of strips/”

SUPERCRITICAL AIRFOILS

Whitcomb’s supersonic airfoil shape is a thing,

Also sweep angle i9s another thing

Transoinci wave drag and swept wings

Mper = <_infcosLAMDA

MDd,swept = Mdd,airfoill/CosLAMDA

For supersonic conditions….

“Mach cone angle”

Mu = asing(1/M_inf

ALSO there’s this thing called the area rule.

ONTO INDUCED DRAG

Cdi= Cl^2/ pieAR

E is the span efficiency factor

The equation is a result of lifting line theory

Elliptical lift has e = 1

Typical is e = 095 – 0.99

Sometimes this equation is bundled in with parasite drag

CDl = Cl^2/ (pi*e0AR)

E0 = Oswald efficiency factor. It's about 0.75 to 0.85

Relationship between e and e0

1/e0 = Cd2*piAR + 1/e

There are several approaches to designing for induced drag.

"Just pick an e or e0.

Can be done from historical data.

2

Find an e from a specified lift distribution thing and run a code

3

Find e from a specified lift distribution.

You can get an elliptical distribution by controlling either c(y) or c(l).

You might not want elliptical lift distribution.

Why? Stall charactertics.

Load distribution

R.T. Jones and Prandtl figured out some shape/lift distribution related to bending moment.

RBM (roto bending moment) and came up with eRBM and equations related to that.

If you choose lift distribution shape, you can get e.

Delta = 8(eRBM – 1)^2

E = 1/(1 + delta)

How does elliptical distribution lead to stall?

Stall occutswhen cl(y) = clmax(y)

Drag polars

So far, we have covered types of drag

-Profile Drag, parasite drag of an airfoil,

Pressure drag and skin prediction

-/Induced drag

And Wave drag

ALL types of drag depends on lift, actually!!!!

-Profile drag, induced drag,…..the ALL have quadratic relationships, too!

SO.

The LIFT NEEDE DETERMINES DRAG

“Drag is the price we py for flying”

We rarely want to maximize Lift.

We need a minimum Lift for the weight of the plane. And for that we want minimiuzed Drag.

Drag Polar

Is Cd = f(Cl) OR other non-dimensional parameters, such as M and Re.

However, it is usually plotted as Cl vs. Cd, though Cl is shown as the y-axes.

Our simplest model is a quadtratic.

It's possible to have a complicated, 3-parameter or more drag polar.

The best thing is to just have a table of numbers.

The 2-parameter drag polar:

Cd = Cd0 + KCl^2

Each point corresponds to a different aq

3- parameter drag polar

Cd = Cd,mindrag + K(Cl – Cl,mindrag)^2

EDET is this empirical drag estimation technique used in a computer program called FLOPS.

ENOUGH about drag

Time for Engine performance.

Beginning with the Thrust equation

T = mdot (vj – vinf) + (pressure terms)

Difference between velocities

If you extend the stream tube out far enough, bypass flow stuff doesn't really count.

Pressure terms mostly come in to play with supersonic exhaust flow and especially rockets.

Looks like there are two ways to make thrust…

Either have a very high mdot and low vj or a low mdot and a high vj.

What determines mdot?

-nigness

-propellers – they take in a lot of flow with relatively little vj

What about a lot of vj?

Small turbojets do that.

If you raise mi, that's more efficient, which connects with… FUEL CONSUMPTION!

The way we measure fuel consumption is connected to engine efficiency.

TSFC = Wdotf / T

Where Wdotf is fuel flow rate.

These are normalized metrics

We also have power specific consumption

SFC = Wdotf/P

The power is engine shaft power.

These are appropriate for piston engines and turboprops.

TSFC is appropriate for turbojects and turbofans.

Some assumptions and simplifcations we can make.

Maximum T is reasonable constant for M, subsonic. For supersonic, Maximum T varies kind of linearly with M.

There’s also this very simple model for Thrust v. altitude:

T = T0(rho/rho0)

BUT THESE ARE BAD!!!! Even though these are bad, they don’t ignore thrust variation with Altitude.

SO.

Fuel burn varies in stange ways with Mach number.

TSFC and SFC fuel flow rate in pou ds per hour, normalized by thrust….. this takes the scale of the engine out!

Simply… for M-inf <1, TSFC increases linearly with Mach.

For approximation, TSFC does not vary with altitude. (EXCEPT THAT IT DOES)

In conclusion….These back-of-the-envelope calculations are Bad!

We need what’s called an engine deck.

Of “5-column data” which is the “od-school” way of calling it.

It comes from the engine performance engineers.

The 5 columns are M, Alt, Throttle Settings, Thrust, fuel flow or TSFC

Sometimes there is a temperature offset.

What is “Power Code?”

-Well, the ingeing output is chosen by the pilot, actually.

-Throttle effects TSFC, Thrust, and fuel flow.

Settings: Power code (PC) (in a military context)

Power lever angle (PLA) (for a commercial context)

POWER CODE

Power code is an index of variales.

The variables describe several conditios

Power code 20 – Ground Idle – this is the minimum stable operating point of the engine. Alternate name: GI.

Power Code 21, Flight idle. This is the min stable operating point pf the engine. FI

Power code 50: Military Power (max dry)

PC 60 Min afterburner

PC 100

Max power

(max wet)

The enginee performance engineer needs to define all of these and do their homewrok.

If you want to put in a Power Code in between 21 and 50….

What you do is Fctargetf(PC) = PC-21 / (50-21) * (Fniam – Fnflightidele) + Fnflightidle

This is a linear interpolation.

If you want to fly in cruize, you know the Thrust and the drag. What you need to do is figure out the power code!

Now – that's an engine deck.

You can use it for turbojet, turbofans, turboprop, and reciprocating prop.

You can create a separate table for propeller performance or make your iengine deck larger.

OK SO….why do engines behave the way they do?

Engine control is really complicated. Has to be designed so that engine doesn't oberheat, flame out, overspool, etc.

Sometimes youl'll see discontinuities in data. This is due to control input.

TWO TERMS:

On-design

-play with design and see what happens

Off-design – engine is fixed. Make sure everything is within operation capabilities.

Example:

On design…. Given would be: Minf, Altitude, Pt3/Pt2, f,   go ahead and FIND A9/A8, F/Wa, TSFC.

For Off-design, given Minf, Altitude, f, and A9/A8, find Pt3/Pt2, F/Wa/ and TSFC..

This is much harder and makes the work interative. This is how you generate the data for an engine deck. It's usually proprietary!

Engine operating line is a graph of Wsqrt(theta)/delta v.s. P3/P2.   Where W = mdot, theta = temp ratio, delta = pressure ratio.

Now time to talk about engine /arirplane performance.

Starting simple with cruize flight:

Sort out EOM for cruize flights.

The richness of the problem is how the flight forces vary across the flight envelope. There is the notion of equilibrium airspeeds.

For steady-level flight, T=D and L=W.

This tells us when to substitude one thing for another.

We can make it more complicated if we want to, but basically this is it.

ANYWAY, LOOK AT THIS!

Graph of Vinf vs. Max thrust.

It’s like a buck-shape.

Where the TA crosses the Tmax graph at two points is the Vequillibrium

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So, for cruize flight: how can we find Veq numerically?

TA is not a straight line.

So we use “root finding” methods, where the fxn equals/reaches zero.

Basic approach: use root-finding algorithm to find the speed at which the expression (D-Tmax) crosses 0.

If D = Tmax, good

If D > Tmax, we’re to the right of the intersection

If D<Tmax, we’re to the left.

Root-finding algorithms --- there are some

For all methods, we have to compute each Mach # Tmax and D. Tmax is power code 50, remember?

Let’s look at airspeed C at given M.

Compute q = rhov^2/2.

Set power code to 50 and find tmax from engine deck.

[Tmax, Wdotf] = enginedeck(fxn inputs)

For D, we need Cl

Cl = W/ qS

-call the drag polar in a fnction.

CD = dragpolar (Cl, M, h)

Then compute D = qsCD

Then compare Tmax to D.

Thry MA

D(Ma) – Tmax(MA) = residual A

-residual A <0

Next guess a second Mb > Ma

D(Mb) – Tmax(Mb) = residua;lB

Residual B > 0

Deive residual toward zero.

Write the code – this is called the “bisection method”

While MB-Ma) > tolerance < & residual C > tolerance

Mc = 0.5(MA + Mb)

ResidualC = D(Mc) – Tmax)c)

If residual C< 0

MA = Mc

Else

Mb = Mc

End if

End

Resulting Mach number is Mc.

Each time we implement this procedure, we cut the search interval in half, thus the name “bisection.”

THE OTHER ROOT-FINDING METHOD: MATLAB FUNCTION FZero.

OR

We can look at a contour plot of excess thrust (Tmax – D) where it crosses zero.

Most of the time, we fly what is best from an efficiency standpoint.

Let’s say we want to gly at Mach M.

The engine can definitely produce more thust than Is necessary. In order to fly at that speed, less than max, the throttle needs to be less than Max.

We need to find the “part pwer” conditions such that T(M) = D(M), M = most efficient

Problem:

For a given true airspeed V or Mach number M, a given altitude h, weight W, find the required engine power setting.

STEPS:

1) Find q
2) 2) comput Cl = W/qs
3) 3) call drag polar
4) CD = dragpolar(Cl, M, h) (you'd have to write this function)
5) 4) compute D = qSCd

We must require T = D

We have this OTHER function called the engine deck.

We can do this by figuring out what power code to call.

(The interpolation equation from vefore.

The equation can be solved for a given thust.

PC = T-Tmin / (Tmax-Tmin) * (50-21) + 21

One nuance we need to be careful about…the engine deck only represents 1 engine.

So Ttot = 2*Tengine.

So we get this function:

PC = D/n(engine) – Tmin /((Tmax – Tmin) * (50-21) + 21.

Where neng = number of engines.

Once you have your power code, you can test it out iwith an enginer deck function.

You should test this by plugging in PC and getting the thrust you expected.

OK SO WHAT?

Well, doing this allows us to calculate fuel burn and fuel efficiency!!!

These are things we care about.

Problems of endurance and range inherently nvolve integrations.

Important things while talking about fuel burn is TSFC.

We can compute specific endurance and specific range.

Specific endurance = 1/ (Fuel flow rate), with units of [hrs/lb]

SE (specific endurance is defined as 1/wdotf

Wdotf = fuel flow into the engine

SE dt/dWf

Specific RANGE = V/Wdotf, units of [nmi / lb]. SR = dx/dWf.

Specific range is the instantaneous efficienct of coverang distance.

Specific rRange is exactly fuell mileage.

SKY MAPS

We are about to start on the content that will be the basis of the second mini-project.

What is a sky map?

It is a flight envelope diagram, Sometimes called a Kaiser diagram or thumbprint plot.

It is a contour plot on cartesian axes.

x-axis is M, VTAS or VEAS.

The type of data will fill the axes with contours. The y-axis is altitude.

When plotting, we enforce EOM for cruise.

With that as a backdrop, we can plot almost anything.

Like TSFC, fuel flow, Tmin, Tmax, aero data, Cl, Cd, L/D, ML/D

We can also plot specific endurance and specific range.

The other important thing is plotting constraints!

E.q…..max Cl and max Texcess

We get limits at a low velocity due to stall.

We also get limits at high Mach numbers due to what's called bufft Clmax.

Clmax varies with airspeed.

We get limits on Tavailable at high altitudes and high mach numbers.